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Risk Assessment of Impacts of Climate Change for Key Marine Species in South Eastern Australia

Part 2: Species profiles

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Risk Assessment of Impacts of Climate Change for Key Marine Species in South Eastern Australia: Part 2

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Statement of contributions

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Institute of Marine and Antarctic Studies (IMAS)
Dr Gretta Pecl co-led the project together with Associate Professor Tim Ward (SARDI). She contributed to the development of the risk assessment methods and analytical framework, and led the synthesis and writing of the main report. Dr Zoe Doubleday coordinated the production of all the individual species assessment profiles, contributed to the development of the risk assessment methods and analytical framework, and led the writing of the aquaculture component of the risk assessment. Associate Professor Stewart Frusher contributed to the development of the risk assessment methods and analytical framework, and wrote some discrete sections of the report.

South Australian Research and Development Institute (SARDI) – Aquatic Sciences and Department of Primary Industries and Resources of South Australia (PIRSA)
Associate Professor Tim Ward co-led the project, contributed to the development of the risk assessment methods and analytical framework, contributed to the writing of the report and coordinated South Australia's contribution to the project. Dr Steven Clarke and Dr Xiaoxu Li developed the risk assessment framework for the aquaculture species, made major contributions to the writing of the aquaculture risk assessment and produced several of the individual species assessment profiles. Dr Keith Jones and Dr Cameron Dixon prepared several of the individual species assessment profiles.

CSIRO Marine and Atmospheric Research (CMAR)
Dr Alistair Hobday contributed to the development of the risk assessment methods, analytical framework, and provided a link to the physical SEAP project. Dr Jemery Day contributed to the development of the risk assessment methods and wrote several of the individual species assessment profiles.

Department of Primary Industry (DPI) Victoria
Dr Daniel Spooner manages the climate change fisheries initiative work being undertaken at the DPI Fisheries Research Branch, Queenscliff and contributed to all aspects of the SEAP risk assessment project. Dr Neil Hutchinson was the lead scientific author on several individual species assessment profiles and contributed to the development of the risk assessment process.

Industry and Investment New South Wales

Dr Philip Gibbs contributed to the development of the risk assessment methods and analytical framework, coordinated New South Wales contribution to the project and prepared several of the individual species assessment profiles.

School of Economics and Finance, University of Tasmania
Dr Sarah Jennings contributed to the development of the risk assessment methods and analytical framework and contributed to written elements of the final report.

E-Systems Pty Limited
Richard Stoklosa assisted with the development of the risk assessment methodology and chaired the risk assessment workshops. He also contributed to written elements of the report.

Other contributors
Many other individuals and organisations contributed their time and expertise towards the success of this collaborative project; their contributions are detailed in the acknowledgements (see Part 1 of this report).

Contents

SECTION A: WILD FISHERIES SPECIES

1.Abalone, blacklip and greenlip *Haliotis rubra* and *H. laevigata*

Authors: Zoe Doubleday, Steve Mayfield, Harry Gorfine, Duncan Worthington

1.1. The fishery

Blacklip and greenlip abalone form the basis of valuable fisheries in Tasmania, Victoria, South Australia and New South Wales (Figure 1.1). The Tasmanian abalone fishery is the largest wild abalone fishery in the world, producing more than 25% of the global catch (Miller et al. 2009). In 2008, the fishery had a gross landed value of $ 90 million. Blacklip abalone (BA), *Haliotis rubra*, is the predominant species harvested in Tasmania with 2461 t landed in 2008, compared to only 122 t of greenlip abalone (GA), *H. laevigata* (Tarbath and Gardner 2009). Since 2003, the BA fishery has been divided into five zones: Eastern, Western, Northern, Bass Strait, and Central West (Tarbath and Gardner 2009). The GA fishery is restricted to the north of the state and is managed by regions and separately from the BA fishery. In Victoria, approximately 1,200 t was landed in 2007/08, however, the current TAC is 774 t (2010/11). Catches are dominated by BA (96%) and the fishery is structured into three zones: Western, Central and Eastern. The South Australian fishery harvests approximately 880 t of abalone each year, about 60% of this is BA with the remainder comprising GA. Like Victoria, the South Australian fishery is divided into the Southern, Central and Western zones. Current annual catches in NSW were less than 75 t in 2009/10 and consist exclusively of BA. The commercial fisheries are assessed on a variable combination of commercial catch, effort and size-composition data, fishery-independent surveys and length-structured models. In Tasmania, 105,500 abalone were taken by recreational fishers in 2006/07, weighing an estimated 49 t. The number of recreational licenses has tripled since 1995, with 12,500 recreational diving licenses issued in 2007/08 (Lyle 2008). Recreational catches in SA are small, probably less than 1% of the TACC (Jones 2009).

Key points:

- Abalone are harvested in Tas, SA, Vic and NSW. The Tasmanian abalone fishery is the largest in the world.
- Catch is predominantly composed of BA.
- In 2007/08, total combined catch was 4,475 t.
- Abalone is an important recreational species.

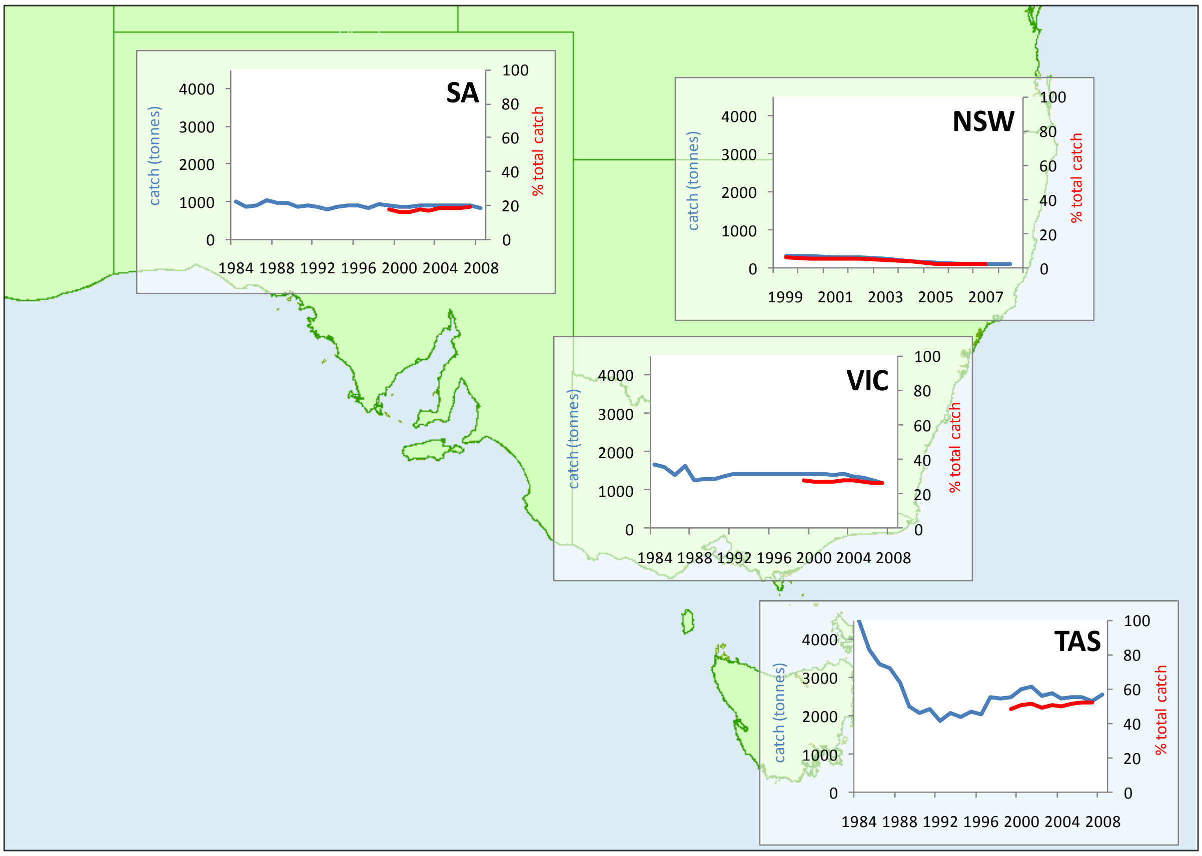

Figure 1.1: Commercial catch (tonnes; blacklip and greenlip abalone combined) and contribution by each jurisdiction to total catch in south-east Australia (%) by year for South Australia, Victoria, New South Wales, and Tasmania. Approximate proportions of BA (current): SA = 60%; Vic = 96%; Tas = 95%; NSW = 100%. Tas data sourced from (Tarbath and Gardner 2009)

1.2. Life history

1.2.1. *Life cycle, age and growth*

Species within the *Haliotis* genus have similar life cycles (Figure 1.2). General life cycle information has been drawn from McShane (1995) and Sloan and Breen (1988). Abalone are broadcast spawners, releasing eggs and sperm into the water where fertilisation occurs. They are highly fecund, with mature females releasing up to 10 million eggs per spawning event. The fertilised eggs are dispersed by currents until they hatch into swimming pelagic lecithotrophic larvae, which undergo a number of different developmental stages.

Planktonic larval duration varies between 3 and 12 days depending on water temperature and species. Successful settlement and survival may depend on environmental stimulus provided by crustose coralline algae. Immediately after settlement, post-larval juveniles (spat) begin to graze on microalgae. During the first 4–6 weeks, juveniles occupy exposed rock surfaces and subsequently undergo a cryptic phase, inhabiting narrow crevices and fissures. At 2–4 years of age, abalone undergo an emergent phase again, occupying open rock surfaces, which may coincide with sexual maturity (Prince et al. 2008). Growth rates in both BA and GA vary considerably among regions (James 1981; Shepherd and Hearn 1983; Hutchinson et al. 2010). In northern Tasmania alone, size at maturity was found to range from 75 to 120 mm (Tarbath and Officer 2003). Based on shell increment counts, Tasmanian BA have been aged at over 20 years of age (Tarbath and Officer 2003).

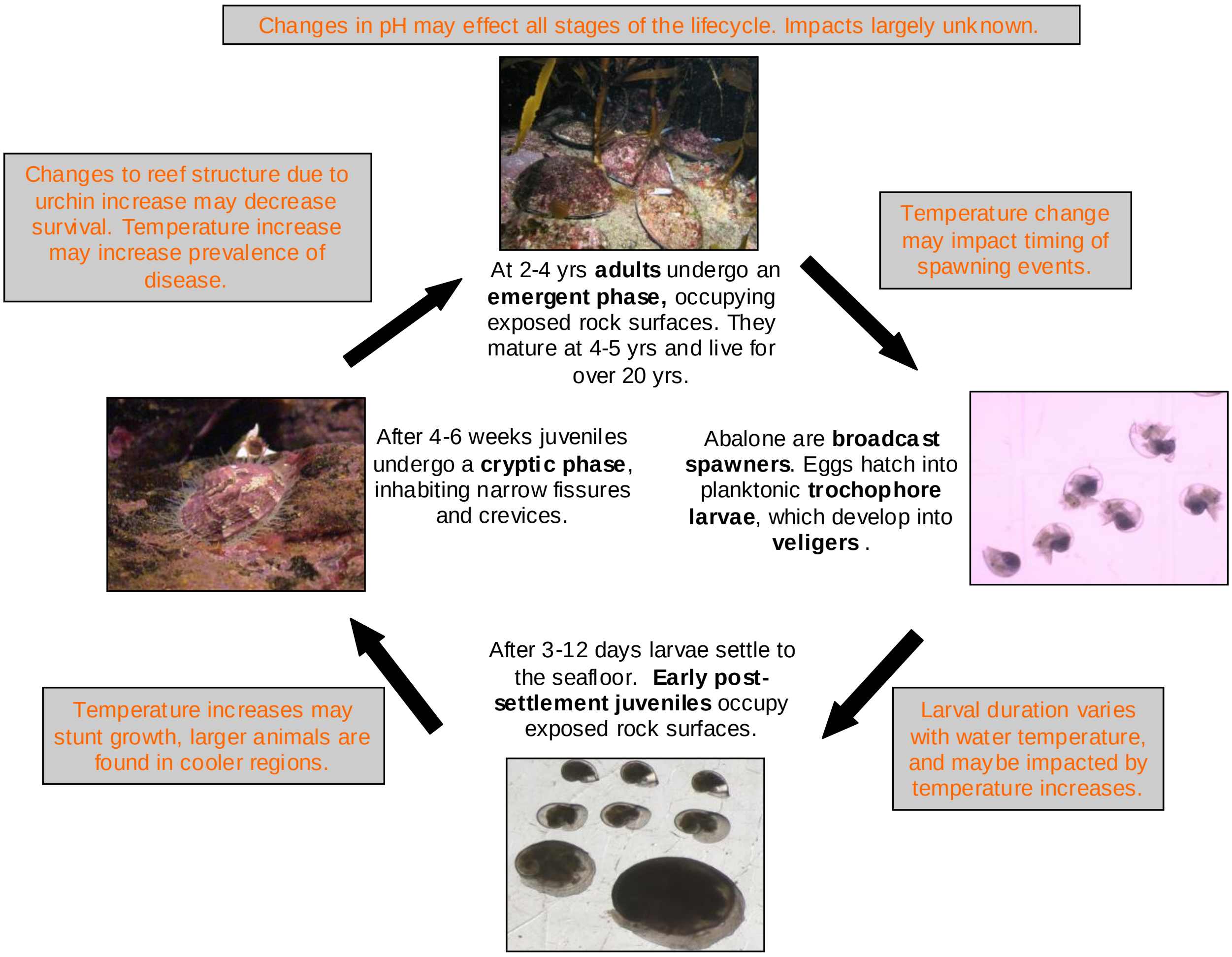

Figure 1.2: Summary of life cycle of *Haliotis* sp. (this section), and points of exposure to relevant climate change drivers or known impacts (subsequent sections). Images are of blacklip abalone. Source: L. Lyall, A. Browne (IMAS).

1.2.2. Distribution, habitat and environmental preferences

BA are distributed from northern NSW, around Tasmania, across SA and into southern WA (Figure 1.3). In contrast, GA are only found along the southern Australian coast from southern WA (Cape Naturalist) to Victoria (Corner Inlet), including northern Tasmania (Kailola et al. 1993) (Figure 1.3). Adult and emergent abalone prefer exposed rocky reef and boulder habitats that are covered with red and brown algae, while the cryptic phase frequently inhabits narrow, deep crevices. They generally inhabit waters up to 40 m in depth. GA are also commonly found attached to low-lying reefs in open sandy environments (often in association with seagrass meadows), and, in exposed areas, at the base of steeply sloping cliffs usually along the sides of gutters or clefts (Kailola et al. 1993). Crustose coralline algae is believed to play an important role in stimulating settlement, which is likely to provide an important source of food and protection from predators (McShane 1995). Field observations have indicated that GA larvae in SA prefer to settle on crustose coralline algae (Shepherd and Turner 1985), while controlled experiments have shown that BA prefers to settle on green algal species, articulated and crustose coralline algae (Huggett et al. 2005).

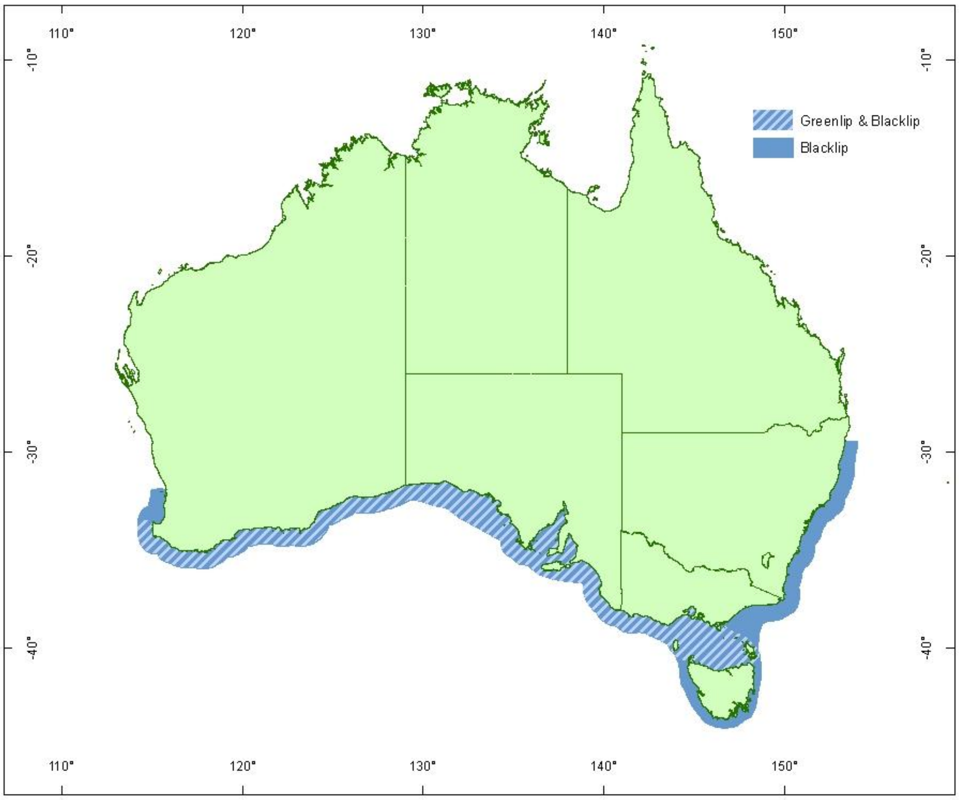

Figure 1.3: Distribution of blacklip and greenlip abalone.

1.2.3. Predators and prey

Abalone predominantly trap drift algae, but they also actively graze on a range of red and brown algae and detritus. Stable isotope and fatty acid analysis in BA revealed that brown algae and detritus was a more important source of food than red algae (Guest et al. 2008). Bacteria and diatoms were also an important dietary component. Juvenile, cryptic abalone are preyed upon by whelks, crabs, octopus and wrasse, while emergent adult abalone are eaten by larger fish, octopus, rock lobster, stingrays, Port Jackson sharks, and starfish (www.pir.sa.gov.au/fisheries/home).

1.2.4. Recruitment

As with other highly fecund invertebrates, abalone recruitment can vary independently from the number of spawners at high densities (McShane 1995). Recruitment variation, particularly at the spatial level, is likely to be influenced by environmental and habitat variation and density-dependent factors. The results from controlled experiments suggest that the abundance of green and red algal species may play a vital role in the recruitment of larvae (Huggett et al. 2005). Measures of BA post-larval recruitment in southern Tasmania (Nash et al. 1995) and SA (Keesing et al. 1995) indicated a peak settlement in August. Aggregative behaviour appears to be critical for healthy recruitment and the maintenance of GA subpopulations (Dowling et al. 2004). Recruitment failures reported for South Australian populations have occurred when densities have fallen below -0.3 animals per m^2 or mean nearest-neighbour distances of 1–2 m (Babcock and Keesing 1999).

Key points:

- Abalone adults are broadcast spawners and have a very short pelagic larval phase. Growth rates vary among regions.
- Distributed throughout southern Australia on reef habitat.
- Abalone graze on algae and detritus, and are preyed upon by crustaceans, fish, sharks, stingrays, octopus and starfish.
- Recruitment can be highly variable and independent of spawning biomass.

1.3. Current impacts of climate change

The continuing southward incursion of the barren-forming urchin *Centrostephanus rodgersii* in eastern Tasmania is likely to impact BA habitat through the overgrazing of important habitat-forming seaweeds (see Section 1.6: Ecosystem level interactions below for more details). Increasing temperature stress is likely to increase the prevalence of the disease perkinsosis (caused by the parasite *Perkinsus olseni*) in SA and NSW, which can cause increased mortality and population die-backs. Laboratory experiments have shown that temperature stress predisposes abalone to the disease (Goggin and Lester 1995), and in NSW most impacts of disease appear to occur in warm water years. In other parts of the world, studies have indicated that warming temperature may cause a reduction in abalone populations by stunting growth and reproduction (Vilchis et al. 2005), increasing prevalence of disease (Travers et al. 2009), changing larval dispersal patterns (Shepherd et al. 1998; Tegner et al. 2001) and changing predator/competitor interactions through range expansions (Rogers-Bennett 2007).

Key points:

- Habitat reduction in eastern Tasmania is occurring due to the southern range expansion of the barren-forming urchin *C. rodgersii*.
- Increasing water temperatures are likely to increase disease prevalence.

1.4. Sensitivity to change

Generally, abalone show little ability to cope or adapt to thermal change and shock (Gilroy and Edwards 1998). BA has a lower thermal tolerance than GA; controlled experiments showed that optimum growth temperature was 17°C and 18.3°C and 50% critical thermal maxima (when 50% of individuals were no longer attached to substrate) was 26.9°C and 27.5°C for BA and GA respectively (Gilroy and Edwards 1998). Size and growth of BA in Tasmanian waters is inversely related to SST, with larger individuals occurring in the south of the state; indicating that growth may be stunted at elevated temperatures (James 1981). Experiments which mimicked ocean warming in California showed that increased temperature stunted growth in red abalone (*H. rufescens*) (Vilchis et al. 2005). Temperature appears to be an important cue for phenology, influencing the timing of spawning and rate of larval development and length of the pelagic phase (Sloan and Breen 1988).

Two genetic studies found that BA sub-populations in Tasmania are largely self-recruiting, with population subdivision and dispersal within scales of 100 m. Dispersal of larvae at scales of 7–20 km is rare, probably limited to once every few years (Temby et al. 2007; Miller et al. 2009). Significant population differentiation has also been observed in BA populations in Victoria and Eden (NSW), with significant differences observed between subpopulations only 55 km apart (Huang et al. 2000). Aggregating behaviour and high population density appears to be vital for fertilisation success and maintaining healthy levels of recruitment in abalone (Babcock and Keesing 1999; Dowling et al. 2004). Depleted populations will be dependent on larval recruits sourced at scales of tens of kilometres, but recovery may take many decades before densities approach those that existed prior to depletion (Miller et al. 2009).

Although nothing is known about the potential impacts of ocean acidification (due to increasing CO_2 levels) on abalone, it may greatly impact their growth, shell development, and survival as demonstrated for other marine $CaCO_3$-producing organisms (eg. Talmage and Gobler 2009).

Key points:

- Abalone reach critical thermal maxima in the high 20s (Celsius). There is some evidence that elevated temperatures retard growth and size of individuals.
- Abalone are very poor dispersers, and subpopulations are largely self-recruiting.
- Temperature is an important phenological cue.

1.5. Resilience to change

BA are distributed across a broad latitudinal and longitudinal range from northern NSW to southern Tasmania, and from the east coast to the south-west coast of Australia. Temperatures within their distribution range from 9–11°C in Tasmania (minimum winter values) to 23–25°C in NSW (maximum summer values). This suggests that they are adapted to a relatively wide thermal range, but that, as also suggested in Gilroy and Edwards (1998), they are at their maximum thermal limit in northern NSW. In contrast, GA are distributed along a broad longitudinal range, but a narrow latitudinal range. However, GA in SA are distributed from offshore islands with cool oceanic waters to Spencer Gulf where water temperatures are higher, suggesting that GA is also adapted to a range of temperatures.

Key point:

- Abalone, particularly BA, have a relatively wide distributional range, which also represents a large thermal range.

1.6. Ecosystem level interactions

The southward incursion of the urchin *C. rodgersii* from NSW and Victoria and its successful establishment in Tasmanian waters is considered the result of larval transport, reflecting changes in the behaviour of the East Australian Current (EAC) (Ling et al. 2008). Once established, *C. rodgersii* denudes coastal reefs by overgrazing important habitat-forming seaweeds and invertebrate fauna and forming persistent barrens (Ling 2008). These barrens are likely to impact reef species through habitat reduction, including BA, and have the potential to increase as a function of a southern range expansion of the urchin. Negative relationships have also been observed between densities of *C. rodgersii* and *H.* rubra in Tasmania. Experiments have shown that increased densities of the urchin caused an increase in abalone mortality rates indicating that it is a superior grazing competitor (generalised verses specialised herbivore) (Strain and Johnson 2009).

Key point:

- The southward range expansion of the barren-forming C. *rodgersii* will impact BA habitat and potentially outcompete BA for food resources.

1.7. Additional (multiple) stressors

The Tasmanian abalone populations are intensively fished and problems can arise when fishing pressure is sufficient to prevent the development of aggregations and rebuilding of the stock (Tarbath and Gardner 2009). Due to market pressures, uneven levels of fishing effort are occurring within some zones, potentially causing under- and over-exploitation and serial depletion on some reefs. Managing this spatial variation in catch is a current challenge facing the fishery. Resilience to fishing pressure also varies between BA populations, with some populations failing to recover after a short period of fishing compared to others which have sustained fishing for over 20 years (Nash et al. 1995). BA populations in eastern Tasmania may be additionally affected by habitat loss due to the southward incursion of the barren-forming sea urchin (see Section 1.6 above for more details). In Tasmania, GA stocks currently appear to be stable throughout the fishery (Tarbath and Gardner 2009). However, use of fishery data to monitor stock levels in the fishery is compromised as fishers report effort when fishing for both species in a single trip.

All BA stocks in SA are classified as either under or fully fished and stable, except for the Central Zone which is fully over-fished and possibly still declining. GA stocks are classified as fully fished and stable in South Australia. However, depletion of important aggregations may exacerbate climate change impacts.

In NSW the legal sized stocks of BA appear to have been over-exploited following the impacts of disease in northern areas and theft of the resource throughout the state, forcing the shift of commercial fishing effort into smaller areas without a corresponding reduction in the allowable catch. The combined impact of disease, pollution, theft and recreational fishing has meant few that abalone remain around the major population centres of Sydney, Newcastle and Wollongong. Major reductions in the commercial catch occurred from 2004 to 2005 (dropping from about 300 t to 200 t and then to 100 t), apparently stabilising and then recovering the legal-sized stock. In southern NSW, the under-sized stock appears to have been relatively stable throughout this period back until at least 1994. An invasive algal species (*Caulerpa* sp.), which consolidates sand and smothers reefs, is threatening abalone habitat in NSW. Mussel infestations (sourced from farms) are also a concern as they cover reef habitat, filling in crevices and holes, leaving little room for abalone.

In 2006, an outbreak of the abalone ganglioneuritis virus (AVG) occurred in wild abalone populations in Victoria (www.vada.com.au). The infected area has so far reached more than 200 km of the coastline with mortalities of up to 95%. AVG is highly pathogenic and can be spread through the water column, possibly via mucous or suspended tissue fragments. This disease outbreak may decrease population resilience to both fishing pressure and climate change in Victoria. Increased temperature has been linked to increasing disease outbreaks in abalone populations in France (Travers et al. 2009) and California (Vilchis et al. 2005). However, AVG has persisted throughout the full range of temperatures in Victoria.

Key points:

- Exploitation will likely compound the impacts of climate change, particularly if densities fall below a critical level to maintain the population.
- The AVG outbreak is an additional stressor in Victoria. Disease, pollution, and invasive species also impact abalone populations in NSW.

1.8. Critical data gaps and level of uncertainty

Although several experimental studies demonstrate that lowered pH levels can have dramatic effects on the growth, mortality and larval development of several bivalve and gastropod species, there is no information on how increasing ocean acidification will affect abalone. This will be crucial in determining the future impacts of climate change. Little is known about the influence of temperature on many aspects of abalone biology such as growth, maturity, egg production, egg viability, fertilisation success, larval survival, and susceptibility to disease. It will also be critical to investigate the potentially synergistic effects of climate-mediated changes, such as elevated temperature and decreased pH, and other multiple stressors, such as pollution, invasive and range-extending species, and disease.

Key points:

- Nothing is known about the potential impacts of ocean acidification on abalone, which has been demonstrated to have negative impacts on other marine calcifiers.
- There is limited knowledge on the potential impacts of elevated temperature on abalone biology.

Table 1.1: Summary of Blacklip and Greenlip abalone species profile, which also indicates level of certainty of the associated information. Level of certainty is divided into high (H) = strong clear evidence, backed by several studies with solid datasets with little confounding interactions; medium (M) = evidence supported by one or more studies, conclusions may be partially ambiguous or confounded; low (L) = anecdotal evidence, limited data and/or predicted conclusions based on theoretical knowledge.

<table>
<tr><th>Life history stage</th><th>Multiple stressors</th><th>Distribution</th><th>Habitat</th><th>Predators and prey</th><th>Current impacts</th><th>Predicted impacts</th><th>Ecosystem interactions</th><th>Data gaps</th></tr>
<tr><td>Eggs</td><td rowspan="4">Disease, invasive species and pollution</td><td rowspan="5">See Fig 3</td><td rowspan="2">Pelagic, do not disperse far from parental population (H)</td><td rowspan="2">Unknown</td><td></td><td rowspan="2">Changes to timing of spawning events, duration of larval phase (L)</td><td></td><td rowspan="5">Effect of ocean acidification on shell development and physiology

Limited knowledge on the effects of elevated temperature on abalone biology</td></tr>
<tr><td>Pelagic Larvae</td><td></td><td></td></tr>
<tr><td>Early post-settlement juveniles</td><td>Exposed rock surfaces (H)</td><td rowspan="3">Prey: red and green algae, detritus, bacteria

Predators: fish, sharks, rock lobster, stingrays, starfish, octopus</td><td rowspan="3">Southern range expansion of C. rodgersii (M)</td><td rowspan="2">Reduced growth rates and maximum size (L)</td><td rowspan="3">Habitat destruction and increased food competition due to southern range expansion of C. rodgersii (M)</td></tr>
<tr><td>Cryptic juveniles</td><td>Narrow crevices and fissures (H)</td></tr>
<tr><td>Emergent adults</td><td>As above plus exploitation</td><td>Exposed rock surfaces (H)</td><td>Increase in disease outbreaks (L)</td></tr>
</table>

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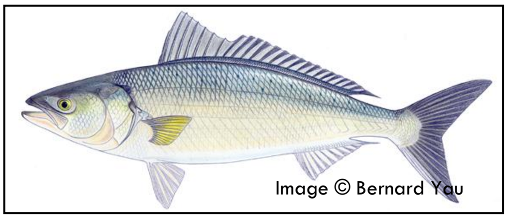
2. Australian salmon

Arripis trutta and *A. truttaceus*

Authors: Philip Gibbs, Keith Jones



Australian salmon in the south-east waters of Australia are a mix of two species: the eastern species Arripis trutta *and the western species* Arripis truttaceus. *In virtually all the available commercial and recreational fishery data from NSW, Victoria, Tasmania and South Australia the two species are not differentiated. The two species can be distinguished by the higher number of gill rakers on the first gill arch of eastern salmon compared with those of the western salmon (Malcolm, 1959).*

2.1. The fishery

In NSW the catch is entirely of the eastern species *A. trutta,* but a few 'museum' specimens of the western species have been collected in commercial catches, especially in the south of the state. Approximately 98% of the catch of eastern Australian salmon is from the ocean hauling fishery and the primary fishing methods are beach haul nets (91%) and purse seine nets (8%) (Anon 2002). The species is caught throughout the year and the highest annual landings tend to occur south of Sydney. The species also has an important recreational harvest with an estimated catch of 150–210 tonnes based on the National Recreational and Indigenous fishing Survey (Henry and Lyle 2003) and onsite surveys undertaken by NSW DPI.

In South Australia, the two species of Australian salmon are known to occur; however, commercial and recreational fishers do not distinguish between them on commercial catch and effort forms or in surveys of recreational fisheries. In the past, the bulk of the SA production has been from the western species; however, it should also be noted that a high proportion (~80%) of the total catch for the western species is taken in the WA fishery (Smith and Brown, 2009).

In South Australia there are two traditional components to the commercial fishery for Australian salmon. A fishery for larger sub-adult fish (1–4 kg) occurred off the high energy coasts of central and western South Australia, in which large modified purse seines were used to encircle large schools of fish up to 50 tonnes. The purse seines were deployed from large vessels, and worked at depths up to 10 m, often just on the outside of the surf zone. Until about 2003, a large proportion (about 80%) of the commercial SA production was taken this way, and the product was mainly used for rock lobster bait. The remainder was taken as juvenile fish (0.5 – 1 kg) either from beach seines off more sheltered beaches or by small mesh (3 and 5 cm) hauling nets deployed from small 6 m planing hull boats in Gulf St Vincent and Spencer Gulf (Jones and Westlake, 2003). This product has traditionally been used for human consumption on the local market. Due to the drop in effort by the large purse seine operator in recent years, the catch taken by the smaller operations now dominates production in this state.

In SA, Australian salmon is traditionally, the most popular sport species taken by shore-based fishers. Sub-adult (1–5 kg) fish are taken by beach casters off high energy beaches throughout most of SA coastal waters. Since the early 1980s, several of the well-known beaches have been closed to net fishing in favour of the use by recreational fishers. Juvenile salmon (locally known as 'salmon trout') are caught off more sheltered beaches and in estuaries by beach fishers, as well as by boat fishers in many of the SA embayments (SA gulfs, west coast bays and the Coorong Lagoon). Two estimates of the statewide recreational harvest of Australian salmon by SA residents are available (Jones, 2009). In 2000/01, the best estimate was 308.2 t and in 2007/08: 91.3 t. The possible reason for lower harvest level in 2007/08 was the significant drop in shore-based fishing effort by recreational fishers (Jones, 2009).

Australian salmon has been fished commercially in Tasmania since 1958. Over the last decade, landings have fluctuated between 280 and 350 t. In 2006/07, just 115 t were harvested, which is the lowest catch recorded. The commercial fishery is comprised of two sectors: a small number of large vessels specifically equipped to capture and store large quantities of salmon, and a large number of small vessels which target the species on an opportunistic basis as part of a diversified fishing operation. The most important fishing areas are along the north coast, including the Bass Strait islands, with smaller catches often taken in the south and east of the state. Beach seining accounts for the majority of catch; however, purse seining and gillnetting are often used by the smaller operators. Commercial catch is frozen whole and sold as rock lobster bait with production levels linked to market demand. Some is sold fresh for human consumption and in past it has been canned for pet food. *(The information in this paragraph has been extracted from Zeigler and Lyle 2010).*

Australian salmon are an important recreational species in Tasmania, mainly taken by line fishing methods, with an estimated 48 t caught in 2007/08 (Lyle et al. 2009).

In Victoria, the main commercial Australian salmon fishery exists in offshore coastal areas of eastern Bass Strait and Port Phillip Bay. Smaller catches reported from other bays and inlets tend to consist mainly of juveniles. While both species occur in catches, western Australian salmon are more prevalent in Port Phillip Bay, while the proportion of eastern Australian salmon increases to the east and makes up the majority of catches in the most easterly fisheries (Hutchinson et al. 2010). Statewide catches of 406 t were reported for 2008/2009, with a value of $519,000 (Department of Primary Industries, 2009).

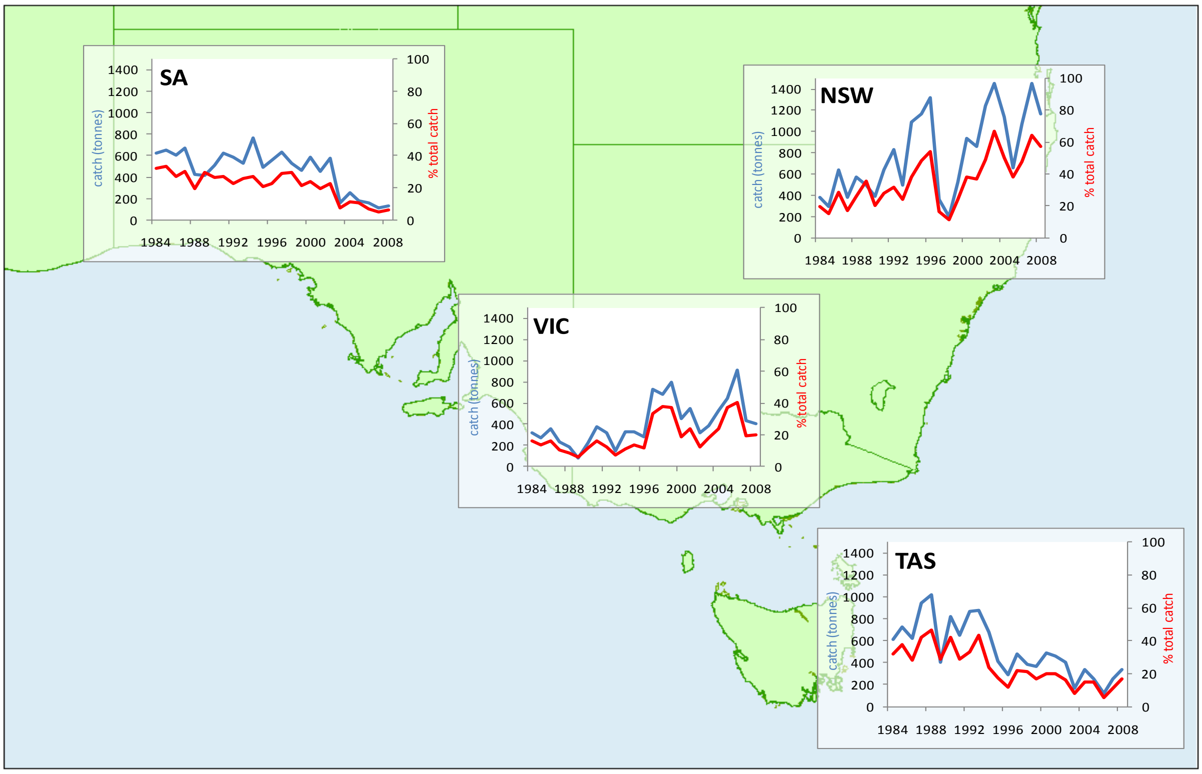


Figure 2.1: Commercial catch (tonnes) and contribution by each jurisdiction to total catch in south-east Australia (%) by year for South Australia, Victoria, NSW and Tasmania.

Key points:

- Australian salmon in the south-east waters of Australia are a mix of two species: the eastern species *Arripis trutta* and the western species *Arripis truttaceus.*
- The species is harvested in all states of the south-east and is an important commercial and recreational species.
- In virtually all the available commercial and recreational fishery data from NSW, Victoria, Tasmania and South Australia. the two species are not differentiated precluding a species assessment.

2.2. Life history

2.2.1. *Life cycle, age and growth*

Eastern Australian salmon, *Arripis trutta*

In NSW, spawning of *A. trutta* occurs in nearshore coastal waters as far north as Port Stephens between October and March, with peak spawning occurring in November. *Arripis trutta* females produce, on average, 230 eggs per gram of fish, up to a maximum of 1.7 million eggs per batch for a large female. Spawning events may occur multiple times over the spawning season. Fifty percent of both male and female *A. trutta* reach sexual maturity at ~30 cm fork length (FL) at an age of ~2–3 years in NSW (Hughes 2010). Hatching occurs ~40 hours after fertilisation. Larvae reach ~4 mm after 4–5 days and have been recorded up to 40 km from the coast from November to May. Spawning does not occur in Tasmanian waters and all *A. trutta* in Tasmania are immature. *Arripis trutta* in Tasmanian waters make a one-way migration across Bass Strait to Victoria and southern NSW with the approach of sexual maturity. This migration takes place in the period September–January (Kailola et al., 1993).

Juvenile *A. trutta* recruit to estuaries, bays and ocean beaches at <4 cm FL. Initial growth is extremely rapid and fish reach an average size of ~16.5 cm FL after one year, ~27.3 cm FL after two years and ~46.8 cm FL after five years. After five years of age, growth slows dramatically. *A. trutta* has been reported to reach 81 cm FL (in NSW) and 26 years of age (in NZ), but the oldest fish recorded in Australian waters was estimated to be 12.7 years old. The size and age structures of *A. trutta* from SE Australia have shown that the largest and oldest fish are found in northern NSW, with progressively smaller and younger fish dominating the populations in southern NSW, Victoria and Tasmania. Once mature in their fourth year, individuals move north from Tasmania and from central Victoria to areas between Lakes Entrance (Vic) and Bermagui (NSW) to spawn (Hutchinson et al. 2010).

Western Australian salmon, *Arripis truttaceus*

The only known spawning area for *A. truttaceus* is off the exposed south-west coast of WA, (near Cape Leeuwin), with peak spawning time in late March–April. This period coincides approximately with the trajectory and timing of the warm-water Leeuwin Current as it follows the coast from the west to the south coast of WA (Li and Clarke, 2004). In most years, newly hatched larvae are advected eastwards by this current, along the edge of the continental shelf and as they grow, they begin to actively swim towards the coast. Newly settled juveniles are found in the more sheltered bays and inlets along almost the entire southern Australian coast from WA through to eastern Victoria and the north and west coast of Tasmania (June–November), with settlement occurring progressively later in the more eastern range of its distribution (Jones, 2008; Hoedt and Dimmlich, 1994). In Victoria, Tasmania and south-east SA, *A. truttaceus* forms mixed schools with *A. trutta* (Hoedt and Dimmlich, 1994; Jones, unpubl. data). Juvenile and adult *A. truttaceus* have been tagged from the 1950s to the 1980s (Malcolm, 1960; Stanley, 1978, Cappo, 1987) and all studies show juveniles and sub-adults remain in embayments, for the first 3–4 years of their life in the more eastern part of their range (south-east WA, SA and Tas/Vic). Then, 4–6-year-old fish rapidly migrate during late summer months to the south-west coast of WA in time for spawning (Cappo 1987). Tagging has demonstrated only a limited back-run of fish along the southern coast of WA after spawning, and no movement of fish back to the more eastern states (Malcolm, 1960).

Although *A. truttaceus* grows to a larger size (10.5 kg, live wt; Kailola et al. 1993) than *A. trutta*, *A. truttaceus* first matures at the same age as *A. trutta* (4 years), but they are longer fish (54 cm FL). The more eastern part of the *A. truttaceus* stock delays its maturity by up to two years before migrating westwards to spawn (Cappo, 1987). Maximum age of *A. truttaceus* is about nine years.

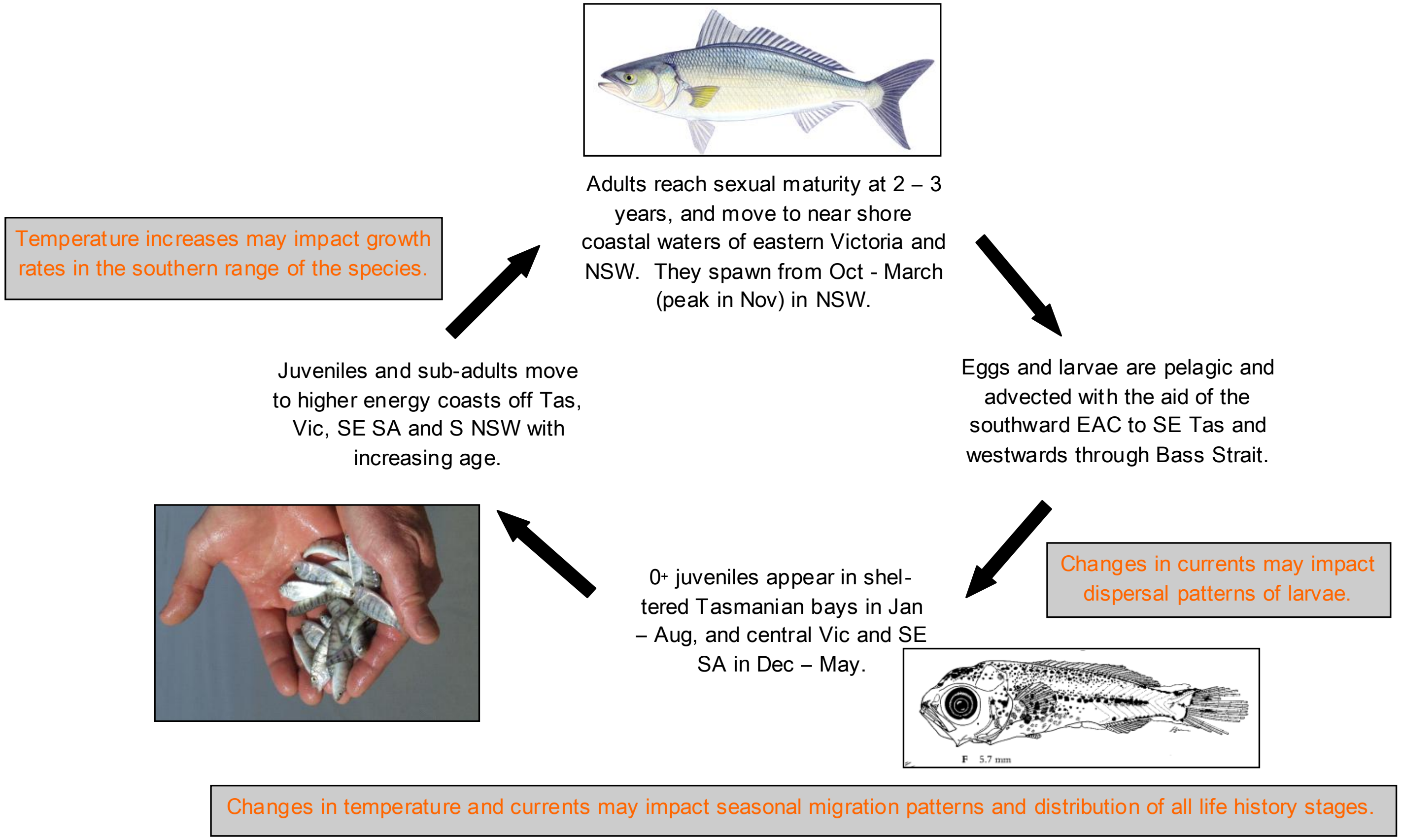


Figure 2.2: Eastern Australian salmon. Summary of life cycle (this section), and points of exposure to relevant climate change drivers or known impacts (subsequent sections). Images: larvae (Neira et al. 1998), juveniles (Jamie McAllister), adult (Bernard Yau).

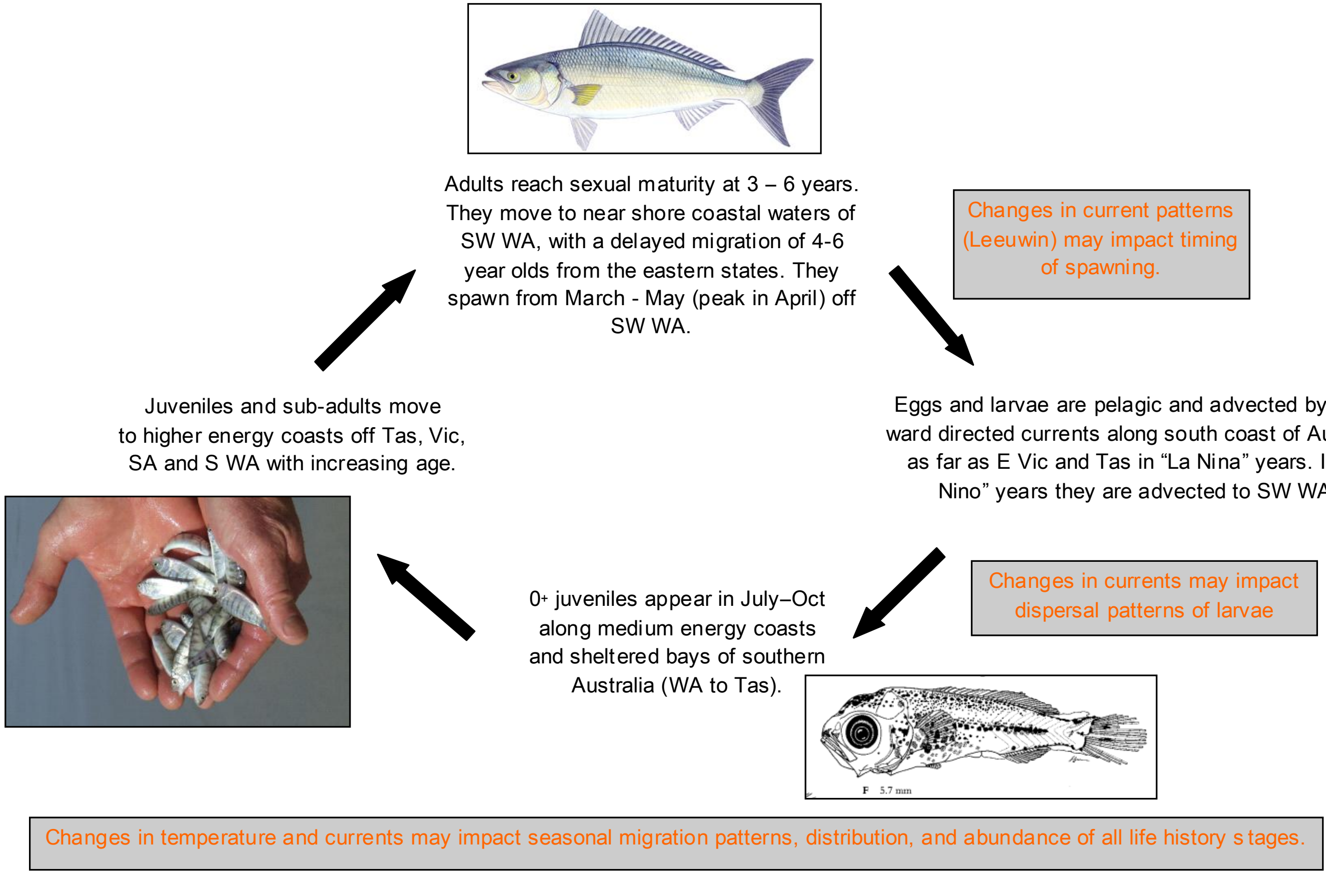


Figure 2.3: Western Australian salmon. Summary of life cycle (this section), and points of exposure to relevant climate change drivers or known impacts (subsequent sections). Images (eastern Australian salmon): larvae (Neira et al. 1998), juveniles (Jamie McAllister), adult (Bernard Yau).

2.2.2. Distribution, habitat and environmental preferences

Arripis trutta is found from Brisbane in Queensland, throughout NSW, south and east to Port Phillip Bay (Victoria), as well Tasmania, Lord Howe Island and Norfolk Island. The same species is also found in northern NZ waters (northern parts of the South Island, the North Island, as well as the Chatham and Kermadec islands). *Arripis trutta* is a strongly schooling inshore pelagic fish commonly found adjacent to ocean beaches, reefs and headlands and also at times in large bays, gulfs and estuaries in water depths up to 30 m, although they have been recorded from 200 m deep water in NZ. (In northern NZ and the Kermadec Island, a second species of salmon, *Arripis xylabion*, has been described by Paulin, C. (1993), based on morphometrics of the caudal fin).

The southward flowing East Australian Current is important in advecting *A. trutta* larvae to eastern Tasmanian waters. As juvenile *A. trutta* are found at times as far west as the south-east coast of SA (Jones and Westlake, 2003), some larvae appear to be advected westwards through Bass Strait. First year juvenile *A. trutta* (4 – 6 cm) appear between January and August in sheltered waters of Tasmania (Nicholls, 1977: Kailola et al. 1993: McAllister 2010) and between December and May on the central coast of Victoria (Robertson, 1982) and south-eastern SA waters (Jones, unpub. data).

As juveniles, both salmon species are commonly found in bays, estuaries and other nearshore areas as well as on open beaches from Tasmania through eastern Victoria to northern NSW, often in association with estuarine seagrass (*Posidonia* sp., *Zostera* sp.) habitats.

A. truttaceus is rarely found in NSW waters, but has been identified in all other southern Australian states. It inhabits the estuaries, bays and inlets through to open coastal waters and also can traverse deeper waters (Bass Strait and the Great Australian Bight). Juveniles are found over soft substrates, often occurring over seagrass in sheltered bays and estuaries, whilst larger fish move into the more exposed coastal waters, around rocky headlands, reefs and the surf zone of high energy beaches, where they often form extensive schools (Kailola et al. 1993). Occasionally, adult migrating *A. truttaceus* are caught as by-catch in shark nets to depths of 100 m in western SA and southern WA waters (Lenanton, pers. com.)

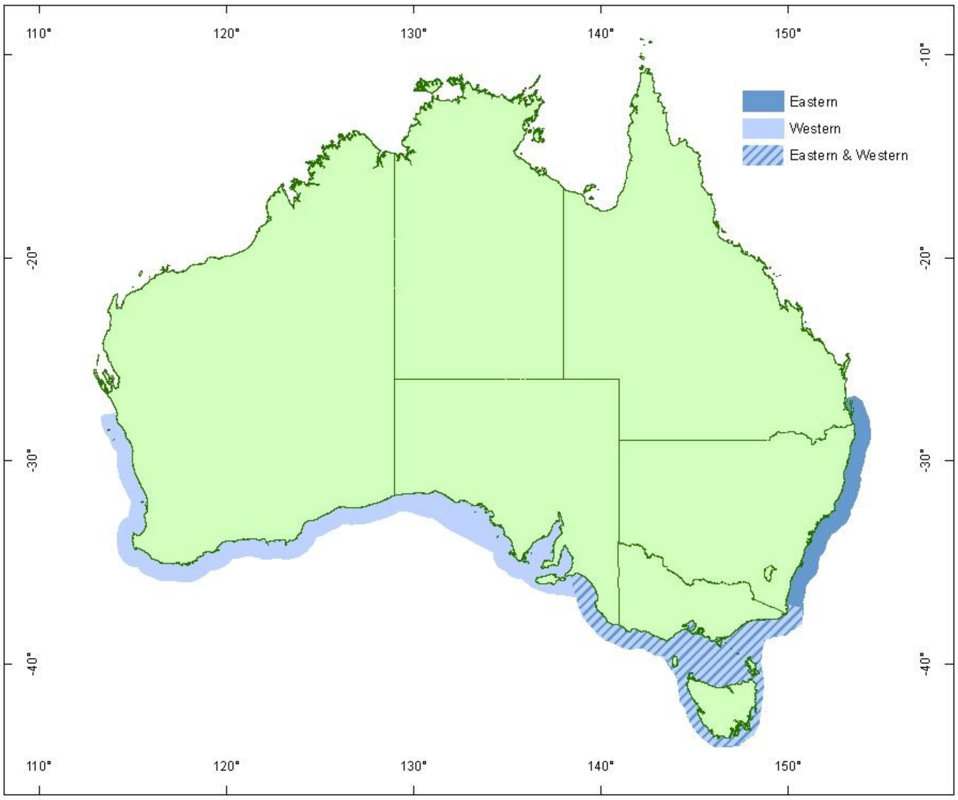


Figure 2.4: Distribution of Australian salmon in SE Australia and northern New Zealand.

2.2.3. *Predators and prey*

While both species are opportunistic feeders, there are distinct differences in their diets. Juvenile *A. trutta* feed on zooplankton and epibenthic species of fish, worms and crustaceans (Robertson, 1982), and adults feed on slightly larger zooplankton, such as Euphausiid crustaceans (Malcolm, 1959). In comparison, juvenile *A. truttaceus* feed on a a range of small pelagic fish (anchovies, sprats and juvenile sardines (Hoedt and Dimmlich, 1994) or benthic fish species and small crustaceans (Robertson, 1982), whereas adults feed predominantly on sardines (*Sardinops sagax*), and to a lesser extent on anchovies (*Engraulis australis*), *A. georgianus*, sea garfish (*Hyporhamphus melanochir*) and southern calamari (*Sepioteuthis australis*) (Cappo, 1987).

Adult *A. trutta* are preyed upon by a suite of apex marine predators like bottlenose (*Tursiops truncates*) and Maui's dolphins (*Cephalorhynchus hectori maui*), killer whales (*Orcinus orca*), Australian sea lions (*Neophoca cinerea*), and tiger (*Galeocerdo cuvier*), great white (*Carcharodon carcharias*), grey nurse (*Carcharias taurus*) and whaler (*Carcharhinus* spp.) sharks.

Migrating schools of *A. truttaceus* are prey to bronze whaler sharks (*Carcharhinus brachyurus*) (Jones, 2008a), dolphins and occasionally seals (Kailola et al. 1993). Coastal seabirds such as cormorants are known to opportunistically prey on juvenile *A. truttaceus*.

2.2.4. Recruitment

The bays and estuaries around Tasmania, eastern Victoria and southern NSW are the main area of juvenile distribution for *A. trutta*. Spawning occurs from late spring to late summer in the mainland waters of NSW and Victoria only. At this time the southward moving Eastern Australian Current (EAC) is at its strongest and this has been suggested to aid the transport and dispersal of larval *A. trutta* south to nursery areas in Tasmania, the south-east coast of Victoria and southern NSW. At the very least, the location of the area of spawning and the area of juvenile distribution provides strong evidence of a southward movement of early life-history phases from NSW and Victoria to Tasmania and eastern SA.

Juvenile recruits (<45 mm) first appear in south-eastern Tasmania in January and continue to recruit until April (McAllister, 2010). Up to three year classes of juveniles are sometimes present in one area, new recruits sometimes arriving before the emigration of the oldest year class. Larval *A. trutta* have been recorded from coastal waters off Sydney from November to May. Also offshore from Sydney, most larval *A. trutta* occur 3 km from the coast (range 3–16 km) in January but up to 40 km offshore in April (range 3–40 km). Larvae have also been recorded from eastern Tasmanian shelf and offshore waters between March and May. The hypothesised model for *A. trutta* larval transport suggests that spawning in mainland Australian waters provide the supply of larvae to Tasmanian waters as no spawning occurs there. It has also been hypothesised that spawning in northern NSW waters (by the largest and most fecund females) potentially provides a crucial supply of larvae to the coastal waters of southern NSW, eastern Victoria as well as Tasmania.

Long-term sampling of juvenile *A. truttaceus* and the con-generic Australian herring (*A. georgianus)* in South Australia show a significant correlation between the relative abundances of newly settled juveniles and the eastward directed current flow between WA and SA (Li and Clarke, 2004; Jones, 2008b, resp.). There is also a significant correlation between the index for current flow and commercial catches, and recruitment indices for these newly settled juveniles and the catch rates of fish newly recruited to the respective and adjacent SA fisheries (Jones and Westlake, 2003), adjusted for a temporal growth lag. Recently, Lenanton et al. (2009) demonstrated a strong stock-recruitment relationship for *A. truttaceus* off the lower west coast of WA, which was driven by fluctuating strength of the Leeuwin Current. In years of high current strength (e.g. 1999 and 2000), low spawning stock size in this area produced low levels of recruitment of juveniles, and in years of low current strength (e.g. 2006 and 2007), high spawning stock size resulted in high recruitment of juveniles in this area.

Key points:

- Both species of salmon undergo one-way migrations as adults.
- From a life history perspective and its relationship to climate change, advection of larvae in ocean currents is critical for the species. The eastern species is associated with the southward flowing EAC while the western species recruits are advected with the southern Australian currents which are westward flowing in 'El Niño' years and eastward flowing in 'La Niña' years.

2.3. Current impacts of climate change

The EAC has strengthened and extended further southward over the past 60 years (Ridgeway and Hill, 2009). However, there is no clear evidence that the climate change is having an impact on the *A. trutta* stock in SE Australian waters. There is a trend in size and age structures of the *A. trutta* population, with the largest and oldest fish being found further north rather than any discernable impacts of climate change. Malcolm (1966) reported that *A. trutta* was rarely observed in SA waters; however, no sampling had been done in the south-eastern part of the state up to the time of that report. More recent sampling during the 1990s in the south-east of SA discovered them in schools mixed with *A. truttaceus* (Jones and Westlake, 2003). More recent sampling in 2009 even further to the west, along the north coast of Kangaroo Island, also revealed their presence (Catalano, 2009). However, again these trends are more likely a result of more rigorous current research methodologies and analysis than definitive demonstration of the impacts of climate change.

The inter-annual fluctuations in the strength of wind-driven eastward directed currents along the southern Australian coast have been linked to the presence of El Niño/La Niña events (Li and Clarke, 2004). In El Niño periods, the westerly winds are less strong, resulting in weaker eastward directed currents. Thus, with the increased frequency of El Niño events, the core distributions and highest abundances of newly settled *A. truttaceus* (and *A. georgianus)* will be shifted further to the west, than in La Niña years (Dimmlich et al. 2000). The recent demonstration by Lenanton et al. (2009) that the location of peak spawning for *A. truttaceus* could be critical in determining whether juveniles recruit either to the west coast of WA or to the more eastern range (SA, Victoria and Tasmania) of its distribution, has also been linked to the presence of El Nino or La Nina years, respectively (Lenanton et al. 2009).

Key points:

- No evidence of climate change impacts currently exist but changes associated with ocean currents are predicted and will have major affects on Australian salmon populations.

2.4. Sensitivity to change

Both seasonal observations of *A. trutta* distribution as well as observations during feeding experiments in aquaria confirm that *A. trutta* do not tolerate water temperatures >~23°C and the generally accepted model for seasonal migrations of this species suggest that it closely associates with cool non-EAC waters, moving northward in winter (as the EAC contracts north) and southward in summer (when the EAC reaches furthest south). Increasing water temperatures as a result of an increasing southern penetration of the EAC may therefore shift the distribution of the SE Australian *A. trutta* population south. Growth rates in NSW are faster than in Victorian or Tasmanian waters. This is hypothesised to be at least partly due to the overall higher water temperatures present further north resulting in increased growth rates.

Changes in strength of the EAC and the eastward directed currents along the southern Australian coast could influence the advective patterns for both species of Australian salmon (and the Australian herring), and the recruitment strength to the immediate fishery in the southern states may thus be affected (see Lenanton et al. 2009).

Key points:

- Temperature limits of approximately 23°C are likely to define distributional range under climate change, in combination with associated ocean currents.

2.5. Resilience to change

Because of the broad geographic range, flexible life-history parameters, high fecundity and dispersal capacity of *Arripis trutta* in SE Australia, the population is likely to be highly resilient to impacts associated with climate change. The *A. trutta* population in SE Australia is also a single well mixed biological stock and is considered separate to the NZ stock only as a result of the geographic separation of the two populations. Although changing EAC conditions (strength and temperature) may have an impact on larval transport patterns and the extent of the adult population, the high larval dispersal capacity into the many ideal recruitment areas present through SE Australia may prevent localised population effects due to climate change and may enable the species to shift distribution to maintain an optimal environment.

Due to their long larval and post-larval lives (3–5 months), the wide dispersal capacity of the currents enables both salmon species to shift their distributions to maintain optimal environments and prevent localised long-term population effects.

Key points:

- Australian salmon are likely to be resilient impacts associated with climate change.

2.6. Ecosystem level effects

Schools of *A. trutta* feed by cooperatively herding baitfish towards the surface to form a 'baitball' and many winter-nesting seabirds such as terns (*Sterna* spp.), petrels (*Pterodroma* spp.), prions (*Pachyptila* spp.) and shearwaters (*Puffinus* spp.) are reliant on this feeding behaviour to make pelagic prey available to them. Historical declines in the abundance of *A. trutta* (mainly in NZ) have been linked to reductions in winter nesting success in each of these species. Any change to the abundance and distribution of *A. trutta* in SE Australia therefore has the potential to affect reproductive success in these seabirds.

As mentioned above, *A. trutta* in SE Australia are preyed up by a suite of large marine predators like dolphins, sharks and fur seals, whilst consuming ~3–4 times their own biomass of a wide range of mainly small pelagic teleosts themselves each year. Any contraction in the overall geographic extent of *A. trutta* distribution will clearly have major implications for the nearshore ecosystems of SE Australia. In southern NSW and eastern Victorian waters, which will experience an increased *A. trutta* population for longer seasonal periods, the predation pressure on pelagic teleosts exerted by *A. trutta* will increase. So too will the availability of *A. trutta* to larger predators like sea lions and dolphins. Similarly, for northern NSW waters, this could have *A. trutta* schools not travelling as far north and also present for a much shorter time periods each year. There will thus be less predation pressure on pelagic teleost prey in northern NSW and *A. trutta* will be available to predators for a shorter period of time.

Arripids are preyed upon by whaler sharks (*Carcharhinus* spp.), and research is currently being undertaken to determine their relative importance in these sharks' diet (P. Rogers, SARDI, pers. com.). Seasonal movements of these sharks appear to be influenced by temperature. At higher temperatures, they are more commonly found in inshore waters of SA than during winter months, when they occur in more offshore warmer waters (Jones, 2008a). In SA, Arripids occur in inshore waters throughout the year, although they are more common during the warmer months. Thus, increasing water temperature, which potentially extends the presence of whaler sharks in waters where Arripids are found, could influence the latter species' abundances.

Key points:

- Ecosystem effects are likely to be distributional changes in seabird feeding in association with salmon feeding on bait fish and predators of arripids.

2.7. Additional (multiple) stressors

The commercial catch of *A. trutta* is currently at the higher end of historical landings and the recreational fishery is also substantial (150–200 tonnes per year); however the species is not considered to be heavily fished. *Arripis trutta* are currently listed as 'fully fished' in NSW, with commercial landings variable between 500 and 1,500 tonnes per year for the past decade. Since 2001, commercial fishers north of Sydney have been restricted to a 100 kg per day by-catch limit for *A. trutta* when targeting other species as well as being permitted to catch *A. trutta* for personal use as bait.

In both the commercial and recreational fisheries of South Australia, we have observed a decrease in both the levels of harvest and fishing effort (see above) for Australian salmon.

Key points:

- No current evidence of climate change impacts exists but changes associated with ocean currents are predicted.

2.8. Critical data gaps and level of uncertainty

At this stage no attempt has been made to examine the fate of larvae spawned in various locations in SE Australia using oceanographic modelling. Very little is known about the geographical areas which are important sources of recruits for various regions in SE Australia. For example, it may be that the population of large, old fish in northern NSW may be supplying areas further south with vast numbers of recruits and thus sustaining the populations in southern NSW, eastern Victoria and Tasmania.

Little is understood about the main predators of the Arripids and how predator–prey interactions may modify Arripid distribution and abundance.

Although information is available on the linkage between current strengths and recruitment for *A. truttaceus* and *A. georgianus*, the linkage between the strengthening EAC and recruitment patterns for *A. trutta* is less well understood, and ongoing monitoring programs of newly recruited juveniles throughout their ranges are a cost-effective way to indicate climate change induced changes in the strengths of the EAC and the Leeuwin Current.

Key points:

- No current evidence of climate change exists but changes associated with ocean currents are predicted.

Table 2.1: Summary of Eastern Australian salmon species profile, which also indicates level of certainty of the associated information. Level of certainty is divided into high (H) = strong clear evidence, backed by several studies with solid datasets with little confounding interactions; medium (M) = evidence supported by one or more studies, conclusions may be partially ambiguous or confounded; low (L) = anecdotal evidence, limited data and/or predicted conclusions based on theoretical knowledge.

<table>
<tr><th>Life history stage</th><th>Multiple stressors</th><th>Distribution</th><th>Habitat</th><th>Predators and prey</th><th>Current impacts</th><th>Predicted impacts</th><th>Ecosystem interactions</th><th>Data gaps</th></tr>
<tr><td>Eggs</td><td rowspan="3">Unknown</td><td rowspan="5">See Figure 2.1 (H)</td><td rowspan="2">Pelagic, offshore (M)</td><td rowspan="2">Unknown</td><td rowspan="5">None (H)</td><td rowspan="5">Southward contraction of species range (M)</td><td rowspan="3"></td><td rowspan="5">Identification of important larval sources areas</td></tr>
<tr><td>Larvae</td></tr>
<tr><td>Juveniles</td><td rowspan="3">Pelagic, nearshore, 0-30 m (H)</td><td rowspan="3">Predators: dolphins, sea lions, sharks (H)

Prey: pelagic teleosts (H)</td></tr>
<tr><td>Pre-spawning adult</td><td rowspan="2">Commercially (500-1500 t/year) and recreationally (150-200 t/year) exploited, fishery is stable, listed as ‘fully fished’ (H)</td><td rowspan="2">Decreased seasonal presence in northern NSW (decreased predation pressure on teleost prey, less A. trutta prey available for predators), increased seasonal presence southern NSW and eastern Victoria (increased predation pressure on teleost prey, more A. trutta prey available for predators) (L)</td></tr>
<tr><td>Post-spawning adult</td></tr>
</table>

Table 2.2: Summary of Western Australian salmon species profile, which also indicates level of certainty of the associated information. Level of certainty is divided into high (H) = strong clear evidence, backed by several studies with solid datasets with little confounding interactions; medium (M) = evidence supported by one or more studies, conclusions may be partially ambiguous or confounded; low (L) = anecdotal evidence, limited data and/or predicted conclusions based on theoretical knowledge.

Life history stage	Multiple stressors	Distribution	Habitat	Predators and prey	Current impacts	Predicted impacts	Ecosystem interactions	Data gaps
Eggs	Unknown	See Figure 2.1 (H)	Pelagic, offshore (M)	Unknown	None (H)	Westward contraction of species range (M)		1. Need for on-going monitoring of newly settled abundance of juveniles at eastern and western edges of its distribution, and correlate with relative strengths of eastward directed currents. 2. On-going monitoring of age structure of commercial and recreational catches.
Larvae								
Juveniles			Pelagic, nearshore, 0-30 m, occasionally to 100 m in the GAB (H)	Predators: dolphins, sea lions, sharks (H) Prey: pelagic teleosts (sardines) (H)				
Pre-spawning adult	Commercially (1000 - 4000 t/year) and recreationally (~500 t/year) exploited (SA + WA). Fishing effort is at ‘acceptable level’, as is the spawning stock (H)						Fluctuations in the availability of prey (sardines) could promote or delay migration of adult western salmon to WA spawning area (L)	
Post-spawning adult								

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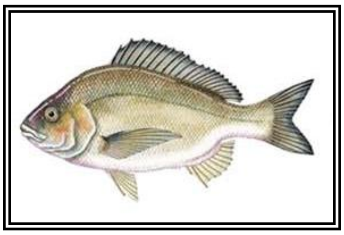
3.Black bream *Acanthopagrus butcheri*



Author: Neil Hutchinson

3.1. The fishery

Victorian stocks are separate to those in NSW and WA (Norriss et al. 2002). The major commercial and recreational fisheries for black bream in Victorian waters occur in the Gippsland Lakes, Lake Tyers, Tamboon Inlet and Mallacoota Inlet. The Gippsland Lakes fishery has historically been particularly important (Munro 1944) and produces 74–88% of the total commercial catch in Victoria; although recreational catch (<200 tonnes) dominates the commercial catch. Commercial Victorian catches in 2008/2009 were ~41.6 tonnes with a value of $462,946 (Figure 3.1). In South Australia, ~2.4 tonnes were caught in 2008/2009, with a value of $22,200.

Black bream is an important recreational species in Tasmania. Most fishing occurs along the northeast and east coasts. An estimated 48,070 (standard error: 20,148) individuals were caught in 2007/08, but about 72.7% of the catch was released. In 2007/08 about 13,134 individuals were harvested (kept), which equates to about 11.54 tonnes (Lyle et al. 2009).

Key points:

- Black bream is an important recreational species.
- In 2008–09 the combined commercial catch was 44 tonnes.

3.2. Life history

3.2.1. *Life cycle, age and growth*

Black bream live for at least 29 years (Morison et al. 1998) and possibly up to 37 years (DPI 2008), with adults reaching 60 cm (4 kg) (Cadwaller 1983). Age at maturity varies widely, with spawning occurring first at ages of 1–4 years, and 50% maturity from ~130–250 mm in Victoria and WA (Coutin et al. 1997; Norriss et al. 2002). Fecundity varies between individuals and increases with length, with an average of ~1,580,000 eggs on average for individuals from the Swan River (WA) (Sarre and Potter 1999) and individuals in SA yielding ~235,000 eggs (Harbison 1974), with these multiple batch spawners producing up to 3 million eggs (Kailola et al. 1993). Eggs are spherical and have a diameter of 0.6 to 0.8 mm (Newton 1996) and spawning occurs in water ranging from 15–28°C (Haddy and Pankhurst 1998; Sarre and Potter 1999; Walker and Neira 2001). There is contradictory evidence as to whether the species has individual sexes, is a protogynous hermaphrodite or undergoes simultaneous hermaphroditism (Sarre and Potter 1999; Norriss et al. 2002).

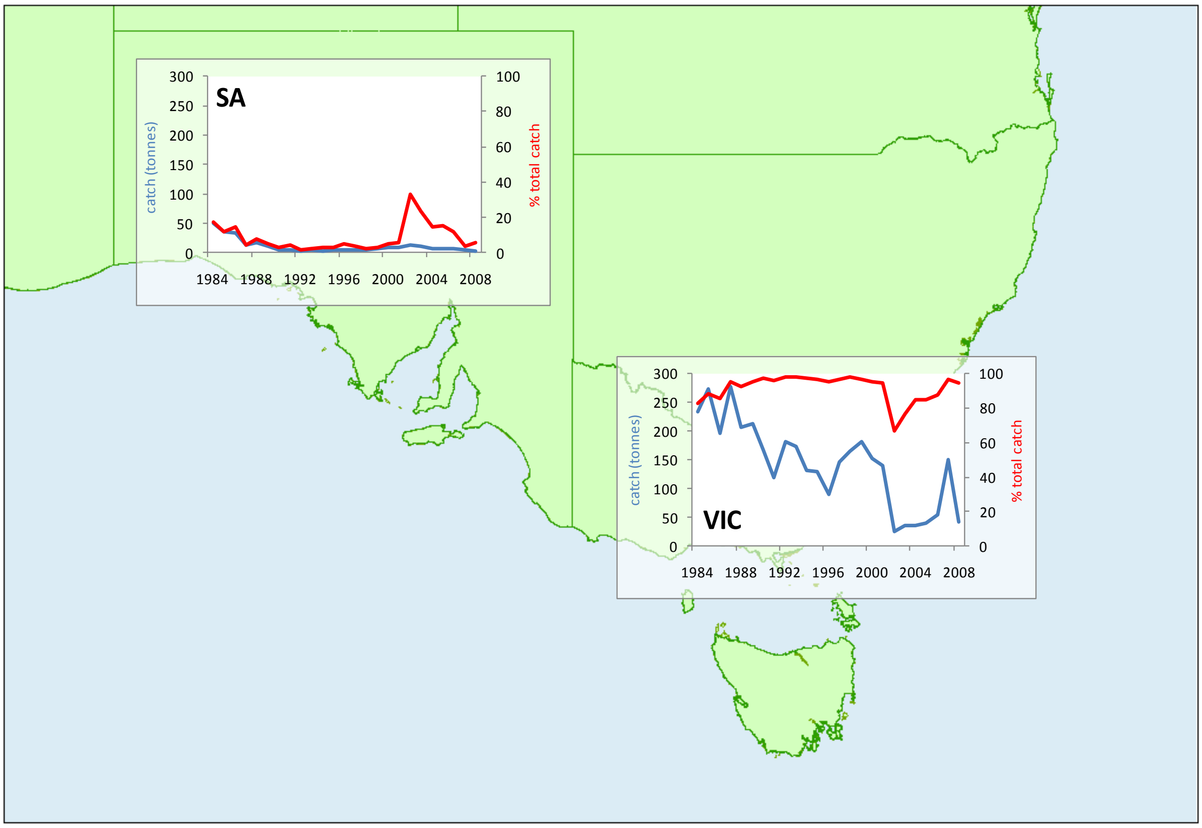


Figure 3.1: Commercial catch (tonnes) and contribution by each jurisdiction to total catch in south-east Australia (%) by year for South Australia and Victoria.

The species generally spawns upstream in sheltered areas of estuaries near the interface between fresh and brackish water (Munro 1944), although it has been known to spawn in closed seawater lakes (Munro 1944) and in lower areas of estuaries (Sarre and Potter 1999). Spawning occurs over wide spatio-temporal ranges, with fish undergoing multiple, extended spawning events (Norriss et al. 2002) (Figure 3.2).

In WA, spawning is between spring and early summer in salinities of 3.5 – 8 to 41–45 (Sarre and Potter 1999) and in Victoria and Tasmania, the spawning period for black bream also occurs in spring and summer (Haddy and Pankhurst 1998; Walker and Neira 2001). In the Gippsland Lakes, the spawning season extends from October to early December (Ramm 1986), with populations in eastern Victorian estuaries thought to spawn earlier than more western populations.

Reproductive success can vary in relation to environmental conditions, with ideal conditions occurring intermittently and varying between years (Coutin et al. 1997). The life cycle of black bream is known to vary depending on the hydrography of the water body that they live in (Norriss et al. 2002); i.e. fish in open estuaries will show different strategies in comparison with those in seasonally closed or closed estuaries (Lenanton and Hodgkin 1985).

Black bream eggs are planktonic and as a function of their buoyancy are mostly found in waters where the salinity is between 15 and 20; at 17 they float in the upper 45 cm of the water column (Butcher 1945a; Butcher 1945b). Eggs generally hatch two days after fertilisation (Haddy and Pankhurst 2000) at a diameter of ~1.7 mm (Neira 1998). Eggs are thought to be restricted to natal estuaries (Newton 1996). Larvae in Hopkins River Estuary, Vic have been found exclusively in pelagic habitats, mainly in upper and middle parts of the estuary (Willis et al. 1999). The larvae remain in the water column for about one month before settling into shallow macrophyte and seagrass beds when they are 10 to 18 mm in length (Ramm 1986; Neira 1998; Willis et al. 1999; Walker and Neira 2001). In eastern Tasmania, newly settled juveniles of ~15mm have been found over rocky areas in the Little Swanport estuary (Morton et al. 2005)

Growth of adults is dependent on season and age, with the fastest growth in summer during the first 6–8 years, with low temperatures and increased rainfall in winter slowing growth (Sarre and Potter 2000a; b). Growth is fastest during first year, with slightly lower growth in second and third years (Butcher 1945a; b)

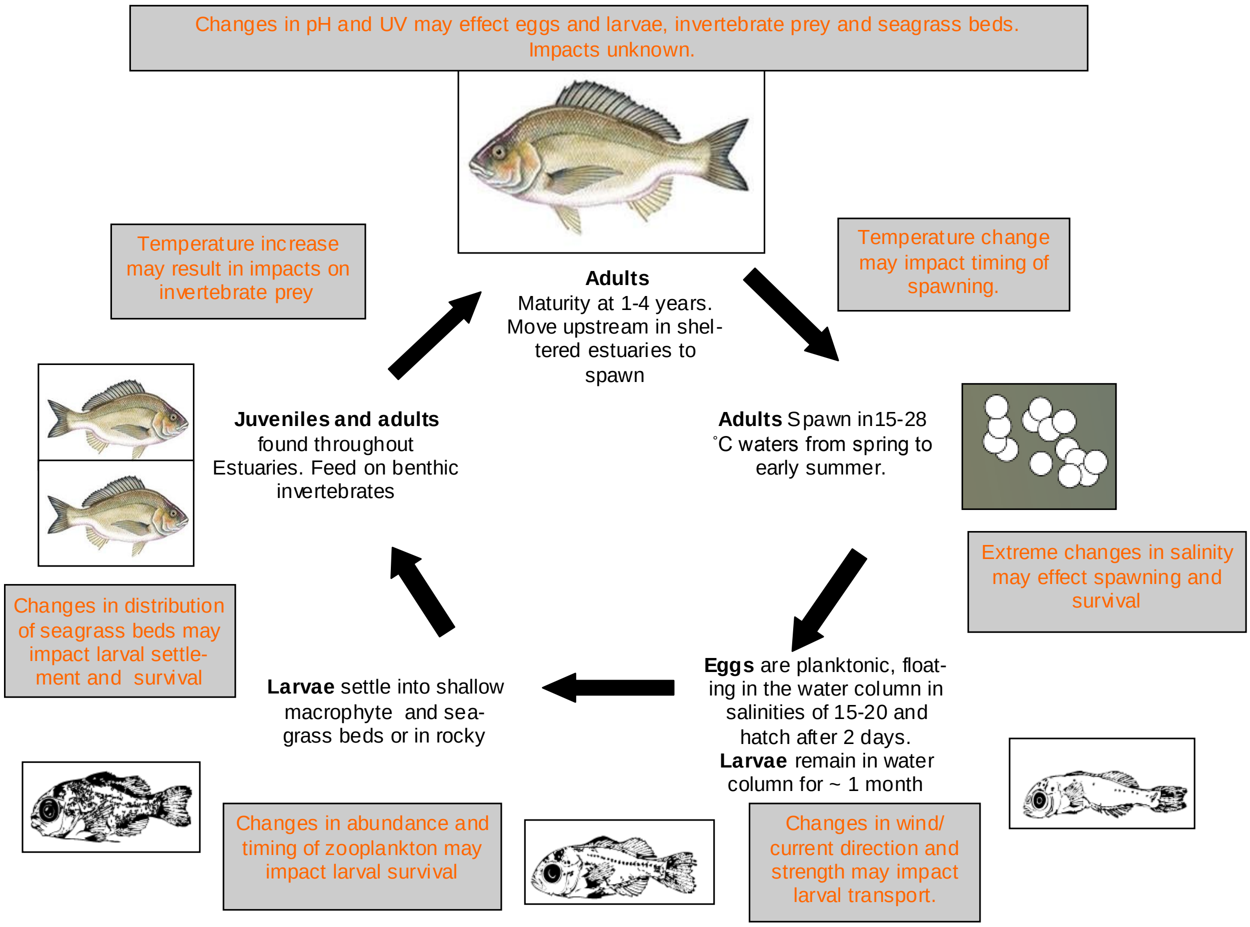


Figure 3.2: Summary of life cycle (this section), and points of exposure to relevant climate change drivers or known impacts (subsequent sections).

3.2.2. *Distribution, habitat and environmental preferences*

Black bream are found from southern NSW to Shark Bay in WA (Gomon et al. 2008) (Figure 3.3). They have a wide salinity tolerance, from seawater to freshwater, with the life cycle of black bream usually completed within a specific estuary (Walker and Neira 2001; Norriss et al. 2002).

The chemical examination of otoliths (Elsdon and Gillanders 2005; Elsdon and Gillanders 2006) indicate that, at least in SA, fish from the same estuarine population can show multiple migratory patterns between estuaries and rivers indicating that migratory behaviour can be fairly complex. For example, some individuals may be freshwater residents while others may be migrants that show either irregular patterns of diadromy or cyclic anadromomy.

Any movement is likely to be by adults, as eggs and larvae have not been recorded outside of rivers and estuaries, with spawning occurring at times of low river discharge when spawning adults move upstream (Potter et al. 1996). Individuals are occasionally known to be flushed out into the open sea due to high levels of freshwater discharge, making sporadic use of coastal habitats (seagrass and rocky reef) (Sherwood and Backhouse 1982) and they may make use of floodwater plumes to move between adjacent estuaries (Chaplin et al. 1998).

Genetic examinations of populations in estuaries appear to show a variety of patterns of distribution. While some have shown that populations in adjacent estuaries are to a certain extent genetically distinct (Chaplin et al. 1998), suggesting that it is unlikely that estuarine populations are replenished by immigrants, others note low levels of contemporary gene flow between estuaries, mainly restricted to adjacent estuaries (Burridge et al. 2004; Burridge and Versace 2007). In Victoria, Farrington et al. (2000) suggested that dispersal may be more widespread than previously thought.

Movement patterns of bream within rivers and estuaries and out of estuaries into nearshore environments have been studied throughout the range of the species using both traditional and acoustic tagging methods. Several studies suggest that there is only occasional movement of black bream between bays and inlets and that their distribution within an estuary varies seasonally with salinity, water temperature and food availability (Hassell et al. 2008).

Victoria: Early studies of fish tagged in Gippsland lakes had a recapture rate of 17% (Gorman 1972). While numerous fish were recovered in the vicinity of where they were tagged, 2.5% of the recaptures were recovered far from their release point, in the Snowy River (~43 km), Seaspray (~72 km), Manns Beach (~145 km), Moruya, NSW (~330 km) and in Duras Lake, NSW (~410 km) (Gorman, 1965, 1972). The individuals caught at Snowy River and Seaspray were caught during or after the spawning season, indicating that limited mixing between populations may occur in east Gippsland. While there was significant movement from the Gippsland Lakes to other coastal inlets, eastern Victoria and southern NSW, there was no movement west of Wilsons Promontory. Butcher and Ling (1962) also tagged bream in the rivers and lakes around East Gippsland, and while the majority of fish were recovered relatively close to their site of release in Gippsland Lakes or a variety of rivers and inlets in East Gippsland, only one showed any signs of seaward migration, moving between Syndenham inlet and Marlo, a distance of ~51 km. It has been suggested that there is immigration of bream into Gippsland Lakes from other areas (Gorman, 1972).

More recent, fine-scale tracking using acoustic telemetry of bream in Gippsland Lakes (Hindell et al 2008) found that fish moved at mean rates of 8.7 km d^{-1} over a one-year period, and exhibited seasonal patterns of use of rivers, river entrances and the lakes themselves. In summer and early autumn, they spent more times in the lakes than rivers, and then began to make more use of rivers than lakes, with a peak in rivers in mid-winter. Diel variation in habitat use during the transitional periods when fish were moving between the habitats (March–May), indicated that fish use lakes more at night and rivers during the day (Hindell 2007, Hindell et al. 2008). Monthly variation in time spent in particular rivers varied positively with freshwater discharge and Hindell et al. (2008) found that bream movement into the rivers in Gippsland Lakes was linked to the salt-wedges formed where haloclines of 17–20 ppt were present, and Sarre and Potter (1999) have suggested that the re-formation of salt wedges after flooding events may trigger spawning.

Western Australia: In WA, individuals have been found in inshore marine waters by some researchers but not others (Sakabe and Lyle 2008), with bream leaving estuaries only rarely when flushed out into the ocean due to extreme flooding events (Lenanton 1977; Lenanton et al. 1999). It has been suggested that such individuals are unlikely to be self-sustaining; i.e. able to reproduce (Lenanton et al. 1999).

South Australia: Weng (1971) tagged bream in SA and found movement was localised, with little proof that individuals moved out of estuaries into the sea, and suggested that bream show two distinct movement types, related to either habitat preference or spawning.

Tasmania: Tracking work in Tasmania (Sakabe and Lyle 2008) showed that the daily movement of black bream was closely linked with the tidal cycle, with a high percentage of individuals moving upstream on the flood tide and downstream on the ebbing tide. In addition, they found that during a flood event, fish moved downstream in the estuary and stayed there for several days. They also found that they were more active during the day than at night.

Ruppia spiralis and *Zostera muelleri* seagrass beds provide important nursery habitats and food resources for juvenile black bream in the Gippsland Lakes, Vic (Edgar and Shaw 1995), while in Tasmania only limited numbers have been reported in seagrass (Jordan et al. 1998). In the Hopkins River, Vic, newly hatched yolk-sac larvae are most abundant in deep pools in mid to upper areas of the estuary that are preferred by adults, where levels of salinity are moderate and dissolved oxygen concentrations are high (Newton 1996). Larger juveniles and adults generally occur in upper estuaries over deeper, unvegetated sand and mud areas and in areas with shelter provided by rocky river beds, macrophytes, snags or jetties and other man-made structures (Coutin et al. 1997; Norriss et al. 2002; Hindell 2007).

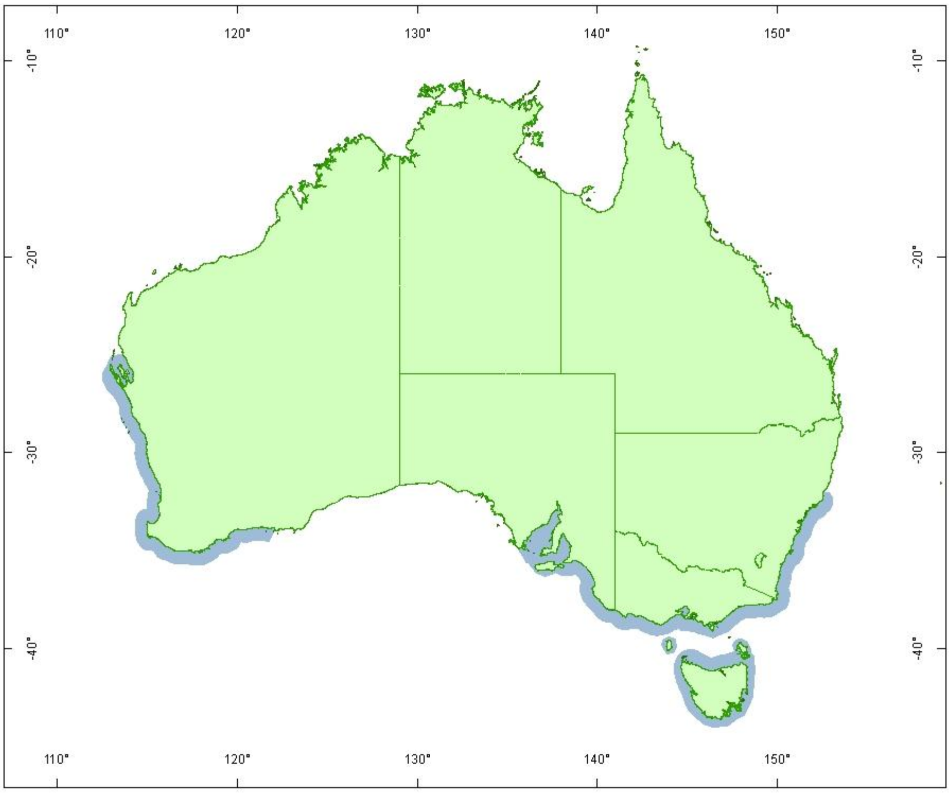


Figure 3.3: Map detailing the distribution of black bream.

3.2.3. *Predators and prey*

Predators that feed on black bream include a range of birds such as cormorants (Phalacrocoracidae) and pelicans (Pelecanidae) (Reside and Coutin 2001), as well as larger fish including sharks, rays, mulloway and flathead. Black bream have been described as opportunistic carnivores and the diet of juveniles and adults is composed primarily of organisms associated with sediments or macrophytes, and may include bivalves, gastropod molluscs, crabs, amphipods and copepods, polychaete worms and small fish (Heald 1984; Coutin et al. 1997) with overlap in diet between juveniles >60 mm and adults (Willis et al. 1999). Wallace (1976) suggested that plant material is consumed with prey items associated with it rather than as a targeted food source as indicated by the undigested nature of the plant material found in stomach contents. When presented with a variety of preferred food types, *A. butcheri* will feed preferentially on items found on or above the substratum, rather than within the substratum (Sarre et al. 2000).

Strong patterns of ontogenetic differences in diet have been identified in several estuaries in Victoria and WA (Willis et al. 1999; Sarre et al. 2000). For example, in the Hopkins River estuary, Victoria, larvae <9 mm fed mostly on calanoid copepod larvae, while larvae >9 mm consumed calanoid copepodites and unidentified larval fish as well as algae (e.g., spirogyra and diatoms), cyclopoid copepods and unidentified eggs (Willis et al. 1999). In this estuary it appeared that larvae consumed resources in the upper water column due to a strongly anoxic and saline layer, in water >4 m deep (Willis et al. 1999). Large numbers of larvae have been recorded in conjunction with high abundances of calanoid copepods after flooding events in the same river (Newton 1996).

Ostle (Norriss et al. 2002) discusses the possible diet of juvenile fish in barred river systems in southern Western Australia, with juveniles potentially feeding on insects, hardyheads, tadpoles, small bream and small crustaceans. In the Hopkins River, Victoria, juveniles <40 mm fed mainly on calanoid copepods; for example, *Gladioferens pectinatus* and *Sulcanus conflicatus* (Willis et al. 1999). As the size of these juveniles increased from >20–40mm to >40–60 mm, copepods became a less important part of the diet, with amphipods, gastropods and polychaetes appearing in the diet, indicating a shift in feeding from the water column to seagrass beds. Once juveniles were >60 mm, polychaetes became the main food items. The wide range of species found in the stomach contents of juveniles suggest that they feed opportunistically (Willis et al. 1999); food items include algae, calanoid and cyclopoid copepods, ostracods, amphipods and decapods, insects, gastropods, polychaetes, nematodes, fish and unidentified eggs.

Wallace (1976) found that black bream in the Blackwood River Estuary, WA opportunistically feed on the most abundant invertebrates in the estuary, as has also been seen in the upper reaches of the Swan Estuary, where diet composition changed spatially but not temporally in relation to the distribution of prey types. Sarre et al. (2000) described how diet composition varied spatially between four estuaries and a saline coastal lake in relation to differences in the abundance of different prey types in each area. For example, at each of the five sites, the major prey types included large quantities of algae (*Cladophora* sp. and *Chaetomorpha* sp.), seagrass (*Ruppia megacarpa*), amphipods, decapods, polychaetes, tube-dwelling amphipods and teleosts. These sites varied in the extent to which they were connected to the sea, with salinities ranging from between 2 and 7‰ in a sporadically open estuary, to >40‰ in a closed estuary.

3.2.4. Recruitment

This species is characterised by variable recruitment and the stock in the Gippsland Lakes is thought to be composed of few age classes (Coutin et al. 1997). Spawning success in the Gippsland Lakes may relate to river flow and spring water temperatures and the distribution and abundance of seagrass beds which form an important habitat for newly recruiting and juvenile black bream in the area (Longmore et al. 1990). Commercial catches in the Gippsland Lakes declined in the 1920s, then grew to record levels in the 1960s which coincided with the loss and subsequent recovery of seagrass beds in Lake King and Lake Victoria (Coutin et al. 1997).

Recent research in Gippsland Lakes has shown that the combination of water column stratification and freshwater flow is a major factor influencing recruitment variation, with such patterns likely to be unique to individual estuaries based on local characteristics such as freshwater flow, topography, entrance opening and closing etc (Jenkins 2010).

Key points:

- Seagrass beds are important in the Gippsland Lakes.
- Water column stratification and freshwater flow are likely to be key influences on recruitment variation.

3.3. Current impacts of climate change

Current impacts of climate change are largely unknown for this species and while a range of potential climate drivers may currently be of risk including temperature; rain/riverflow (salinity); UV; acidification; winds and currents; sea level change; and extreme events, high levels of uncertainty are linked to these risks, particularly in the impacts of climate change on the larval stages of this species. However, climate change predictions for the Gippsland Lakes region are for reduced rainfall and increased evaporation, which is likely to lead to higher salinities and lower stratification in Gippsland Lakes, which would negatively affect bream recruitment and the bream population (Jenkins 2010).

Key points:

- Little is known about current climate change impacts.
- Lower rainfall/freshwater flow may negatively affect bream populations in the Gippsland Lakes

3.4. Sensitivity to change

Environmental factors such as water temperature, salinity and dissolved oxygen are important determinants of the timing and success of bream spawning and larval survival (Hassell et al. 2008). While bream are known to spawn when salinities are ~15ppt (Sakabe 2008), juveniles have been found in salinities of ~0–48$^0/_{00}$ (Partridge and Jenkins 2002) and adults with developed gonads have been observed in salinities from ~3.5 to 45$^0/_{00}$ (Sarre and Potter 1999), although this does not mean they spawn in these conditions.

Under laboratory conditions, it has been determined that larval survival and fertilisation of eggs are reduced at salinities $<10^{0}/_{00}$ (Haddy and Pankhurst 2000; Hassell et al. 2008). Oxygen levels of 50% lower embryo survival by up to 15% and hatch rates by up to 28% compared to normal conditions (>80% saturation) with hypoxic conditions resulting in <10% of eggs hatching. Hatching has been shown to be delayed by 24 hrs at 16°C, and almost no hatching takes place in hypoxic conditions at salinities of 15 and $23^{0}/_{00}$ (Hassell et al. 2008). There can be additive effects of these different factors; e.g. lowered salinities have been shown to reduce embryo survival at 20°C but not 16°C and where salinities are reduced at 20°C the proportion of larval deformities is high (Haddy and Pankhurst 2000).

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Juvenile and adult bream become osmotically stressed at salinities of $60^{0}/_{00}$ and grow slower at this salinity than at those $<35^{0}/_{00}$ (Partridge and Jenkins 2002; Hoeksema et al. 2006). While larger fish are more susceptible to death with salinity changes than more tolerant juveniles, all ages of bream begin to die at <85 ppt (Hoeksema et al. 2006).

These factors are particularly important in sites such as the Gippsland lakes where hypoxic and anoxic conditions are increasing due to a range of factors such as stratification, runoff etc (Hassell et al. 2008) and eggs that are carried to affected areas by currents etc are unlikely to survive (Nicholson et al. 2008). The suspension of eggs in the water column is related to salinity, and more specifically the presence of salt wedges and haloclines, which can keep eggs away from hypoxic water and prevent them from being washed out of estuaries (Newton 1996). It has been suggested that eggs which lose buoyancy and sink would enter more hypoxic, cooler areas and hatching and survival would be affected, with eggs also coming into contact with benthic predators (Hassell et al. 2008). In addition, flooding events may play an important role in spawning, with year classes from the Gippsland Lakes missing from years that had low levels of flooding (Hobday and Moran 1983).

Key points:

- Black bream are able to tolerate a relatively wide range of physical conditions at juvenile/adult life stages.
- Egg development and larval survival is dependent on salinity and oxygen concentrations.

3.5. Resilience to change

Black bream are relatively long-lived, highly fecund and are able to live in a relatively wide range of salinities and temperatures. Conditions for spawning and larval survival, however, are relatively specific.

As noted previously, black bream are generalists and it is therefore likely that they will be able to continue to utilise changing invertebrate communities as food sources which could occur with shifting prey availability that may be caused by climate change. These prey species may themselves be influenced by climate change.

Key points:

- Black bream are relatively long lived and highly fecund.
- This species is a generalist; it is likely to be able to adapt to changes in prey species.

3.6. Ecosystem level interactions

- In some areas, such as the Gippsland lakes, seagrass beds are an important resource for juvenile bream (Edgar and Shaw 1995). Coutin et al. (1997) suggest that carp, poor water quality and the growth of epiphytes have a major impact on seagrass beds and hence fish as seen in Paynesville. Anecdotal reports that seagrass beds in Gippsland Lakes are degraded require follow-up with an examination of trends in the distribution and abundance of seagrass in the lakes. Healthy seagrass is regarded as being critical to the maintenance of stocks of this species, as can be seen in a drop in abundance of the species in Gippsland lakes that coincided with loss of seagrass in Lake Victoria and Lake King in the early/mid 1900s. A subsequent recovery of stocks coincided with recovery of seagrass (Coutin et al. 1997).

- The virulence of viruses and parasites will increase with predicted climate change and their impact may be increased due to a combination of other stressors (Marcogliese 2008). It has been suggested that 'climatic effects on parasites and diseases of key species may cascade through food webs, with consequences for entire ecosystems' (Marcogliese 2008). A number of ectoparasites are currently known from the species, including species from the Monogenea, Copepoda, Branchiura, Isopoda and Hirudinea (Byrnes and Rohde 1992).

- With predicted temperature increases, the distributional range of yellowfin bream may extend southwards. Increases in the abundance of this species in areas such as the Gippsland Lakes, Victoria, could lead to increases in the rate of hybridisation between this species and black bream, depending on how often and for how long estuaries/lagoons are closed (Roberts et al. 2010). Reproductively viable hybrids, including backcross hybrids, of black bream (*A. butcheri*) and yellowfin bream (*A. australis*) are known to occur on occasions; for example, in landlocked lakes (Rowland 1984), although until recently this was not thought to be widespread (Farrington et al. 2000). Recent research shows that while hybridisation between the two species occurs in permanently or intermittently open lagoons (12–27%), it is apparent to a much greater extent in closed lagoons (79–97%) (Roberts et al. 2010). The majority of these hybrids were 'later generation hybrids or *A. butcheri* backcrosses, which are likely multi-generational residents within lagoons' (Roberts et al. 2010).

Key points:

- Seagrass is important for some populations.
- Viruses and parasites may become more virulent.
- Hybridisation with yellowfin bream may increase.

3.7. Additional (multiple) stressors

- This species is sensitive to overfishing as it completes its whole life cycle in estuaries (Chaplin et al. 1998; Potter and Hyndes 1999).

- The frequency of algal blooms has been increasing in the Gippsland lakes since 1995, and while generally caused by the cyanobacteria *Nodularia spumigena* (Van Buynder et al. 2001; Anon 2009), also includes blooms of other species such as *Synechococcus* sp., *Noctiluca scintillans* and *Gymnodinium catenatum* (Anon 2009). *N. spumigena,* when consumed by organisms, leads to a build up of toxins, which has previously resulted in seafood and fishing bans in the lakes. Other species occur in such numbers that light penetration in the water column is reduced. The blooms of these species occur due to a variety of variables including warm water temperatures, increased salinity, and nutrient inflows as well as being in response to high abundances of food in the case of the predatory dinflagelate *Noctiluca scintillans* (Anon 2009). Blooms of *N. scintillans* have been increasing in southern Australia due to increases in seawater temperature, and it is now a predominant red-tide species in Australian waters. Toxic diatom species such as *Chaetoceros convolutes* and *Pseudo-nitzschia* spp. have also been found at Lakes Entrance, and can cause fish deaths (Anon 2009). The reduction of wetlands and marshes adjacent to the lakes and forest cover in the catchment area over several decades may also influence levels of sedimentation and nutrient flow into the lakes which in turn may lead to an increase in algal blooms.

- At Gippsland Lakes, the creation of a permanent entrance in 1889 led to a major change in the ecology of the lakes with impacts on tidal level and salinity within the lakes (Barr 2000). Other human activities that reduce freshwater flow or increase marine incursion are likely to exacerbate climate change impacts by reducing stratification, leading to reduced bream recruitment (Jenkins 2010).

- The closure of estuaries and lagoons can lead to populations made up mostly of hyrbrids between black and yellowfin bream (Roberts et al. 2010). It has been suggested that such closures, caused by anthropogenic disturbances, facilitate hybridisation and may continue to increase the number of hybrid-dominated lagoons/estuaries over a wider geographical range, decreasing the availability of habitat for black bream (Roberts et al. 2010). Once such hybridisation occurs in an estuary, it is thought to be unlikely that historical genetic structure; i.e., populations of genetically pure black bream could be restored, even with stocking programs (Roberts et al. 2010).

Key points:

- Bream are sensitive to overfishing.
- Algal blooms are potentially detrimental.
- Anthropogenic manipulation of estuaries can be detrimental.
- Hybridisation with yellowfin bream changes population genetics.

3.8. Critical data gaps and level of uncertainty

- A lack of knowledge of key habitat and environmental conditions essential for spawning, survival and growth, are significant risks to the fishery in Victoria.
- Surveys of current patterns of seagrass abundance and distribution in the Gippsland Lakes and a comparison with historical records would be useful to inform predictions in the region.
- It may be important to monitor genotype frequencies within other southern Australian estuaries with the aim of determining baseline levels of hybridisation and responses to natural and artificial impacts on these estuaries (Roberts et al. 2010).
- The observed relationship between stratification, freshwater flow and bream recruitment in Gippsland Lakes needs to be tested in other estuaries.

Key points:

- There is a lack of knowledge of key habitat conditions essential for spawning.
- Monitoring of seagrass beds in Gippsland lakes would help inform management decisions.
- It may be important to monitor genotype frequencies in estuaries throughout the species range.
- There is a need to determine the stratification, flow and recruitment relationships in other estuaries.

Table 3.1: Summary of black bream species profile, which also indicates level of certainty of the associated information. Level of certainty is divided into high (H) = strong clear evidence, backed by several studies with solid datasets with little confounding interactions; medium (M) = evidence supported by one or more studies, conclusions may be partially ambiguous or confounded; low (L) = anecdotal evidence, limited data and/or predicted conclusions based on theoretical knowledge.

Life history stage	Multiple stressors	Distribution	Habitat	Predators and prey	Current impacts	Predicted impacts	Ecosystem interactions	Data gaps
Eggs	Salinity, temperature and oxygen concentrations (H)	See map 1 (L)	Pelagic, mid-water (H)		Declining freshwater flow, decreasing stratification (H)	Changes in salinity, etc may impact development (M)	Seagrass is important as a habitat to some populations (M), Viruses and parasites may become more virulent (L) Increased hybridisation with yellowfin bream (M)	Habitat conditions essential for spawning Changes in habitats, e.g., seagrass beds Level of hybridisation throughout range Broader-scale importance of freshwater flow/stratification
Larvae				Predators: other fish, benthic predators (L) Prey: Copepods, other larval fish, algae and eggs (H)				
Juveniles		See map 2 (H)	Seagrass beds (Vic, H), rocky areas (Tasmania, H)	Predators: Birds and larger fish (H) Prey: Sediment associated invertebrates, e.g., molluscs, crustaceans, polychaetes, small fish (H)				
Pre-spawning adult	Exploited, 44 tonnes caught commercially each year; fishery is stable		Upper estuaries, unvegetated sand and mud, rocky river beds, snags and manmade structures (H)					
Post-spawning adult								

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4. Blue grenadier *Macruronus novaezelandiaei*

Author: Jemery Day

4.1. The fishery

The Australian blue grenadier fishery has operated since the late 1970s. Blue grenadier are found from New South Wales around southern Australia to Western Australia, including the coast of Tasmania. Blue grenadier are caught by demersal otter trawl gear in depths of 300–800 m.

The total allowable catch (TAC) for blue grenadier was steadily reduced from 10,000 t in 2002 to 5000 t in 2005, and has varied between 3500 t and 5000 t since then. There are two defined sub-fisheries: the spawning and non-spawning fisheries, with the spawning fishery restricted to the western Tasmanian fishery in the months of June, July and August. The non-spawning fishery catches have been relatively poor over the last few years, whereas the spawning fishery catches have shown a marked increase since the mid 1990s. A small quantity (up to 50 t) of blue grenadier is caught in the Great Australian Bight Trawl Fishery.

Between 1999 and 2003 catch rates fluctuated between 7500 and 8000 t and then dropped markedly, with only 3773 t caught in 2009 (Figure 4.1). Consequently, the value of the blue grenadier fishery has fallen, with a value of $21.5 million in 1999/00 and $10.9 million in 2007/08 (ABARE 2008).

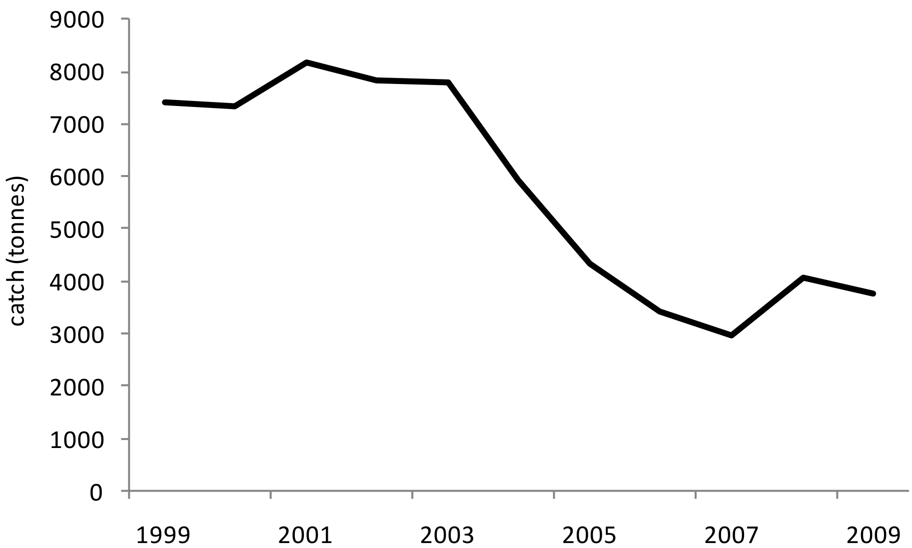

Figure 4.1: Commercial catch (tonnes) of blue grenadier by year for the Commonwealth.

Key points:

- Fisheries targeting spawning and non-spawning populations operate at different times of the year.
- There has been a reduction in catch from around 8000 t in 2003 to around 4000 t since 2005.

4.2. Life history

4.2.1. Life cycle, age and growth

Blue grenadier is a moderately long-lived species with a maximum age of about 25 years and an age at maturity of 4–5 years. Spawning occurs off western Tasmania, centred off Cape Sorell, between late May and early September. Adults migrate to the spawning area from throughout SE Australia, with large fish arriving earlier in the spawning season.

Female blue grenadier produce about 1 million eggs on average, and these are all released in the spawning period, possibly in two to three batches. The eggs are pelagic, spherical and about 1 mm in diameter. Fertilised eggs hatch within 55–60 hours, releasing pelagic larvae. The duration of the pelagic phase is unknown. Some larvae are carried southwards and may end up on the east coast of Tasmania. Small pelagic juveniles have been caught along the shelf break off eastern Tasmania and also in coastal bays. However, it is likely that most of the population recruits offshore from the Tasmanian west coast.

Females mature at between 4 and 7 years of age and live up to 25 years, with a maximum size of around 110 cm.

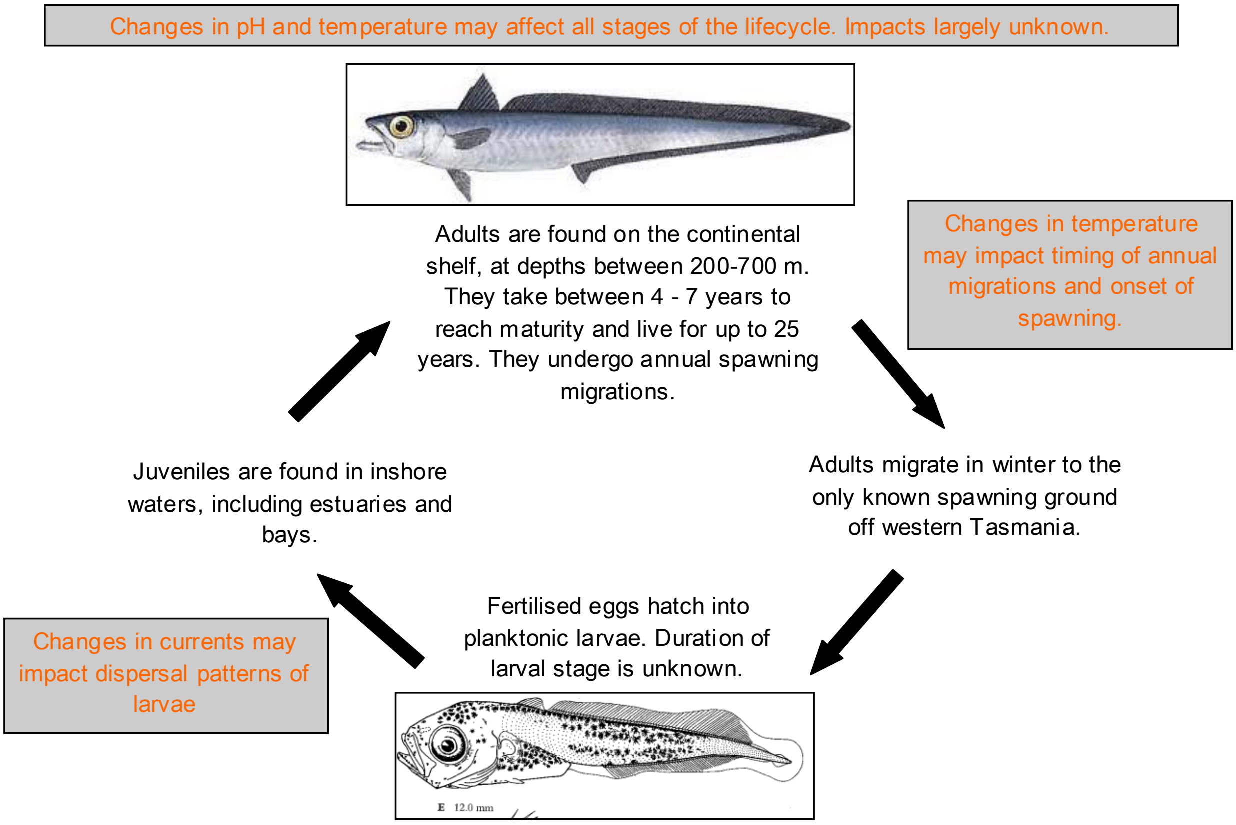

Figure 4.2: Summary of life cycle (this section), and points of exposure to relevant climate change drivers or known impacts (subsequent sections). Image of larvae: Neira et al. 1998.

4.2.2. Distribution, habitat and environmental preferences

Blue grenadier are found in temperate southern waters, including New Zealand. In Australian waters they range from New South Wales around southern Australia to Western Australia, including the coast of Tasmania (Figure 4.3). Data suggest there is a single breeding population in Australian waters.

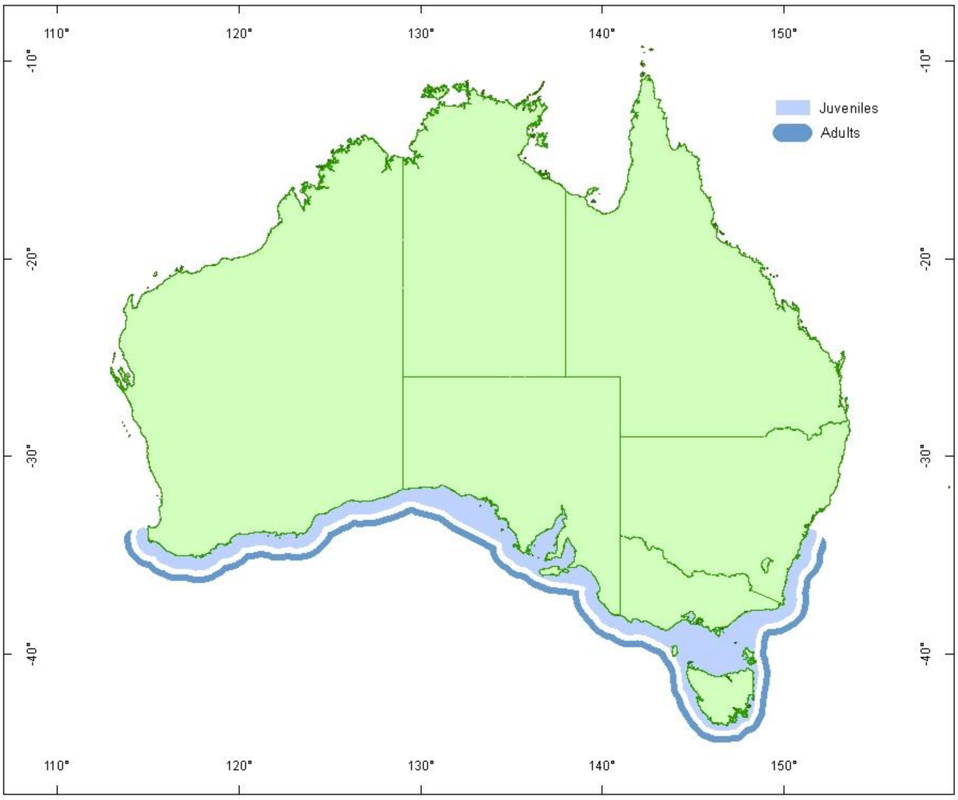

Figure 4.3: Distribution of blue grenadier in Australia.

Blue grenadier is a demersal species that occurs in the range of 33–54°S within a depth range of 0–1000 m, usually 200–700 m. This species is an inshore and offshore species, with juveniles found in estuaries and adults found on the continental shelf. Blue grenadier appear to live usually on or near the bottom, but may occasionally move up into mid waters. Large adult fish generally occur deeper than 400 m, while juveniles may be found in shallower water, more commonly found in large estuaries and bays.

Adult blue grenadier in Australia are known to form dense schools on the seabed during the day, and disperse into the water column at dusk. They annually migrate from their feeding grounds in autumn to the primary spawning area off western Tasmania, and disperse again during spring. Blue grenadier do not have a uniform arrival and departure on the spawning grounds but rather have a staggered arrival and departure for the duration of the spawning period.

4.2.3. *Predators and prey*

The prey of blue grenadier includes fish, squid and crustaceans.

Predators of juvenile blue grenadier include adult blue grenadiers and pink ling.

4.2.4. Recruitment

Larvae are pelagic, with some larvae carried southwards following the coast to the continental shelf break on the east coast of Tasmania. Most of the population is thought to recruit offshore from the Tasmanian west coast.

Key points:

- Blue grenadier are largely demersal.
- Their main spawning grounds are off the Tasmanian west coast.
- They are distributed throughout southern Australia.

4.3. Current impacts of climate change

While there are potential impacts of climate change, none has been observed so far.

Key point:

- There is no evidence of current climate change related impacts on blue grenadier.

4.4. Sensitivity to change

There is a potential reduction in suitable habitat for blue grenadier with increases in water temperature. The impact of climate change on the winter spawning grounds could see a disruption or delay to the spawning season, as there is evidence that the onset of spawning varies according to differences in water temperature. Broad-scale temporal differences at the start of spawning of up to one month have been observed, which is thought to relate to variation in the development of coastal current patterns around Tasmania (Thresher et al. 1988; Gunn et al. 1989).

Good recruitment years for blue grenadier have been sporadic but regular in recent years. If spawning is disrupted or if the years of good recruitment are driven by environmental factors, blue grenadier could be sensitive to climate change.

Key point:

- Changes to water temperature could result in changes to blue grenadier distribution.

4.5. Resilience to change

Resilience to change is largely unknown.

4.6. Ecosystem level interactions

Variation in the availability of prey may affect the distribution and abundance of blue grenadier.

Key points:

- Prey availability could affect abundance.
- There is limited information on predators.

4.7. Additional (multiple) stressors

Blue grenadier is a key commercial species and hence is subject to continual fishing pressure. If the regular large recruitment event fails to continue, this could result in a considerable reduction in biomass of blue grenadier.

Key points:

- Blue grenadier is a key commercial species.
- Blue grenadier have strong episodic recruitment.

4.8. Critical data gaps and level of uncertainty

The proportion of mature fish that spawn each year is unknown. Recruitment seems to have a regular pattern, with strong year classes recruiting every few years. However, the drivers for these strong recruitment years are unknown and consequently it is not known if these are environmental drivers or not.

Key points:

- Proportion of mature fish spawning annually is unknown.
- Driving influence behind periodic recruitment is unknown.

Table 1: Summary of blue grenadier species profile, which also indicates level of certainty of the associated information. Level of certainty is divided into high (H) = strong clear evidence, backed by several studies with solid datasets with little confounding interactions; medium (M) = evidence supported by one or more studies, conclusions may be partially ambiguous or confounded; low (L) = anecdotal evidence, limited data and/or predicted conclusions based on theoretical knowledge.

Life history stage	Multiple stressors	Distribution	Habitat	Predators and prey	Current impacts	Predicted impacts	Ecosystem interactions	Data gaps
Eggs		Single known spawning ground, off the west coast of Tasmania (H)	Pelagic, offshore (M)	Unknown	Unknown	Southward contraction of range (L) Possible impacts on winter spawning grounds (L)		Spawning frequency for adults
Larvae								
Juveniles		Southern Australia. See fig 3 (H)	Coastal estuaries and bays (M)	Predators: pink ling adult blue grenadier (H) Prey: fish, squid and crustaceans (H)			Prey variability could be important (L)	
Adult	Exploited, about 4000 t caught each year in the Commonwealth		Continental shelf, largely demersal (M)					

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5. Blue swimmer crab *Portunus pelagicus*

Author: Cameron Dixon

5.1. The fishery

The blue swimmer crab fishery is a very popular past time in South Australia (SA) comprised of three fishing sectors: a) a managed commercial quota fishery within Spencer Gulf and Gulf St Vincent; b) a commercial fishery in the west coast region; and c) a recreational fishery in all SA waters. In 2008/09, the commercial fishery production was 658 tonnes, with an estimated value of $5.4 million from all waters (Figure 4.1). Commercially, crabs are harvested by two main gear types, either by crab pots (95% of the catch) or crab nets (5% of the catch).

The statewide recreational blue swimmer crab retained (harvested) catch was estimated at 1,144,837 individuals for this period, with an estimated weight of 283,687 kg. Of this total weight, 48% was harvested from Spencer Gulf, 46% from Gulf St Vincent and Kangaroo Island and 6% from the west coast. Crab nets are the main recreational method for catching crabs (77%), followed by crab rake (18%), whilst fishing line is used for the remaining 3% (Jones 2009, Table 1).

The blue crab fishery is managed by Primary Industries and Resources South Australia (PIRSA) under the framework provided by the *Fisheries Management Act 2007*. General regulations pertaining to commercial and recreational harvest of blue crabs in SA are described in the Fisheries Management (General) Regulations 2007, with specific legislation located in the Fisheries Management (Blue Crab Fishery) Regulations 1998, and the Fisheries Management (Marine Scale Fisheries) Regulations 2006. These documents provide the statutory framework for management of SA's blue crab resources.

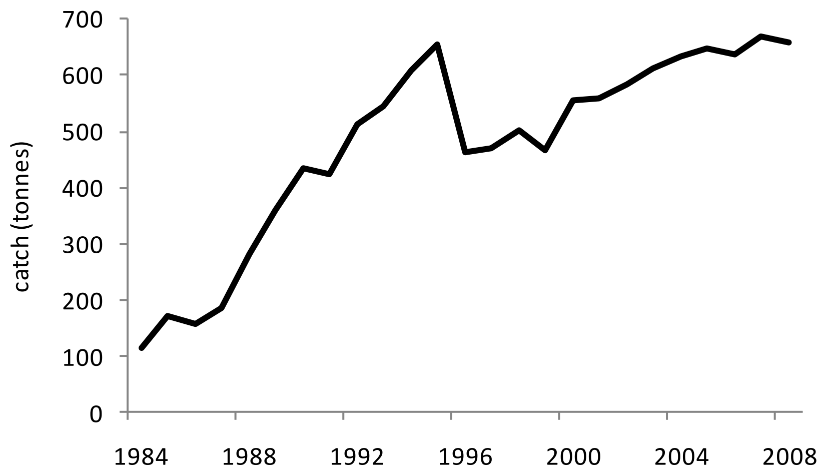

Figure 5.1: Commercial catch of blue swimmer crab in SA.

Table 5.1: Estimates of recreational harvested catch (numbers and weight; kg) of blue swimmer crab caught by South Australian residents in 2000/01 and 2007/08 (Jones, 2009).

Year	Harvested catch (numbers)	Harvested weight (kg, live wt)
2000/01	1,055,101	360,845
2007/08	1,144,837	283,687

Key points:

- Blue crabs are harvested by the three sectors in South Australia:
  - A managed quota fishery in Spencer Gulf and Gulf St Vincent
  - A commercial marine scalefish sector in the West Coast region
  - A significant recreational fishery throughout the state.
- Blue crabs are harvested using a variety of gear types, with most of the catch being captured in pots.

5.2. Life history

5.2.1. *Life cycle, age and growth*

Male and female *P. pelagicus* generally reach sexual maturity at a size of 70–90 mm in carapace width, when they are approximately one year old (Figure 5.2). The spawning season lasts for 3 to 4 months over the summer/autumn period. The duration of the growing season varies among individuals because those settling in early summer have a longer growing season than those settling in mid-to-late summer. While egg-bearing females have been observed throughout the year, there is a substantial increase in the proportion of berried females in late spring. Kumar et al. (2000) found that a female blue crab can produce between 650,000 and 1,760,000 eggs per spawning.

To grow, it is necessary for crabs to shed their hard external shell. Growth is achieved through the process of ecdysis (moulting). The blue crab has five larval stages before settling as juveniles when they are about 5 mm across the carapace. Juvenile crabs occur in mangrove creeks and mud flats for 8–12 months by which time they attain a size of 80–100 mm carapace width. Crabs close to the minimum legal size (110 mm) are approximately 14 to 18 months old, sexually mature, and females have produced at least two batches of eggs within one season (Kumar et al., 2000, 2003).

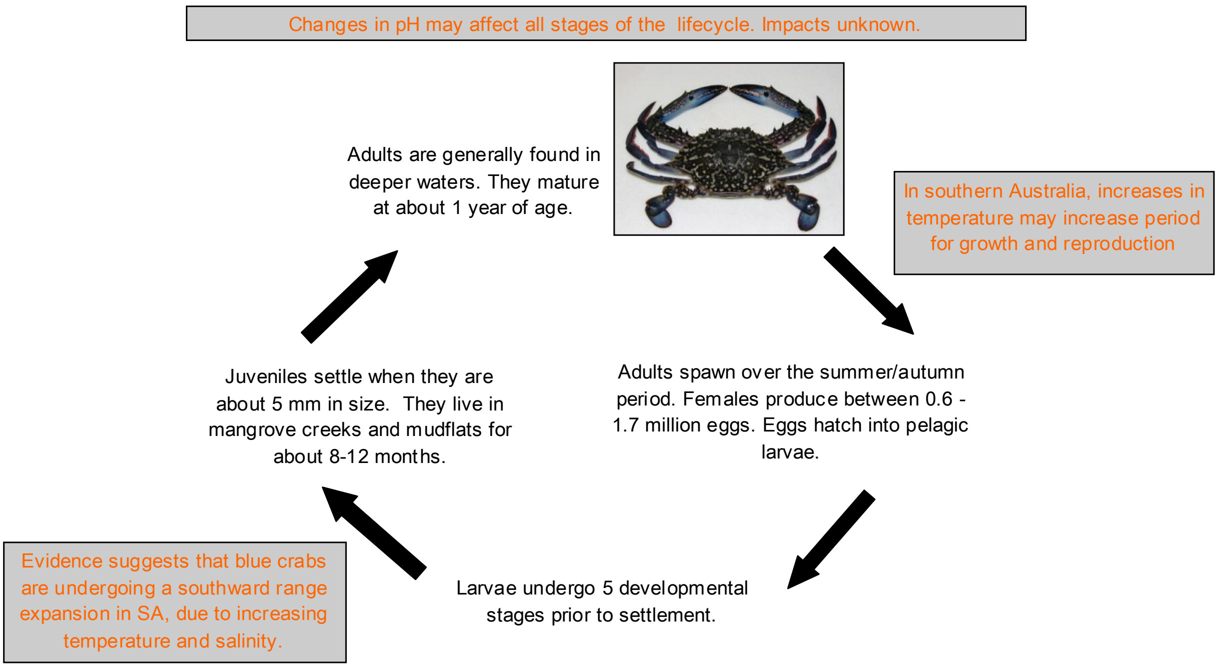

Figure 5.2: Summary of life cycle (this section), and points of exposure to relevant climate change drivers or known impacts (subsequent sections).

Key points:

- Blue crabs reach sexual maturity at approximately one year of age.
- The main spawning season is 3–4 months during summer and autumn.
- Female blue crabs are highly fecund, producing 650,000–1,760,000 eggs per clutch.
- The growth rate of blue crabs is poorly understood in South Australia.

5.2.2. Distribution and habitat

Portunus pelagicus is distributed throughout the coastal waters of the tropical regions of the western Indian Ocean and the Eastern Pacific (Kailola et al., 1993); they are adapted to a life in warmer waters. In Australia, they are distributed from southern WA, along the northern coast of Australia and down to southern NSW; they also occur in isolated populations in SA (Figure 5.3). In the relatively colder, temperate parts of Australia, the life cycle has evolved to increase growth and reproduction during the warmer part of the year when water temperatures increase to those similar in tropical regions. Activity reduces during the colder winter months.

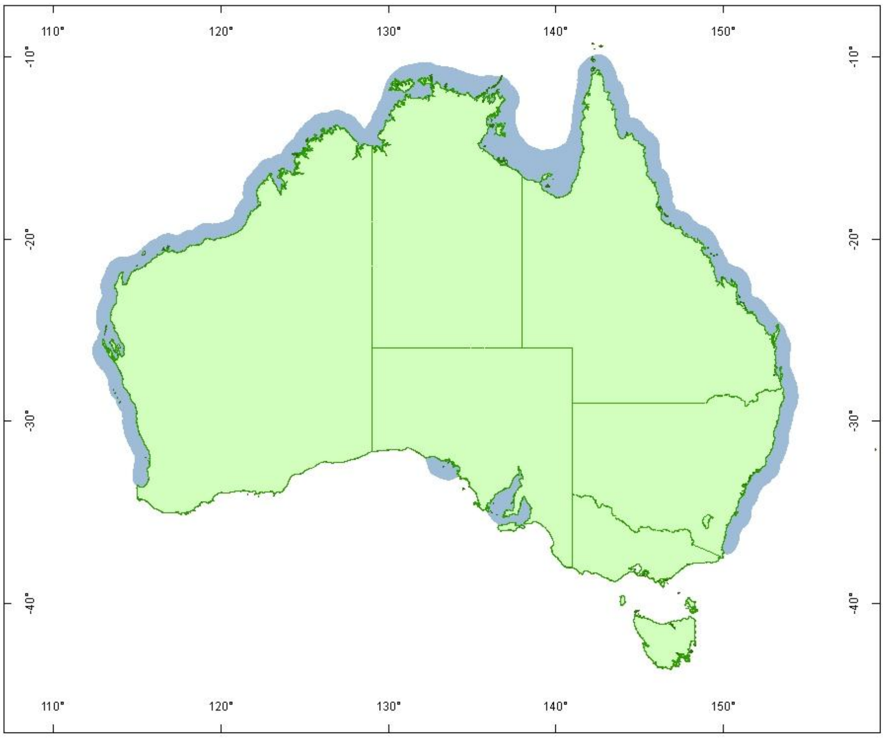

Figure 5.3: Distribution of blue swimmer crab in Australia.

P. pelagicus occurs in a wide range of algal and seagrass habitats and on both sandy and muddy substrata, from the intertidal zone to at least 50 metres of depth (Williams, 1982; Edgar, 1990). In coastal waters, smaller crabs are found in shallow waters, while adults are found in comparatively deeper waters. Within SA, there is a distinct seasonal pattern of adult crab movements into shallow inshore waters during the warmer months of September to April and to deeper offshore waters during the colder months of May to August (Smith, 1982).

Key points:

- Blue crabs are found throughout the western Indian Ocean and eastern Pacific.
- Within Australia their range extends from south-western WA to the NSW/Victoria border. South Australian populations are geographically isolated.
- Blue crabs inhabit a wide range of habitat types, from the intertidal zone to >50 m in depth.

5.2.3. Predators and prey

Studies on the feeding ecology of *P. pelagicus* indicate that it can be either a predator or a scavenger, depending on the local availability of prey species (Patel et al. 1979; Williams 1982; Wassenberg and Hill 1987). Research undertaken in Western Australia on the dietary composition of *P. pelagicus* illustrated that its diet comprised a variety of bivalves, gastropods, amphipods, polychaetes, echinoderms, teleosts and plant material (de Lestang et al. 2000). Small (<50 mm carapace width) crabs mainly forage on sand flats, whilst larger individuals were most abundant amongst seagrass and non-vegetated habitats further offshore (Edgar 1990). There is currently no scientific evidence to illustrate the feeding behaviour in waters adjacent to SA; however it is assumed that the same interactions are occurring.

During the moulting process, prior to hardening of the new shell, the crab is extremely vulnerable to predation and will often go into hiding. Of 132 fish species collected, over half of all fish species examined from Spencer Gulf had some combination of crabs, prawns and amphipods (Currie and Sorokin 2010). Blue swimmer crabs are known to be preyed upon by adult snapper (*Pagrus auratus*) (Matthew Lloyd, pers comm). In a study of the by-catch species of the Spencer Gulf Prawn Trawl Fishery (Currie et al 2009), blue crabs were the third most abundant species caught and the second highest in terms of biomass.

Key points:

- Blue crabs can be either a predator or scavenger and feed on a wide variety of organisms.
- Their high abundance and low trophic order suggest that they are a particularly important component of the tropho-dynamics of South Australia's gulf systems.

5.2.4. Recruitment

Recruitment to the fishery primarily occurs during the winter months of the year, i.e. June and July (Kumar et al., 2000). Estimates of recruitment strength are provided annually through a fishery independent survey conducted in winter months. Data on recruitment is also obtained from commercial logbook and commercial pot sampling data.

Key point:

- Recruitment of blue crabs is highly variable and primarily occurs during the winter months of the year.

5.3. Current impacts of climate change

As for prawns, the intuitive response to the current and potential impacts of climate change for blue crabs in South Australia is deemed positive, particularly for the favourable climatic changes of increased water temperate and salinity. There is some evidence to indicate that in the last five years the range and distribution of blue crabs has altered in both Gulf St Vincent and Spencer Gulf, with a general increase in range as crabs are found (and fished) further south than previous years.

Key point:

- Recruitment of blue crabs is highly variable and primarily occurs during the winter months of the year.

5.4. Sensitivity to change

Climate change would appear overwhelmingly favourable for blue crabs in SA. The only sensitivities may occur with associated changes in the ecosystem it inhabits.

Key point:

- Further climate change would be likely favourable for blue crabs in SA.

5.5. Resilience to change

As blue crabs in South Australia are at the southern extent of their range, increases in water temperature are likely to be favourable to the species. This may result in a greater period of growth and reproduction, which is seasonal in South Australia unlike most other regions within its range. In a prawn trawl by-catch survey conducted at trawl shots >10 m in depth throughout Spencer Gulf (Currie et al 2009), the distribution of blue crabs appeared to be limited by abiotic factors, with a 'line' that stretched east to west about half way up the gulf below which no crabs were caught. This may reflect tolerances to salinity and or temperature. Increases in temperature and salinity may therefore extend this boundary, which probably reflects the changes in distribution observed in both of the gulfs over the last five years.

Key point:

- Increases in water temperature and to some extent salinity, would appear to be favourable for blue crabs in SA.

5.6. Ecosystem level effects

Extension in the range and distribution of blue crabs further south into the gulfs will likely have substantial effects on the local communities that have previously not been affected by this species. The Spencer Gulf by-catch study demonstrated that several different benthic communities existed within its range, with discrete boundaries best explained by latitude (Currie et al 2009). It is likely that these boundaries will shift with climate change.

Key points:

- Extension of the range and distribution of blue crabs is likely to influence community structure in some regions.
- The plastic nature of the blue crab diet suggests that their populations will be unaffected by changes in community structure.
- Blue crabs may be affected by changes in predator abundance.

5.7. Additional stressors

5.7.1. *Exploitation*

The South Australian blue crab fishery is quota managed by PIRSA Fisheries. Most of the quota is caught on an annual basis by the pot fishing sector (Dixon and Hooper 2010). There is also significant recreational catch (Jones 2009). Recruitment to the fishery appears to be highly variable and as such the level of exploitation likely varies among years. While the fishery is <30 years old, catches appear to have been maintained in a sustainable manner and current catch quotas are below historical peak catch (Dixon and Hooper 2010).

Key points:

- The fishery appears to be managed sustainably.
- Increases in the range and distribution of blue crabs are unlikely to have a negative influence on sustainability.

5.7.2. Pollution, habitat degradation

A number of anthropogenic factors may cause environmental degradation, resulting in negative effect on marine species (Highsmith et al., 1996; Hooten and Highsmith, 1996; Stekoll et al., 1996; Carman et al., 2000; Huntingford et al., 2006) (Table 5.2). Environmental stressors can substantially increase the risks associated with spread of disease and pests, and push species towards their physiological thresholds. These are limiting factors in marine animal populations, although generally overlooked in fisheries management (Harvell et al. 2004). These issues are of particular relevance to the sustainability of fisheries located within South Australia's semi-enclosed and isolated gulf systems, although this area of research is limited for these regions.

Inter-tidal sand/mud flats, associated shallow water environments (including seagrass meadows) and mangrove forests in South Australia's gulfs are important juvenile nursery habitats for a number of commercially and recreationally important species. These coastal habitats are highly susceptible to anthropogenic coastal impacts such as oil spills, acid sulphate soil disturbance from coastal development, heavy metals, wastewater and stormwater discharge.

In upper Spencer Gulf, several key industrial complexes have discharged large amounts of heavy metals and nutrient-rich water into the coastal environment for decades (Harbison, 1984; Tiller et al. 1989; Ross et al. 2003; Corbin and Wade, 2004.). Trace metals subsequently enter the food web, and may have lasting effects on the physiology, reproduction and survival of local marine organisms (Ward, 1982). Further, coastal discharges can negatively affect seagrasses (Ward, 1987; Bryars, 2003), with losses previously reported in the region (Seddon et al. 2000). While oil spills from shipping within SA's gulfs are rare events, when they do occur the consequences can be catastrophic and directly affect economically important species (Wardrop et al. 1993; Roberts et al. 2005).

Acid sulphate soils exist along South Australia's coastline, and may be disturbed by coastal developments and dispersed and augmented by rainfall (SA Coast Protection Board, 2003). In Gulf St Vincent, acid sulfate discharge has been identified as a major cause of habitat degradation, including mangrove dieback at St Kilda and contaminated tidal flats in the Barker Inlet (Edyvane, 1999; SA Coast Protection Board, 2003). Disturbance of these soils has previously been attributed to massive mortalities of fish, crustaceans, shellfish and other organisms, affecting both coastal aquaculture and fisheries (Russell and Helmke, 2002; SA Coast Protection Board, 2003). Resultant acidic waters enhance the breakdown of metal-bearing sediments, and increase trace metal concentrations in the environment. Stock collapse of the Australian Bass (*Macquaria novemaculeata*) in NSW, due to recruitment failure, has been partially attributed to acid sulfate discharge (Harris, 1989).

Table 2: Environmental degradation, as a result of human activities, identified by Huntingford et al. (2006) that potentially compromise fish health and welfare.

Activity	Examples of potential effects on welfare
Environmental degradation	• Reduced availability of natural food. • Introduction of exotic species into existing fish communities. • Habitat modification, creating (*e.g.*) sub-optimal hydrological regimes. • Loss of or displacement from natural habitats. • Reduced population densities (or crowding) and abnormal social experiences. • Disturbance through tourism. • Acute and chronic exposure to pollutants and litter.

Key point:

- Blue crabs are susceptible to environmental degradation, especially in their nursery habitats. This is particularly the case for the two gulf populations where heavy industry and urban runoff are critical factors that may affect recruitment to the fishery.

5.8. Critical data gaps and level of uncertainty

The growth rates and movement patterns of blue crabs in South Australia are poorly understood. This is largely because it is difficult to apply appropriate tagging techniques for this species. While reliable fishery-independent data are consistently obtained on recruitment patterns for the fishery, some uncertainty exists in these measures due to the variable timing and highly variable extent of annual recruitment events. The collection of additional reliable and cost-effective measures for recruitment strength would substantially augment the current assessment. Also, there is some uncertainty regarding the impact of climate change on the oceanographic patterns of water movement that are critical to larval advection and adult movement in South Australia

Key points:

- Critical data gaps include:
  - Knowledge on growth rates and movement patterns
  - Need for additional measures of recruitment to improve reliability of assessment
  - An understanding of the effect of climate change on larval advection pathways.

Table 5.1: Summary of blue swimmer crab species profile, which also indicates level of certainty of the associated information. Level of certainty is divided into high (H) = strong clear evidence, backed by several studies with solid datasets with little confounding interactions; medium (M) = evidence supported by one or more studies, conclusions may be partially ambiguous or confounded; low (L) = anecdotal evidence, limited data and/or predicted conclusions based on theoretical knowledge.

Life history stage	Multiple stressors	Distribution	Habitat	Predators and prey	Current impacts	Predicted impacts	Ecosystem interactions	Data gaps
Eggs		See Fig 3			Over last 5 years, the population has extended its range further south in SA (L).	Temperature increases may result in a greater period for growth and reproduction (L).	Range extension of blue crab may impact local communities in SA (L).	
Larvae			Pelagic					Growth and movement patterns. Additional measures for recruitment. Effects of climate change on larval advection pathways
Juveniles	Shallow water habitats are highly vulnerable to pollution		In coastal waters, smaller crabs are found in shallow waters.	Prey: invertebrates, teleosts and plant material (H) Predators: various fishes, including snapper (M)				
Adults	Exploitation, sustainable		Algal and seagrass habitats, both sandy and muddy substrata, from intertidal zone to 50 m deep. Adults are found in deeper waters.					

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6.Commercial scallop *Pecten fumatus*

Author: Zoe Doubleday

6.1. The fishery

Scallop fisheries are generally described as 'boom and bust' fisheries with a very variable annual production. In Australia, commercial scallops (CS; *Pecten fumatus*) are harvested by benthic dredge in Tasmanian, Victorian and Commonwealth waters. Currently, important commercial fishing grounds include off Lakes Entrance (Victoria), central Bass Strait (Commonwealth), and several locations on the east coast of Tasmania ranging from Flinders Island to Marion Bay. In South Australia there is a small-scale targeted dive fishery and scallops are also taken as by-product from the prawn fisheries. Until recently the Tasmanian CS fishery was the major scallop fishery in south east Australia, with an estimated value of $7.5 million in 2006/07; however, the fishery has been closed since 2009.

Scallops are vulnerable to overfishing as they are an easily exploitable resource. In 2003, after a three-year closure due to stock collapse, the Tasmanian fishery has been managed under a rotational closed-area spatial management regime to help ensure long-term sustainability (Harrington et al. 2007). A simple explanation of the new regime is that only relatively small regions of known scallop stock (generally <30 km x 30 km blocks) are opened to commercial fishing and all other regions of the fishery stay closed (Harrington et al. 2008). In 2008 the Commonwealth fishery applied a similar spatial management regime, and the fishery was re-opened in 2009. In Victoria, the CS fishery contributes ~5% to the value of the states commercial catch, with production highly variable between years. For example, from 2002 to 2007, catches varied from 266 to 738 tonnes with a value of $ 0.4 – 1.1 million (DPI 2008). Catches in Victoria are managed under a quota system, with annual management decisions made in consultation with industry to determine when the fishery should open, and the Total Allowable Commercial Catch (TACC). The under-utilisation of the TACC in some years has been attributed to economic factors, and not due to lack of available scallops (DPI 2008). CS are a significant recreational species in Tasmania, with approximately 402,000 individuals caught in 2007/08 (Lyle et al. 2009).

Key points:

- Commercial scallops are harvested by Tas, Vic, and the Commonwealth.
- Annual production is highly variable, and fisheries are subject to periodic closures.
- Scallop is an important recreational species.

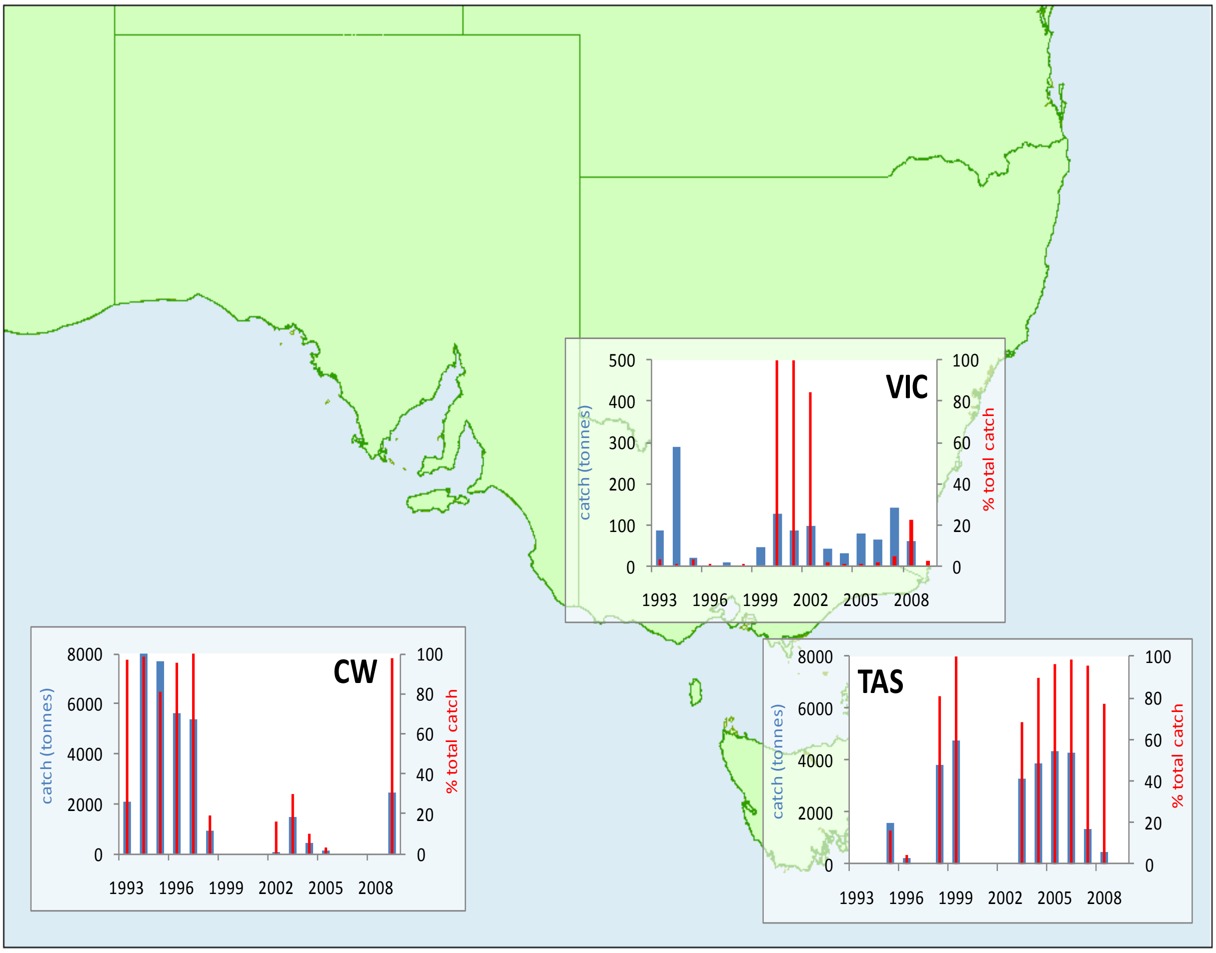

Figure 5.1: Commercial catch (tonnes) and contribution by each jurisdiction to total catch in south-east Australia (%) by year for Commonwealth, Victoria and Tasmania. Zero catch = fishery closure. Note different scale on y axis for Victoria.

6.2. Life history

6.2.1. Life cycle, age and growth

Commercial scallops are functional hermaphrodites and broadcast spawners, releasing eggs and sperm into the water column (Figure 6.2). They are highly fecund, producing up to 10 million eggs during a single spawning event (Dix and Sjardin 1975). CS typically spawn from August to October in Tasmania, June to November in Victoria, and April to December in NSW (Young et al. 1999, and references therein). A study of two *P. fumatus* populations in Bass Strait found that a seasonal cycle of gonadal development occurred, commencing at the time of lowest water temperatures and highest nutrient concentrations, with development progressively increasing as nutrient concentrations declined (Young et al. 1999). The larvae are planktonic and planktotrophic and have two key developmental stages – trochophore larvae and veligers (Cragg 2006). At the end of larval life, veligers metamorphose and settle to the seafloor as juveniles or spat. Larval development (the time between fertilisation and metamorphosis) is strongly influenced by temperature in pectinids (Heasman et al. 1996). Laboratory studies observed that the larval duration of *P. fumatus* was 31 days at 13–15°C (Dix and Sjardin 1975) and 15–16 days at 18–19°C (Frankish et al. 1990, in Heasman et al. 1996). *P. fumatus* typically reach sexually maturity in their second year (Dredge 2006). Research indicates that growth rates vary significantly in CS; however, average shell length is about 30–40 mm in their first year of life and 70–80 mm in their second year (Dredge 2006). Year classes over 10 years have been recorded in the early 1950s from shell increment counts in south east Tasmania (Fairbridge 1953).

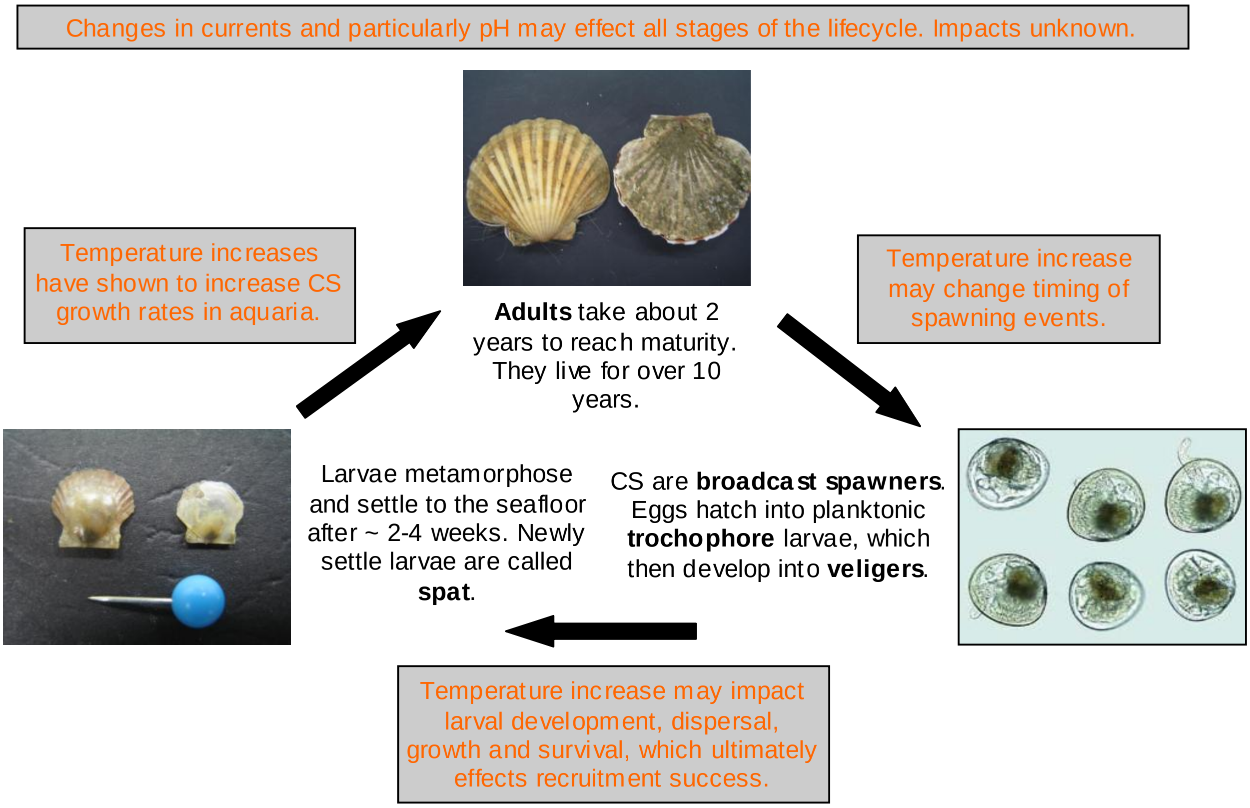

Figure 6.2: Summary of life cycle (this section), and points of exposure to relevant climate change drivers or known impacts (subsequent sections). Image of larvae: *Argopecten gibbus* veliger, sourced from Helm et al. (2004). Images of spat and adults: *Pecten fumatus*, Z. Doubleday (IMAS).

6.2.2. Distribution, habitat and environmental preferences

Commercial scallops are distributed from mid-NSW, around Tasmania, and west across to mid-WA (Shark Bay) (Kailola et al. 1993) (Figure 3). There are some reports that CS are found as far north as southern Queensland; however, their taxonomy is uncertain. CS were once considered four species based on shell morphology: *P. fumatus* (NSW), *P. albus* (Vic and SA), *P. meridionalis* (Tas) and *P. modestus* (WA) (Kailola et al. 1993). A genetic study indicates that all south-east Australian populations are at least a single species complex (Woodburn 1988); however, there still appears to be some debate in the literature about the species status of *P. fumatus* populations in WA.

CS occur on substrates ranging from muddy sand to course sand both in enclosed bays and exposed oceanic environments (Young et al. 1999). They live at depths ranging from 7 to 60 m. Scallop species typically have an aggregated patchy distribution; within their geographical range there is usually a number of distinct regions or 'beds', typically an area of several km^2, where scallop abundance is higher than elsewhere (Brand 2006). Furthermore, within scallop beds, individuals may be aggregated into 'patches' which cover tens or hundreds of square metres.

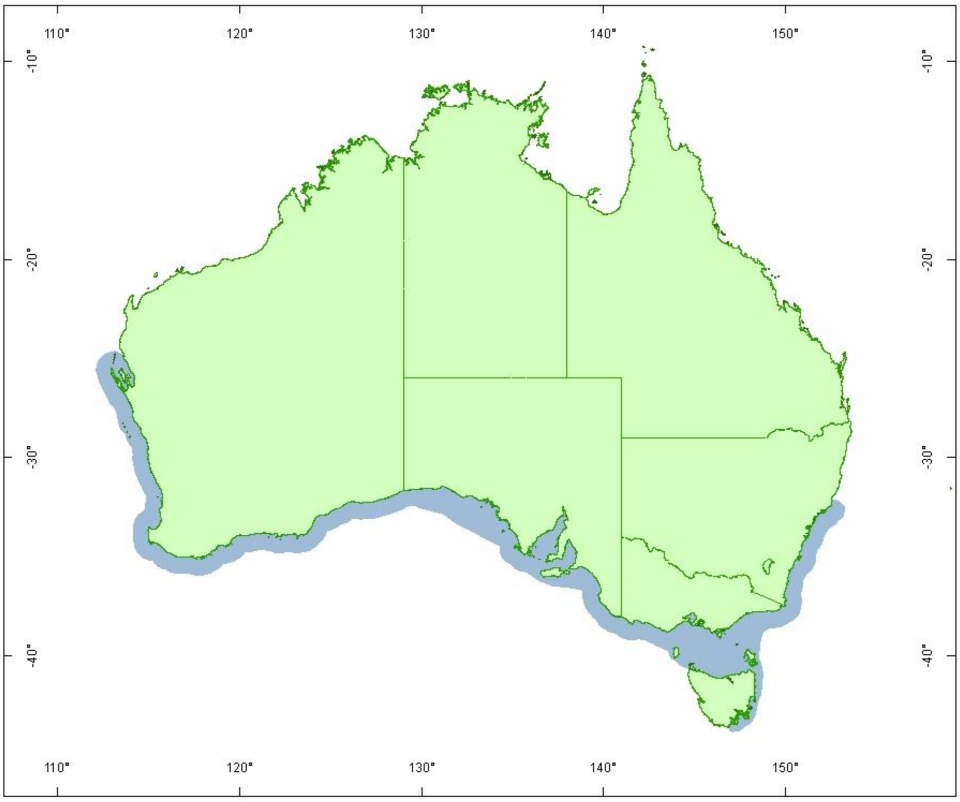

Figure 6.3: Distribution of commercial scallops.

6.2.3. *Predators and prey*

Scallops are filter feeders and consume phytoplankton and detritus from the water column (Kailola et al. 1993). Predators include demersal fish, demersal sharks, rays, starfish and octopus. Predators in high concentrations can limit scallop distribution and abundance, with spat and juveniles being particularly vulnerable (Brand 2006). One study estimated that predation by the eleven-armed spiny starfish resulted in a mortality rate of 75–80% over four years in a scallop bed in south-east Tasmania (Olsen 1955).

6.2.4. *Recruitment*

Recruitment is highly variable in scallops; in *P. fumatus* recruitment is typified by irregular pulses of high abundance followed by periods of scarcity. Timing of spawning, larval development and advection in scallops is strongly linked to temperature, which in turn influences recruitment and recruitment variability (Orensanz et al. 2006). Increasing temperature in the Irish Sea has been correlated to increased recruitment in *P. maximus* due to increased gamete production (Shephard et al. 2010). In contrast, a study which analysed scallop catch data from the 1940s and 1960s in Tasmania in relation to climate variability found that a high incidence of zonal westerly winds appeared to favour scallop recruitment, which are associated with colder water and increased productivity (Harris et al. 1988).

Settlement patterns may also depend on suitable habitat and density-dependent factors. Scallop beds frequently show spatial variations in population age structure, indicating spatial variation in settlement and recruitment (Brand 2006). However, due to the difficulties associated with studying larval and early settlement stages in the field, little is known about the recruitment processes which determine these spatial differences in year-class distribution.

Key points:

- CS are benthic, but have a short pelagic larval phase.
- CS are patchily distributed throughout southern Australia in sandy habitats.
- Scallops are filter feeders; predators include sharks, fish, rays, octopus, and starfish.
- Recruitment is highly variable, both on a temporal and spatial scale.

6.3. Current impacts of climate change

There are no known impacts of climate change on CS. However, a significant positive correlation between recruitment and increasing temperature in the Irish Sea has been observed in *P. maximus* over a 16 year period (Shephard et al. 2010). The study indicated that greater gamete production was the key underlying cause of increased recruitment, which was probably due to greater food availability.

Key point:

- There are no known impacts of climate change.

6.4. Sensitivity to change

Scallops, like other $CaCO_3$-producing organisms, may be particularly sensitive to ocean acidification (due to increasing CO_2 levels). A recent study found that increased levels of CO_2, predicted to occur later this century, significantly decreased larval size and survivorship (>50%) and delayed metamorphosis in the scallop *Argopecten irradians* (Talmage and Gobler 2009).

As larval development, and thus the duration of the planktonic larval phase, is largely dependent on water temperature (Cragg 2006) (see also Section 6.2.1) increasing temperature may thus impact the dispersal capacity of the species. One study hypothesised that higher temperatures would lead to greater retention of the larvae inshore (i.e. due to reduced dispersal capacity), leading to good settlement and recruitment (Dickie 1955, in Orensanz et al. 2006). However, the relationship between temperature and scallop development, growth and survival is complex. A laboratory study found that the optimal rearing temperature for *P. fumatus* varies ontogenetically: 18 °C for development of eggs to veligers; 21°C for larval growth and survival, although growth rates reached their peak at about 24°C, they did not survive to metamorphosis; and 24°C for the growth and survival of spat (Heasman et al. 1996). Spat showed increasing growth rates from 13 to 24°C, which then declined at 27°C. These ontogenetic differences may reflect thermal adaptation between the embryonic, larval and benthic environments (Cragg 2006). Synchronous spawning is important for scallop reproduction and temperature is an important spawning trigger (see Orensanz et al. 2006, and the three documented examples therein). Temperature change in the future, therefore, may disrupt the timing and synchronicity of spawning events.

Key points:

- Research demonstrates that increasing acidification may have a profound impact on $CaCO_3$-producing organisms such as bivalves; however, impacts on CS specifically are unknown.
- Temperature strongly influences larval development, growth and timing of spawning events.

6.5. Resilience to change

Commercial scallops have a large distributional range with mean sea temperatures varying from 9 to 11°C in Tasmania (minimum winter values) and 23–25°C in NSW (maximum summer values) (Heasman et al. 1996), and thus an expected large thermal tolerance. A genetic study found relatively low genetic variability amongst CS populations in south-east Australia, particularly in the Bass Strait region, suggesting a level of gene flow, probably via the dispersal of planktonic larvae, within the region (Woodburn 1988). However, genetic markers, and particularly allozyme markers which are used in the latter study, are particularly conservative at estimating population variability at the intra-specific level. Although changing oceanic currents may impact larval transport patterns, larval dispersal may prevent localised population effects due to climate change and may enable the species to shift distribution to maintain an optimal environment.

Key points:

- CS have a large distributional range which represents a wide thermal range.
- CS have a moderate dispersal capacity, potentially increasing the species' resilience to changing environmental conditions.

6.6. Ecosystem level interactions

There are no known novel ecological interactions which have occurred as a result of climate change, either due to changes in CS or changes to other species which may affect CS.

Key point:

- There are no known current or predicted future novel ecosystem interactions as a result of climate change.

6.7. Additional (multiple) stressors

Scallops are vulnerable to overfishing and production can be highly varied. As a result the Tasmanian, Victorian and Commonwealth fisheries undergo periodic closures due to stock depletion (see Figure 1). For example, in Victoria, catches from Lakes Entrance have varied from 8269 t in 1993 to negligible or zero catches in 1995, 1998, 1999 and 2010 (DPI 2008). However, to ensure the long-term sustainability of CS there has been increasing use of spatial management methods in both Tasmanian and Commonwealth waters (Harrington et al. 2008), with indications that this method can limit the duration of the 'bust' period.

Additional pressures on CS populations include the impact of introduced species. Field experiments have shown that the exotic clam *Corbula gibba* has a negative impact on the size and growth of juvenile CS in Port Phillip Bay, which is probably a function of resource competition (Talman and Keough 2001). Of particular concern is the introduced predatory sea star *Asterias amurensis* (or northern Pacific sea star), which was first observed in Tasmania in 1986. The sea star is a veracious predator of bivalves; in Tasmania it has been reported that losses of scallop spat over settlement season due to *A. amurensis* predation may be as high as 50% (Hutson et al. 2005). Furthermore, a study found that CS did not elicit an escape response in the presence of *A. amurensis*, which is normally elicited in the presence of the native sea star *Coscinasterias muricata* (Hutson et al. 2005). The absence of such predator recognition may have serious consequences for CS populations; however, the sea star is currently rare in the exploited open coast habitats.

Key points:

- CS are vulnerable to overfishing and exploitation will likely have a strong influence on the impacts of climate change on CS.
- Introduced species, such as the northern Pacific sea star, may place additional stress on CS populations.

6.8. Critical data gaps and level of uncertainty

Although several experimental studies demonstrate that lowered pH levels can have dramatic effects on the growth, mortality and larval development of several bivalve and gastropod species (eg. Gazeau et al. 2007; Talmage and Gobler 2009), there is no information on how increasing ocean acidification will affect CS. This will be crucial in determining the future impacts of climate change. In general, little known is known about the effects that environmental factors, such as temperature, food availability, turbidity, currents, salinity, and oxygen concentration, have on scallop growth, reproduction and recruitment (Brand 2006). There are also limited studies on the spatial population structure, dispersal patterns, and the relationship between stock abundance and recruitment patterns.

Key points:

- Nothing is known about the potential impacts of increasing ocean acidification on CS, which is known to have negative impacts on other marine calcifiers.
- Limited knowledge on how environmental factors effect scallop growth, reproduction and recruitment.

Table 6.1: Summary of commercial scallop species profile, which also indicates level of certainty of the associated information. Level of certainty is divided into high (H) = strong clear evidence, backed by several studies with solid datasets with little confounding interactions; medium (M) = evidence supported by one or more studies, conclusions may be partially ambiguous or confounded; low (L) = anecdotal evidence, limited data and/or predicted conclusions based on theoretical knowledge.

Life history stage	Multiple stressors	Distribution	Habitat	Predators and prey	Current impacts	Predicted impacts	Ecosystem interactions	Data gaps
Eggs	Unknown	See Figure 2 (M)	Planktonic (H), little known on dispersal pathways	Unknown	Unknown	Ocean acidification may have a negative impact on scallop development and survival (L) Temperature increase may disrupt larval development, dispersal, growth and timing of spawning (L)	Unknown	Effect of decreasing pH on shell development and survival Effects of environmental change on CS biology Understanding recruitment variability
Larvae								
Spat	Invasive species (M)		Sandy substrates, in bays and oceanic environments (H)	Filter feeders (H) Predators: fish, sharks, rays, starfish, octopus (H)				
Adult	Exploitation (H), and invasive species (M)							

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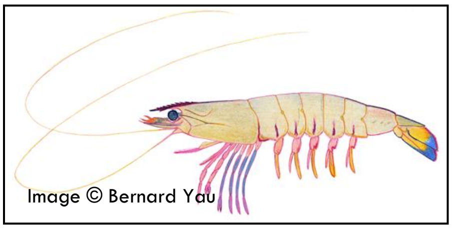
7.Eastern king prawn *Melicertus plebejus*

Author: Philip Gibbs



7.1. The fishery

The eastern king prawn (*Melicertus plebejus*) resources of NSW are fished in estuaries by recreational and commercial fishers and at sea by commercial fishers. The Ocean Prawn Trawl Fishery dominates the contributions to the annual reported landings both in terms of weight and value followed by the Estuary General and Estuary Prawn Trawl Fisheries. Recreational landings of prawns from estuaries contribute 5% by weight to the total landings (Montgomery and Reid, 1995 and Henry and Lyle, 2003). The dominance of eastern king prawns rather than school prawns in the recreational sector is because recreational fishers fish for prawns at night when eastern king prawns are most active. Methods used by recreational fishers include fishing with scoop nets, scissor nets or six metre hand haul nets. The annual recreational harvest of eastern king prawn in NSW is likely to be about 110 t. This estimate is based upon the results of the offsite National Recreational and Indigenous Fishing Survey (Henry and Lyle, 2003) and onsite surveys undertaken by NSW DPI.

Eastern king prawns constitute a single population along the east coast of Australia and are managed as a unit stock by NSW DPI. The Ocean Prawn Trawl and Estuary General (prawn) fisheries can operate in all fishing zones along the NSW coast during the whole year. Eastern king prawns are caught along the whole coast of NSW and, like school prawns, annual reported commercial landings by weight in the Ocean Prawn Trawl and Estuary General Fisheries are greatest in the north of the state. Whilst the seasonal pattern of landings from estuaries is variable, the greatest landings from the ocean occur during March to July, when the prawns have emigrated from the estuaries and are moving northwards along the coast. In the far south of the state the greatest annual landings from estuaries occur during summer, whilst those from the ocean show no consistent pattern.

Catches of eastern king prawn increased for the Ocean Prawn Trawl fishery in 2007/08. Catch rates remained high in 2008/09 but landings returned to pre-2007/08 levels. Strong evidence exists that fishing power in Queensland is increasing and there has been increased targeting by the Queensland fleet on the mature offshore population.

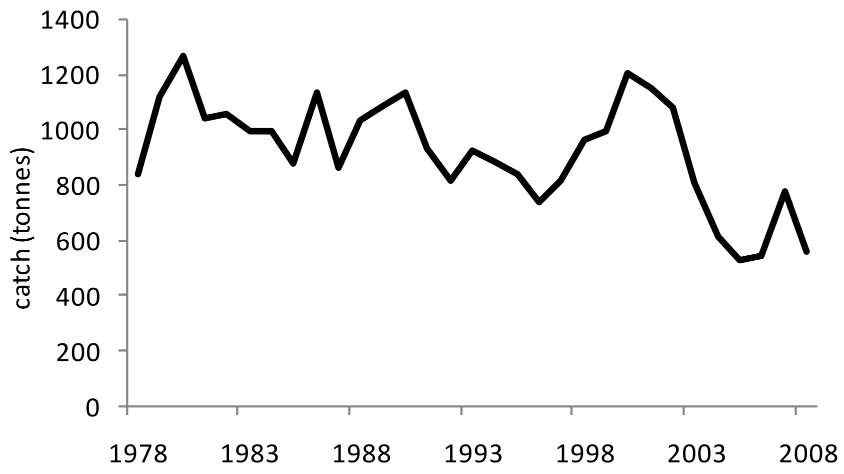


Figure 7.1: Commercial catch (tonnes) by year for NSW.

Key points:

- Eastern king prawns are a single stock on the east coast
- The species is very important in both the commercial and recreational catch

7.2. Life history

7.2.1. Life cycle, age and growth

Eastern king prawns spawn predominantly in waters from northern NSW to Swains Reef in Queensland. One female may carry up to 200,000 eggs. Larger female prawns carry more eggs than smaller ones. There is no information on the length of the larval phase of the life cycle of eastern king prawns in the wild, but generally for prawn species it is around three weeks. Nauplius larvae hatch and develop through a series of moults into post-larvae. This is the transitional phase between the planktonic larva and benthic living juveniles. Post-larval to adolescent eastern king prawns inhabit bare and vegetated substrates in areas of marine influence within estuaries and probably within shallow embayments in ocean waters. They emigrate from estuaries over spring and summer and then move northwards over long distances prior to spawning. They do not spawn in estuaries but rather once at sea migrate over distances of sometimes in excess of 1000 km in a northerly direction to spawn in waters off northern NSW to central Queensland (Montgomery, 1990; Montgomery et al., 1995). The size of maturity for this species is around 38 mm carapace length (CL) and 42 mm CL for males and females, respectively.

Eastern king prawns live for a maximum of three years and in NSW waters reach maximum lengths of around 6 cm CL and 4.5 cm CL for females and males respectively. The shortest length at which 50% of female eastern king prawns carry eggs is 4.2 cm CL.

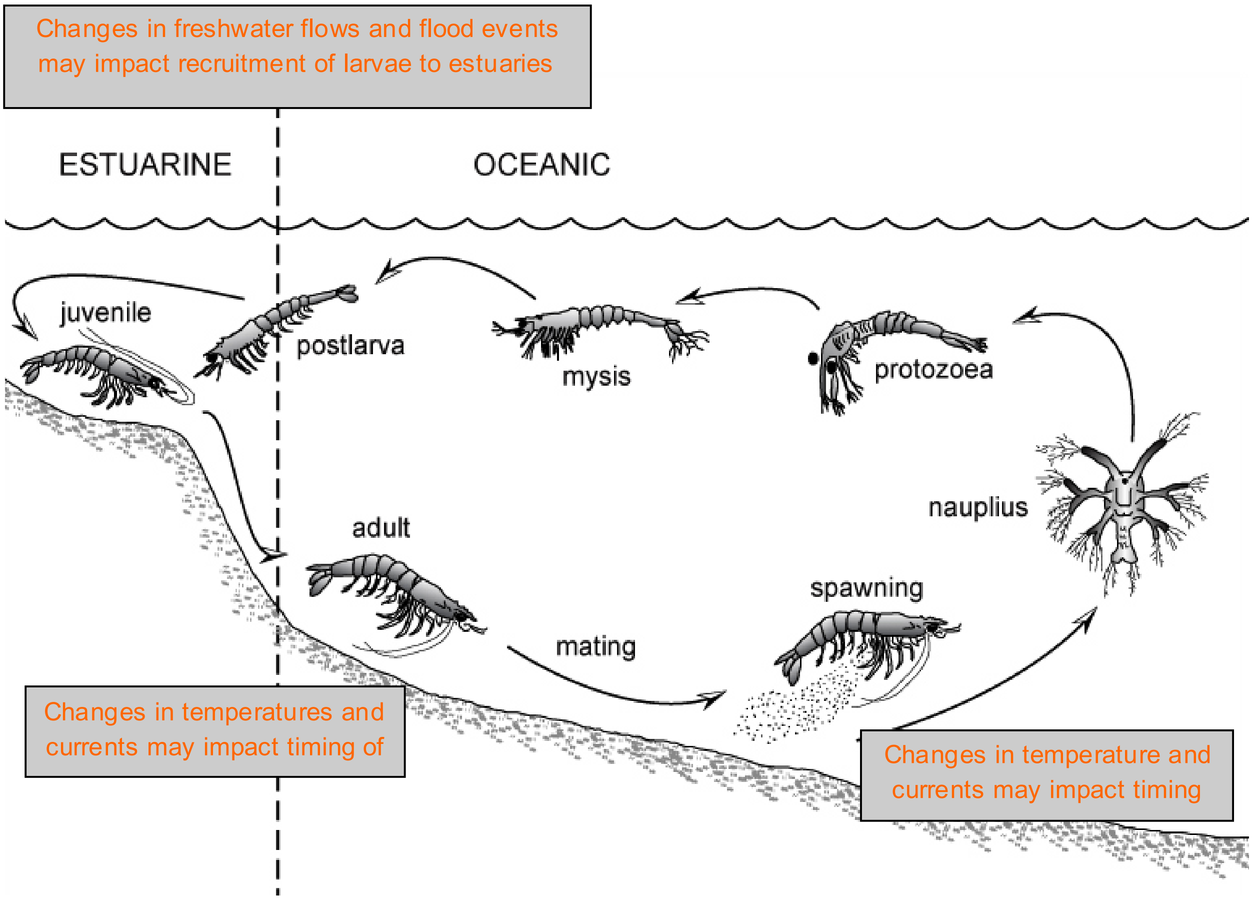


Figure 7.2: Summary of life cycle (this section), and points of exposure to relevant climate change drivers or known impacts (subsequent sections).

7.2.2. *Distribution, habitat and environmental preferences*

Eastern king prawns are endemic to the waters off eastern Australia; they have been recorded from Mackay (Queensland) to north-eastern Tasmania in depths from 1 m to 200 m, and off Lord Howe Island.

Eastern king prawns are distributed on sandy substrates in waters out and beyond the continental shelf.

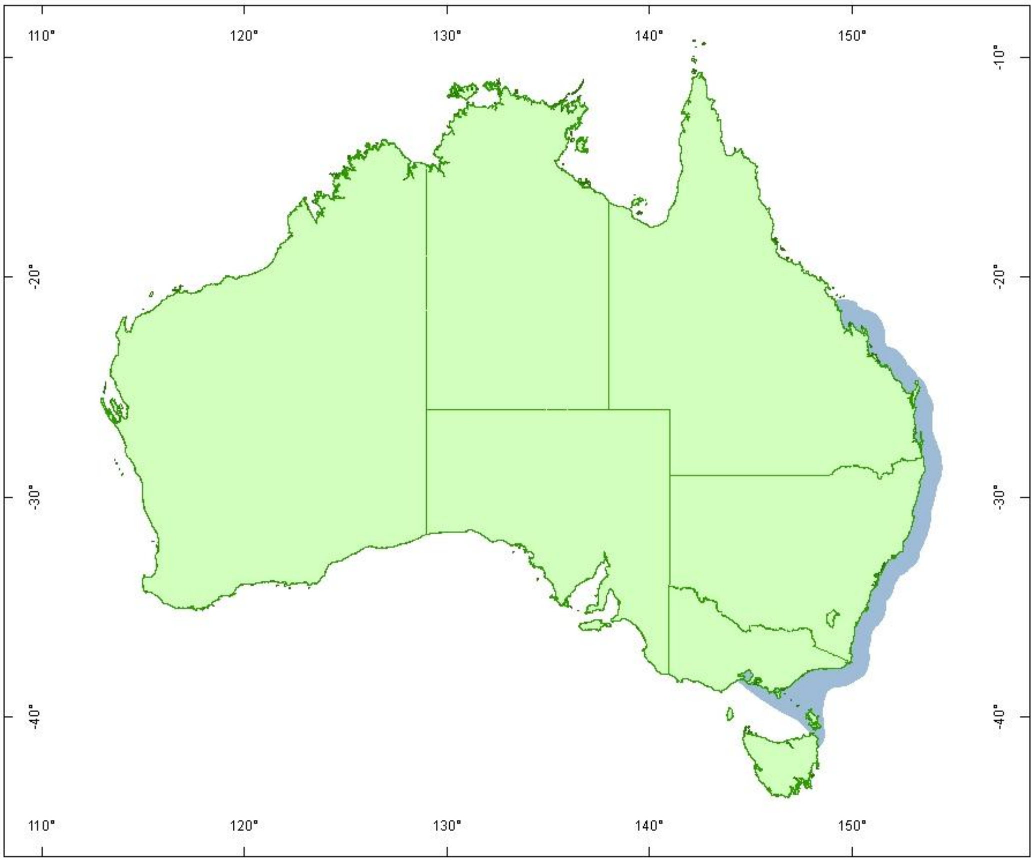


Figure 7.3: Distribution of eastern king prawns.

7.2.3. Predators and prey

Eastern king prawns are opportunistic omnivores. Food items include small crustaceans, annelid worms, bivalve molluscs and foraminifers.

Eastern king prawns are eaten by most carnivorous marine fish species and higher order predators including birds and marine mammals.

7.2.4. Recruitment

The greatest abundance of female eastern king prawns capable of spawning occurs northwards from Ballina (28° 52'S) to Swains Reef (21° 05'S) (Courtney et al., 1995, Montgomery et al., 2007). There are no available data about the relative abundance of the breeding stock of eastern king prawns.

The basic conclusion by Glaister et al. (1990) from investigations of eastern king prawns in waters off northern NSW was that prawns were being exploited at a very high level and that further increases in fishing effort would cause declines in catch per operator. Montgomery (2000) concluded that the eastern king prawn resource was being exploited at about the level of maximum sustainable yield but the sizes of the prawns being caught were far smaller than the optimal sizes at first capture. Results from modelling the population suggested that the optimum size at first capture for eastern king prawns is within the range of 28–40 mm CL. However, increasing numbers of small prawns are being caught as offshore fleets fish further southwards and fishing pressure from recreational and commercial fishers in estuaries increases.

Eastern king prawns first appear in the catches of the Estuary General Fishery and the recreational fishery as juveniles around the size of 12 mm CL. The distribution of sizes of prawns in the catch will depend upon the geological features and geographic locality of the estuary where the prawns were caught. Estuaries in more southern waters have larger prawns as do those which open intermittently to the ocean.

Results from the model by Gordon et al. (1995) suggested that there may be both biological and economic benefits in allowing eastern king prawns from estuaries in certain areas to move to ocean waters before being caught.

Recent Bayesian modelling of eastern king prawn stocks (Ives and Scandol 2007) under differing harvest strategies and a range of depletion rates suggests the stock is not at high risk of over exploitation provided continued and robust recruitment continues in the north of the species' range.

Key points:

- Eastern king prawns live to about 3 years and undergo significant downstream migration in estuaries and significant northerly migrations in the ocean.
- The stock of EKP is fully exploited.
- EKP are a food source for many other fish and crustacean species.

7.3. Current impacts of climate change

No current impacts of climate change on eastern king prawn are documented. However, Montgomery (1990) presents a prediction of possible effects related to a southern strengthening of the EAC, increased water temperature and changing freshwater flow to estuaries. It is predicted that eastern king prawns may emigrate from estuaries earlier in the year than at present; they may spawn earlier in the year and spawn further south; and there may be an overall southward extension of their geographic distribution.

7.4. Sensitivity to change

The estuarine phase in the life cycle of eastern king prawn is the most sensitive to climate change, especially in relation to freshwater input to the estuaries. Recruitment of the larval prawns to estuaries is reduced during high freshwater input or floods. In addition, the increasing southern flow of the EAC is likely to shift the northern spawning grounds of the species south and this may impact stock levels in NSW.

7.5. Resilience to change

The broad geographic range, high fecundity and lower trophic level of the species and large variations in growth, mortality and recruitment of the species in both space and time suggest it is resilient to the predicted rate of change under most climate shift scenarios.

Population modelling (Ives and Scandol, 2007) indicated that the NSW stock was very resilient under the assumption of stable levels of recruitment from Queensland.

7.6. Ecosystem level interactions

Prawns are low on the feeding pyramid and the prey items for many other species. Therefore ecosystem interactions are likely to be widespread in terms of trophic dynamics.

7.7. Additional (multiple) stressors

No current information.

7.8. Critical data gaps and level of uncertainty

Current modelling of the NSW king prawn stock and the effect of changing commercial harvest rates on sustainability (Ives and Scandol 2007) highlighted data gaps. These related to significant uncertainties in the calculated biomass and the lack of contrast in the catch and effort data. The models were highly sensitive to recruitment and the mode outputs are very dependent on the assumption of strong ongoing recruitment from Queensland. Under most climate scenarios, the EAC moves south and may change current recruitment patterns.

Table 7.1: Summary of species profile, which also indicates level of certainty of the associated information. Level of certainty is divided into high (H) = strong clear evidence, backed by several studies with solid datasets with little confounding interactions; medium (M) = evidence supported by one or more studies, conclusions may be partially ambiguous or confounded; low (L) = anecdotal evidence, limited data and/or predicted conclusions based on theoretical knowledge.

Life history stage	Multiple stressors	Distribution	Habitat	Predators and prey	Current impacts	Predicted impacts	Ecosystem interactions	Data gaps
Eggs	Unknown	See Figure 4 (H)	Offshore (H)			Distribution strongly impacted by changes in the EAC (H) High resilience to change provided recruitment remains stable (H)		Stock biomass estimates and knowledge of the recruitment strength from Queensland
Larvae					None (H)			
Juveniles			Estuaries and offshore (H)	Prey for most omnivorous and carnivorous esturine species (H)			Reduction in lower food chain prey for many fish species (L)	
Pre-spawning adult								
Post-spawning adult	High commercial harvest (H)							

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8. Flatheads (Platycephalidae)

Author: Neil Hutchinson

Southern sand flathead *Platycephalus bassensis*
Dusky flathead *Platycephalus fuscus*
Southern bluespot flathead *Platycephalus speculator*
Rock flathead *Platycephalus laevigatus*
Tiger flathead *Platycephalus richardsoni*

8.1. The fisheries

Flatheads form a valuable part of Commonwealth offshore fisheries as well as commercial and recreational fisheries in each state in the south-eastern region of Australia. Recreational catches vary between state, with estimated total flathead catches of 13,461,567 individuals caught nationally; ~45% of these are released/discarded (Henry and Lyle 2003). Approximate numbers caught per year for each state are 2,217,059 in New South Wales, 3,316,071 in Victoria, 380,947 in Queensland, 72,105 in South Australia, 79,061 in Western Australia, 1,377,350 in Tasmania and 1467 in the Northern Territory (Henry and Lyle 2003) (Figure 8.1).

8.1.1. Data from states where catch was recorded as individual species

Southern sand flathead

- Within Victoria, sand flathead are the species most frequently caught by recreational fishers, with an estimated recreational catch of up to 400 t in 2000/01 (Jenkins and McKinnon 2006), but make up only a small proportion (<1%) of the commercial catch. Statistically significant declines in biomass have occurred in Port Phillip Bay since the mid-1990s, particularly since 2000 (DPI 2008), with general declines recorded for at least 20 years, suggesting a 90% decline in stock biomass since 1970s (Hobday et al. 1999; Koopman and Morison 2002).

- A smaller proportion of the Tasmanian commercial fishery is composed of sand flathead, which is caught by handline (Ziegler and Lyle 2009). Catches have remained stable since the 1990s.

- The recreational fishery in Tasmania is composed mainly of sand flathead (95%) and represents almost two thirds of the total finfish recreational fishery, with an estimated 1.07 million kept (approximately 293 tonnes) and 0.74 million released in 2007–08 (Lyle et al. 2009). The fishery is highly seasonal with a strong peak in January–February.

Dusky flathead

- Within Victoria, dusky flathead make up only a small proportion (<1%) of the commercial catch. The commercial state-wide catch in recent years has averaged around 30 t (Department of Primary Industries 2008). The size of the recreational catch is unknown but the recreational fishery is thought to be increasing in importance in East Gippsland.

Southern bluespot flathead

- Within Victoria, southern blue-spotted flathead make up only a small proportion (<1%) of the commercial catch, although they are an important recreational species in Victoria, Tasmania and Western Australia (Kailola et al. 1993; Hindell 2006).

Rock flathead

- In Victoria, annual rock flathead commercial catches were historically in the order of 100 t (Brown 1977), and recently state-wide catches have averaged around 75 t, the majority of which comes from Corner Inlet (Department of Primary Industries 2008). They are also an important recreational species in Victoria (Hall and Mac.Donald 1986; Kailola et al. 1993; Hindell 2006).

Tiger flathead

- Tiger flathead form a valuable part of the Commonwealth offshore fishery (Kailola et al. 1993; Chen et al. 1998). The commercial fishery has declined since 1915 (Kailola et al. 1993; Klaer 2001) to a steady level of ~2–3000 t per year (Kailola et al. 1993). The majority of the commercial catch is taken by otter trawls and Danish seine nets, with the majority of fish caught between October and March in 100–150 m depth (Kailola et al. 1993), and more fish caught during day-time trawls (Klaer 2004).

- The Tasmanian commercial fishery is dominated by tiger flathead, which is caught by Danish seine (Ziegler and Lyle 2009). Seventy-four tonnes were caught in 2007–08. Effort is concentrated on the south-east, east, and north-east coasts of Tasmania.

- There is a recreational fishery for the species in most states, with anglers catching fish on inshore grounds with hand lines (Kailola et al. 1993).

8.1.2. Data from states where reported catches were for all species combined

South Australia

Much of the data for this state is available for combined catch rather than for individual species as commercial fishers rarely distinguish between species when reporting on their catch and effort forms, and is therefore discussed separately below. Species that are caught in the fishery include *Platycephalus richardsoni*, *Platycephaus bassensis*, *Platycephalus speculator, Platycephalus aurimaculatus, Leviprora inops* and *Thysanophrys cirronasa*.

- In South Australia, the Marine Scalefish Fishery (MSF) and Lakes and Coorong (L and C) Fishery are the only two SA commercial fisheries permitted to harvest flathead, although the trawl fisheries in Spencer Gulf, Gult St Vincent and west coast waters take a number of flathead species as by-catch (Currie and Sorokin 2010). The MSF takes most of the harvest (98% of total harvest in 2008/09; SARDI, unpubl. data). In the MSF, flathead are rarely targeted; however, southern blue spot and sand flathead are taken as by-product when fishers are targeting, either with handlines for King George whiting (KGW), or inshore hauling nets for garfish or KGW (Fowler et al. 2009). Since 1984/85, annual commercial harvests have ranged between 1.8 and 7.0 tonnes, with relatively high landings occurring in the early 1990s and a 2008–09 catch of 2.865 tonnes with a value of $18,698.

- The number of licence holders reporting flathead has declined over time, which is a function of licence buy-back or transfer arrangements in place for the MSF over this period. Recently, there has been an increasing demand for flathead, as seen in the rise in wharf value of flathead. Release rates of flathead in the MSF are low compared with other species: 0 – 0.3 fish per fishing event (Fowler et al. 2009).

- Like with the commercial fisheries in this state, recreational fishers do not distinguish between species when they are reporting on their flathead catches (Jones 2010). State-wide estimates of flathead catches taken by SA residents are available for two years, 2000/01 and 2007/08 (Table 8.1).

- Since 2005, there has been a licensed South Australian recreational charter boat fishery in all marine waters of the state (Knight 2010). Charter boat clients include both SA residents as well as interstate and international visitors. Flathead (species not distinguished) are a minor species in this fishery, with a very low level of target fishing (234 hrs out of a total of 129,429 hrs for all species in 2008/09). In the same year the numbers of flathead harvested amounted to 7% of the total retained catch (1260 fish). There is no information available on the numbers of flathead released in this fishery, nor the average weight of harvested fish.

Commonwealth fisheries

Most Commonwealth flathead catches are not distinguished between species when reported by commercial fishers. For Commonwealth management purposes, 'flathead' refers to a group of flathead species consisting predominantly of tiger flathead (*Neoplatycephalus richardsoni*) but including sand flathead (*Platycephalus bassensis*) and, from 1996 onwards, southern or 'yank' flathead (*Platycephalus speculator*), bluespot flathead (*Platycephalus* *caeruleopunctatus*) and gold-spot/toothy flathead (*Neoplatycephalus aurimaculatus*) (ShelfRAG 2009).

Tiger flathead have been caught commercially in the south-eastern region of Australia since the development of the trawl fishery in 1915. Most of the Australian commercial catch comes from depths between 50 m to 200 m. Historical records (e.g. Fairbridge 1948; Allen 1989; Klaer 2005) show that steam trawlers caught tiger flathead from 1915 to about 1960. A Danish seine trawl fishery developed in the 1930s (Allen 1989) and continues to the present day. Modern diesel trawling commenced in the 1970s (Klaer 2009).

Catches of flathead are recorded back to 1915 and tend to show a cyclical pattern. In recent years there has been evidence to support that these cycles may be a result of environmental changes. Average Commonwealth catches have been about 2600 t per year since 1986 (Trawl and Danish Seine combined). Discard levels are generally low: about 5% for the trawl sector in recent years. The bulk of historical catches have come from NSW, eastern Victoria and Bass Strait zones, accounting for 92% of Commonwealth catches since 1986. Catches off eastern Tasmania have increased markedly in recent years. The total landing of flathead from all sectors of the Commonwealth Southern and Eastern Scalefish and Shark Fishery (SESSF) during 2008 was 3442 t. The 2008 landed weight by the trawl sector was 3197 t (3197 t in Commonwealth waters and 0.4 t in state waters). The Commonwealth catch was up on the 2007 catch by 350 t (2847 t). Non-trawl catches were negligible, but the total state catches were 244 t (ShelfRAG 2009).

The production value for tiger flathead in the SESSF Commonwealth Trawl Sector in 2007/2008 was $12,181,000 with a total catch of 3000 t. Production value is the assessed value at the point of landing for the quantity produced and excludes transport and marketing costs (ABARE 2009).

Table 8.1: Estimated catch of flathead (combined species) by SA resident recreational fishers in 2000–01 and 2007–08 (Jones 2010).

Year	Harvested (retained) Catch (numbers)	Harvested weight (kg, live wt)	Released catch (numbers)	Released rate (% of total catch)	Total catch (numbers)
2000/01	57,077	15,011*	41,126	41.9	98,202
2007/08	38,873	18,387	13,700	46.8	73,119

* The average weight of retained flathead for 2000/01 used to estimate harvest weight is based on minimal information and therefore the harvested weight is only a best estimate.

Key points:

- Flathead are harvested throughout the SE region, and are a variable value commercial and recreational fisheries for the states and high value commercial fishery for the Commonwealth.
- In 2008/09 the combined commercial catch was 3647 tonnes.

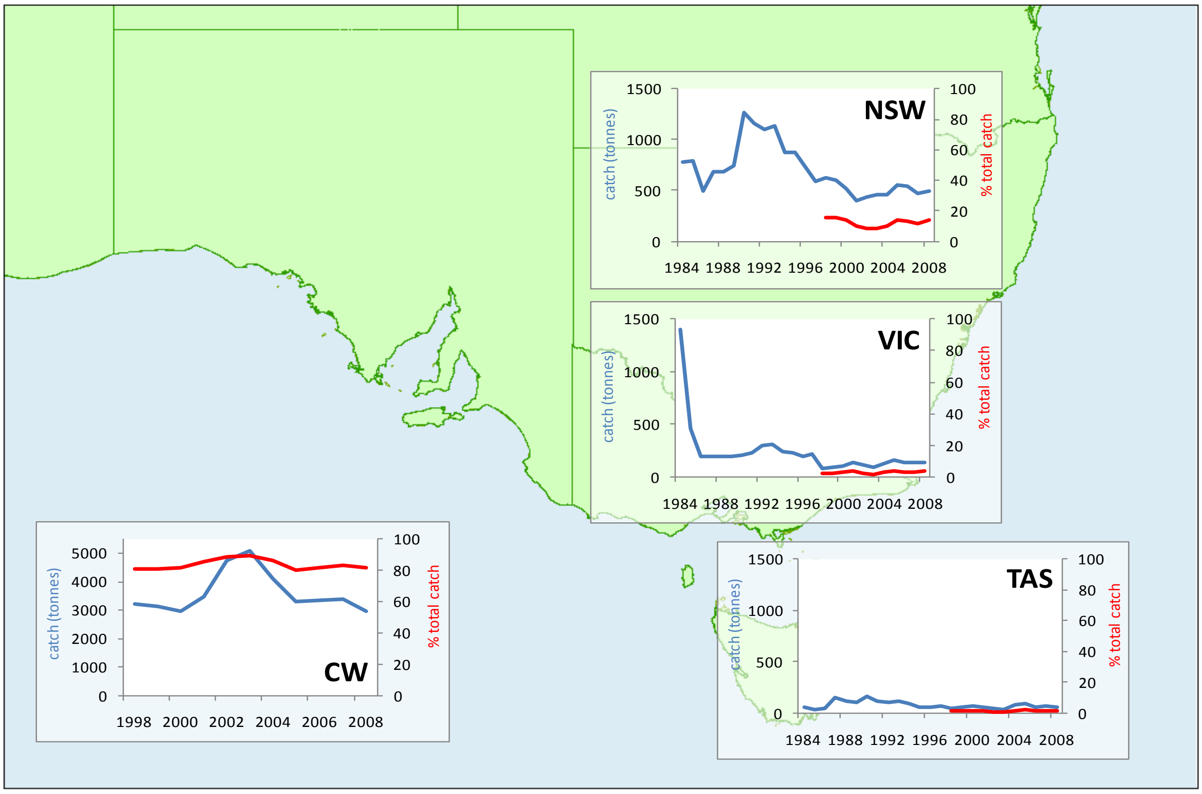

Figure 8.1: Commercial catch (tonnes) and contribution by each jurisdiction to total catch in south-east Australia (%) by year for Commonwealth, Victoria, NSW and Tasmania. Note different scale on y axis for CW. SA catch (not pictured) is <5 t.

8.2. Life history

8.2.1. *Life cycle, age and growth*

Southern sand flathead

Sand flathead are relatively long-lived with 23-year-old individuals identified in Victoria (Koopman et al. 2004). Spawning occurs between 10.5°C and 17.4°C in Tasmania; 17.0°C in Victoria (Brown 1977; Jordan 1998), but the timing of spawning activity is highly variable. Bani (2008) identified patterns of inter-annual variation in both the time of initiation and duration of spawning activity in several locations in Tasmania, although there was no general pattern of change. For example, one site had a two-month spawning season while another, tens of kilometres away, where larger fish were present, had a six-month spawning season (Figure 8.2a).

In Port Phillip Bay, while minimum water temperature is not thought to be linked with gonad growth, ovary weight has been shown to increase significantly in relation to minimum daylight hours (9.5 hrs) and decreasing ambient temperature (11°C), with spawning taking place after the spring equinox at 12°C when water temperature increases (Brown 1977). Differences in temperature and hours of daylight have also been proposed as causes of differences in spawning in Tasmania, as have plankton production and endogenous hormones (Bani and Moltschaniwskyj 2008). Females appear to peak in their spawning activity at first light, with a clear pattern of diel periodicity in spawning (Bani et al. 2009).

While sand flathead have recently been described as serial spawners (Bani et al. 2009), there is considerable variation in spawning patterns between states:

- **Victoria:** In Victoria, sand flathead become sexually mature at 19–21 cm (Brown 1977) and observations indicate that spawning occurs in spring and early summer in Port Phillip Bay (Brown 1977). The ratio between gonad weight and fish length indicates that ovary weights increase threefold between autumn and spring, with a drastic increase in ovary size in July and a peak in September, providing further support for spring spawning (Brown 1977). At the same time, testis weight increases even more dramatically (Brown 1977). Brown (1977) suggested that 'average sized' individuals, i.e., those between 22 and 26 cm, spawn at the end of September and that spawning is generally over by November. It has been suggested that spawning may occur during this period to reduce sympatric competition with other flathead species (Brown 1977).
- A significant proportion of sexually mature adults fail to spawn in spring, and two possible outcomes have been suggested for the two size classes of eggs that are observed. While Brown (1977) suggested that GSI is not a useful indicator in this

species and that females reabsorb ova, including those that are mature, by the beginning of the following year, more recent research examining GSI in conjunction with egg diameters suggests that this species spawns twice a year in Port Phillip Bay, with a secondary spawning event in January–February (Koopman et al. 2004). Sand flathead from offshore Victorian waters are larger at all ages than those from Port Phillip Bay, which may indicate some resource limitation in Port Phillip Bay (Brown 1977; Koopman 1999; Koopman 2003). Those in offshore waters were similar in size to individuals in Tasmania (Jordan 2001).

- **Tasmania:** In Tasmania, the size at first maturity is 19.0 – 24.5 cm (♂) and 20.0-29.5 cm (♀), with 50% maturity at 21.0 (♂) and 23.5 cm (♀) (Jordan 1998). Spawning occurs over periods of up to six months throughout estuaries, embayments and inshore shelf waters on the southern and eastern coasts (Jordan 2001). Spawning may occur over this period to increase genetic isolation (i.e., spawning occurs at different times to other flathead species, reducing the chance of hybridisation) or because conditions in Tasmania are unfavourable for the survival of eggs, larvae or juveniles, and so spawning is spread over a longer period to negate this (Jordan 2001; Koopman 2003).
- **Other states:** Spawning in WA has been described as being between January and mid-April (Thomson 1957b), while in SA, this species is known to spawn over the sand flats of Gulf St Vincent in November and December and subsequently, about 3–4 months later in February–March, the new year class (40 mm, length) appears in fine mesh sampling nets in the same areas where spawning took place (Jones, unpubl. data).

Dusky flathead

This is the largest species of the flathead in Australia, up to 1.2 m SL, typically weighing ~4 kg but reaching 15 kg (Gomon et al. 2008). They grow relatively quickly (Gray and Barnes 2008), potentially reaching 18 cm in one year, and 40 cm in three years (Dredge 1976; West 1993) (Gray et al. 2002; Gray and Barnes 2008) and grow to larger sizes in warm water than in cool water; e.g., size at first maturity of individuals varies from 26 cm in Victoria to 46–56 cm in Queensland (Kailola et al. 1993) (Figure 8.2b)

Spawning may be related to seasonal increases in day length and water temperature (Dredge 1976) and occurs from September to March in northern Queensland, November to February in Moreton Bay and January to March in NSW and Victoria (Kailola et al. 1993). Dusky flathead spawn in the lower reaches of estuaries and nearshore coastal waters (Dredge 1976; Kailola et al. 1993). They produce ~294,000 – 3,948,000 eggs, and may be serial spawners (Gray and Barnes 2008). The eggs are pelagic and floating eggs and larvae are dispersed by tides and currents (McDonall 1982).

While it has been suggested that the species may be a protandrous hermaphrodite, with sex reversal potentially occurring at 4–5 years (Dredge 1976; Kailola et al. 1993), this is based on observations of sex-ratios for the species rather than physiological studies, and contradictory evidence suggests that the species simply shows a dimorphic growth pattern between the sexes (Gray and Barnes 2008).

This species has been successfully reared under laboratory conditions from the egg at 23°C, and as 12 mm hatchlings they were moved to 24–26.5°C ponds before release at 35–50 mm (Butcher et al. 2000; 2003).

Southern bluespot flathead

Individuals can live for at least 14 years (Brown 1977), with females growing larger than males (Brown 1977), up to 90 cm (May and Maxwell 1986). Males tend to reach sexual maturity after one year, while females become mature after two years (Hyndes et al. 1992). Although this species typically spawns in the sea, they have been found to spawn in salinities down to less than 30‰ (Potter et al. 1993) and, in WA, have been shown to be multiple spawners (Hyndes et al. 1992; Kailola et al. 1993). In Port Phillip Bay, ovary weight is at its maximum from October to December (Brown 1977). It has been suggested that fish spawn when day length is at its maximum (14.5 hours) and water temperature is increasing (~17 °C) (Brown 1977) and similar patterns have also been described elsewhere (Hyndes et al. 1992) (Figure 8.2c).

In SA, this species is known to spawn over the sand flats of Gulf St. Vincent in November and December and subsequently, about 3–4 months later in February–March, the new year class (40 mm, length) appears in fine mesh sampling nets in the same areas where spawning took place (Jones, unpubl. data).

Rock flathead

Individuals grow to over 50 cm (Francesconi et al. 1997; Koopman et al. 2004) and weigh up to 2 kg (Gomon et al. 2008) living up to 21 years, females growing larger than males (Koopman et al. 2004). Age at 50% maturity has been recorded as 1.8 years for males (~23 cm) and 1.4 years for females (26.4 cm). It has been suggested that the species may be a protandrous hermaphrodite (CSIRO pers. comm.), but there is no data to confirm this (Koopman et al. 2004) (Figure 8.2d). In Victoria, while males and females are found in spawning condition throughout the year, peak spawning appears to occur from September to February (Koopman et al. 2004).

Tiger flathead

Individuals grow up to 65 cm in length and weigh up to 2.5 kg (Gomon et al. 2008). They spawn from October to May in NSW (Fairbridge 1951; Scott 1954), with earlier spawning in the north and from December to February in Bass Strait (Kailola et al. 1993). It is thought that mature individuals concentrate in shoals on inshore fishing grounds and migrate to shallow waters prior to spawning (Kailola et al. 1993). They produce a maximum of ~1.5 –

2.5 million eggs, which are thought to be pelagic, as are the larvae (Kailola et al. 1993). Fecundity increases considerably from the year of first maturity, but little is known about larval development. The majority of females live to 12 years, and males to 8–10 years (Kailola et al. 1993), although 15-year-old females have been found (Morison 1992; Troynikov and Koopman 2009) (Figure 8.2e). Males exhibit slower growth and reach maturity at 30 cm after 3–5 years, while females are 36 cm at maturity over a similar age range (Fairbridge 1951; Scott 1954; Kailola et al. 1993). It has been suggested that there is a single stock of this species (Kailola et al. 1993).

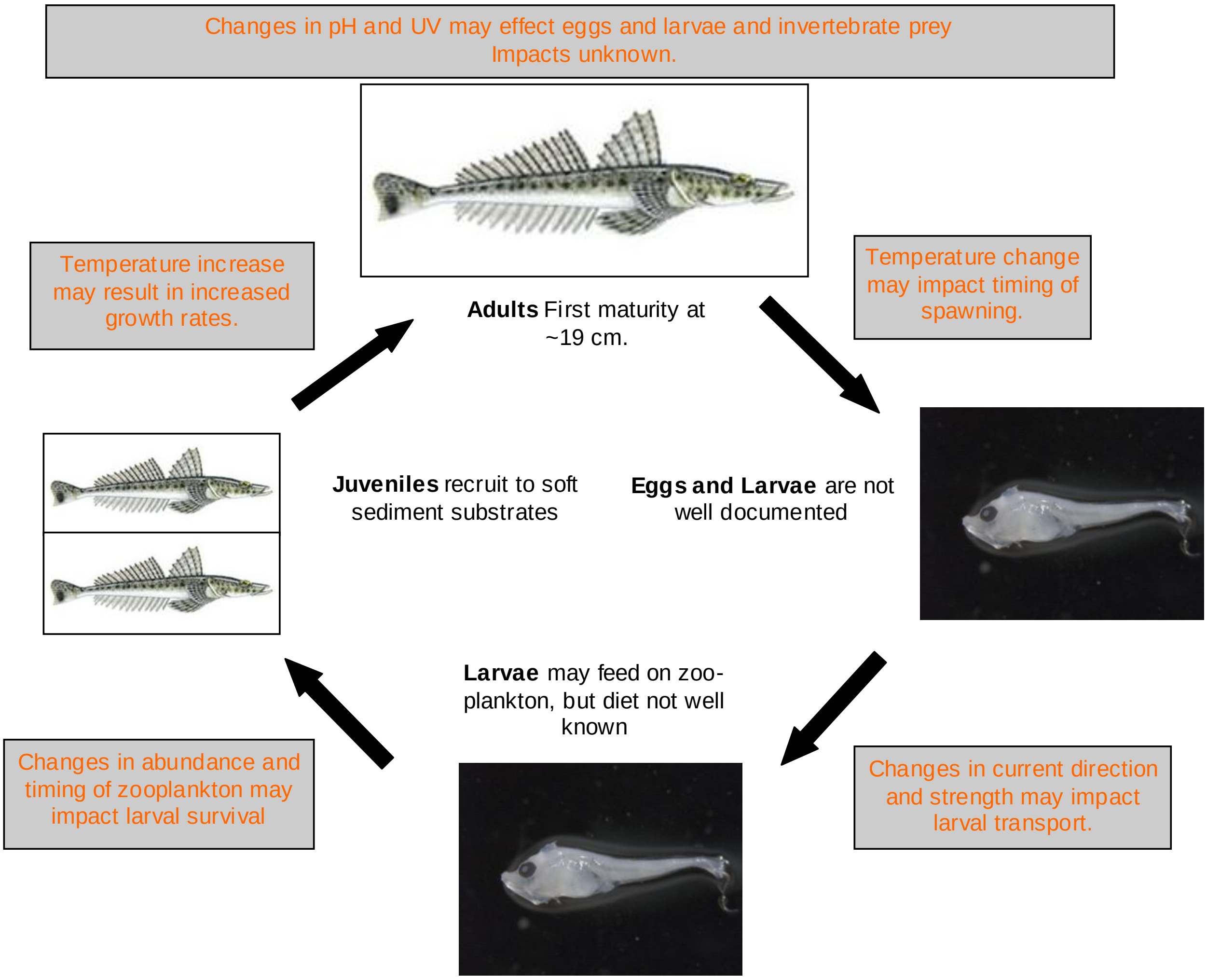

Figure 8.2a: Southern sand flathead. Summary of life cycle (this section), and points of exposure to relevant climate change drivers or known impacts (subsequent sections).

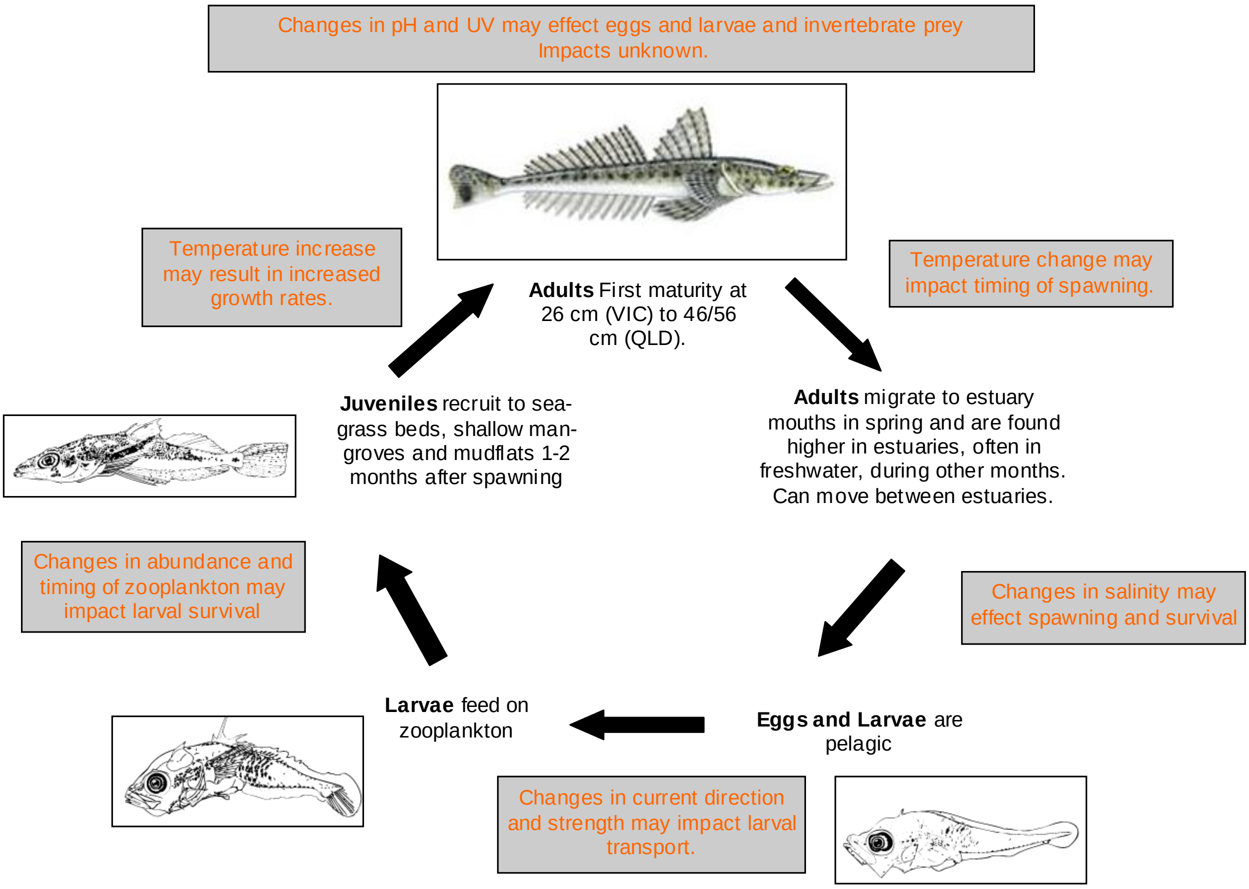

Figure 8.2b: Dusky flathead. Summary of life cycle (this section), and points of exposure to relevant climate change drivers or known impacts (subsequent sections). (Illustrations of larvae, Neira 1998).

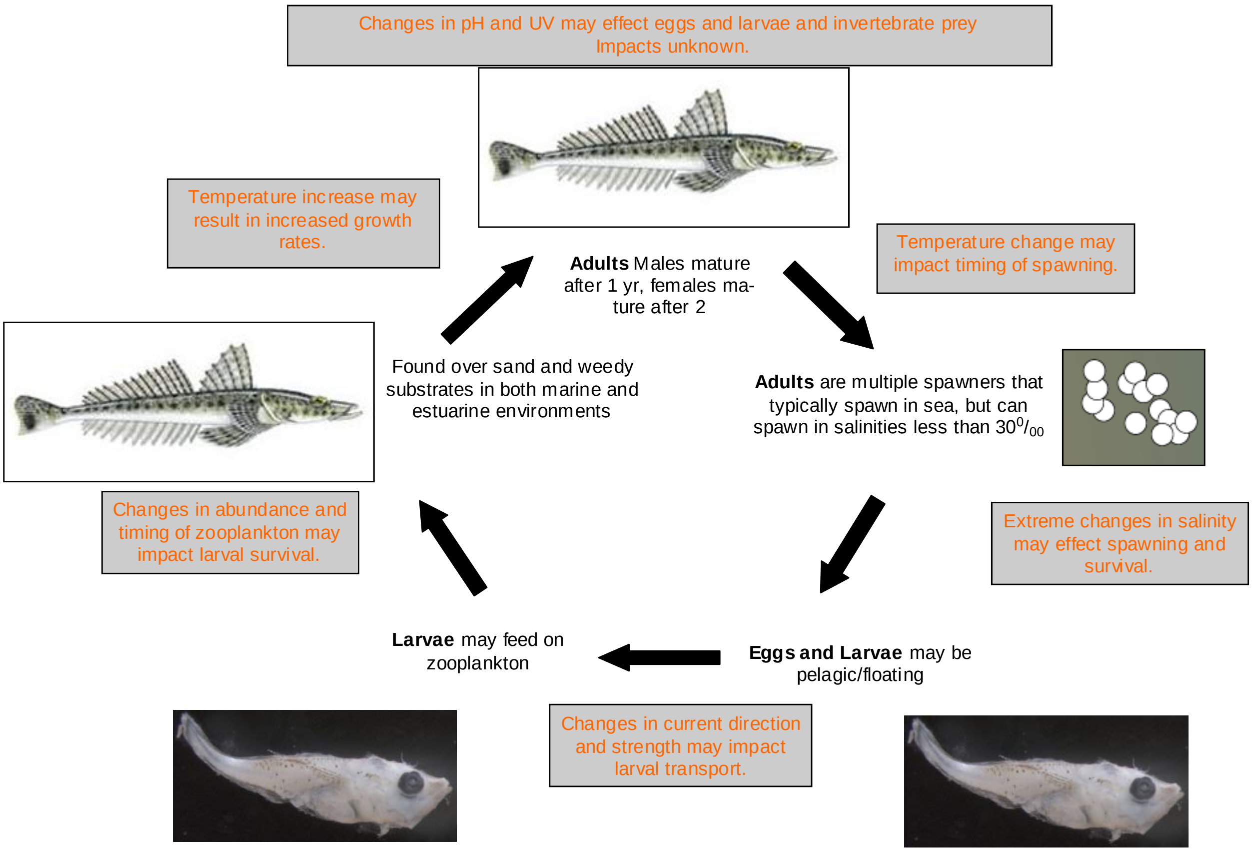

Figure 8.2c: Southern bluespot flathead. Summary of life cycle (this section), and points of exposure to relevant climate change drivers or known impacts (subsequent sections).

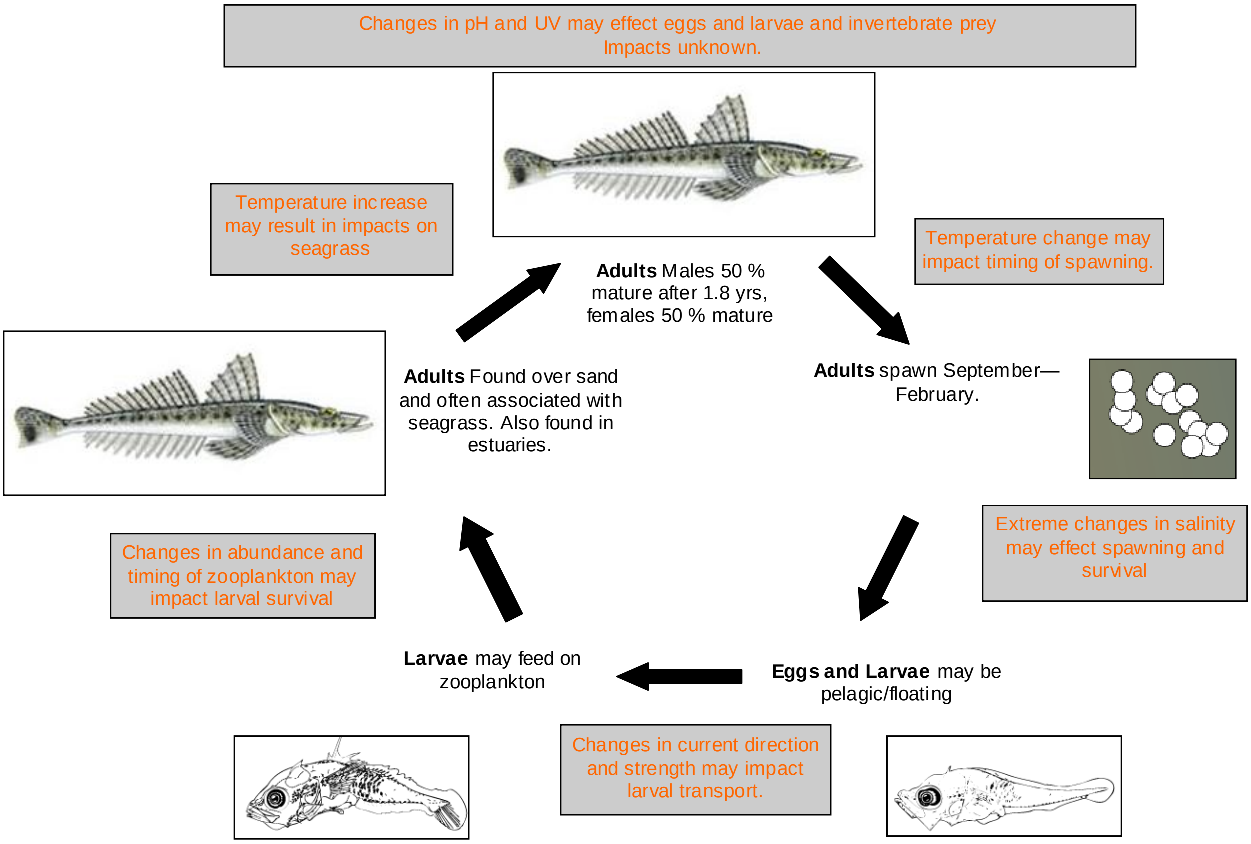

Figure 8.2d: Rock flathead. Summary of life cycle (this section), and points of exposure to relevant climate change drivers or known impacts (subsequent sections). (Illustrations of larvae, Neira 1998).

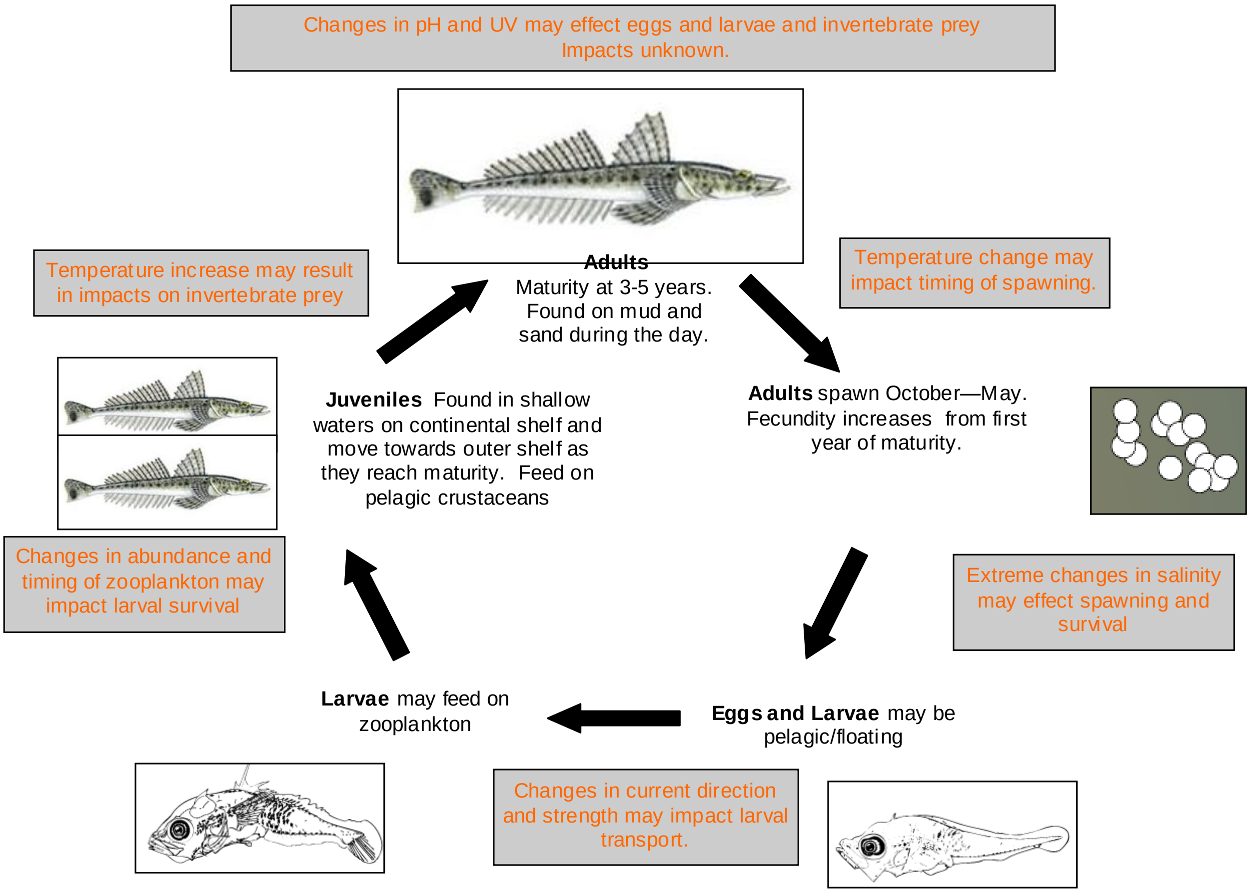

Figure 8.2e: Tiger flathead - Summary of life cycle (this section), and points of exposure to relevant climate change drivers or known impacts (subsequent sections). (Illustrations of larvae, Neira 1998).

8.2.2. Distribution, habitat and environmental preferences

Southern sand flathead

Sand flathead are distributed from 30°S to 43°S (Fishbase), from Lancelin, WA to Red Rock, NSW and around Tasmania (Hutchins and Swainston 1986) (Figure 8.3a). They are found over sand, shell grit, silt and mud in bays and inlets as well as the open coast in depths to ~100 m. Studies in Western Port suggest that juvenile sand flathead utilise unvegetated subtidal habitats as nursery grounds (Edgar and Shaw 1995). In Tasmania, where newly settled individuals measure ~2.1 cm, juveniles also show a preference for unvegetated areas, where they occur in significantly larger numbers, although they are also found in *Heterozostera tasmanica* beds (Jordan 2001). There is no indication that there is an ontogenetic shift in habitat by juveniles (Edgar and Shaw 1995; Jordan 1998).

These fish spend the majority of their time on the sea floor (Whitley 1951) and appear to be neither territorial nor to occupy a specific home range (Brown 1977). As ambush predators they tend to exhibit short bursts of swimming close to the substratum (Brown 1977; Yanase et al. 2007; Yanase et al. 2009) and are known to bury themselves (Brown 1977).

Victoria

Within Port Phillip Bay, the highest abundances of individuals have been recorded around the central basin at depths ≥15 m depth, where water movement is minimal and substrates contain a high proportion of fine sediments, and in the east of Port Phillip Bay (Brown 1977). Brown (1977) also found individuals were abundant at certain stations off St Leonards although CPUE for the same area was very low.

Haematological, and pollution studies suggest that individuals stay within a 'general' area long enough for physiological and mercury content changes to occur (Dix et al. 1975; Walker 1982), and early studies suggested that the species is non-migratory within the bay (Dix et al. 1975).

Tag and release studies within Port Phillip Bay have shown that individuals are able to move tens of kilometres within a relatively short time period (1 month) (Anon 1973; Brown 1977). While in the short term, sand flathead stayed in a relatively small area, over the longer term the mean minimum rate of movement was ~125 m per day (Brown 1977). Little is known about the behavioural ecology of this species; e.g., the scale of movement in Port Phillip Bay and to what extent individuals move through Port Phillip Heads, although Koopman (2003) suggests that sand flathead in Port Phillip Bay may predominantly be isolated from populations in coastal waters due to the physical, habitat barrier of Port Phillip Heads.

A sharp seasonal decline in the proportion of fish older than two years old in samples collected near St Leonards in October may be related to a seasonal spawning movement by older fish towards the mouth of the bay (Koopman 2003), and recreational anglers have been known to catch larger numbers of sand flathead near Port Phillip Heads during the spawning period (Koopman, pers. comm.).

Within Victoria, there is spatial overlap between sand flathead and southern bluespot flathead *Platycephalus speculator* in Port Phillip Bay; however different dentition suggests that there may be differential use of resources by different flatheads (Brown 1977).

Tasmania

In Tasmania, seasonal variability in the distribution of sand flathead can be seen with individuals essentially disappearing from inshore waters and appearing on the shelf during autumn, potentially in a response to decreased food availability (Jordan 1998). Close to the size of maturity, a proportion of the juvenile population is also thought to move seasonally from inshore areas to the inner and mid-shelf region on a temporary basis (Jordan 1998). In addition, the sex ratio of this species varies for populations found inshore and on the shelf, with females dominant inshore and males dominant on the shelf (Jordan 1998).

South Australia

In SA, sand flathead occur throughout inshore sandy habitats (low energy estuaries – high energy beaches), with low numbers in estuaries and higher abundances along the more medium energy beaches and sand flats (Jackson and Jones 1999).

Dusky flathead

This species is found from Cairns, Queensland to Gippsland Lakes, Victoria (although individuals have been found west of Wilsons Promontory in Port Phillip Bay, Vic), from depths of less than 1 m, down to 25 m (Kailola et al. 1993; Gomon et al. 2008) (Figure 8.3b). They are found in bays and estuaries, migrating to the mouths of estuaries and along channels in spring, and living higher in the estuary in other seasons, often in freshwater (Kailola et al. 1993; Potter et al. 1993; Gomon et al. 2008). The species inhabit channels and seagrass beds (mainly *Zostera* spp.) as well as areas of soft sediments, sand, gravel and mixed sand and weed patches. Observations indicate that this species frequently buries in sediments and that juveniles occur in large numbers in mangrove-lined estuarine areas (Dredge 1976). Traditional and acoustic tagging studies show that they can move relatively long distance in short time periods (Hindell 2008) and can move between estuaries (West 1993; Gray and Barnes 2008).

Southern bluespot flathead

This species is found on inshore sandy bottoms from the surf zone (Ayvazian and Hyndes 1995) to 30 m (Gomon et al. 2008). They have also been described as inhabiting 'nearshore to continental shelf and slope waters (70–360 m) over sand and weedy substrates (Kailola el al. 1993), although this disparity may be due to the incorrect identification of species (Gomon et al. 2008). They are distributed from Lakes Entrance, Victoria to Albany, WA, including Tasmania (Kailola et al. 1993; Gomon et al. 2008) (Figure 8.3c). This species is found in marine and estuarine environments (Kailola et al. 1993), and it has been suggested that distribution patterns are governed more by depth than by substrate type (Brown 1977). In Port Phillip Bay, it has been noted that biomass of individuals is highest in the centre and south-east of the bay in deeper areas with a substrate of fine sediments, and it has been suggested that the species shows a degree of habitat partitioning with other flathead species (Brown 1977).

Southern bluespot flathead is the most abundant flathead species in inshore waters of the SA gulfs, occurring from estuaries to the medium energy beaches of the SA gulfs and other embayments (Jackson and Jones 1999). It is the second most abundant flathead species in Spencer Gulf, mainly occurring on the northern and central Spencer Gulf trawl grounds, at depths 10–20 m (Abundance: 0.7 fish / ha; Biomass: 113 g / ha.) (Jackson and Jones 1999).

Rock flathead

This species can be found from 0 to 20 m depth, often associated with seagrass (Gomon et al. 2008). Individuals rarely bury themselves in sand, but are often found in low algae during the day and are active at night (Gomon et al. 2008). The species has also been described as being associated with reefs (Paxton et al. 1989).

They are distributed from Queensland to WA, including Tasmania (Gomon et al. 2008) and have been described as marine 'stragglers' in estuaries (Potter et al. 1990) (Figure 8.3d).

Tiger flathead

This species is mainly found in offshore areas, mostly commonly at depths less than 200 m, but are found from 10–400 m (Hobday and Wankowski 1987; Kailola et al. 1993), occasionally occurring in inshore areas such as Port Phillip Bay (Troynikov and Koopman 2009). This species is distributed from Coffs Harbour, NSW to Portland, Victoria, including Bass Strait and Tasmania (Kailola et al. 1993) (Figure 8.3e).

Individuals are normally found during the day on mud and sand substrates, and it is thought that they show nocturnal patterns of movement into the water column searching for prey (Colefax 1934). Juvenile fish are found in shallow waters on the continental shelf and move towards the outer shelf when they reach maturity (Kailola et al. 1993), with increasingly larger individuals towards the outer areas of the shelf (Chen et al. 1998).

This is the most abundant of the flathead species found through the prawn trawl grounds of Spencer Gulf (depth range: 10–40 m), with abundances of 3.6 fish per hectare and a biomass of 260 g.ha^{-1} (Currie and Sorokin 2010). The species has not been recorded in inshore waters of South Australia (Jackson and Jones 1999).

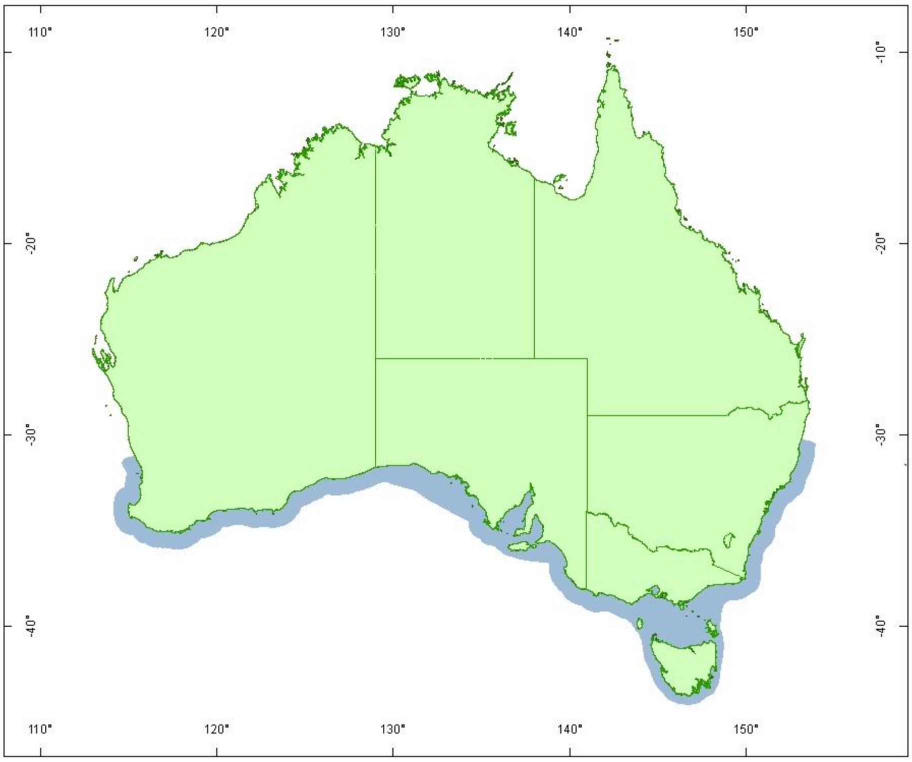

Figure 8.3a: Map detailing the distribution of southern sand flathead.

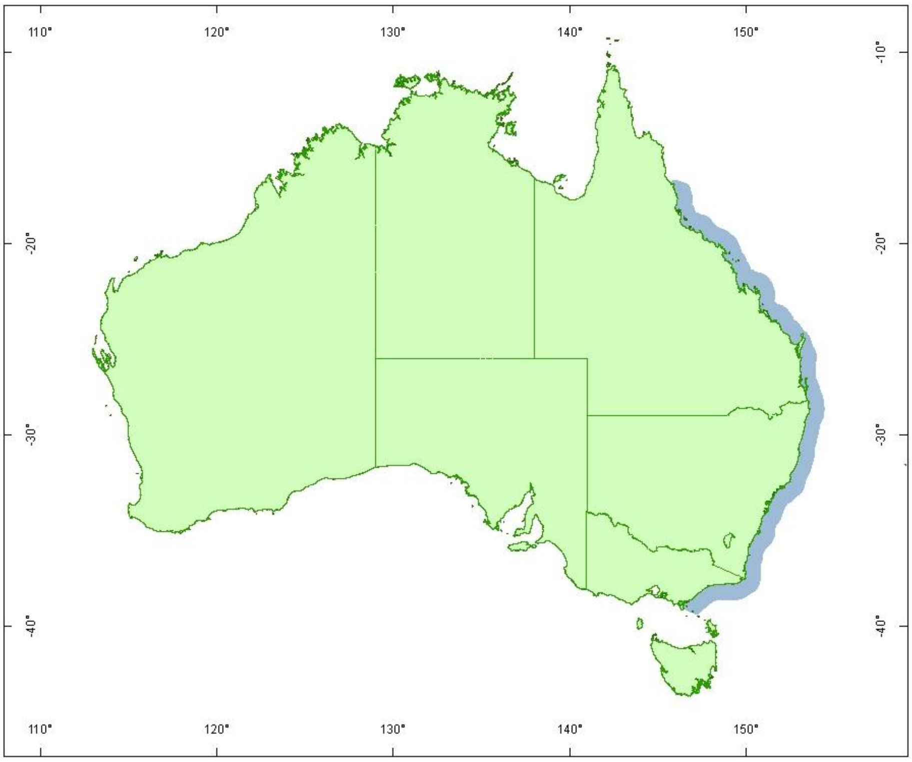

Figure 8.3b: Map detailing the distribution of dusky flathead.

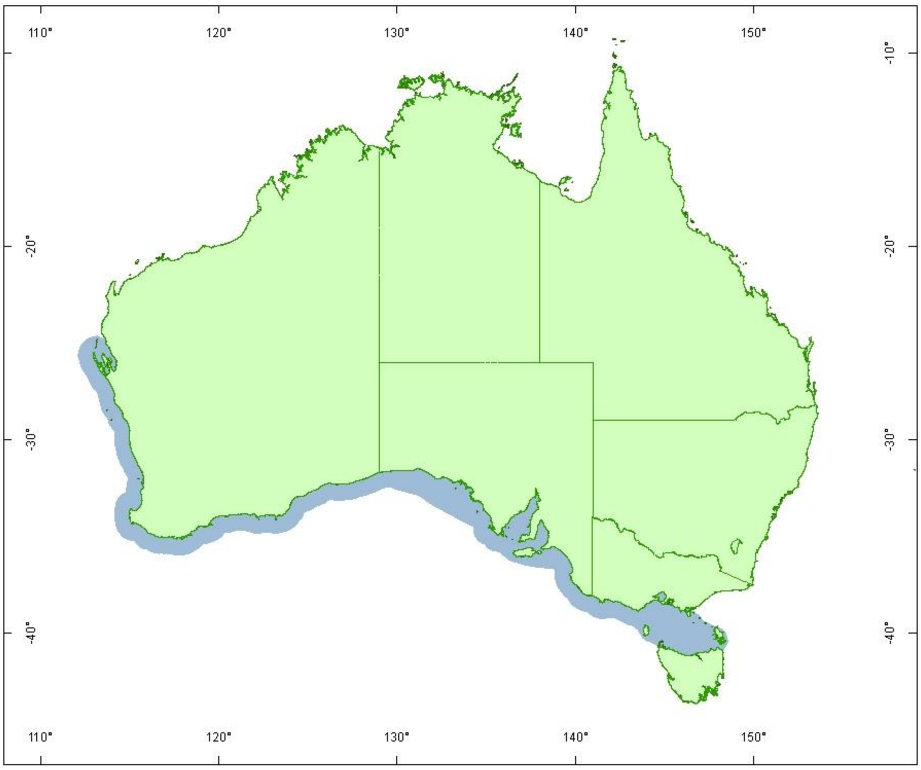

Figure 8.3c: Map detailing the distribution of southern bluespot flathead.

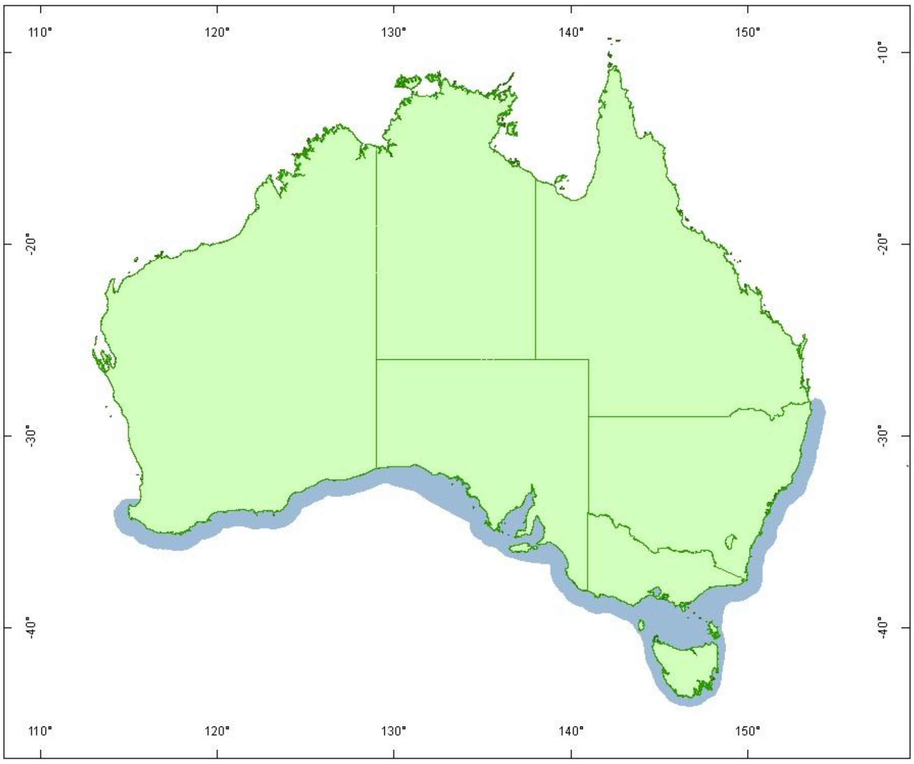

Figure 8.3d: Map detailing the distribution of rock flathead.

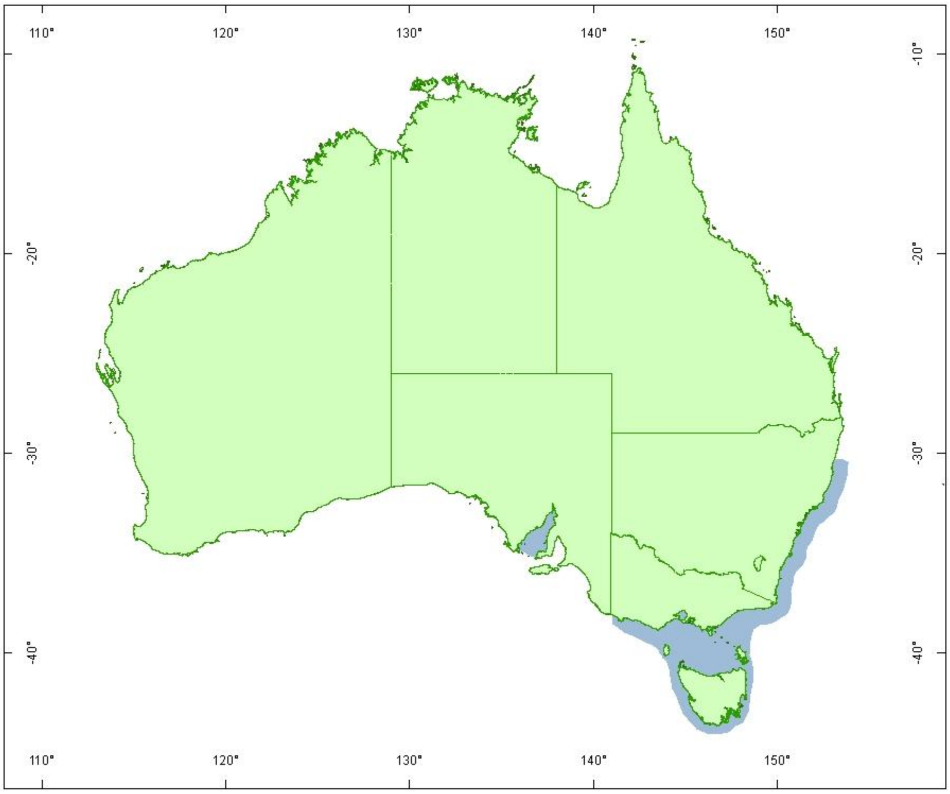

Figure 8.3e: Map detailing the distribution of tiger flathead.

8.2.3. *Predators and prey*

As well as man, general predators of flatheads include teleost fish, Australian fur seals (*Arctocephalus pusillus doriferus*), dolphins (Parra and Jedensjö 2009) and elasmobranchs (Walker 1989; Braccini et al. 2005; Treloar et al. 2007). For tiger flathead, some cannibalism of smaller individuals has been recorded, and other predators include teleost fish such as John dory (Kailola et al. 1993).

Most species of flathead in South Australia are ambush predators, and prey is predominantly smaller fish (unidentified species: Currie and Sorokin 2010).

Southern sand flathead

Sand flatheads have been described as opportunistic generalists consuming crustaceans, molluscs, polychaetes and fish, with studies varying in their conclusions about the most prevalent/important prey species (Table 8.2). It has been suggested that they feed at a constant rate during both day and night (Brown 1977).

Table 8.2: Important prey groups found in stomach contents of southern sand flathead.

Reference	Site	Prey groups (in order of importance)	Primary prey
Brown (1977)	Port Phillip Bay (Vic)	Shrimp (*lucifer hanseni*)	Shrimp (*lucifer hanseni*)
Thomson (1957a)	Wilsons inlet (WA)	Fish and shrimps	Fish and shrimps
Andrews (1988)	Vic	Crustaceans, teleosts, molluscs, polychaetes	Crustaceans
Officer (2000)	Port Phillip Bay (Vic)	Crustaceans, teleosts, molluscs and polychaetes	Crustaceans (by %) Sprat (by number)

Several studies have found a seasonal difference in diet (Brown 1977; Andrews 1988; Officer and Parry 2000), with intense feeding in winter and early spring (Brown 1977), for example with sandy sprat (*Hyperlophus vittatus*) being important, but found in stomach samples only during August (Officer and Parry 2000).

In Victoria, Brown (1977) found that more fish are found in the diet in winter, due to either reduction in invertebrate availability or an increase in fish availability which causes overlap in diet with other flathead species. This switch to a 'high lipid content' fish diet occurs at a time when large quantities of lipids are reserved for later use by developing gonads (Brown

1977). The spatial pattern and distribution of prey species is also thought to explain differences in prey types found in stomach contents of individuals (Officer and Parry 2000). Dietary analysis (G. Parry, pers. comm.) has indicated a recent increasing dependence on fish year round, particularly anchovy. One hypothesis is that increasing competition for prey resources is driving a dietary shift (G. Parry, pers. comm.).

Dusky flathead

Dusky flatheads have been described as active foragers that occasionally scavenge. Food items include fish, small crustaceans (e.g., crabs and prawns), molluscs (e.g., squid and octopus) and polychaete worms (Dredge 1976). They have also been described as ambush predators, burrowing into soft sediments in order to capture prey (Dredge 1976; Kailola et al. 1993). The importance of the prey groups appears to vary with age, but the pattern varies from place to place; e.g., the ratio of crustaceans to fish has been shown to increase with age in Botany Bay, with the opposite pattern at Moreton Bay (Kailola et al. 1993). Larvae of the species consume zooplankton (Butcher et al. 2000).

Southern bluespot flathead

Southern bluespot flathead are common ambush predators (Humphries et al. 1992) in unvegetated sediments and seagrass beds (Bell and Pollard 1989; Hindell et al. 2000; Hindell 2006) that actively forage for fish, benthic and pelagic crustaceans, bivalve and gastropod molluscs and polychaete worms (Hindell et al. 2000; Platell et al. 2006). They also show seasonal patterns of diet change (Platell et al. 2006).

Early research in Port Phillip Bay indicated that they have a highly specialised, mainly piscivorous diet (Brown 1977), with >50% of the diet in some areas consisting of seagrass associated species (Hindell 2006). It has been suggested that they predominantly feed on prey found on and just above the substratum (Platell et al. 2006) and that the importance of prey groups varies with age, with more fish consumed as size increases (Platell et al. 2006). In certain estuaries this species competes with cormorants for food resources (Humphries et al. 1992) and there is some dietary overlap with co-occurring flathead species (Brown 1977).

In SA, calamari make up 14% of the diet of this species (Currie and Sorokin 2010).

Rock flathead

Rock flathead feed mainly on benthic macrofauna, including demersal fish that are associated with seagrass (Klumpp and Nichols 1983; Francesconi et al. 1997; Hindell 2006). An ontogenetic shift in diet from small fish, cephalopods and crustaceans to large crabs has been observed at some sites (Klumpp and Nichols 1983), as have seasonal shifts in diet and a decrease in feeding intensity during the winter (Klumpp and Nichols 1983). A decline in feeding intensity has also been recorded during the spawning period (Klumpp and Nichols 1983).

Foraging activity of adult rock flathead has been correlated to noctural or crepuscular high tides when their main prey are also active (Klumpp and Nichols 1983).

Tiger flathead

Juveniles feed mainly on pelagic crustaceans such as krill (Colefax 1934). While adults can feed on crustaceans, they are mainly piscivorous (Colefax 1934) and feed on a variety of fish including smelts and cardinalfish (Kailola et al. 1993). In SA, 24% of the diet of tiger flathead is made up of western king prawns (Currie and Sorokin 2010).

An ontogenetic shift in diet results in individuals becoming less reliant on benthic fauna and moving into the water column to feed (Colefax 1934). This is associated with the fact that their prey show nocturnal patterns of vertical migration (Kailola et al. 1993) to feed on zooplankton (Colefax 1934).

8.2.4. Recruitment

Little is known about the recruitment of most species.

Southern sand flathead

Brown (1977) suggested that the pelagic larval stage of this species in Port Phillip Bay is brief and work in Tasmania has found that larvae are concentrated in mid-waters which retain larvae due to onshore currents, with settlement occurring over an extended period (Bani and Moltschaniwskyj 2008; Bani et al. 2009).

Annual variation in reproductive output has been described in both Victoria and Tasmania. High zooplankton production during the spawning period is thought to result in strong recruitment (Jordan 1998), and changes that result in advancing or delaying spawning may cause larvae to miss peak densities of optimally sized planktonic prey (Bani and Moltschaniwskyj 2008). For example, during one year in Tasmania an increase in plankton linked to increased wind stress coincided with a strong year class, and it has been suggested that this was due to an extended optimal window for larval feeding, growth and survival (Jordan 1998). Recruitment in Port Phillip Bay, Victoria is highly variable, and has been linked to freshwater flows into Hobsons Bay, and the Southern Oscillation Index in the month of spawning (Koopman et al. 2004). For example, recruitment decreased with increasing river discharge in February–April of one spawning year, and the strong fit of a statistical model suggested the stock responded more to environmental factors than to fishing pressure. This relationship did not hold over the longer term and more recent analysis has shown a positive correlation between freshwater flow and flathead recruitment in Port Phillip Bay (Jenkins 2010), possibly as a result of increased nutrients stimulating plankton production.

In Victoria, sand flathead abundance can vary by up to 200% between years depending on recruitment during the previous year and it has been suggested (Koopman and Morison 2002) that a large decline in abundance during the 1990s has subsequently affected recruitment of this species within Port Phillip Bay. The decreasing trend has continued in the past decade and the abundance of sand flathead in Port Phillip Bay has decreased by an order of magnitude since 1990 (Jenkins 2010).

Dusky flathead

Larvae have been captured in estuaries and coastal waters of NSW between September and May (Gray and Miskiewicz 2000) and juveniles appear in bays 1–2 months after spawning, where they are found in seagrass beds, shallow mangroves and on mudflats (Kailola et al. 1993; Hindell 2008).

Southern bluespot flathead

Eggs and larvae are pelagic and have been captured in estuaries from January to March, with settlement occurring at ~13 mm (Hyndes et al. 1992).

Rock flathead

In Corner inlet, Victoria, recruitment has been shown to vary considerably between years, linked to freshwater input during the winter months (Koopman et al. 2004).

Tiger flathead

Little is known about the recruitment of this species. Based on long term beach seine surveys in and adjacent to the Barker Inlet, Gulf St Vincent (Jackson and Jones 1999) the relative abundance of newly settled inshore species of flathead can show some degree of inter-annual variation (Jones, unpubl. data); however, it is unknown whether this variation is site specific, or the same pattern is spatially more widespread.

The stock structure of tiger flathead is still poorly understood. There is some evidence of morphological variation across the species distribution range with observed regional differences in growth, appearance and the timing of reproduction, especially off eastern Tasmania (ShelfRAG 2009).

Key points:

- Recruitment is dependent on spawning coinciding with zooplankton production.
- Recruitment of sand flathead in Port Phillip Bay is correlated with freshwater flow.
- These flathead species are benthic and distributed throughout southern Australia over soft sediments and, in some cases, seagrass.
- Patterns of movement vary geographically.
- Reproductive patterns vary geographically, and at relatively small scales.

8.3. Current impacts of climate change

Current impacts of climate change are largely unknown for these species. This section therefore discusses potential climate drivers that may currently be of risk including temperature; rain/riverflow (salinity); UV; acidification; winds and currents; sea level change; and extreme events. It should, however, be noted that high levels of uncertainty are linked to these risks, particularly in the impacts of climate change on the larval stages of these species, as little is known about the larval development of most species.

Some impacts of climate change may be positive. For example, Hobday et al. (2008) suggest that growth rates of fish in SE Australia have responded to an average increase of 1°C over the last century with increased growth. Continued patterns are uncertain, and it is unknown whether this positive relationship would apply to larvae given their reliance on plankton.

In SA, flathead species are of minor importance in the fisheries of the state, and also occur in relatively low abundances, compared with the same species in more eastern parts of their distributions. Information on their ecology in this state has only been collected as an adjunct to studies directed at other species, and is therefore insufficient to provide any comment on the impact of climate change in this state.

Temperature

Temperature may pose a moderate risk for these species, because of the effects on range distribution and spawning cues and also a potential increase in susceptibility to disease. For example, while southern sand flathead spawning occurs between 10.5˚C and 17.4˚C in the southern areas of its range, the species is distributed over a fairly wide latitudinal range, and may therefore be resilient. For sand flathead, it is not certain whether the current trend of decline in Victoria is related to climate change impacts. Recent analysis has shown a negative correlation between spring water temperature and recruitment of sand flathead in Port Phillip Bay, suggesting the population decline may be partly related to increasing temperatures (Jenkins 2010)

Rain/riverflow

Sand flathead recruitment in Port Phillip Bay has been found to be correlated with freshwater flows, suggesting that recent declines in freshwater flow have led to a reduction in nutrients and associated production of zooplankton food for larvae (Jenkins 2010). Conversely, while there is variation between species, low salinity may not be optimal for spawning of some species, and increased freshwater input may therefore impact populations, such as those within bays and estuaries. However, the extent to which such impacts occur are unknown.

Winds

Within Victoria, it is predicted that zonal westerly winds will shift south, and this weakening of westerly winds may impact recruitment of offshore populations of flathead species. Winds also drive upwelling in eastern and western (Bonney upwelling) Victoria and central areas of Bass Strait, which may impact both the transport of eggs and larvae and the availability of planktonic food sources for these early life stages.

Currents

A variety of currents are of potential importance in transporting pelagic eggs and larvae of some flatheads. For example, Victoria is strongly influenced by the Leeuwin Current to the west and the East Australian Current to the east.

UV radiation

Increased levels of UV may lead to increasing mortality of eggs and larvae, both directly through damage to skin and eyes, and indirectly through impacts on planktonic food sources. This may be less problematic for species where larvae are concentrated mid-water; for example southern sand flathead in Tasmania.

Acidification

Increased acidity may have an indirect effect on flathead species due to its potential impact on plankton and other food sources, particularly in bays and estuaries where acidification may also occur due to lowering of the water table. Prey items such as molluscs and crustaceans may be directly affected, and in the case of piscivorous flatheads, where prey fish themselves feed on zooplankton, these impacts could me more widespread.

Extreme events

Extreme events such as bush fires and flash floods are likely to have impacts on bay and estuarine populations, with potential impacts on nutrient flows and primary production impacting food chains. There could be particular impacts at the larval stage, as well as on habitat forming species such as seagrass and algae.

Key points:

- Limited information is available on specific impacts of climate change.
- There is a possible negative effect of increasing water temperature on sand flathead in Port Phillip Bay, as well as a negative effect resulting from declining freshwater input.

8.4. Sensitivity to change

While all of these flathead species are associated with soft sediments to a certain degree, several are associated with seagrass (e.g. rock flathead) that provides habitat as well as food resources and are likely to be impacted by changes in the distribution of seagrass. Seagrass in Australia is expected to be influenced by climate change in several ways, including general decreases in productivity, local-scale losses due to decreased light, a change in community structure to more heat/CO_2 tolerant species, long-term declines of seagrass health, and changes in the distribution of seagrass both with latitude and with height on the shore (Connolly 2009).

The majority of these flathead species are generalist feeders on benthic invertebrates and are likely to be able to adapt to changing prey types, while their larvae are reliant on zooplankton in the water column. Zooplankton distribution patterns have seen major changes in some areas in relation to climate change (Roessig et al. 2004; Parmesan 2006). Zooplankton is expected to respond quickly to climate change, which may lead to a mismatch between zooplankton abundance and predator abundance (Richardson et al. 2009), which may impact the larval stages of flathead. Strong year classes of southern sand flathead, for example, have been linked to peaks in plankton abundance in Tasmania (Jordan 1998).

While information does exist regarding salinities and temperatures where spawning occurs, laboratory studies have not been conducted to examine the tolerances of different life-history stages. There is also variation for all species throughout their geographical range; for example, spawning times of dusky flathead occur from September to March in northern Queensland and January to March in Victoria (Kailola et al. 1993). What is not clear is to what extent local populations will be able to adapt to subtle/complex interactions that may occur between changes in food abundance, habitat type, spawning cues etc. Populations restricted to local bays and estuaries, for example, may be particularly sensitive to a wide range of factors and where estuaries are closed for extended periods of time, factors such as hybridisation between closely related species may be detrimental to populations (Roberts et al. 2010).

Based on its observed restricted distributions in Spencer Gulf, SA (Currie et al. 2009), *P. speculator* may be more sensitive to climate change than the other species of flathead. It is found only in the central and northern waters of Spencer Gulf, an environment that is characteristic of relatively high summer water temperatures (>23˚C) and salinities (>42 ppt). With the potential for a southward extension of these environmental conditions due to climate change, it is possible that this species could extend its southern distribution.

Key points:

- Controlled aquaria experiments have not been performed on the larval stages of these species as they are not probable candidates for aquaculture.
- Flathead are mainly generalist feeders, but may be sensitive to changes, particularly at the larval stage.
- Species which rely on seagrass may be particularly sensitive to habitat changes.

8.5. Resilience to change

It is not clear to what extent populations mix throughout the species' ranges. Where populations have the potential to dispense and mix with neighbouring populations, resilience to climate change may be increased. While species found on the open coast may mix with neighbouring populations due to larval exchange between populations and mixing of adults, it is not clear to what extent populations in bays and estuaries mix.

As noted previously, many flatheads are generalist feeders and it is therefore likely that they will be able to continue to utilise changing invertebrate communities as food sources. Shifts in diet have been noted recently for southern sand flathead with one hypothesis being that increasing competition for prey resources is driving a dietary shift (Coutin et al. In Prep); such patterns may also occur with shifting prey availability that may be caused by climate change. These prey species may themselves be influenced by climate change; for example anchovies that form part of the southern sand flathead diet may undergo large changes in distribution patterns (Roessig et al. 2004).

As the egg and larval phases of these species are pelagic, their dispersal is governed to some extent by winds and currents and this may enable flathead to shift distribution to maintain an optimal environment.

Based on their known distributions in Spencer Gulf, SA (Currie et al. 2009), *N. richardsoni* is distributed in waters over a larger depth range than any of the other flathead species in SA, and therefore, it can be inferred that they are able to tolerate wider temperature and salinity ranges than the other three flathead species.

Key point:

- Flatheads show variable reproductive timing throughout their ranges and eggs and larvae are pelagic, potentially increasing the resilience of these species.

8.6. Ecosystem level interactions

Flatheads are preyed upon by a variety of species, including elasmobranchs and marine mammals, and it is expected that populations of these predators will themselves be impacted by climate change, with changing ranges etc (Learmonth et al. 2006; Chin et al. 2010). It is unclear at this stage how flathead species will be affected, as range changes in flatheads and their predators may not be of the same latitudinal magnitude. Predators of flathead tend to be generalist feeders, and therefore the disappearance of flatheads from an area is unlikely to have a major impact on them.

For flathead species which rely heavily on seagrass beds to provide habitat and food resources, the loss of seagrass would have dramatic impacts on flathead populations in an area.

In Spencer Gulf, the most common flathead species is *N. richardsoni,* and of all the other 395 demersal species sampled, it is the twentieth most abundant and the tenth most important species in terms of biomass (Currie et al. 2009). Any changes to the ecosystem due to climate change may be observed for this species of flathead.

Key points:

- Little is known about interactions between flathead and other species.
- Range changes of predators and prey may not mirror range changes of the different flatheads.
- Loss of seagrass would be detrimental for dusky and rock flatheads.

8.7. Additional (multiple) stressors

Flatheads are heavily exploited which may place additional stress on the population, and decrease resilience to environmental perturbations even though the fisheries are managed. Flathead species that are currently under stress, such as sand flathead in Port Phillip Bay, Victoria, that are showing long-term declines, are likely to be more sensitive to climate change impacts.

With the recent increase in wharf price of commercially caught flatheads in the Marine Scalefish Fishery in SA, there is the potential for increased targeting of these species in this fishery. The effects of changes in their relative abundance due to fishing would need to be separated from any effects specifically due to climate change.

Other stressors are likely to act in combination to effect flathead populations. For example:

- Flathead absorb a wide range of pollutants (Dix et al. 1975; Fabris et al. 1992; Mondon et al. 2001), and while they are able to maintain healthy populations under such circumstances, they are physiologically stressed (Brown 1977) which may make them more susceptible to climate change impacts.
- Seagrass beds that form habitats for several flathead species are likely to degrade due to the effects of climate change (Connolly 2009).
- Potential competitors may be introduced to areas inhabited by flathead species, with their own ranges extending south due to climate change (Cheung et al. 2009).
- The virulence of viruses and parasites will increase with predicted climate change and their impact may be increased due to a combination of the stressors above (Marcogliese 2008). It has been suggested that 'climatic effects on parasites and diseases of key species may cascade through food webs, with consequences for entire ecosystems' (Marcogliese 2008).
- While flathead fisheries are managed, some species are impacted by non-targeted fishing impacts; for example, tiger flathead are taken as by-catch by inshore fisheries and discarded at sea where mortality is thought to be high (Chen et al. 1998).

Key point:

- Little is known about the cumulative impacts of exploitation, pollution and climate change on these species.

8.8. Critical data gaps and level of uncertainty

- Very little is known about the sensitivity of eggs and larvae of flatheads to variation in physicochemical factors, ocean acidification, UV etc.
- There is a paucity of aging studies for some species.
- At local scales, little is known about the extent to which populations mix. Genetic examinations of populations may give some indication, as would traditional and telemetry tagging studies.
- While some species appear to be robust to changes in salinity in the short term, little is known about the repercussions of long-term salinity changes on the eggs and larvae of most species.
- Little is known about the ecological role of flatheads and how they compete for resources with other species, or how they would be impacted by competition with species not currently resident in their area.

- More information is required on habitat preferences at the various life history stages for the key flathead species.
- Further analysis of historical data is needed to provide long-term information on recruitment variability.
- Links between flathead recruitment and water temperature and freshwater input require further investigation.

Key points:

- Limited information on sensitivity of eggs and larvae
- The ecological role of these species is not well understood
- Little is known about the degree of mixing between populations.

Table 8.3: Summary of flathead species assessment, which also indicates level of certainty of the associated information. Level of certainty is divided into high (H) = strong clear evidence, backed by several studies with solid datasets with little confounding interactions; medium (M) = evidence supported by one or more studies, conclusions may be partially ambiguous or confounded; low (L) = anecdotal evidence, limited data and/or predicted conclusions based on theoretical knowledge. Species include: sand flathead (SF), dusky flathead (DF), southern bluespot flathead (BF), rock flathead (RF), tiger flathead (TF).

Life history stage	Multiple stressors	Distribution	Habitat	Predators and prey	Current impacts	Predicted impacts	Ecosystem interactions	Data gaps
Eggs	Unknown	See maps (L)	Pelagic, bays and coastal waters (SF, BF; M)	Zooplankton (M)	High levels of uncertainty	Change in distribution patterns (L) Larval survival due to zooplankton changes (L) Variation in prey types available (L) Habitat and prey loss (Seagrass; RF, DF; L)	Unknown	Impacts of physicochemical factors, ocean acidification, UV etc Degree of mixing between populations Ecological role Causes of recruitment variation
Larvae								
Juveniles		See maps (H)	Seagrass/Estuaries (RF, DF; L) Offshore (TF; M)					
Pre-spawning adult	Exploited, 3647 tonnes caught commercially each year, fishery is stable Pollution Introduced pests		Demersal (All, H) Soft sediments, bays and coastal waters (SF, BF; M) Seagrass/Estuaries (RF, DF; H) Offshore (TF; H)	Predators: teleosts, seals, dolphins, Elasmobranchs (M) Prey: range of molluscs, crustaceans, fish, polychaetes, urchins (H)			Changes in predator abundance (L) Seagrass community changes (RF, DF; L)	
Post-spawning adult								

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9.Gummy shark *Mustelus antarcticus*

Authors: Jemery Day, Susan Osborn

9.1. The fishery

Victorian fishers began fishing for sharks in offshore waters in the 1920s, with gummy shark largely a by-catch of this targeted school shark line fishery. This fishery expanded to South Australia and Tasmania in the 1940s and Western Australia in the 1970s. In 1964 the Victorian fishers introduced gillnets which are more efficient at catching gummy sharks than hooks, but it was not until the early 1970s that gillnets replaced longlines as the preferred fishing method, and then starting with Bass Strait gummy shark became the target species. In South Australia (SA) the targeted gummy shark fishery did not develop until the 1980s. Catches prior to 1970 were only reported as combined catches of school and gummy shark. Gummy shark catches ranged between 1000 t and 2000 t from the mid 1970s to the present.

Sixty-seven per cent of the total catch of gummy shark from south-eastern Australia during 1976–1996 was taken from Bass Strait. There is a small recreational fishery. Of the total catch of gummy shark from southern Australia, by all fishing methods, during 2002–04, 77% was taken by the Gillnet Hook and Trap Fishery (GHATF), 3% by the South East Trawl Fishery (SETF), 2% by the Great Australian Bight Trawl Fishery (GABTF), 3% by state-licensed vessels in South Australia, Victoria, Tasmania, and New South Wales, and 15% by state-licensed vessels in Western Australia. For management purposes, gummy shark is now the only species of shark recognised as a target species in the GHATF.

The targeted gillnet fishery for gummy shark has two important distinctive features, which strongly influence stock assessment and management. The first notable feature of the fishery is that the catch is comprised principally of just four year classes of sub-adult animals and the adult biomass remains relatively unfished. Second, catches remain remarkably stable over wide ranges of effort in Bass Strait since 1973 when the fishery can be considered to have been fully developed.

This feature of the fishery's dynamic produces a negative relationship between catch rates and effort so that catch rates decline as effort increases and *vice a versa* and during the 1980s when a large portion of the fleet might switch between scallop and shark fishing large inter-annual variations in catch rate were normal. With successive management interventions – net length reductions (1980s), mesh size regulation (1990s) and ITQ management and buy-out (2000s) – effort levels in this sector have returned to levels recorded in the 1970s. As a consequence, catch rates are returning to levels of that period.

These features of the fishery's dynamics mean that there is no index of adult abundance, and commercial catch rate data provide a poor index of sub-adult abundance for the quantitative stock assessments developed for the fishery (SharkRAG 2000). In contrast the stability of the catch of 4–7-year-old sub-adults through a 30 year period of fishing and a four-fold range in effort levels, means that the wide variety of assessment models applied by SharkRAG over the years since its inception in 1994 all estimate that recruitment to the fishery has remained stable at its original level. Consequently, SharkRAG members are confident of the current stability of recruitment to this fishery and far less confident of estimates of adult biomass or of pup production derived from the estimates of adult biomass (*SharkRAG 2009*).

The production value for Gummy Shark in the Southern and Eastern Scalefish and Shark Fishery Commonwealth Trawl Sector, Gillnet Hook and Trap Fishery and Great Australian Bight Fishery in 2007/2008 was $18,000,000 with a total catch of 2848 t (Figure 9.1). Production value is the assessed value at the point of landing for the quantity produced and excludes transport and marketing costs (*ABARE 2009*).

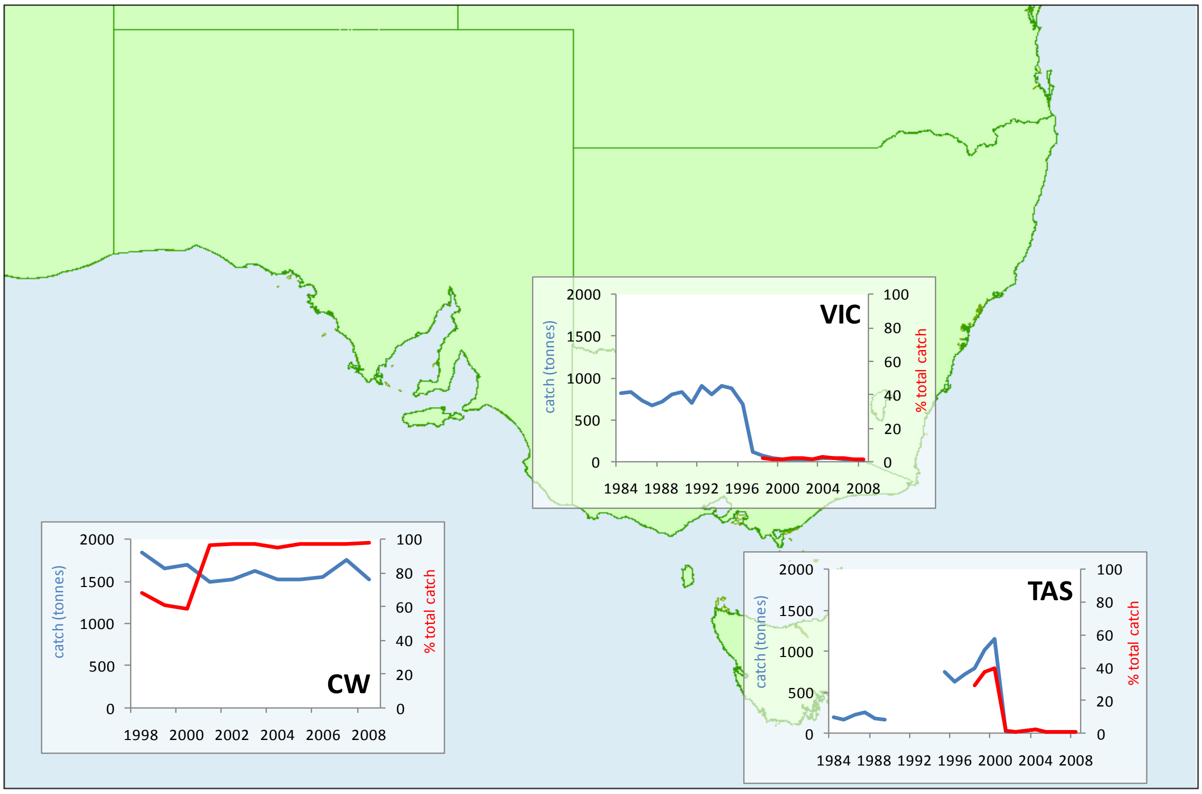

Figure 9.1: Commercial catch (tonnes) and contribution by each jurisdiction to total catch in south-east Australia (%) by year for Victoria, Tasmania, and the Commonwealth. Since 2001/02 Tasmanian shark catches have been reported in Commonwealth logbooks.

Key points:

- Gummy shark are caught in Vic, Tas, SA and WA.
- In 2008/09 combined catch was 1,550 tonnes.
- Small recreational catches

9.2. Life history

9.2.1. Life cycle, age and growth

Gummy sharks are ovoviviparous (internally fertilised eggs). Ovulation occurs between October and mid December in Bass Strait and South Australia and between November and February off Western Australia. Pregnant sharks carry between 1 and 38 young (average 14), with large females carrying more than smaller ones. Gestation period ranges from 11 to 12 months. The length at first maturity and proportion of pregnant females at this length increases from east to west. In Bass Strait, about half of the large females breed each year, whereas in South Australia and Western Australia, most breed each year. The sex ratio at birth is 1:1 and mean birth length is 33 cm.

Female gummy sharks grow to 177 cm and males to 145 cm with a maximum weight of around 25 kg and a longevity of about 16 years. The age at maturity is about four years for males and about five years for females with a size range at maturity of 80–130 cm, and the length at which 50% of female sharks mature is 120–130 cm.

A significant proportion of large females move to waters off South Australia and perhaps Western Australia.

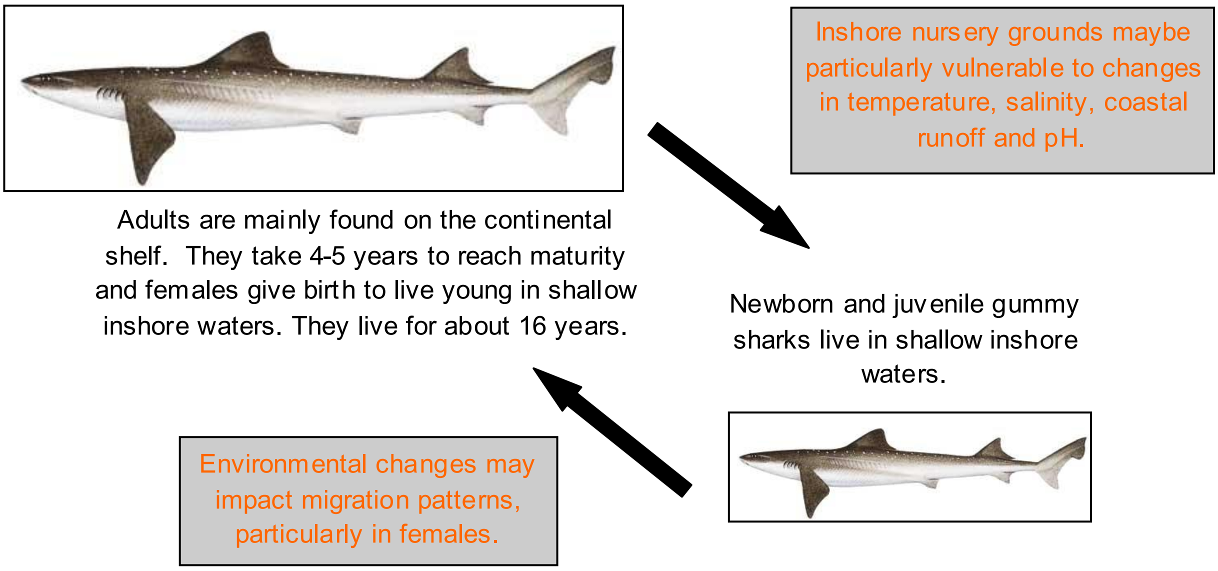

Figure 9.2: Summary of life cycle (this section), and points of exposure to relevant climate change drivers or known impacts (subsequent sections).

9.2.2. Distribution, habitat and environmental preferences

Gummy Shark are a demersal species that occur in the range of 28°S – 44°S within a depth range of 0–350 m, although they are mainly found on the continental shelf to about 80 m depth. Newborn and juvenile gummy sharks aggregate in many areas across southern Australia, inhabiting shallow water nursery areas including coastal/inshore, intertidal, shallow water, beaches, nearshore and bays, but it is not known whether they inhabit defined shallow-water nursery areas. Adults inhabit the continental shelf.

Their spatial distribution is Eastern Indian Ocean: endemic to southern Australia, from Western Australia through Bass Strait to Tasmania and northern New South Wales (Figure 9.3). Their range possibly extends northward to southern Queensland and Shark Bay in Western Australia. Confused with another undescribed species whose southern distribution extends to Dampier (20°40'S) (possibly Shark Bay) in the west and Bowen (20°S) (possibly Coffs Harbour) in the east, occurring in the range of about 17° and 30° South in depths between 120 and 400 m. There is assumed to be a single stock of gummy sharks in the area with low mixing rates, so regional sub-stocks are likely across Southern Australia.

These sharks are capable of long oceanodromous migrations with females travelling longer distances than males, and with tagging evidence suggesting migration west from Bass Strait as sharks increase in age.

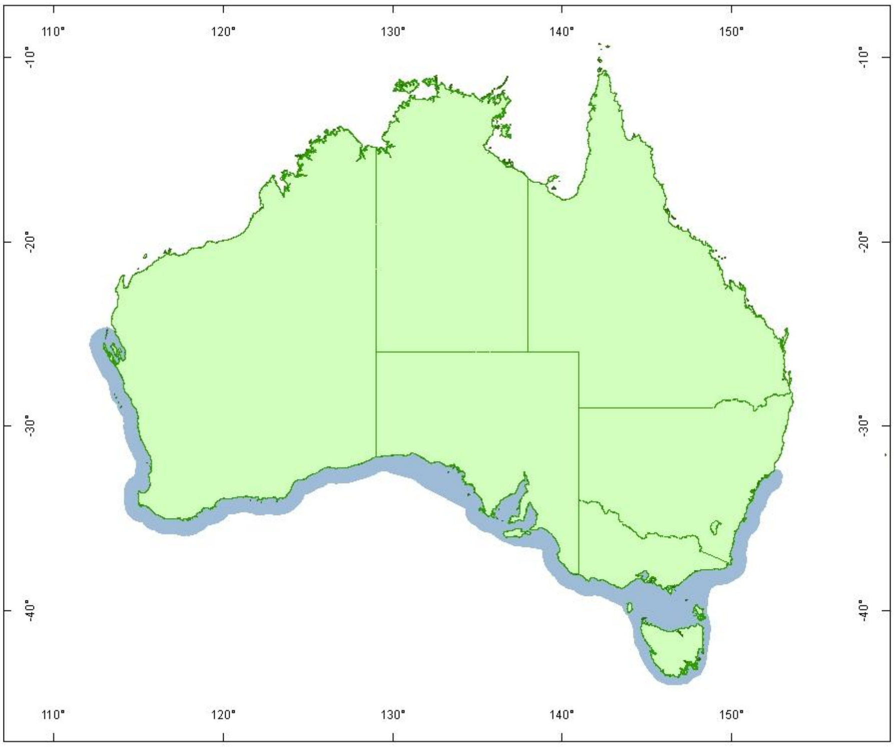

Figure 9.3: Map detailing distribution of gummy shark.

9.2.3. Predators and prey

Gummy shark prey on a wide variety of demersal species, from areas of sandy and, to a lesser extent, rocky substrate. In Bass Strait, the main component by weight of their diet is squid and octopus (36%) crustaceans (25%) and scale fish (11%) and also includes marine worms. Commercial species included in their diet include southern rock lobster, southern calamari, arrow squid and barracouta.

The predators of gummy shark are unknown.

9.2.4. Recruitment

The sex ratio at birth is 1:1 and mean birth weight is 33 cm. Young are usually born in shallow coastal areas and they are thought to be unlikely to have well defined shallow-water nursery areas.

Key points:

- Gummy shark are demersal, with some evidence of adult migration out of Bass Strait.
- They are distributed throughout southern Australia, mostly in waters to about 80m depth.
- It is suspected that Bass Strait is a source of recruits.

9.3. Current impacts of climate change

Current impacts of climate change are largely unknown for this species.

Key point:

- Current impacts of climate change are largely unknown for this species.

9.4. Sensitivity to change

There is limited juvenile dispersal, although adult females are known to migrate large distances. The reproduction potential and ability for rapid increase in population is limited by the relatively low fecundity. There is assumed to be one stock with low mixing rates. Water temperature changes are expected to cause a decrease in the spatial southward distribution and population abundance of the gummy shark population, particularly during early life stages, due to the species' reliance on shallow water areas and inshore habitats including coastal/inshore, intertidal, shallow water, beaches, nearshore and bays. Sea-level rise, rainfall, coastal runoff and salinity changes may also impact newborns and juveniles in shallow-water nursery grounds. Ocean acidification may negatively impact 'shelled' prey such as crustaceans, and thus have an indirect effect on gummy sharks, particularly in bays and estuaries where acidification may also occur due to lowering of the water table.

Key points:

- Limited information is available on specific impacts of climate change.
- Gummy sharks exhibit relatively low fecundity.
- There is one stock with low mixing rates.
- Shallow inshore nursery grounds may be more vulnerable to changes in temperature, salinity, and pH.

9.5. Resilience to change

Gummy sharks are generalist feeders so may have some resilience to changes in prey species.

Key point:

- Gummy sharks are generalist feeders.

9.6. Ecosystem level interactions

The main prey species include squid and octopus (36%) and crustaceans (25%), so if there are climate change impacts to these prey species, this could have an impact on gummy sharks. There is little information on gummy shark predators.

Key points:

- There is limited information on gummy shark predators.
- Changes to prey species could be important, especially changes to squid, octopus and crustaceans.

9.7. Additional (multiple) stressors

Gummy shark has a stable catch history. However, there is some pressure to decrease fishing intensity in the future to comply with the targets set by the adoption of the Commonwealth Harvest Strategy Policy, largely to comply with by-catch issues for associated species.

Key points:

- Gummy shark has a stable catch history.
- The exploitation rate may be reduced in the near future.

9.8. Critical data gaps and level of uncertainty

Very little is known about the main predators of gummy shark, or how predator–prey interactions may modify gummy shark distribution and abundance. There is no knowledge of well defined nursery areas, other than a range of aggregations of newborn and juvenile gummy sharks across Southern Australia.

Key points:

- There is limited information on nursery areas.
- There is no information on predators.

Table 9.1: Summary of gummy shark species profile, which also indicates level of certainty of the associated information. Level of certainty is divided into high (H) = strong clear evidence, backed by several studies with solid datasets with little confounding interactions; medium (M) = evidence supported by one or more studies, conclusions may be partially ambiguous or confounded; low (L) = anecdotal evidence, limited data and/or predicted conclusions based on theoretical knowledge.

Life history stage	Multiple stressors	Distribution	Habitat	Predators and prey	Current impacts	Predicted impacts	Ecosystem interactions	Data gaps
Newborn young and juveniles		See Fig 3 (L)	shallow water nursery (H) continental shelf 0-350 m (H)	Predators: unknown Prey: squid, octopus and crustaceans (H)	Unknown	Possible reduction in suitable nursery areas (L)	Unknown	Information on predators Specifics of nursery areas
Adults	Exploitation, ~1500t are caught each year, fishery is stable							

9.9. References

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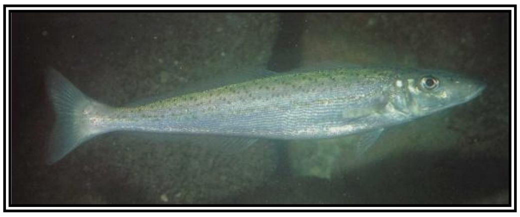
10. King George whiting *Sillaginodes punctatus*

Author: Neil Hutchinson



10.1. The fishery

The main commercial fishery for King George whiting (KGW) is in South Australia (SA), from Gulf St Vincent to Ceduna, with smaller fisheries in central Victoria and south-western WA, operating from September–November and April– June (Kailola et al. 1993). Fish are caught by seine nets, gillnets, powerhauling and handline, with the majority of fishing effort targetting 2–7-year-old fish, with larger individuals caught by hand line (Kailola et al. 1993). In Victoria, King George whiting is the highest value commercial finfish species, with commercial catches, for 2007–2008, of 215 t / $3,027,000. Commercial catches were 329 t / $4,704,000 for SA, (ABARE 2009) (Figure 10.1).

A popular species for recreational fishers, recreational angler catches account for large percentages of the fishery; e.g., the current Victorian catch of about 400 t is evenly divided between commercial and recreational sectors (DPI 2008). Corner Inlet and Port Phillip Bay (PPB) are the major commercial fishing areas, while PPB and Western Port dominate the recreational catch. Recreational anglers target immature fish, with an estimated total catch in 2000/01 of 3,621,629 individuals caught nationally, with ~26% of these released/discarded (Henry and Lyle 2003). Approximate numbers caught per year for each state were 975,349 in Victoria; 2,238,071 in SA and 408,209 in WA (Henry and Lyle 2003). In 2007/08, SA residents caught a total of 1,797,148 throughout SA, with 30.5% of these released as mainly undersized fish (Jones 2009). The harvested (retained) weight was estimated at 324.4 tonnes, live weight. Relatively high total catches occurred in Spencer Gulf, Gulf St Vincent / Kangaroo Island and west coast waters, and low catches were taken from the SE (Jones 2009).

Key points:

- King George whiting are harvested in SA, Vic and south-western WA; and is an important recreational species in these states.
- In 2008/09, the combined commercial catch was 479.9 tonnes.

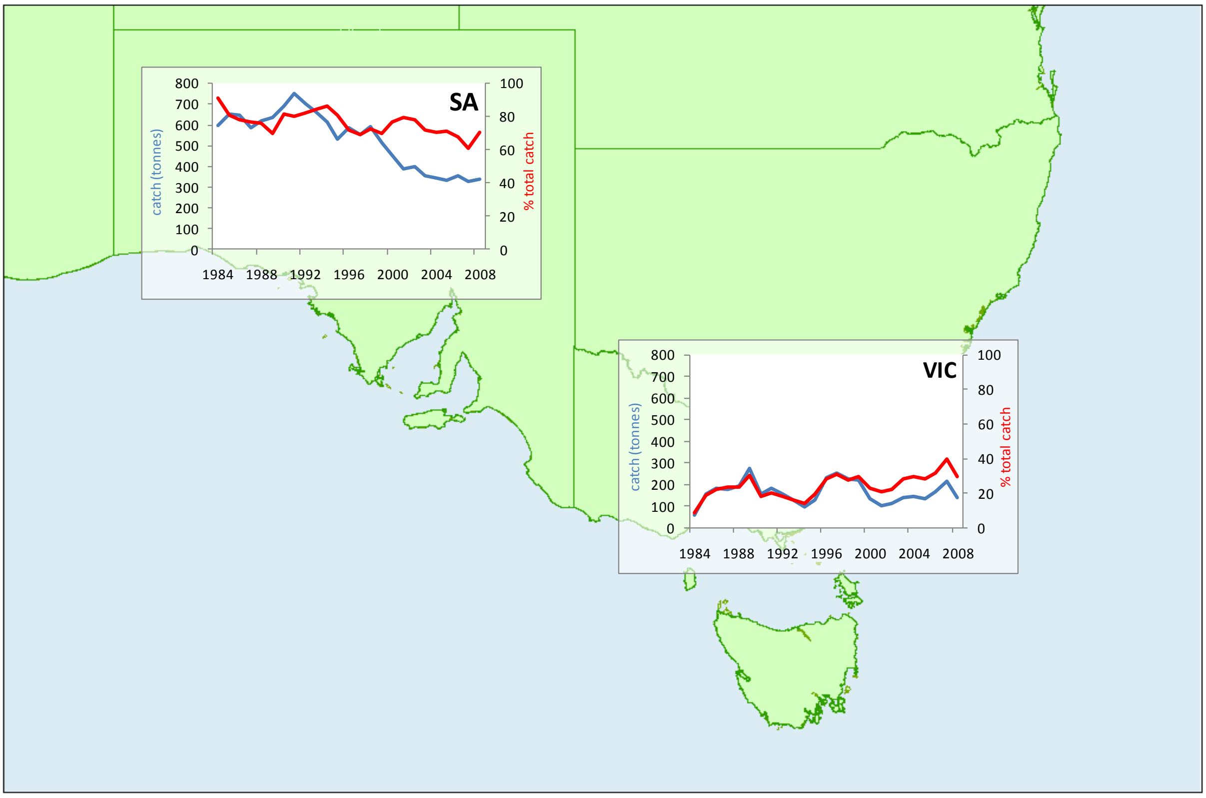


Figure 10.1: Commercial catch (tonnes) and contribution by each jurisdiction to total catch in south-east Australia (%) by year for South Australia and Victoria.

10.2. Life history

10.2.1. Life cycle, age and growth

King George whiting live for 15 years and reach sexual maturity at three to five years when fish are 30–35 cm in length (Scott 1954; Jones et al. 1990; Potter et al. 1996; Fowler and McGarvey 2000; Jenkins 2005). It has been suggested that possible cues that may influence the success of maturation include the presence of mature, older fish and some effect of spawning habitat, specifically exposed, deep water, reef habitats (Fowler and McGarvey 2000).

Adults in spawning condition or life history stages less than 100 days old are rarely found in near-shore central Victorian waters, which suggest that there is little or no spawning activity in the vicinity (Hamer et al. 2004). The increasing age of individuals towards the west of Victoria (Hamer et al. 2004) and increasing larval duration from western to eastern Victoria suggests that spawning may take place in coastal waters to the west of Victoria’s major bays and inlets, with the Victorian KGW population derived from spawning in South Australian waters (Jenkins et al. 2000; Hamer et al. 2004). Similar patterns have been observed regarding the timing of recruitment in SA (Fowler and McGarvey 2000). Adults from Port Phillip Bay may return to SA waters to breed, but this is uncertain (Hamer et al. 2004).

KGW are multiple batch spawners that spawn at least 20 times annually (Fowler et al. 1999; Fowler and McGarvey 2000). In SA, individuals have been found to produce approximately 40–60,000 eggs per spawning event (Fowler et al. 1999), with annual fecundity ranging from ~112,000 to ~6,000,000 eggs (Scott 1954; Fowler and McGarvey 2000). There are large spatial differences in fecundity, for example between Kangaroo Island and south-eastern Spencer Gulf, possibly due to differences in habitat (Fowler and McGarvey 2000) (Figure 10.2).

King George whiting eggs are buoyant, and hatch after a few days at a size of 2–3 mm (Bruce 1995). Natural KGW spawning in South Australia seems to occur when seawater temperatures are between 17°C and 19°C (Fowler et al. 1999).

Six days after hatching at 19˚C, larvae (3.5 mm) in the laboratory absorb the yolk sac and their mouth and eyes open (Partridge 2001). In SA, the duration of the larval stage of KGW ranges from 67 to 80 days for early-settling juveniles (June–July) to approximately 120 days old for later-settling juveniles (after September) (Ham and Hutchinson 2003). These differences are attributed to the date of spawning with earlier-spawned larvae metamorphosing and recruiting at a younger age than later spawned larvae (Ham and Hutchinson 2003).

After spawning in SA, larvae are transported by water currents and may drift from 3 to 5 months, during which time they undergo an extended development stage, before entering sheltered marine habitats in Victorian bays and inlets during spring (Jenkins and Black 1994; Jenkins and May 1994; Jenkins et al. 2000). Larvae are concentrated in the surface layers during daylight but are distributed throughout the water column at night (Jenkins et al. 1998c). Settlement occurs in or near shallow-water seagrass beds, mainly in Port Phillip Bay, Western Port and Corner Inlet (Jenkins et al. 2000). While these larvae are mostly thought to come from SA, it has been suggested that some may also come from the western boundary of Bass Strait and that there may be an additional source of the larvae near Corner Inlet (Jenkins et al. 2000). Larvae are ~15–20 mm long when they settle in Port Phillip Bay and high settlement of post-larval whiting is correlated with strong westerly winds and warm water temperatures off western Victoria (Jenkins and McKinnon 2006). Ingress of larvae to Port Phillip Bay occurs when strong westerly winds and low barometric pressure cause the sea level on the coast and in the bay to rise (Jenkins et al. 1997a). The recruitment of post larvae into shallow sub-tidal beds of *Zostera* and *Heterozostera* spp has been shown to occur between July and November each year in SA (Fowler and Short 1996) and in spring in Victoria (Jenkins and May 1994; Jenkins et al. 2000). Seagrass is probably crucial to newly settled larvae through the provision of food (Jenkins and Hamer 2001) and protection from predators (Hindell et al. 2000b).

In South Australia, KGW post-larvae in the wild are known to inhabit sand and seagrass beds in the sheltered, shallow waters of west coast bays and gulf waters (Bruce unpublished data as per Jones et al. 1990). At this stage juveniles can be exposed to water temperatures that range from 14˚C to 23˚C (Fowler and Short 1996).

In the wild, KGW have a larval period which extends for 80–146 days to the post settlement (early juvenile) phase, at which point KGW are still very small, typically weighing 0.1 – 0.2 g. (Fowler and Short 1996). The larval period has been shortened in reared KGW larvae, depending on the temperature and feeding regime during culturing (Ham and Hutchinson 2003).

After settlement, juvenile development occurs over the next 2–4 years before the onset of sexual maturity (which occurs at lengths of between 27 and 36 cm and approximately three years of age). The rate of growth varies depending on the water temperature, with very little growth occurring during the winter and rapid growth from December to March (Coutin 2000). As the juveniles age, they move from shallow areas near seagrass to unvegetated sand with patchy seagrass (3–5 months) and then into deeper water over sandy or muddy areas with patchy seagrass. During the summer months, when water temperatures are relatively warm, growth is rapid and most fish reach a size of about 28 cm at two years of age. King George whiting migrate out of bays and inlets just prior to reaching maturity (35 cm long, at about three years of age). The mature fish then migrate offshore to join other adult stock in deeper waters (to at least 100 m) (Jones et al. 1990; Coutin 2000; Fowler et al. 2002; Hamer et al. 2004).

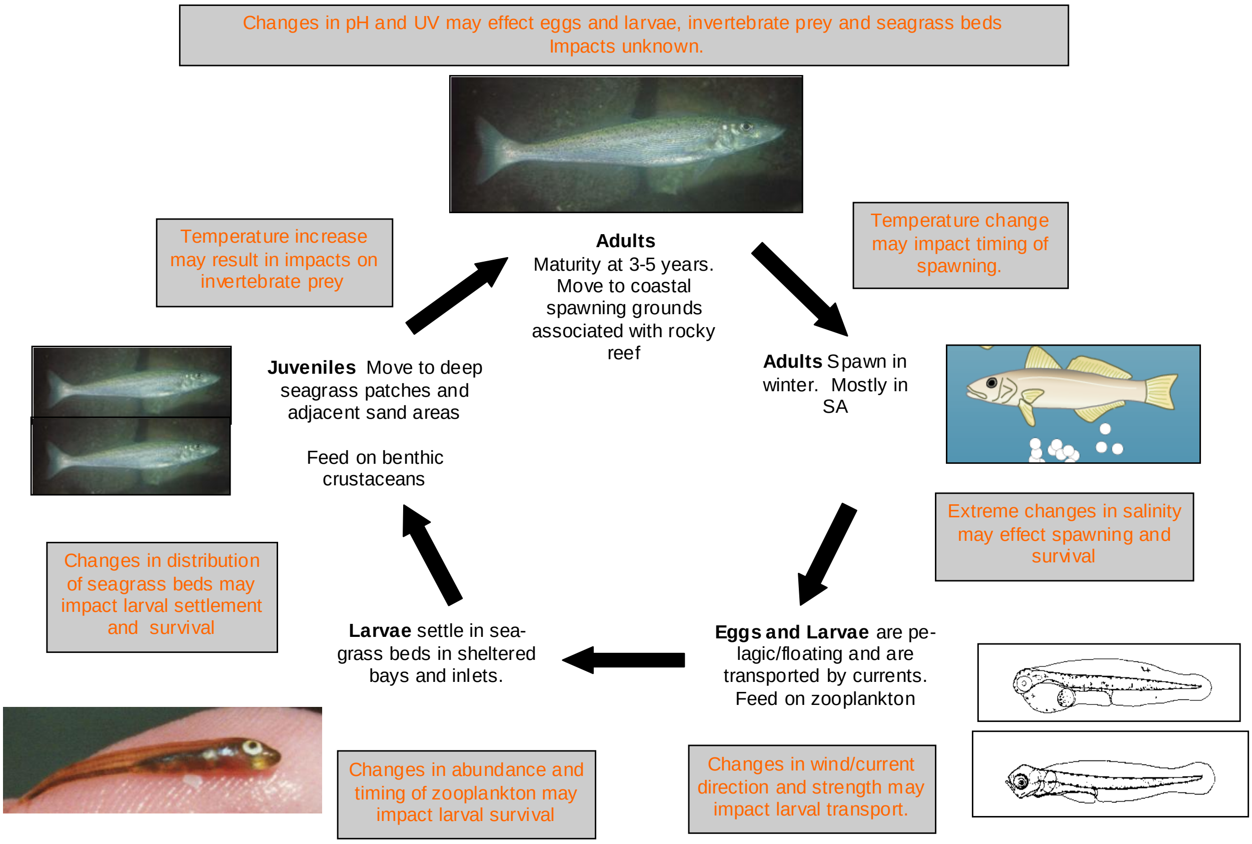


Figure 10.2: Summary of life cycle (this section), and points of exposure to relevant climate change drivers or known impacts (subsequent sections). (Images from: Neira 1998; Hutchinson et al. 2010; Jenkins, G.J.).

10.2.2. Distribution, habitat and environmental preferences

King George whiting are native to southern Australian coastal waters and inhabit near-shore shallow waters as well as bays and inlets from Port Jackson (NSW), to northern Tasmania and Jurien Bay in Western Australia (Gomon et al. 2008) (Figure 10.3). Juvenile fish are restricted to bays and inlets while adults are found in open coastal waters (Kailola et al. 1993).

KGW show a change in habitat preference with growth. In Victoria, post-larvae initially settle in or near shallow-water seagrass beds and reef-algae at depths of 0–2 m, mainly in PPB, Western Port and Corner Inlet (Jenkins et al. 1996; 1998a; b; 2000). The location of the seagrass beds, rather than their 'quality', is thought to be most important (Jenkins et al. 1998b; Jenkins and McKinnon 2006) and sheltered seagrass/algal nursery areas where currents deliver larvae are the most important habitats. Post-larvae show a preference for the centre of seagrass patches, potentially as shelter from predators (Smith 2010).

Ingress of larvae occurs when strong westerly winds and low barometric pressure cause the sea level on the coast and in the bay to rise (Jenkins et al. 1997a). The suitability of seagrass beds is further influenced by wave exposure, with exposed beds carrying fewer larvae than protected ones (Jenkins et al. 1997a). Seagrass is probably crucial to newly settled larvae through the provision of food (Jenkins and Hamer 2001) and protection from predators (Hindell 2000; Hindell et al. 2000a).

Although settlement is primarily associated with shallow seagrass and reef-algal beds (Jenkins and Wheatley 1998), newly settled individuals at some sites have been found in bare unvegetated mud patches within seagrass beds (Jenkins et al. 1997b). The importance of a particular habitat may depend on the amount of food available (Jenkins and Hamer 2001) as well as the local current patterns that deliver the larvae to the habitat (Jenkins et al. 1998a).

From five to six months, most fish are found on sand amongst vegetated habitats (Jenkins and Wheatley 1998). Older juveniles then move into deeper water over sandy or muddy areas with patchy seagrass. When mature, the fish migrate offshore to join other adult stock in offshore waters (Jones et al. 1990; Coutin 2000; Fowler et al. 2002; Hamer et al. 2004). Spawning adults are associated with exposed, deep water, reef habitats (Fowler and McGarvey 2000).

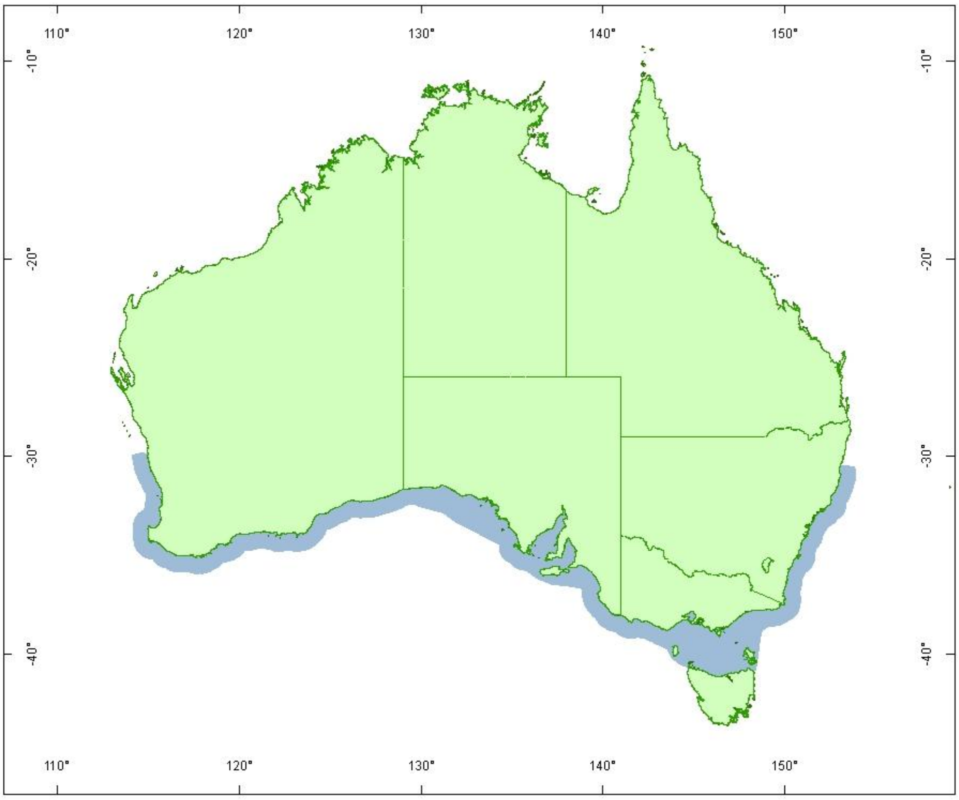


Figure 10.3: Map detailing the distribution of King George whiting.

10.2.3. Predators and prey

Predators that feed on post-larvae/juveniles include predatory fish associated with seagrass beds such as Australian salmon (*Arripis* spp.) (Hindell et al. 2000b; Hindell et al. 2002; Smith 2010), flatheads (Platycephalidae) and barracouta (*Thyrsites atun*) (Kailola et al. 1993), while sharks (Elasmobranchidae) (Kailola et al. 1993), seabirds such as cormorants (Phalacrocoracidae) (Humphries et al. 1992), and marine mammals including seals and dolphins are known to feed on adults (Long and Reid 1997; Page et al. 2005).

Under laboratory conditions, pre-settlement larvae have been fed with rotifers (*Brachionus* spp.), prior to feeding with *Artemia* sp. further along in their development (Partridge 2001; Ham and Hutchinson 2003). In Port Phillip Bay, the diet of late-stage planktonic King George whiting larvae is composed primarily of planktonic calanoid copepods; however, a range of other zooplankton are also important (Jenkins et al. 1998c). Pre-settlement larvae in PPB have been observed at night throughout the water column and feeding in daylight in the surface stratum (Jenkins et al. 1998c). While this diurnal migration does not appear to be in response to changes in the distribution of their prey, Jenkins et al. (1998c) suggested that the larvae may exhibit this behaviour in order to find adequate light levels for visual predation, which is backed up by laboratory work in WA that suggests that surface light intensity impacts food intake; e.g., higher light = higher intake (Partridge 2001). Laboratory results also indicate that as larvae develop and refine their prey catching techniques they are able to ingest prey items greater than half their mouth gape, and that at SL = 7.36 mm, KGW larvae have become efficient predators (Ham and Hutchinson 2003). A sudden change in prey size can, however, kill larvae; i.e. if small food disappears too early, then larvae are unable to utilise larger prey (Ham and Hutchinson 2003).

The diet of young juveniles is dominated by benthic and epifaunal organisms such as harpacticoid copepods and amphipods, and a range of other small crustaceans that live near the bottom (Edgar 1993; Jenkins et al. 1996). As individuals grow, their diet expands to include larger benthic organisms such as Bass yabbies (*Callianassa australiensis*), polychaete worms (e.g., *Nephtys australiensis*, *Nereis* spp. and *Arenicola* sp.), molluscs (e.g., cockles and squid) and peanut worms (Sipuncula) (Scott 1954; Robertson 1977). Polychaetes may dominate the diet of the larger King George whiting in Victorian bays (Parry et al. 1995). In the SA gulfs, the diet of adults (up to 430 mm) consists mainly of Polychaete, Sipunculid and Pectinariid worms (Currie and Sorokin 2010).

10.2.4. Recruitment

Recruitment of KGW to PPB is related to the strength of westerly winds and the offshore water temperature in the larval stage (Jenkins 2005; Jenkins and King 2006). Settlement of post larvae into shallow sub-tidal beds of *Zostera* and *Heterozostera* spp has been shown to occur between July and November each year in SA (Fowler and Short 1996) and in spring in Victoria (Jenkins and May 1994; Jenkins et al. 2000). The suitability of seagrass beds is influenced by wave exposure, with exposed beds carrying fewer post larvae than protected ones (Jenkins et al. 1997a). Seagrass is probably crucial to newly settled larvae through the provision of food (Jenkins and Hamer 2001) and protection from predators (Hindell 2000; Hindell et al. 2000a).

Key points:

- KGW have floating eggs and larvae, and the transport of individuals from spawning grounds to nursery grounds is linked to currents and coastal winds.
- Seagrass beds provide important habitat for recruiting larvae and developing juveniles.

10.3. Current impacts of climate change

There is little information on current impacts of climate change on this species. However, in Victoria, the zonal westerly wind (ZWW) index has shown a long-term downward trend since about 1970, suggesting that the strength of the westerly wind flow over Victoria has decreased over the past 40 years and it is possible that this could negatively influence the long-term catch of King George whiting (Jenkins pers. comm.). The decline in the ZWW is consistent with the prediction that westerly winds will weaken in southern Australia under climate change due to a southward migration of the high-latitude westerly wind belt south of Australia (Cai et al. 2005). The predicted increase in the frequency of El Niño events under climate change would also be expected to have a negative effect on the King George whiting catch. As SA is the centre of the population of KGW, and the distance of advection of larvae to the nursery areas appears to be less than in Victoria, it is uncertain what effect the increased frequency of El Niño events will have on the stocks occurring in South Australia.

Key points:

- Little is known about current impacts.
- Changing wind patterns may be influencing recruitment in Victoria.
- There is uncertainty about the factors influencing recruitment in SA.

10.4. Sensitivity to change

Laboratory-based studies have examined spawning and egg development at a variety of temperatures and salinities, factors that have been shown to have both independent and interactive effects on hatching success (Partridge 2001; Ham and Hutchinson 2003). For example, laboratory studies have found that KGW require seawater temperatures >15°C for spawning, with extreme changes in temperature; e.g., cold spikes <15°C potentially causing spawning to end (Ham and Hutchinson 2003). Trials with varying salinities found that hatching success was greatest at 16–22°C and at salinities between 35–50 ppt, with a peak at ~20°C and ~40 ppt. Hatching times in actual hours was shortest in 22°C treatments and longest in 16°C treatments.

Development is relatively swift, as shown by a laboratory study in WA, where eggs took 36 hours to hatch at 19°C (Partridge 2001). Other laboratory studies assessing the growth of this species at elevated water temperatures were conducted by Ham and Hutchinson (2003). KGW fingerlings were exposed to a range of water temperatures incorporating those that they experienced by in the wild, as well as temperatures higher than those found under natural conditions. Results indicated that at temperatures of 22–26°C, KGW larvae showed increased growth over a 70-day period in comparison to larvae at 18–20°C and found that larvae 120–190 days post hatching were able to tolerate these elevated temperatures. In the event of water temperatures elevating due to climate change, this species could benefit at this stage of their development if sufficient food was available.

Higher water temperatures especially during winter months, due to thermal effluent from a power plant located adjacent to an important KGW nursery area in Gulf St Vincent, have been inferred as the cause of substantially higher than normal growth rates of juvenile KGW (Jones et al. 1996). It appears that the changes in the growth rates and species diversity due to thermal effluent may be used to model the effects of climate change in key nursery areas (Jones et al. 1996).

KGW have been listed in Victoria as 'environmentally limited' because environmental conditions in bays, inlets and estuaries are thought to control recruitment. In Victoria, a comparison of 50 years of KGW catch data and data on zonal westerly winds (ZWW) found decadal cycles of variability in both factors across all of the major bays, with a positive correlation between ZWW and larval settlement from 10 years of data collected in Port Phillip Bay (Jenkins 2005). Further analysis found a positive relationship between catch at 0 lag and the El Niño southern oscillation index (ENSO), with highest catches during La Niña periods (Jenkins 2005). It is not clear whether this is due to increased rainfall during La Niña years in southern Australia (Chiew et al. 1998) resulting in increased nutrient runoff and hence benthic productivity, or other mechanisms (G. Jenkins, pers. comm.). In Western Port, Victoria there was a major decline in the long-term catch from the early 1970s that corresponded to major seagrass loss in this bay, suggesting that the long-term trend in population abundance may be strongly influenced by habitat availability in the juvenile stage (Jenkins 2005). The importance of seagrass beds for KGW in SA was similarly highlighted by Scott et al. (2000), who developed a seagrass residency index for a number of economically important species covering all their life history stages. A relatively high index (0.75 out of 1.0) was calculated for KGW.

Sea surface temperature (SST) in the area of larval distribution may also have an important influence on KGW larval survival and recruitment. Abundance of post-settlement whiting in seagrass beds in Port Phillip Bay, Victoria has been shown to be strongly correlated with growth in the larval stage determined from otolith daily increments (Jenkins and King 2006). The relationship between SST measured near the presumed spawning area to the west of Port Phillip Bay was also significantly correlated with post-larval abundance in Port Phillip Bay (Jenkins and King 2006). Increased water temperature would have had the direct effect of increasing larval growth and therefore contributing to larval survival, but may also have been indicative of enhanced physical transport and/or plankton productivity. Zooplankton distribution patterns have seen major changes in some areas in relation to climate change (Roessig et al. 2004; Parmesan 2006). Zooplankton is expected to respond quickly to climate change, which may lead to a mismatch between zooplankton abundance and predator abundance (Richardson et al. 2009), which may impact the larval stages of KGW. Other benthic prey may also be impacted by temperature, pH and salinity changes.

In Victoria, relationships between KGW recruitment and catch with factors such as ZWW and SST may also relate to oceanographic variability off the coast of western Victoria in the area of larval distribution. Winter circulation is characterised by a west to east coastal current that would facilitate transport of larvae eastwards to Port Phillip Bay (Cirano and Middleton 2004). Any changes to this current, which is driven by westerly winds and the eastward extension of the Leeuwin Current (Ridgeway and Condie 2004), or the timing of spawning in SA, could directly affect larval supply to Victorias bays.

Key points:

- Controlled aquaria experiments show that cold spikes can cause a cessation of spawning.
- Increased temperatures lead to an increase in the speed of larval development (observed in laboratory and wild populations).
- Seagrass loss can negatively affect KGW populations.

10.5. Resilience to change

The Victorian stock is believed to be a single stock arising from spawning in west Victorian and South Australian waters from Portland to near Kangaroo Island. Spawning occurs in South Australia between February and July (Autumn–Winter) near coastal reefs (Scott 1954; Bruce 1989; Cockrum and Jones 1992; Fowler et al. 2000b), and in WA between July and August (winter) (Potter et al. 1996). In contrast, it is thought that there are several discrete stocks in SA with spawning grounds 40–150 km from identified nursery grounds such as Barker Inlet (Gulf St Vincent), Franklin Harbour (Spencer Gulf), Coffin Bay and Streaky Bay (West Coast of SA) (Fowler et al. 2000a; Fowler and McGarvey 2000).

Climate modelling predicts significantly increased water temperatures in south-eastern Australia with future climate change (Poloczanska et al. 2007). Modelling predicts no obvious strengthening of the Leeuwin Current of western Australia; however, southern Australia will experience more westward transport (Poloczanska et al. 2007). Increased water temperature should have a positive effect on larval survival and recruitment. Laboratory tests found that KGW larvae showed increased growth at increased temperatures of 22–26°C, and that 120–190 days post hatching, larvae were able to tolerate these elevated temperatures (Ham and Hutchinson 2003). In contrast to temperature effects, more east to west transport in southern Australia could have a negative effect on KGW recruitment in Victoria (Jenkins 2010).

Increased water temperatures in SE Australia could have significant effects on juvenile and adult distributions depending on physiological tolerances. In general there is expected to be a southward shift in temperate fish distributions under climate change (Poloczanska et al. 2007). It is possible that the distribution of KGW could contract further south on the Australian mainland and also become more widespread in Tasmania. Because spawning occurs in winter and may be partly triggered by low water temperatures, the timing and intensity of spawning could be affected. Salinity of bay and inlet nursery areas would be expected to rise under climate change due to decreased rainfall in catchments (Suppiah et al. 2004), but laboratory experiments indicate that hatching is successful up to 50 ppt.

Key point:

- KGW have a high dispersal capacity, potentially allowing resilience to changing environmental conditions.

10.6. Ecosystem level interactions

KGW are preyed upon by a variety of species, including fish, elasmobranchs and marine mammals, and it is expected that populations of these predators will themselves be impacted by climate change, with changing ranges etc (Learmonth et al. 2006; Chin et al. 2010). It is unclear at this stage how KGW will be affected, as range changes in this species and its predators may not be in the same latitudinal direction. Predators of KGW tend to be generalists, and therefore the disappearance of KGW from an area is unlikely to have a major impact on them.

Seagrass in Australia is expected to be influenced by climate change in several ways, including general decreases in productivity, local-scale losses due to decreased light, a change in community structure to more heat/CO_2 tolerant species, long-term declines of seagrass health, and changes in the distribution of seagrass both with latitude and with height on the shore (Connolly 2009). KGW rely heavily on seagrass beds to provide habitat and food resources, and therefore the loss of seagrass beds in key bays could have dramatic impacts on KGW populations.

Key point:

- Changes in seagrass bed distribution patterns are likely to have a large impact on recruitment of KGW.

10.7. Additional (multiple) stressors

There is a large, managed fishery for this species and some KGW are caught as by-catch in the southern sea garfish (*Hyporhamphus melanochir*) fishery (Kailola et al. 1993).

KGW may be fully exploited throughout most of their shallow coastal range, and there appears to have been a reduction in size at first maturity in the SA fishery since the 1960s (Kailola et al. 1993).

Another factor that may be acting on this fishery is that the life-history loop appears to straddle the borders of two jurisdictions (Victoria and SA) but the management is separated between the states.

Key point:

- Exploitation may have an influence on the impacts of climate change on KGW.

10.8. Critical data gaps and level of uncertainty

- Little is known about the ecological role of KGW and how they compete for resources with other species, or how they would be impacted by competition with species not currently resident in their area.
- Further climatic and oceanographic studies are required, including modelling, on trends in variables such as zonal westerly winds, the Leeuwin Current, and sea surface temperatures, and in particular how variation in westerly winds and the Leeuwin Current affects the eastern coastal current and associated sea surface temperatures of western Victoria. Confidence in predictions of the long-term trend in those variables under climate change needs to be based on increased knowledge and also sophistication of computer modelling techniques.
- Research focusing on the larval stages of King George whiting larvae in western Bass Strait would be beneficial in determining what factors relating to environmental variables are key to survival and recruitment. Research would aim to determine the relative importance of enhanced larval growth through higher water temperatures; enhanced nutrition based on planktonic productivity, and enhanced physical transport based on current patterns in determining successful recruitment. This would help us to focus on the most important factors that may be influenced by climate change.
- Annual monitoring of settlement of King George whiting post-larvae to seagrass beds in Port Phillip Bay has been underway for approximately 10 years and has already shown positive correlations with ZWW and SST off western Victoria. This monitoring needs to be continued in Victoria and other states as it will be an important tool for monitoring the effects of climate change on King George whiting recruitment. Catch and effort monitoring of King George whiting in SE Australian bays also needs to be continued as this provides and index of the abundance of 2–4-year-olds and therefore acts as a fishery recruitment index that can be used to monitor climate change effects.
- Predictions of climate change effects on King George whiting are hampered by uncertainties relating to the species' life cycle. For example, the spawning locations producing larvae that recruit to Victorian bays and inlets are only known in the broadest sense (i.e. western Victoria to central South Australia); this knowledge needs to be refined to more specific localities. Also unknown is the proportion of whiting from central Victorian bays and inlets that return to the spawning areas and contribute to reproduction compared to the resident fish in western Victoria/South Australia. Improving this knowledge will require the application of innovative techniques such as otolith microchemistry and acoustic tagging.

- Although relationships between KGW and seagrass are well understood in the early post-settlement stage, knowledge of linkages between older juveniles and seagrass is poor. This knowledge is necessary to understand the consequences of future changes to seagrass under climate change to KGW populations.

Key points:

- There is limited information on the ecological role of KGW.
- Climatic and oceanographic models are needed to predict potential climate change effects.
- More information is required on larval development.
- SE Australia-wide monitoring of recruitment is required.
- More information on source spawning populations is required for some states.
- Better understanding is needed on links between older juvenile KGW and seagrass beds.

Table 10.1. Summary of king George whiting species profile, which also indicates level of certainty of the associated information. Level of certainty is divided into high (H) = strong clear evidence, backed by several studies with solid datasets with little confounding interactions; medium (M) = evidence supported by one or more studies, conclusions may be partially ambiguous or confounded; low (L) = anecdotal evidence, limited data and/or predicted conclusions based on theoretical knowledge.

Life history stage	Multiple stressors	Distribution	Habitat	Predators and prey	Current impacts	Predicted impacts	Ecosystem interactions	Data gaps
Eggs	Unknown	See map 1 (L)	Pelagic, offshore (H)	Predators: Unknown		Growth rates to reach a maximum and then start to decline (L) Recruitment trend uncertain; increasing SST positive, but potential seagrass loss negative (L) Greater east – west transport in southern Australia negative (L)		Ecological role Oceanographic changes Larvae in Bass Strait Post-larval settlement Physico-chemical tolerances Spawning site identification for all stocks Seagrass links for older juveniles
Larvae			Pelagic, settle on reef-algal beds and seagrass patches (H)	Predators: predatory fish (M) Prey : Zooplankton, e.g., calanoid copepods	Increasing SST, winds potentially influencing recruitment (L)		Loss of habitat, seagrass (M)	
Juveniles		See map 2 (H)	Sand patches among reef-algal beds and seagrass patches (H)	Predators: predatory fish, seabirds, marine mammals (H) Prey: range of benthic invertebrates, e.g., Bass yabbies, polychaetes (H)				
Pre-spawning adult	Exploited, 479.9 tonnes caught commercially each year, fishery is stable		Bare sediments, reefs, macroalgae, seagrass (bay/coastal), oceanic waters (H)					
Post-spawning adult			Exposed, deep water, reef habitats (H)					

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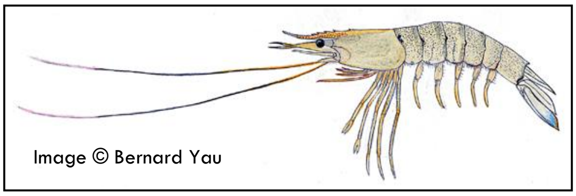
11. School prawn *Metapenaeus macleayi*

Author: Philip Gibbs



11.1. The fishery

School prawns *Metapenaeus macleayi* in the south-east of Australia are primarily caught in New South Wales (NSW) waters with some prawns caught in the 'Bay' prawn fishery of southern Queensland and small catches landed from the Gippsland Lakes in eastern Victoria (Anon 2002). Large school prawns form a valuable domestic market for human consumption, and substantial quantities of smaller prawns, especially from the Clarence and Hawkesbury Rivers in NSW, are sold for use as bait for recreational fishing. Commercial landings in NSW of this species fluctuate between 500 t and 1000 t, dependent on rainfall levels.

The school prawn is one of three target penaeid species of commercial and recreational importance in estuaries of NSW. It contributes around 64% by weight and 46% by value to prawn production in NSW and is harvested by three commercial fisheries: estuary prawn trawl (64% by weight of commercial landings), the estuary general fishery (28% by weight of commercial landings) and, especially after periods of high rainfall or flooding, the ocean trawl fishery (8% by weight of commercial landings). A diverse range of gears including hauling nets, running nets, set pocket nets, trawl nets and seine nets are used across these fisheries, for a description of gears (see Broadhurst 2008). The fisheries are all managed by a suite of input controls that include limits on gear dimensions, numbers of operators, area and time of operation and minimum and maximum legal mesh openings (Anon 2003).

The estuary general fishery targets school prawns in around 60 of the 130 coastal estuaries of NSW with average annual reported landings between 2003–04 and 2007–08 (inclusively) of 182 tonnes, worth approximately $1.4 million per annum. Stock status may vary between different estuaries, as each probably represents a separate population.

The estuary prawn trawl fishery is restricted to three estuaries in NSW: the Clarence, Hunter and Hawkesbury rivers and uses otter trawl nets of 11 m total headline length, towed as either single or double rig combinations. Times of operation are restricted and vary between estuaries (Anon 2003). Average annual reported landings are approximately 406 tonnes, worth $2.9 million per annum.

The ocean trawl fishery operates year around (Anon 2007) but targets school prawns primarily between January and June when the species emigrates from estuaries. Otter trawl nets of varying headline lengths are towed in triple, double or quadruple configurations. School prawns are caught by ocean trawl fleets from Shoalhaven Heads (34°S) to Tweed Heads (28°S). Annual landings average approximately 52 tonnes and are worth $349 thousand per annum.

The annual recreational harvest of school prawn in NSW is likely to be less than 30 t. This estimate is based upon the results of the offsite National Recreational and Indigenous Fishing Survey (Henry and Lyle, 2003) and onsite surveys undertaken by NSW DPI.

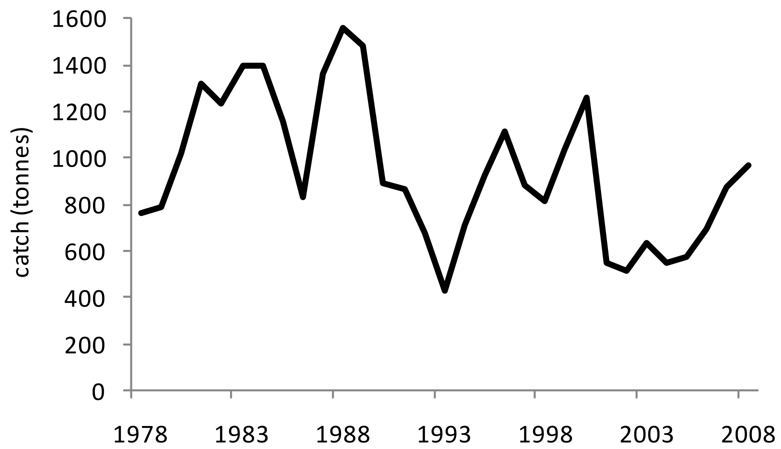


Figure 11.1: Commercial catch (tonnes) by year for NSW.

Key point:

- School prawns are an important commercial and recreational harvest species with a significant estuarine catch.

11.2. Life history

11.2.1. Life cycle, age and growth

Figure 11.2 shows a generalised life cycle for a prawn. School prawns live for probably no more than two years. School prawns have an estuarine phase to their life cycle and are very tolerant to waters of low salinity and are distributed to the upstream reaches of estuaries. The species is found in greatest numbers on vegetated habitat, but they are also found on bare substrate.

School prawns emigrate from estuaries as adolescents or adults and may spawn in waters of oceanic characteristics at the estuary entrance or the immediate nearshore coastal waters. Once at sea, school prawns stay within a radius of about 120 km of the estuary from which they emigrated and are distributed on grounds in waters to depths of about 50 m. The species reaches maturity at around 25 and 23 mm carapace length for males and females, respectively, but these sizes may vary between stocks (Ruello, 1971). Because school prawns stay primarily around the estuary from which they emigrate scientists recommend that this species be managed as a series of unit stocks that centre about the main estuaries along the coast.

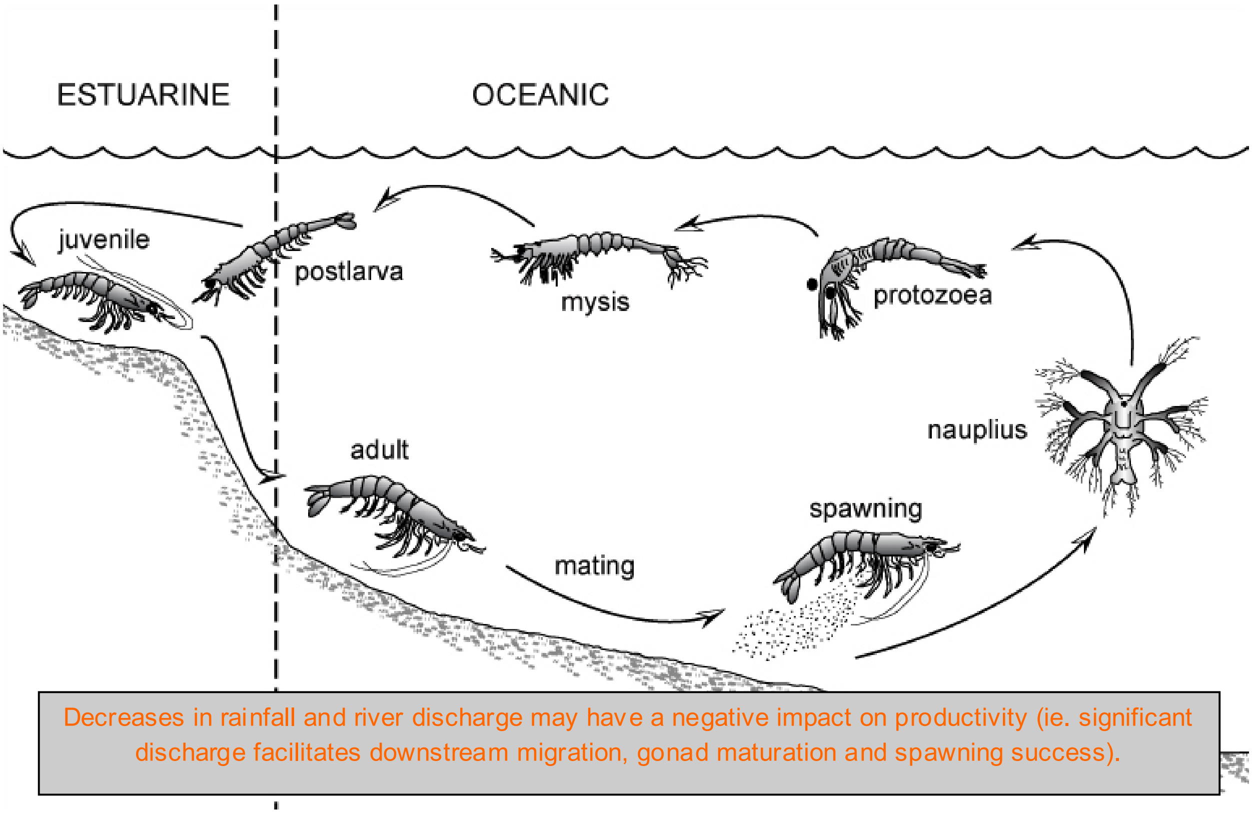


Figure 11.3: Summary of life cycle (this section), and points of exposure to relevant climate change drivers or known impacts (subsequent sections).

Age growth and mortality in school prawns has been documented and reviewed by Montgomery et al. (2010). School prawns grow to a total length of 13 cm (males) and 16 cm (females) and generally live for 12 to 18 months. Because all stocks could not be studied, Montgomery et al. (2010) adopted the approach of choosing those that were expected to include the greatest variability about growth and mortality parameter estimates. Growth was investigated by doing monthly fishery independent surveys on the Clarence and Hunter rivers. Monthly length frequencies were separated into groups of prawns of similar age and these data were then fitted to the Schnute growth models.

Female prawn growth was best fitted by a special case of the Schnute model which is equivalent to the von Bertalanffy growth function (VBGF; $L\infty$ = 36.6 and 40.2 CL mm and κ = 0.005 and 0.005 day -1, for Clarence and Hunter, respectively), whilst male growth was best fitted by a four parameter Schnute curve ($L\infty$ = 21.3 and 33.5 CL mm and κ = 0.025 and 0.009 day-1, for Clarence and Hunter, respectively). Male school prawns grew to smaller maximum lengths and had faster rates of growth than females and lived for less than two years. While female growth data fitted the VBGF, much of the observed growth was linear and female prawns never reached the maximum lengths predicted by the growth model, probably because of high rates of mortality. Male growth differed between stocks but female growth did not.

Natural mortality was estimated using meta-analyses that use known associations between natural mortality (dependent variable), longevity and life history. Natural mortality was greater in males than females and was greater in the more northern Clarence stock (0.002 to 0.007 and 0.006 to 0.025 for females and males, respectively) than in the Hunter stock (0.001 to 0.005 and 0.004 to 0.016).

Fishing mortality is the product of fishing effort and the catchability coefficient (the proportion of the stock taken by one unit of fishing effort). A total of 21,096 school prawns were tagged and released in replicated tag-recapture experiments on the Clarence River and Wallis Lake to estimate the catchability coefficient, whilst the records from the Clarence River and Wallis Lake Fishermen's cooperatives and a daily log book were used to calculate fishing effort. Montgomery et al. (2010) addressed the assumptions of tag-recapture experiments by randomly dispersing tagged prawns throughout the school prawn population and by doing experiments in the laboratory and in the field to quantify the impacts of tagging and non-reporting of captured tagged prawns. It was estimated that 50–60% of prawns survived the tagging process and that between 100 and 80% of the captured tagged prawns were reported. Numbers of tagged prawns released were adjusted for these effects. Fishing mortality was estimated by fitting the tag-recapture and fishing effort data together with numbers of tagged prawns released and a range of natural mortality values to a population model and using minimum likelihood optimisation to solve for the catchability coefficient. Estimates for the catchability coefficient and therefore fishing mortality varied between years and the values of input parameters. Daily values ranged between 0.00008 and 0.00137 for the Clarence stock and, 0.00008 and 0.00147 for the Wallis stock. Fishing mortality values ranged from 0.0014 to 0.0358 (per day) and 0.0008 to 0.009 for the Clarence and Wallis stocks respectively. The catchability coefficient was estimated with little precision but values for this parameter, natural mortality and fishing mortality were within the ranges of those documented for other penaeid fisheries around the world. There was evidence to suggest that catchability and therefore fishing mortality increased greatly at times of high river discharge. Exploitation ratios (ratio of fishing mortality to total mortality) again varied with values ranging between 13.3% and 94%, and 8.4% and 87% for the Clarence and Wallis stocks, respectively, but were generally greater than 40% for both stocks.

11.2.2. Distribution, habitat and environmental preferences

The school prawn (*Metapenaeus macleayi*) occurs along the east coast of Australia, between Corner Inlet, Victoria, to Tin Can Bay, Queensland, and they are distributed in estuaries and ocean waters out to depths of around 50– 55 m (Ruello 1971). Throughout this range, school prawns inhabit both estuaries (mostly as juveniles and sub-adults) and inshore ocean waters (as adults). Within estuaries, they prefer soft muddy substrates and areas of seagrass, and can be found well upstream into brackish to fresh waters.

School prawns have been studied to a significant extent in the past concentrating on the distribution and abundance or movements, (Ruello 1971, 1973a,b, 1977 and Glaister 1977, 1978a,b). Few studies addressed the question of declining catches, attributing patterns in catch to the level of river discharge or rainfall (e.g., Ruello 1973b, Glaister 1978a).

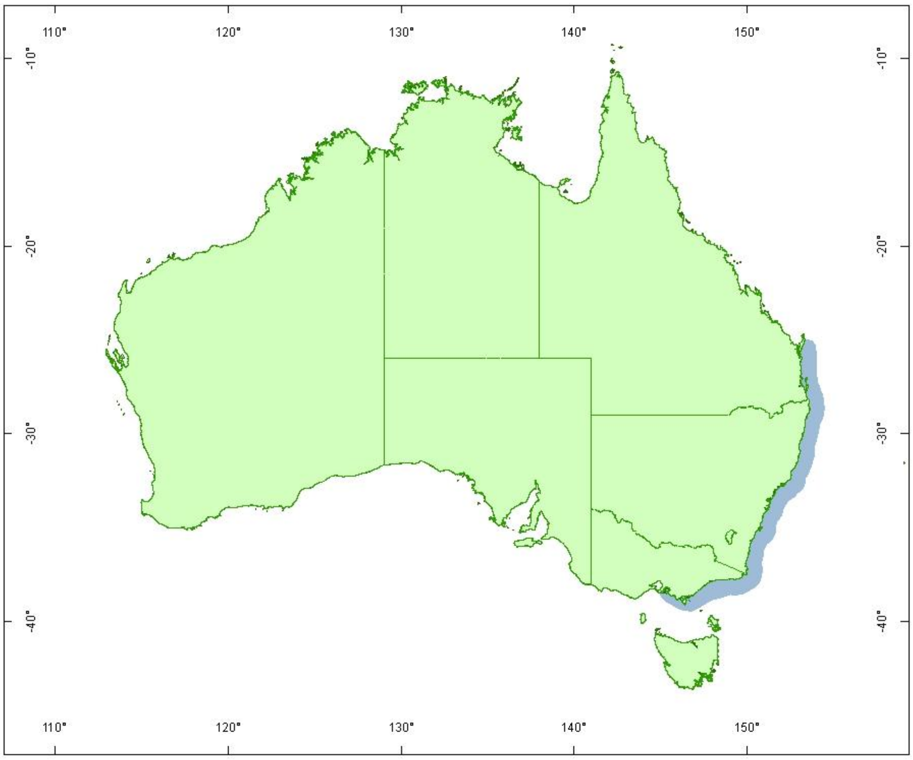


Figure 11.2: Distribution of school prawns.

11.2.3. Predators and prey

School prawns are opportunistic benthic omnivores and eat a variety of small invertebrates and detritus. Like other penaeids, school prawns are low on the food chain and are prey items for many fish, birds and marine mammals.

11.2.4. Recruitment

School prawns spawn in nearshore ocean waters off NSW between February and May. After a larval stage of about 2–3 weeks, the post-larval prawns enter estuaries and move upstream. By the following spring, the now adolescent prawns return downstream and, if conditions are suitable in late summer, they emigrate to sea to mature and spawn (Ruello 1971).

School prawns spawn only once. Rainfall and the associated river discharge are thought to be important cues in the life cycle of school prawns, in that significant freshwater discharge appears to facilitate downstream migration, gonad maturation and spawning success. School prawns may undertake oceanic migrations of up to 100 km (Anon 2003).

Key points:

- The centre of the school prawn distribution is NSW.
- The species undergoes downstream migration from estuaries to the ocean but does not undertake significant oceanic migration.
- School prawns live to a maximum of 2 years and only spawn once.

11.3. Current impacts of climate change

No current impacts of climate change on school prawn are documented. However, the relationship between fisheries and climate is particularly important for school prawn fisheries, where there are documented positive correlations with the rates of river discharge in northern NSW and productivity. A simulation model was developed to analyse the dynamics of the prawn stock for 10 years under alternative river discharge scenarios (representative of possible climate effects), and the effectiveness of a series of management strategies to provide a sustainable yield, under these scenarios was examined (Ives et al. 2009). The size-based metapopulation model incorporated the dynamics of school prawn populations in three habitats being harvested by three different fishing methods. The model indicated that both the growth and movement of prawns were affected by the rates of river discharge, and that higher rates of river discharge usually generated increased commercial catches, but this outcome was not certain. Over exploitation of the prawn stocks did not occur under the scenarios tested.

Key point:

- The relationship between river discharge and school prawn growth, migration and commercial catch has been modelled to assist fisheries management under varying climate scenarios.

11.4. Sensitivity to change

If, as suggested by recent research (Hennessy et al. 2004), climate change results in lower future river discharge levels and increased variability for the Clarence River, the various school prawn fisheries could be significantly affected. However, some reassurance can be found from a modelling study in that none of the alternative discharge scenarios showed a significant depletion in the school prawn stock if the current fisheries were maintained (Ives et al 2009).

11.5. Resilience to change

Based on the modelling of Ives et al. (2009) the resilience of school prawn stocks to altered river discharge effects as a function of climate change is high.

11.6. Ecosystem level interactions

Given the role that *M. macleayi* plays in the Clarence River food web as a primary prey item for many fish and birds, school prawns high resilience to change is an important finding for the long-term condition of the estuarine ecosystem, which could be susceptible to the ability of key species to cope with drought and changing river discharge (Martin and Michael 2000).

11.7. Additional (multiple) stressors

No information.

11.8. Critical data gaps and level of uncertainty

In modelling the effects of climate change, especially aspects related to the sensitivity analysis, Ives et al. (2009) showed some clear insights into the main drivers of the population dynamics. In particular, the catchability of the prawns was shown to have a significant impact on all three of the management indicators. Given that these populations are known to school, this process may well be more complex than that represented, yet little research was available to understand this important process for school prawn. Also significant in the sensitivity analysis were parameters associated with larval and juvenile mortality and the stock-recruitment process. Unfortunately, these are also areas in which little research was available to parameterise the model. The sensitivity of the results to these parameters suggests that research into recruitment and early-life survival of prawns could significantly improve the understanding of such stocks (Werner et al. 1983). Also, the fact that the recreational catch of school prawns was included in 'natural mortality' could be a significant oversimplification of this process, particularly as recreational catch is most likely to have increased over time with increases in coastal populations and more current data on recreational catch is needed.

Table 11.1. Summary of school prawn species profile, which also indicates level of certainty of the associated information. Level of certainty is divided into high (H) = strong clear evidence, backed by several studies with solid datasets with little confounding interactions; medium (M) = evidence supported by one or more studies, conclusions may be partially ambiguous or confounded; low (L) = anecdotal evidence, limited data and/or predicted conclusions based on theoretical knowledge.

<table>
<tr><th>Life history stage</th><th>Multiple stressors</th><th>Distribution</th><th>Habitat</th><th>Predators and prey</th><th>Current impacts</th><th>Predicted impacts</th><th>Ecosystem interactions</th><th>Data gaps</th></tr>
<tr><td>Eggs</td><td rowspan="4">Unknown</td><td rowspan="5">See Figure 4 (H)</td><td rowspan="2">Offshore (H)</td><td rowspan="2"></td><td></td><td rowspan="5">Modelled linkage to higher rates of river discharge impacting commercial harvest (H)

Linkage to the EAC (H)</td><td rowspan="2"></td><td rowspan="5">Estimates of the recreational catch.

Knowledge of the recruitment processes and the survival of early life history stages.</td></tr>
<tr><td>Larvae</td><td rowspan="4">None documented (H)</td></tr>
<tr><td>Juveniles</td><td rowspan="3">Estuaries and Offshore (H)</td><td rowspan="3">Prey for many aquatic fish birds and mammals (H)</td><td rowspan="3">The resilience of school prawns to change reduces the possible impacts on higher food chain organisms (H)</td></tr>
<tr><td>Pre-spawning adult</td></tr>
<tr><td>Post-spawning adult</td><td>High recreational and commercial harvest (M)</td></tr>
</table>

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12. Small pelagic fish

Author: Keith Jones

Small pelagic fish *– for the purpose of this report, we define these as schooling species in SE Australian waters, less than 50 cm in length, most commonly found in shallow embayment and shelf waters, and occupying intermediate trophic levels.*

Australian sardine (*Sardinops sagax*)
Australian anchovy (*Engraulis australis*)
Blue sprat (*Spratelloides robustus*)
Sandy sprat (*Hyperlophus vittatus*)
Blue mackerel (*Scomber australasicus*)
Jack mackerel (*Trachurus declivis*)
Yellowtail scad (*Trachurus novaezealandiae*)
Redbait (*Emmelichthys nitidus)*

12.1. The fisheries

This section describes the development and catch history of the commercial fishery for each species in south-eastern Australian waters. Where available, it also summaries the status of the stock, in terms of the fisheries exploitation rate. Finally, where relevant, it summaries the catch information by the recreational fisheries.

Australian sardine

In SE Australian waters, commercial fisheries for Australian sardine exist in South Australia, Victoria and New South Wales (NSW), with catches off the coast of South Australia (SA) being by far the most significant.

Off SA, relatively very small catches were taken during the 1960s to early 1990s using small purse seine nets in the bays of southern Eyre Peninsula and the west coast of SA. The product was used for live bait in the southern bluefin tuna (SBT) pole fishery. However, with the demand for fodder in the developing sea ranching industry for SBT in south-western Spencer Gulf, the sardine fishery greatly expanded during the 1990s, so that now it has become the largest single species fishery in Australia. Up to 14 vessels are licensed to harvest the species in the SA fishery. Since 1995, the fishery has been managed by TACCs, with catch limits set, based on less than 20% of the annually estimated spawning biomass (Ward et al. 1998, 2009).

Application of the daily egg production method (DEPM) to estimate spawning biomass off the central and west coast of SA has facilitated the rapid development of the SA sardine fishery, despite the effects of mass mortality events in 1995 and 1998, both of which killed over 70% of the adult population in South Australia (Ward et al. 2001). Figure 11.1 shows the development of the fishery since 1990. The current harvest strategy indicates a baseline TACC of 30,000 t will be maintained while the latest estimate of spawning biomass remains between 150,000 and 300,000 t (exploitation rate 20–10%). The most recent estimate (2009) is 171,000 t (122,000–242,000 CL), which equates to an exploitation rate of 17.5%. (Ward et al. 2009). The use of catch and effort data is clearly of little use in obtaining meaningful information on changes in stock abundance.

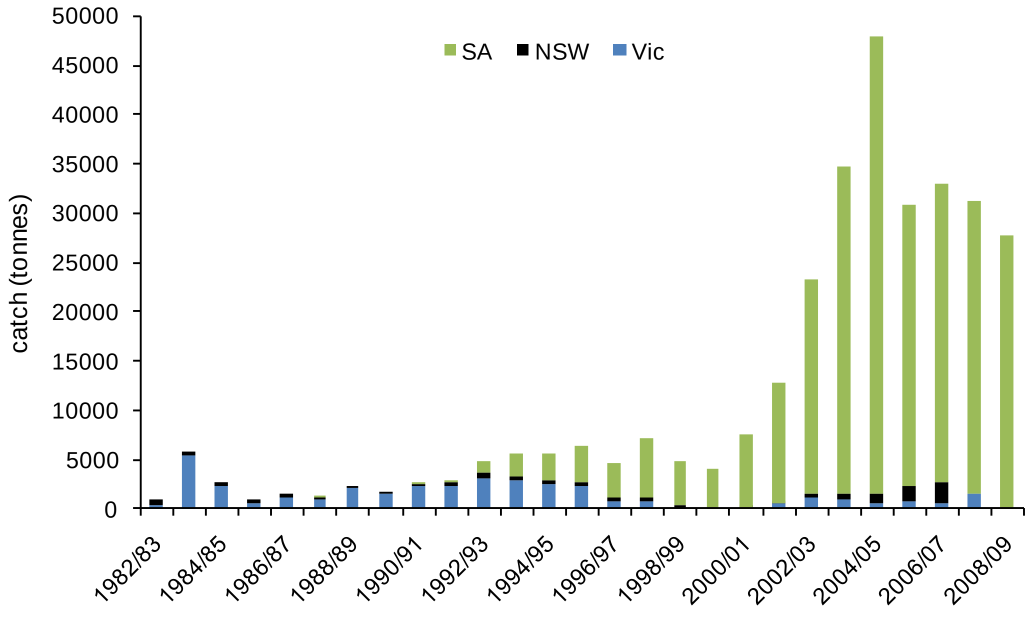

Figure 12.1: Catch history of Australian sardines in SE Australia, 1982/83 – 2008/09.

The sardine fisheries of NSW and Victoria, although currently smaller compared to that in SA, have a much longer history of production. In NSW, dating back to the late 1940s, the species has been fished in the ocean hauling fishery with small purse seines and bait nets. During the 1980s and 1990s, annual catches fluctuated between 10 and 500 t; however, since 2002–03, they have steadily risen to about 2000 t in 2006–07 (Figure 12.1). Highest catches occur in winter/spring, and the product is locally sold for recreational bait, pet food and for human consumption (Scandol et al. 2008). During 2002–04, pelagic egg surveys were undertaken off the NSW coast and have estimated spawning biomass of Australian sardine between 25 and 35,000 t (Scandol et al. 2008). With a 3,000 t fishery off NSW, Commonwealth and Victorian fisheries, this makes the exploited fraction of the spawning biomass at 8–12%, and it has been concluded that the stock off the east coast is moderately fished (Scandol et al. 2008).

The commercial fishery for sardines in Victoria has seen larger fluctuations in annual catch than for NSW (Figure 12.1). Sardines have been harvested in two main regions off the Victorian coast. A traditional small purse seine fishery has existed in Port Phillip Bay since the 1930s, with catches of less than 500 t taken up to the late 1970s. Since then, catches rapidly increased to more than 2000 t in the early 1990s (Jackson et al. 1998) and then dropped significantly during the late 1990s. Since then, catches have recovered steadily to range between 500 and 1,000 t in recent years. The fishery is largely seasonal, with highest catches made during late summer/early winter. Port Phillip Bay is the only semi-enclosed, shallow marine embayment in temperate Australia that supports a sardine fishery that is based on predominantly juvenile fish (Neira et al. 1999).

The high catch of more than 4800 t in 1983–84 was attributable to one large purse seine vessel operating off Lakes Entrance for several years during the 1980s, processing the product for fish meal and oil; however, this operation ceased in 1985 (Jackson et al. 1998).

In all states of SE Australia, the recreational fishery for sardines is very small (Henry and Lyle, 2003).

Australian anchovy

In SE Australian waters, small hauling seines fisheries have taken this species for many years in NSW and Victoria (Kailola et al. 1993), with consistently highest catches over the past 25 years from Port Phillip Bay, Victoria (DPI, 2006). Small commercial catches (1–20 tonnes) were also made in the Gippsland Lakes. In Victoria, the fishery is generally seasonal, with highest catches between March and September. In Port Phillip Bay, the annual catch has varied between 32 and 491 t since the late 1970s (Figure 12.3), and this variation is strongly affected by fishing effort (Parry et al. 2009).

Fishery-independent trawling surveys for anchovy in Port Phillip Bay began in 2008 for the purpose of estimating the distribution and abundance of anchovy (Parry et al. 2009). In June, 2009, the biomass (± s.e.) captured was 1.64 t and the estimated total anchovy biomass in Port Phillip Bay was 1222 (± 446) t, which equates to <10% of the estimated biomass captured commercially (Figure 12.2). Anchovy egg and larval surveys have been conducted in Port Phillip Bay annually during November–January since 2004–05. The egg and larval abundances have not been used to estimate anchovy spawning biomass in this area; however, the time series of relative egg and larval abundance does suggest that the size of the anchovy population in Port Phillip Bay is subject to fluctuations in year class strength, recruitment (Acevedo et al. 2009) and abundance.

In NSW, anchovies are annually landed at low levels throughout the year, with large catches up to 80 t taken in 2001–02, but are mostly less than 40 t (Scandol et al. 2008). In Tasmania and South Australia, small quantities are caught occasionally for live bait for SBT. Estimates of the spawning biomass of anchovies for gulf and shelf waters off SA are available (Dimmlich et al. 2009), showing a relatively high biomass (101,000 t) in shelf waters compared with those in the gulfs (25,000 t). The implications of these results in relation to their life history and climate change are fully discussed later in this report.

The commercial product is marketed either for human consumption or as bait in the recreational fishery (marketed as ‘frogmouth pilchards’). The recreational harvest throughout SE Australia is very small (<1 t Scandol et al. 2008)

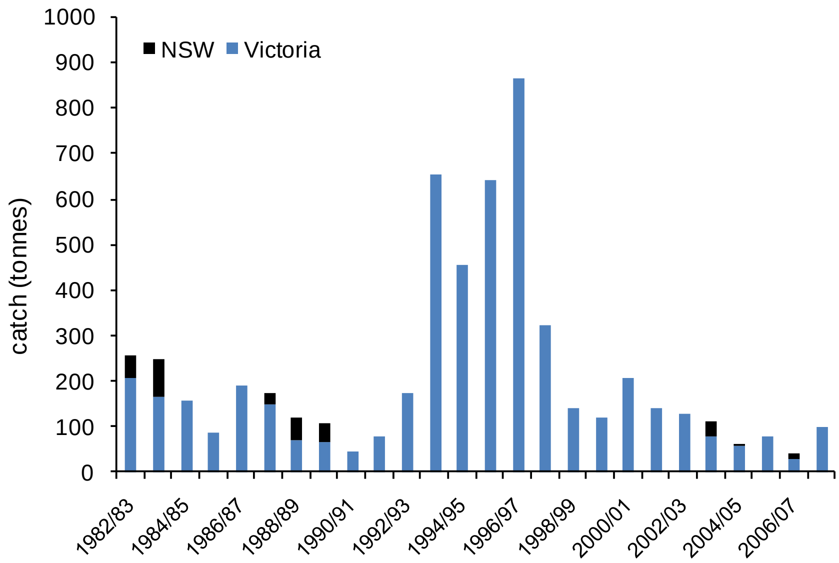

Figure 12.2: Annual commercial catch of anchovies in SE Australian waters, 1982/83 – 2007/08. Note: Victorian catch data for 2006/07 and 2007/08 only for Port Phillip Bay.

Blue sprat

Because of its small maximum size and mesh size restrictions on types of commercial and recreational net fishing gear, there is no dedicated fishery for this species; however, it may be taken in small quantities as by-product in the fisheries for anchovies (Scandol et al. 2008). There are no estimates of the size of its harvest.

Sandy sprat

In SE Australia, sandy sprats are taken commercially in NSW and Victoria, mostly by small mesh hauling nets. Combined catches in both states rose steadily to almost 200 t in 1991–92, with declining catches in Victoria till 1997–98, with those in NSW remaining relatively high throughout this period (Figure 12.3). Victorian catches again rose in 1998–99 to over 100 t but have declined since then, probably due to declining effort (Parry et al. 2009).

In NSW, they are a target species in the ocean hauling net fishery and they are also taken in from some estuaries as by-product with blue sprats and anchovies (Scandol et al. 2008). In Victoria, Port Phillip Bay is the main region of harvest, and in both states, they are marketed as 'whitebait', for human consumption as well as bait in the recreational fishery.

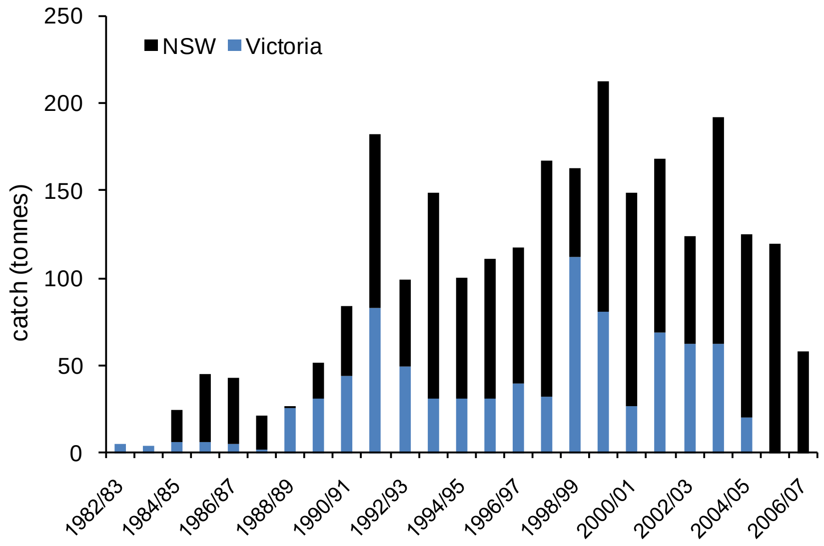

Figure 12.3: Annual catch of sandy sprat in SE Australian waters (1982/83 – 2006/07). Note: no data for NSW in 1982/83 and 83/84, and data for Victoria from 1982/83 – 1994/95 is for Port Phillip Bay only). No data available for the Victorian fishery in 2005/06 and 2006/07, for confidentiality reasons.

There are no reports of any commercial catches in SA, nor Tasmania. In all SE Australian states, the recreational harvest is very small.

Blue mackerel

The commercial harvest of blue mackerel in the Pacific Ocean is estimated to have reached 16,000 t, with the purse seine catch from New Zealand dominating this level of harvest (FAO). By contrast, the size of harvest of the commercial fisheries in SE Australian waters is small, but has increased recently to about 2000 t (see Figure 12.5).

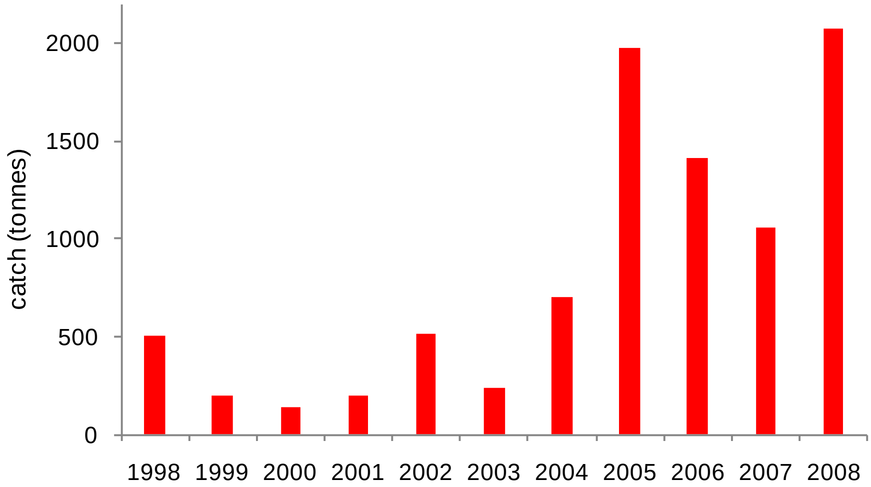

Figure 12.4: Commercial catch (tonnes) of blue mackerel by year (1998–2008) in SE Australian waters. (Source: BRS)

The commercial fishery for blue mackerel in SE Australia comprises several Commonwealth- and state-managed components. Off NSW, catches are taken for live bait in the Commonwealth-managed eastern tuna and billfish fishery (ETBF), as well as the Commonwealth-managed small pelagic fishery (SPF) and as by-product in the SE Commonwealth Trawl Fishery. The NSW-managed ocean hauling fishery (OHF) takes ~85% of the catch of these combined fisheries, with total catches ranging between 420 and 790 t over the last four years (2004–2007) (Sands et al. 2009) (Figure 12.4). Catches off Victoria and Tasmania are minimal, and in the SA-managed marine scalefish fishery, only small quantities are taken.

The daily egg production method (DEPM) was used in 2005 to estimate spawning biomass for blue mackerel off the east and southern Australian coasts (Ward and Rogers, 2006), and current catches are below 10% of the 2005 biomass estimate for both stocks (BRS, 2009), indicating the stocks are not overfished.

The recreational fishery is dominated by rod and line fishing from inshore boats, and the harvest is mainly used for game-fish bait or human consumption. The recreational harvest is estimated at almost 0.5 million fish (~200 t) in 2000–01 (Henry and Lyle (2003) of which almost 90% was taken in NSW. Subsequent recreational fishing surveys in Tasmania and SA in 2007–08 indicate little change in catches in these states (Lyle et al. 2009; Jones, 2009).

Jack mackerel

In SE Australian waters, jack mackerel have mainly been caught off the east coast of Tasmania. During the mid 1980s this species was the subject of the largest single species fishery in Australia. It took place off Triabunna, Tasmania, where a fish meal processing plant had been established. More than 35,000 tonnes were harvested there in 1986–87 (Figure

12.5) using purse seines. Since then, catches have fluctuated and declined and it is generally considered that the decline has been mostly due to environmental fluctuations as well as low market demand (DEWH assessment of the Small Pelagic Fishery, 2006). Early in 2001, with the development of the mid water trawl fishery for redbait, jack mackerel was harvested as by-product and rose to >1000 t in 2008 (Figure 12.6). Commercial catches of jack mackerel in other states are insignificant in comparison, and are largely taken as by-product in inshore netting operations (SA) and the NSW ocean hauling fishery (Sands et al. 2009).

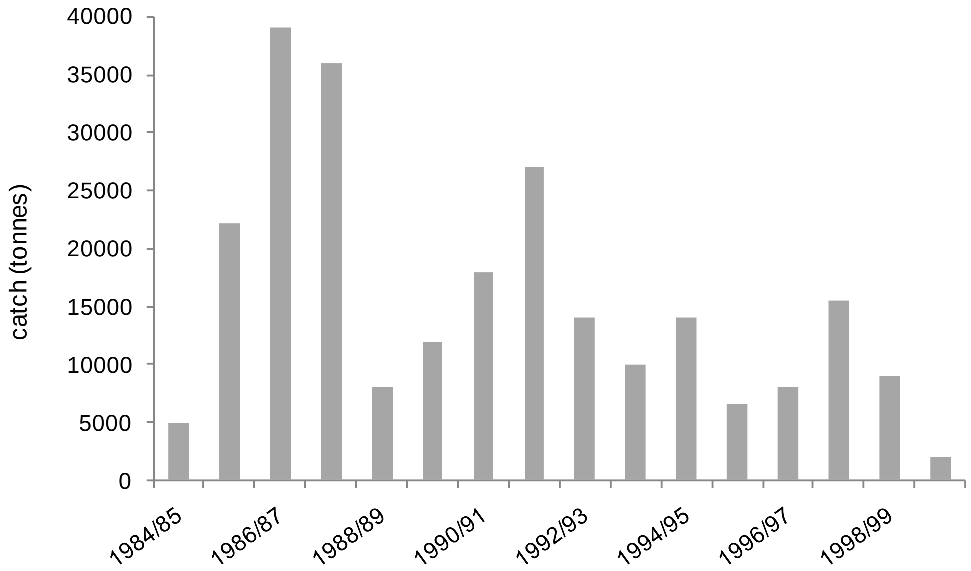

Figure 12.5: Commercial catch of jack mackerel (1984/85 – 1999/2000) off east coast of Tasmania. (Source: Welsford and Lyle 2003)

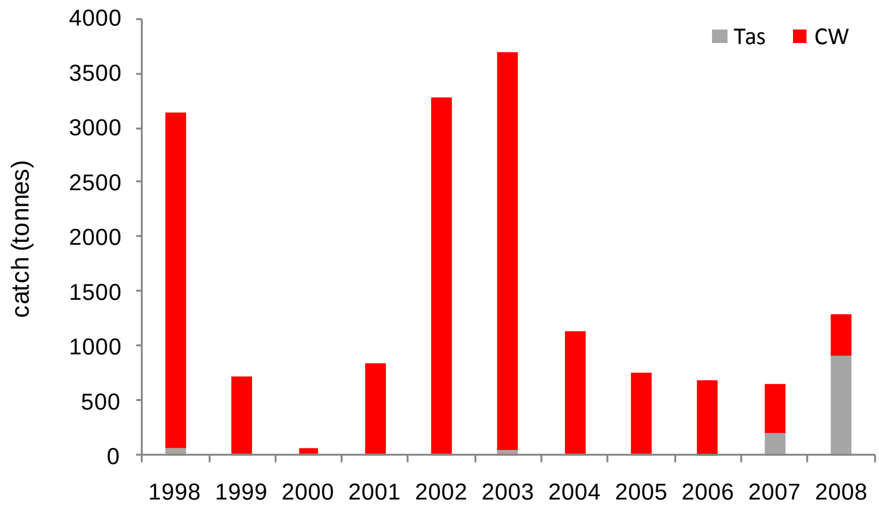

Figure 12.6: Commercial catch of jack mackerel (1998–2008) in Tasmanian and Commonwealth fisheries (SE Australian waters). (Source: CW data, BRS; Tas data, Ziegler and Lyle 2010)

Catches by recreational fishers using rod and lines occurs throughout the SE Australian inshore waters, and in 2000–01, the estimated harvest (combined with yellowtail scad) for these states was about 0. 25 million fish (30 tonnes), with about 85% caught in NSW waters (Henry and Lyle, 2003). They are either used for bait in game-fishing operations or for human consumption.

Yellowtail scad

In SE Australian waters, yellowtail scad are mainly harvested commercially in NSW waters by a small inshore purse seine fleet, with catches steadily rising to almost 800 tonnes in 2002, and then significantly dropping to just over 200 tonnes in 2006 (Figure 12.7) (Scandol et al. 2008). Total commercial catches off the NSW coast by the combined Commonwealth- and NSW-managed fisheries ranged between 380 and 500 t between 2004 and 2007 (Sands et al. 2009). Catches other states are very low; however, identification at the species level is difficult, leading to the possibility of under-representation of the catch.

The only estimate of recreational harvest (combined with jack mackerel) in SE Australian waters is approximately 0.25 million fish (~30 tonnes) in 2000–01 (Henry and Lyle, 2003). More than 80% of this was taken in NSW.

Redbait

In SE Australia, redbait was first caught as a by-catch of the jack mackerel purse seine fishery developed off the eastern Tasmanian coast during the 1980s (Pullen, 1994). The redbait catches initially peaked at 1300 t in 1986–87 at the same time as the record catches of jack mackerel occurred (Welsford and Lyle, 2003). However, as redbait were not targeted by the purse seiners during this period, these catch levels do not necessarily reflect their abundance. In 2001–02, midwater trawling targeting jack mackerel was trialled off eastern Tasmania but redbait quickly became the dominant catch (4000 t) and is now the main target species in this mid-water trawl fishery, being utilised as whole food for the SBT feed industry (see Figure 12.8). Catches peaked in 2005 at about 8000 t (Figure 12.7) and since then, have dropped to about 1000 t.

Off Tasmania, the estimated spawning biomass of redbait in 2005 and 2006 (estimated by the DEPM; Neira et al. 2008) showed no significant differences between the two years (average 69,000 t). The exploitation rate (percentage of the spawning biomass) would have been about 11%, which is lower than the recommended biological catch for this species (Neira et al. 2008). Off NSW, the spawning biomass was estimated at about 20,500 t (Neira et al. 2008). The species is not targeted in the remainder of SE Australian waters.

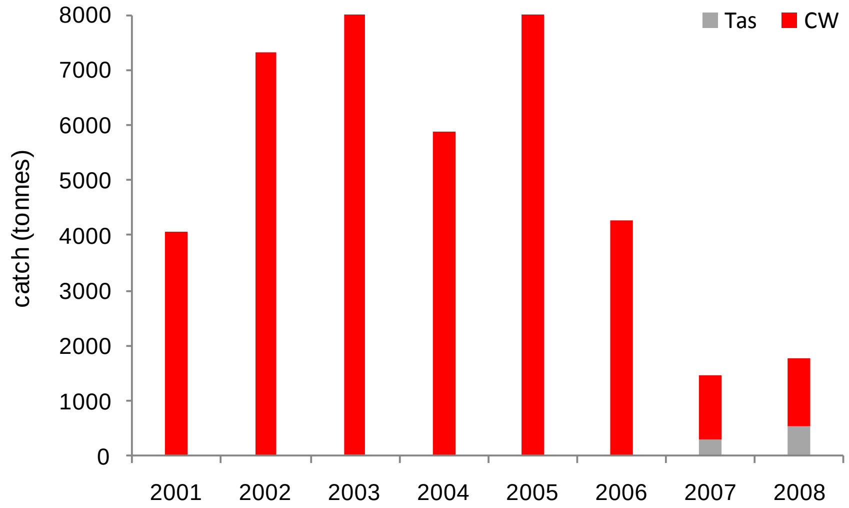

Figure 12.7: Commercial catch of redbait in SE Australian waters (2001–2008). (Source: CW data, BRS; Tas data, Ziegler and Lyle 2010)

Key points:

- Over the past 20+ years, the small pelagic fisheries in SE Australia have been dominated by two purse seine fisheries: one off the east coast of Tasmania for jack mackerel and the other in the eastern GAB for Australian sardines. Both these fisheries developed as a response to increasing demand for fish meal or fodder in the aquaculture of SBT, respectively. Mid-water trawling for redbait off eastern Tasmania has now largely superseded the jack mackerel fishery.
- Smaller inshore purse seine fisheries for sardines, anchovies and sandy sprats have existed for many years off the NSW coast and in the Port Phillip Bay, Victoria.
- With spawning biomass estimates becoming increasingly available for many of the small pelagic species (e.g. sardines, blue mackerel and redbait), all show that their current respective harvest levels are sustainable (i.e. <20% of the spawning biomass).

12.2. Life history

12.2.1. Life cycle, age and growth

This section reviews our current knowledge on the growth rates, reproductive biology and location of spawning for each species.

Australian sardine

In SE Australian waters, Australian sardines are relatively short-lived (up to seven years of age), and growing up to 170–190 mm, FL (L_{inf} ;Rogers and Ward, 2007), which is smaller than for sardines found off South Africa (Thomas 1985) and California (Butler et al. 1996) (Figure 12.8). Their growth rates vary according to whether they occur in highly productive waters (e.g., von Bertalanffy growth constant, k up to 1.07 off South Australia, Rogers and Ward 2007) than from oligotrophic waters off sthn Queensland (k up to 0.63; Staunton Smith and Ward, 2000). They quickly grow to sexual maturity (50% mature at 145 mm; Ward and Staunton Smith, 2002, age two years; Rogers and Ward, 2007). The spawning season for sardines varies considerably throughout SE Australia, with egg production occurring from May–October off the NSW coast (Scandol et al. 2008), Dec–January in Victoria (Hoedt and Dimmlich, 1994; Neira et al. 1999) and late summer – early autumn in South Australia (Ward and Staunton-Smith, 2002). In all these areas, spawning occurs mainly offshore in shelf waters, and least in the embayments (e.g. Port Phillip Bay and Western Port) and the SA gulfs.

In SA, the timing and location of spawning coincides largely with areas of high zooplankton biomass, which in turn were found in the upwelled waters of the Flinders Current (Ward et al. 2006; see review of Flinders Current dynamics; Middleton and Bye, 2007). At the northern-most range of its distribution in northern NSW and southern Qld, sardines migrate into southern Qld during winter-spring to spawn (Ward and Staunton-Smith, 2002). Off the NSW coast, the timing of spawning coincides with the southward movement of the Eastern Australian Current (EAC) during winter – summer, with upwelling areas occurring at the juxtaposition of the EAC and the Tasman Front ((Uehara et al; 2005).

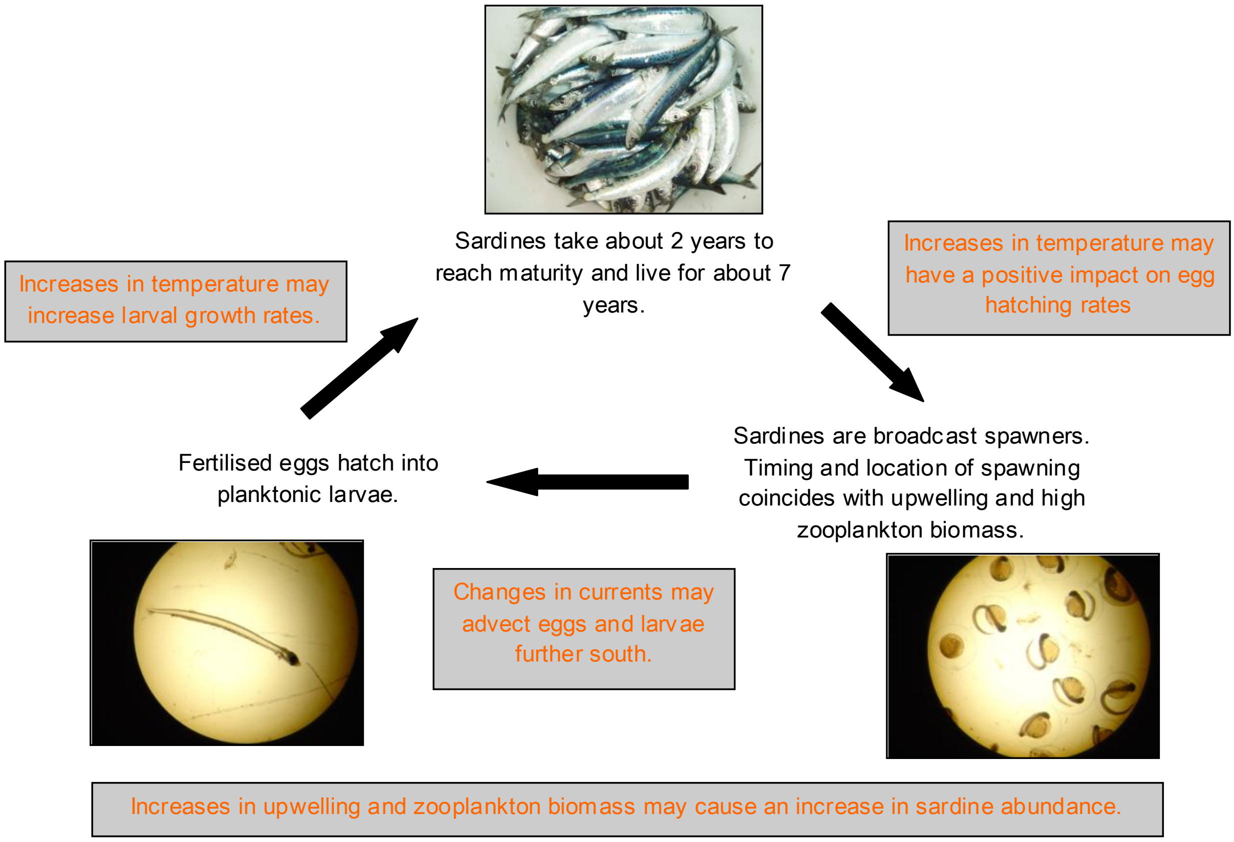

Figure 12.8: Summary of life cycle (this section), and points of exposure to relevant climate change drivers or known impacts (subsequent sections). Example is based on sardines, and not relevant for all small pelagic species. Images: Paul Rogers (SARDI Aquatic Sciences).

Australian anchovy

E. australis is a fast growing species, reaching close to its maximum size of above 140 mm after two years, but are known to live to at least five (Dimmlich and Ward, 2006). The Von Bertalanffy growth parameters for the SA population were estimated at: L_{inf} = 145 mm and k = 1.3 (Dimmlich and Ward, 2006).

The Australian anchovy is a serial batch spawner, producing approximately 15,000 eggs per batch every seven days (Dimmlich et al. 2009). Anchovies become reproductively mature at between 70 and 125 mm (50% maturity at 99 mm, or less than one year of age; Dimmlich and Ward 2006). The fertilised eggs of anchovies are small, elliptical and buoyant. Spawning occurs over a wide seasonal range (October–April), with a tendency for fish in their more northern distributions spawning earlier than the more southern population (Blackburn 1963). Peak spawning is around January (Hoedt and Dimmlich 1995; Dimmlich and Ward 2006).

Blue sprat

This small pelagic fish has only been studied in South Australia (Rogers et al. 2003). They grow to only a small size (100 mm, CFL) and live up to one year of age. Spawning occurs throughout the SA gulfs during the warmer months (peaking November–February), at temperatures ranging between 19 and 26°C. They are multiple batch spawners producing between 200 and 1800 eggs per female every 1–2 days. Fertilised eggs have not been found in the zooplankton, and it is suspected that they may be demersal (as is the case with other tropical *Spratelloides* spp.; Rogers pers. comm.).

Sandy sprat

Sandy sprats are known to grow to about 100 mm, and are as old as four years of age. They are multiple batch spawners, but the batch fecundity is low to medium (740–5600 per batch). In SA, females mature between 58 and 75 mm CFL (1–2 yrs of age) and spawning occurs in spring–summer (Rogers and Ward 2006). In SA, the spawning season extends from October to February and peaks in November. In NSW, spawning may be later as larvae are found in April/May (Gray et al. 1992).

Blue mackerel

In Australia, blue mackerel grow to at least 40 cm FL and at least 1.5 kg (Gomon et al. 2008). The otoliths of blue mackerel are difficult to age, and difficulty increases with the age of the fish (Rogers et al. 2007). In SE Australian waters, their maximum age is estimated at 7^{+} years, with these fish occurring off SA. The age composition of fish off SA was higher than in other SE Australian waters (NSW and Tasmania) with fish up to two years and five years of age found, respectively. Growth rates are similar for NSW and SA (Table 11.1).

Blue mackerel is a serial spawner, with indeterminate fecundity. Batch fecundity as high at 180,000 for 400 mm females have been recorded (Rogers et al. 2007). Males become reproductively mature (50% maturity) at 237 mm and females at 287 mm, FL (~2 years of age). Off eastern Australia, the species spawns during 'winter–spring' months (July–October) and in southern Australia, during 'summer–autumn' (November–April) (Rogers et al. 2009). Based on egg and larval surveys, spawning occurs mainly over the continental shelf with depths between 40 and 120 m and at surface temperatures between 18 and 22°C.

Off eastern Australia, a key spawning area is off southern Queensland and northern NSW. In southern Australia waters, spawning extends in waters offshore from at least Encounter Bay, SA to Esperance, WA (Neira et al. 2007). In SA, there is a tendency for smaller fish (<300 mm) to occur in the shallower gulf waters, with fish >300 mm in southern gulf and offshore waters of the eastern Great Australian Bight (Rogers et al. 2007).

Table 12.1: Von Bertalanffy growth parameters for blue mackerel (combined sexes) for SE NSW, eastern Australia and South Australia (adapted from Ward et al. 2001).

Region	L_{inf}	K	t_0	Age range (yrs)	Reference
SE NSW	41.05	0.26	-2.8	0 – 7	Stewart and Ferrell (2001)
NSW	37.11	0.46	-1.00		Rogers et al. (2007)
Eastern Australia (NSW, Qld)	37.89	0.43	-1.12		Rogers et al. (2007)
GAB (SA)	44.1	0.24	-1.79	1 - 9	Stevens et al. (1984)
South Australia	38.295	0.49	-0.53		Rogers et al. (2007)
Sthn Australia (WA, SA, Tas, Vic)	39.26	0.45	-0.61		Rogers et al. (2007)

Jack mackerel

In SE Australia, jack mackerel reach a maximum size of about 50 cm TL (Gomon et al. 2008). The age and growth of jack mackerel has been determined from the analysis of assumed annual rings on otoliths (Webb and Grant 1979; Stevens et al. 1984); however, more recent age validation using marginal increments and radiocarbon analyses have confirmed the previous age determinations (Lyle et al. 2000; Browne 2005). Jack mackerel have been aged up to 25 years (Lyle et al. 2000). The von Bertalanffy growth parameters are seen in Table 11.2. The decline in age structure in the Tasmanian fishery since the beginning of the fishery in 1985, as observed here in the drop in L_{inf} from the late 1970s (Webb and Grant 1979) to the early 2000s (Browne 2005) has been attributed a range of reasons including changes in fishing practice (purse seine to mid water trawling), changes in recruitment variability, changes in fish schooling behaviour as a result of environmental influences (Browne 2005).

Table 12.2. Von Bertalanffy growth parameters for jack mackerel (combined sexes) from SE Australian waters from 1979– 2005.

Region	L_{inf}	K	t_0	Reference
SE Australia (north of 39^0 S)	46.4	0.2	-0.87	Stevens and Haustfeld (1982)
SE Australia (sthn NSW – SW Tas)	46.3	0.23	-0.1	Webb and Grant (1979)
GAB (WA – SA)	41.7	0.19	-2.08	Stevens et al. (1984)
GAB (SA)	44.1	0.24	-1.79	Stevens et al. (1984)
SE Australia - Tas	36.2	0.267	-1.21	Lyle et al. (2000)
SE Australia – Tas 2003/04	35.52	0.28	-1.08	Browne (2005)

Jack mackerel are serial spawners with indeterminate fecundity, and the mean size at first maturity is 31.4 cm FL (Marshall et al. 1993). The eggs are pelagic and spherical (Neira et al. 1998); however, they cannot be distinguished from the eggs of yellowtail scad. Spawning occurs in spring and summer months in southern NSW – Tasmania (Jordan et al. 1995) and the Great Australian Bight (Stevens et al. 1984). However, some residual spawning was evident in Feb–March, 2003–05, as seen from egg surveys off the SA and southern NSW/Tasmanian coast (Neira et al. 2007). Off eastern Tasmania, spawning usually takes place at the shelf break, with some occurring in more inshore waters in years when there is a strong intrusion of EAC waters (Jordan et al. 1995).

Yellowtail scad

This species reaches a length of over 50 cm TL (Gomon et al. 2008). In SE Australian waters, the only research on age and growth was undertaken by Stewart and Ferrell (2001) from fish sampled in the inshore purse seine fishery off northern and southern NSW, which may not be representative of the entire population. There were apparent growth differences between the two regions, with lower rates in the more southern distributed fish. Max average lengths were 30.7 and 23.7 cm FL, respectively and their maximum ages were 14 years, compared with 28 years for fish taken in the deeper water purse seine fishery off New Zealand (Stewart and Ferrell 2001).

The eggs of the *Trachurid* species are indistinguishable; however, given the known ranges of adult yellowtail scad and jack mackerel, from egg and larval surveys along the east coast of Australia, it is considered that yellowtail scad spawn mainly in the northern NSW/Queensland waters on the shelf during winter–spring (Neira et al. 2007). Larvae have been found throughout the year in coastal waters of central NSW (Gray et al. 1992). There is no information on their reproductive biology (i.e. fecundity, size/age at maturity).

Redbait

Emmelichthys nitidus grows to a maximum fork length of 36 cm (Kailola et al. 2003). Sectioned otoliths have been aged and validated using marginal increment analysis (Welsford and Lyle 2003; Neira et al. 2008). Von Bertalanffy parameters for combined sexes were $L_{inf.}$ = 28.7 cm, k = 0.56 yr^{-1}) and t_0 = -0.36 yr. There is no significant difference between sexes. The maximum age is 21 yrs (Neira et al. 2008).

Redbait is a serial batch spawner with indeterminate fecundity. Peak spawning off the south-east coast of Australia (mainly eastern Tasmania) occurs between September and November, peaking in September and October. Off south-western Tasmania, limited sampling suggests that spawning peaks one month later, and in northern Bass Strait, the spawning season may extend as late as February/March (Neira et al. 2008). There are marked differences in the size/age at 50% maturity between these two areas, with eastern Tasmanian fish reproducing at a smaller size (157 mm, females) / younger age (two years) compared with fish from SW Tasmania (261 mm; 4.1 years, females) (Ewing and Lyle 2009).

Key points:

- In terms of their growth rates and maximum ages, the small pelagic species of SE Australia can generally be grouped into either the very rapid growing (growth constant usually >1.0), short lived (1–7 years of age) species including Australian sardines, anchovies, blue and sandy sprats, or the relatively slower growing (k = 0.2 – 0.5) and longer lived (>10 years of age) species, including blue and jack mackerel, yellowtail scad and redbait.
- All species are serial batch spawners with indeterminate fecundity. Most become sexually mature by the age of two; however, jack mackerel and redbait off SW Tasmania mature at older ages (up to 4 years and 4 years, respectively) and blue sprats at 132–137 days.
- The peak period of spawning for most of the species shows regional variation in SE Australian waters. Generally, those small pelagic species occurring off the NSW coast spawn during winter or spring (sardines, blue mackerel, anchovies, jack mackerel), whereas for those in the more southern mainland Australian waters, summer or autumn months (sardines, anchovies, blue and sandy sprats, jack mackerel, redbait). In Tasmanian waters, for jack mackerel and redbait, the peak spawning period is in spring–summer.
- Spawning location – either embayments or gulfs – blue and sandy sprats, anchovies in SA, or shelf (sardines, anchovies, jack mackerel) or edge of shelf waters (jack mackerel, redbait).
- With the possible exception of blue sprats, all other small pelagic species reviewed here produce floating eggs.

12.2.2. Distribution and habitat

This section reviews our knowledge on the number of stocks for each species and their distribution in relation to key environmental features in SE Australian waters (i.e. currents and upwelling areas).

Australian sardine

The Australian sardine belongs to the cosmopolitan Pacific sardine species *Sardinops sagax*, found in temperate Australia, New Zealand, Japan, South Africa, Chile and western North America. Genetic studies (mtDNA) throughout their global distribution suggest that currently there is little gene flow between among geographically distinct populations (Okazaki et al. 1996; Grant and Leslie 1996). In Australia, it is found throughout temperate shelf waters from north of Perth, WA to southern Queensland. Within its SE Australian geographic distribution there is some evidence of complex population structure, comprising several stocks of fish along the eastern and southern coasts, but with considerable overlapping of populations (Yardin et al. 1998; Figure 12.9).

In similarity with its other populations elsewhere, the distribution and abundance of sardines in SE Australia is closely associated with upwelling areas (e.g. eastern GAB (Ward et al. 2006). In these waters, upwelling occurs during late summer / autumn months, resulting in localised increases in surface chlorophyll a and downstream enhancement of zooplankton biomass. High densities of sardine eggs occur in waters of high zooplankton biomass.

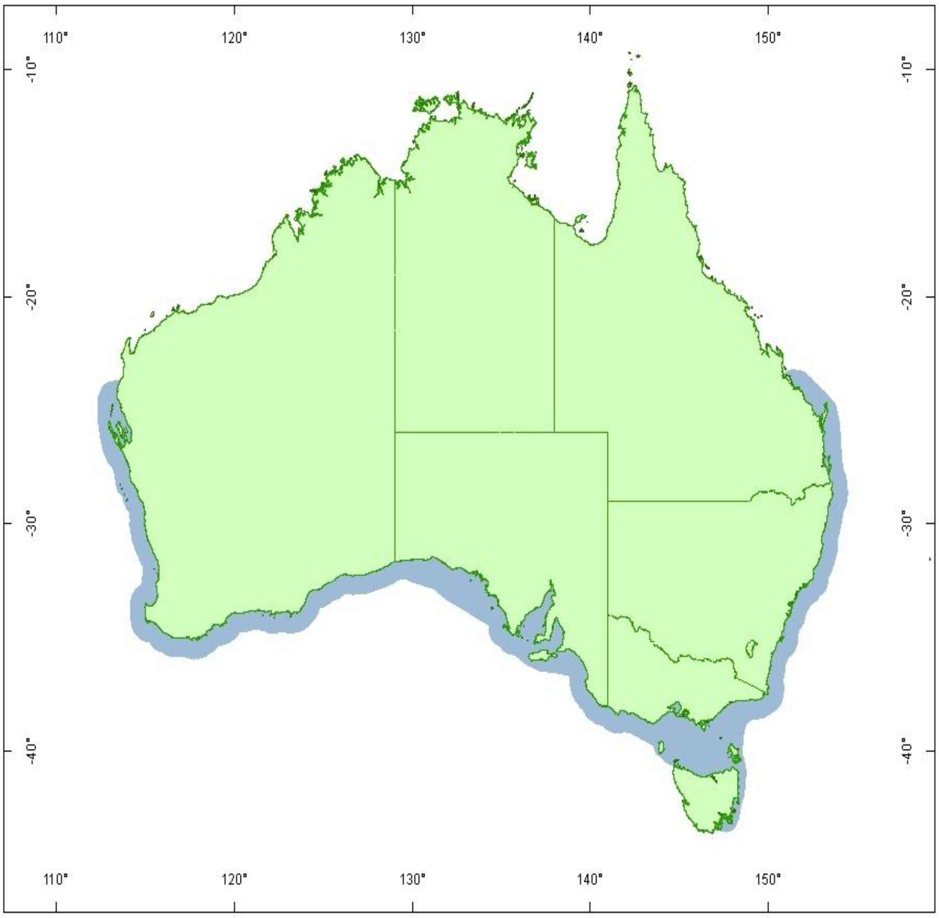

Figure 12.9: Distribution of sardines (*Sardinops sagax*) in Australian waters.

Australian anchovy

E. engraulis is found throughout coastal temperate and sub-tropical waters of Australia (Kailola et al. 1993) and in SE Australian waters it is found from NSW, Victoria to SA, but only occasionally in Tasmania (Gomon et al. 2008). Whereas in the eastern states, where it is mainly confined to shallow emabyments, off the South Australian coast it occurs not only in the gulfs but also on shelf waters (Dimmlich and Ward 2006). The latter study, which used otolith microstructure analysis, hypothesised that Australian anchovy move offshore with age to utilise upwelling areas which provide suitable spawning and nursery areas. In contrast, in its more eastern range, anchovies appear to generally spawn in inshore bays (e.g. Western Port, Hoedt and Dimmlich 1995; and Port Phillip Bay, Parry et al. 2009).

A meristic study (Blackburn 1950, 1963) and some preliminary genetic studies (Coyle et al. 1998) suggest that there are two distinct populations off SE Australia. An eastern population is found along the Queensland and NSW coasts, and the southern population ranges between southern NSW and South Australia (Blackburn 1950). A separate population exists off Western Australia.

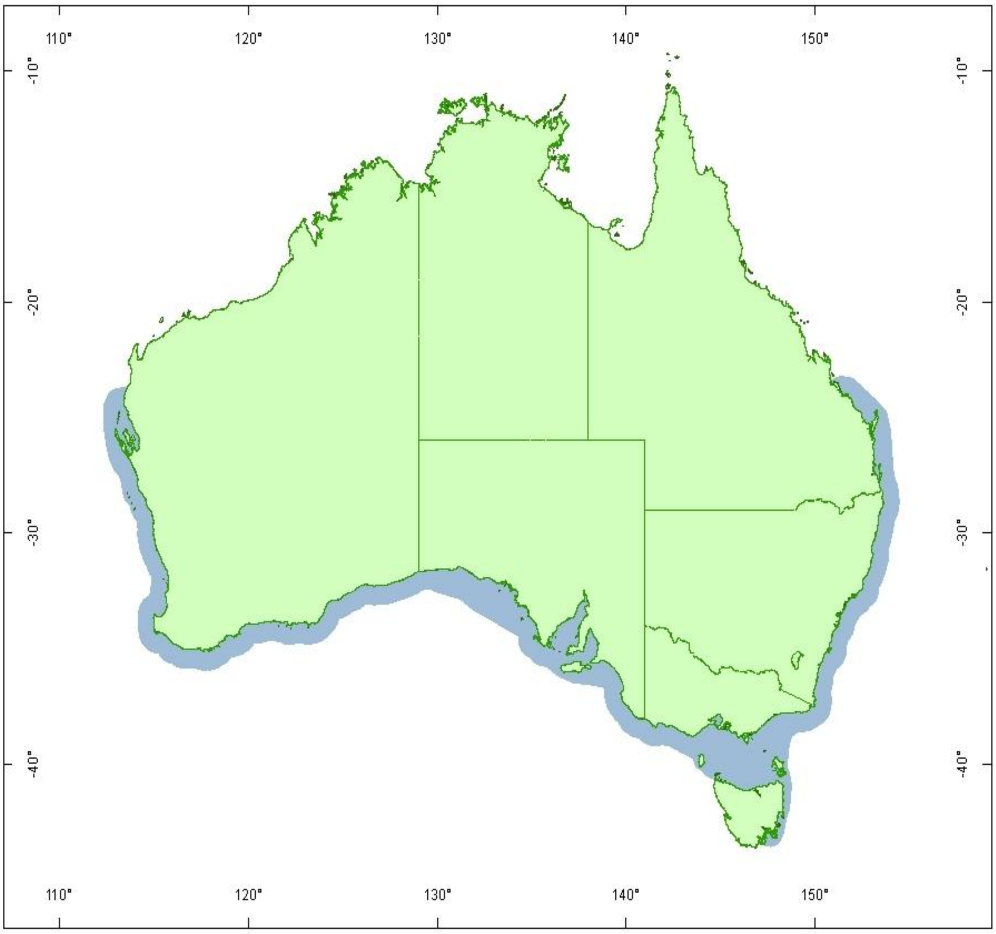

Figure 12.10: Distribution of Australian anchovy (*Engraulis australis*) in Australian waters.

Blue sprat

S. robustus, which has tropical biological characteristics, is a small pelagic species confined to southern Australia. In SE Australia it is found in coastal waters, but does not occur in Tasmania. In South Australia it is confined to the two gulfs and the eastern Great Australian Bight embayments (Rodgers et al. 2003). Little is known about its stock structure throughout its range.

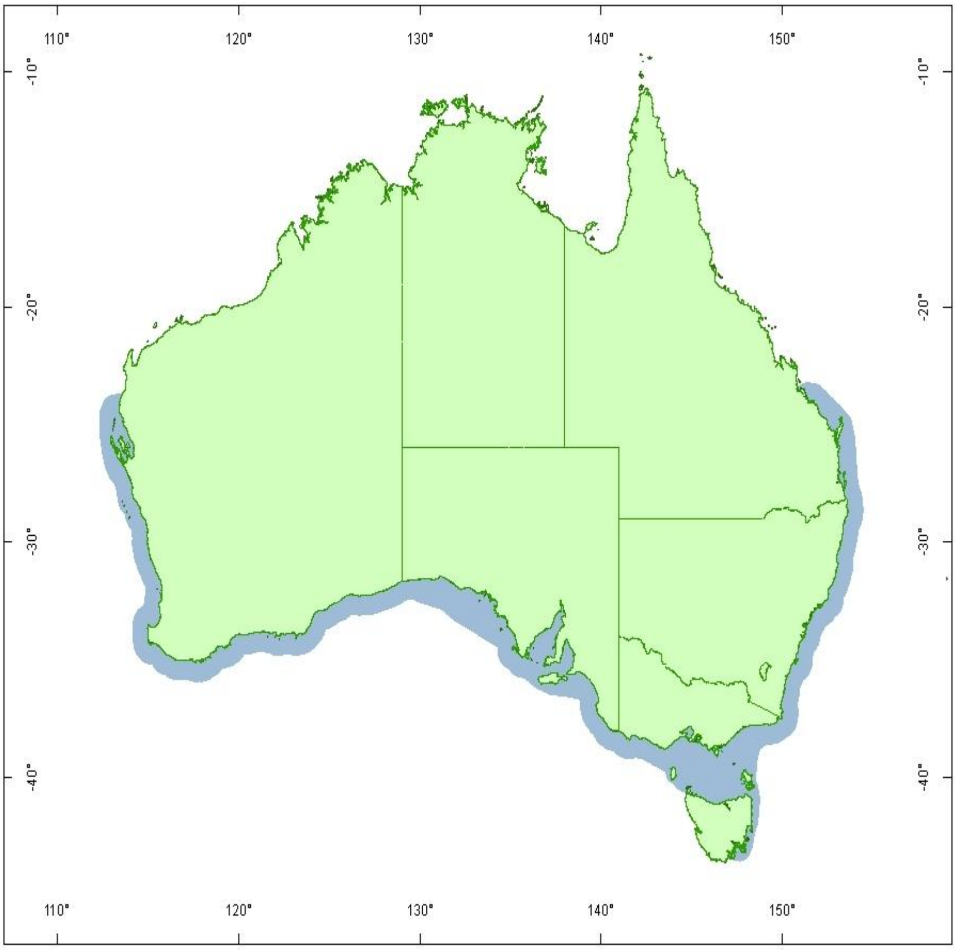

Figure 12.11: Distribution of blue sprat (*Spratelloides robustus*) in Australian waters.

Sandy sprat

This species is found in coastal waters and estuaries right around the SE Australian coast as well as south-western WA and southern Queensland (Kailola et al. 2003); however, little is known about the stock structure throughout its range.

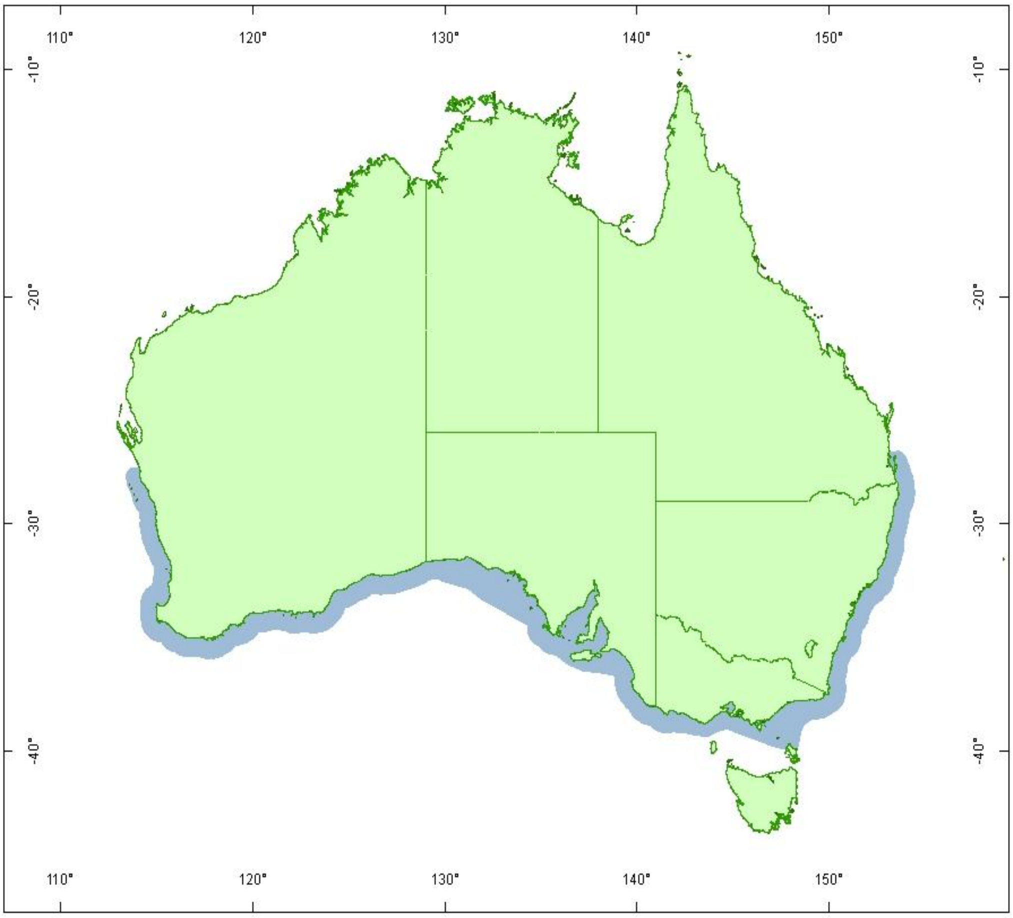

Figure 12.12: Distribution of sandy sprat (*Hyperlophus vittatus*) in Australian waters.

Blue mackerel

Scomber australasicus is distributed throughout much of the Indo-Pacific shelf waters (Kailola et al. 1993). They are found off most of Australia's coast, except the Gulf of Carpentaria in NT (Gomon et al. 2008). The SE Australian study area (GAB to northern NSW) is considered to be the core distributional area in Australia; they have been reported in commercial fishing surveys in the Great Australian Bight (Shuntov 1969; Collins and Baron 1981) and are more common in mid-summer at times of higher water temperatures. Their distribution may be continuous around Tasmania and through Bass Strait; however, this is uncertain due to lack of trawling through Bass Strait (Ward et al. 2001).

Considerable research has been undertaken throughout SE Australia and beyond on the stock structure of blue mackerel. Methods including genetics (mtDNA), long-lived parasite markers and otolith microchemistry have all been employed (see review by Schmarr et al. 2007). There appears to be two spatially distinguished populations, one along the entire coast of Australia (Queensland – east coast of Tasmania) and a southern Australian population occurring in SA. These distributions could be related to oceanographic and biogeographic features in SE Australian waters including Bass Strait, the Eastern Australian

Current and the Flinders Current (Schmarr et al. 2007). In both populations, fish generally increase in size with increasing depth.

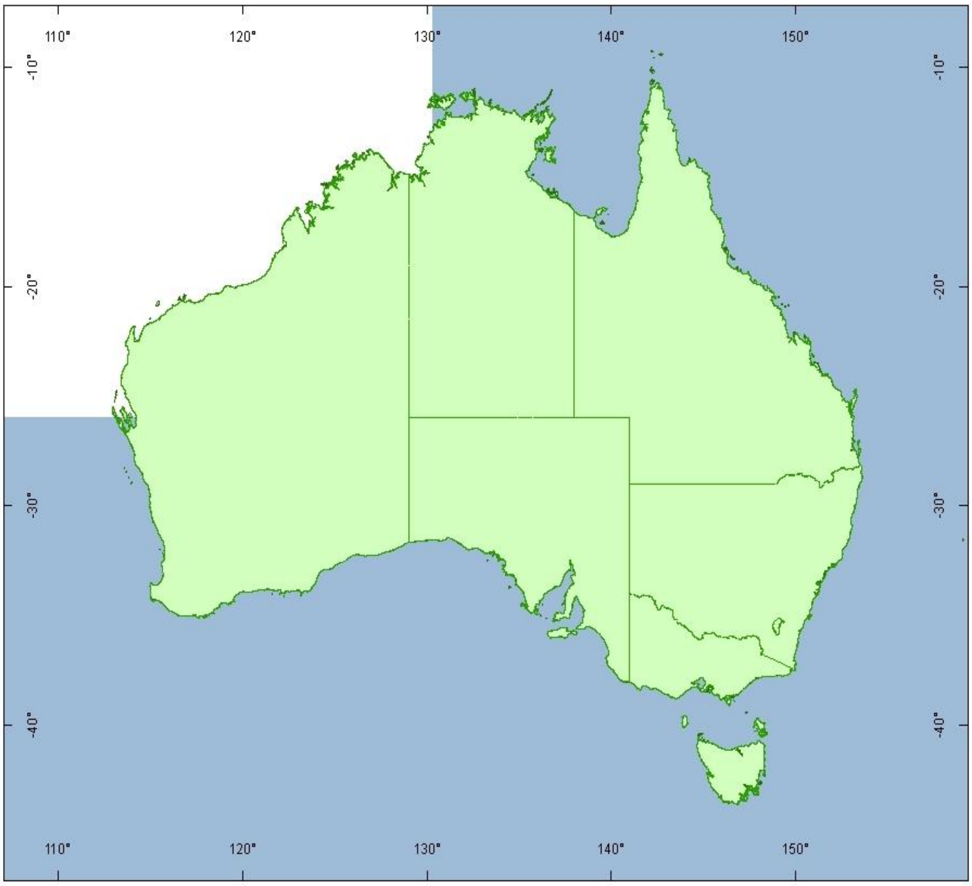

Figure 12.13: Distribution of blue mackerel (*Scomber australasicus*) in Australian waters.

Jack mackerel

Trachurus declivis is a wide ranging species, extending well beyond the SE Australian region, in temperate shelf waters of Australia (Wide Bay, Queensland – Shark Bay, WA) and New Zealand (Richardson 1982). A sub-species, *T. d. capensis* occurs off the South African coast. The Australian population is genetically distinct from that in New Zealand. Based on genetic and morphometric studies, within the Australian population there are distinct WA and eastern sub-populations (western Bass Strait to eastern Australia) (Richardson 1982; Lindholm and Maxwell 1982). Throughout the SE Australian region, it is found throughout shelf waters, with juveniles found in both inshore and offshore waters, but adults are generally found in the offshore waters, to the edge of the continental shelf (Kailola et al. 1993).

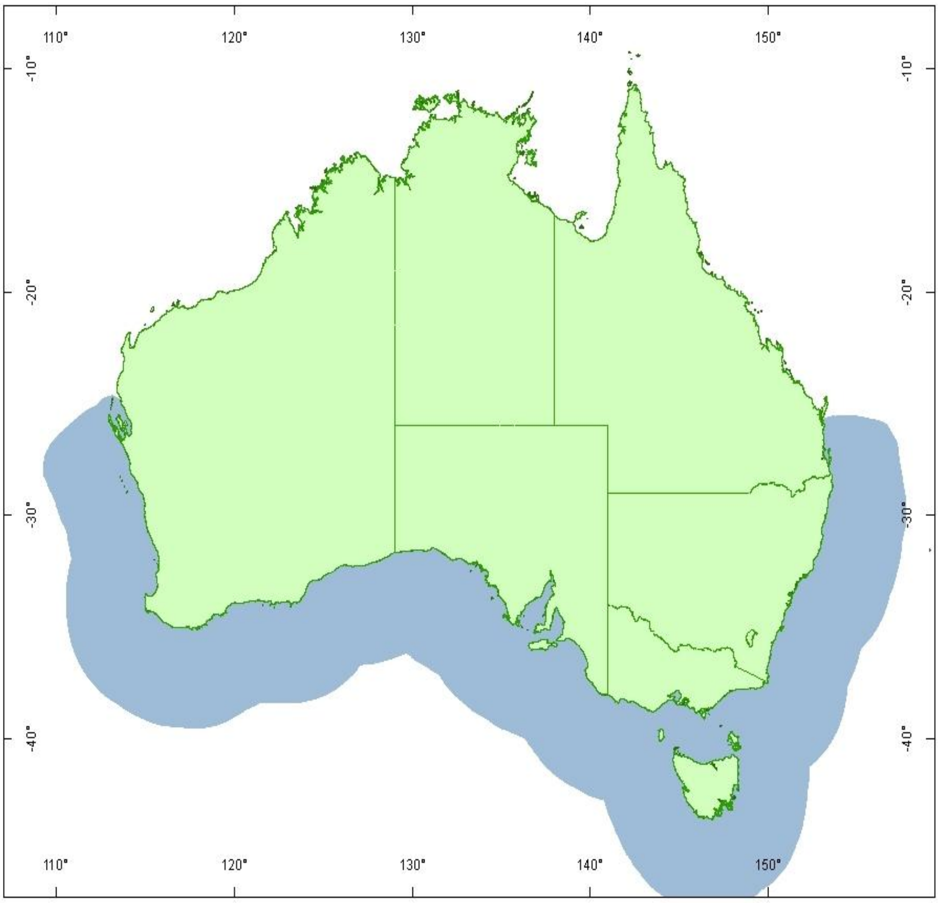

Figure 12.14: Distribution of jack mackerel (*Trachurus declivis*) in Australian waters.

Yellowtail scad

This species is found in southern Australian (Exmouth Gulf to southern Queensland), New Zealand and Lord Howe Island waters (Gomon et al. 2008). Off the east coast of Australia it is more commonly found off the northern NSW and southern Queensland than its congeneric species, *T. declivis* (Kailola et al. 2003). Here, they form large schools in estuaries and embayments as well as over inshore rocky reefs but can also be found to depths of 500 m. A pilot electrophoresis study on yellowtail scad sampled from northern and southern NSW suggested separate populations; however, more extensive sampling was required to confirm this hypothesis (Coyle et al. 1998). It is found in lower abundances throughout the rest of the SE Australian shelf waters; however, their distribution in these latter areas is uncertain due to the possible misidentification with jack mackerel.

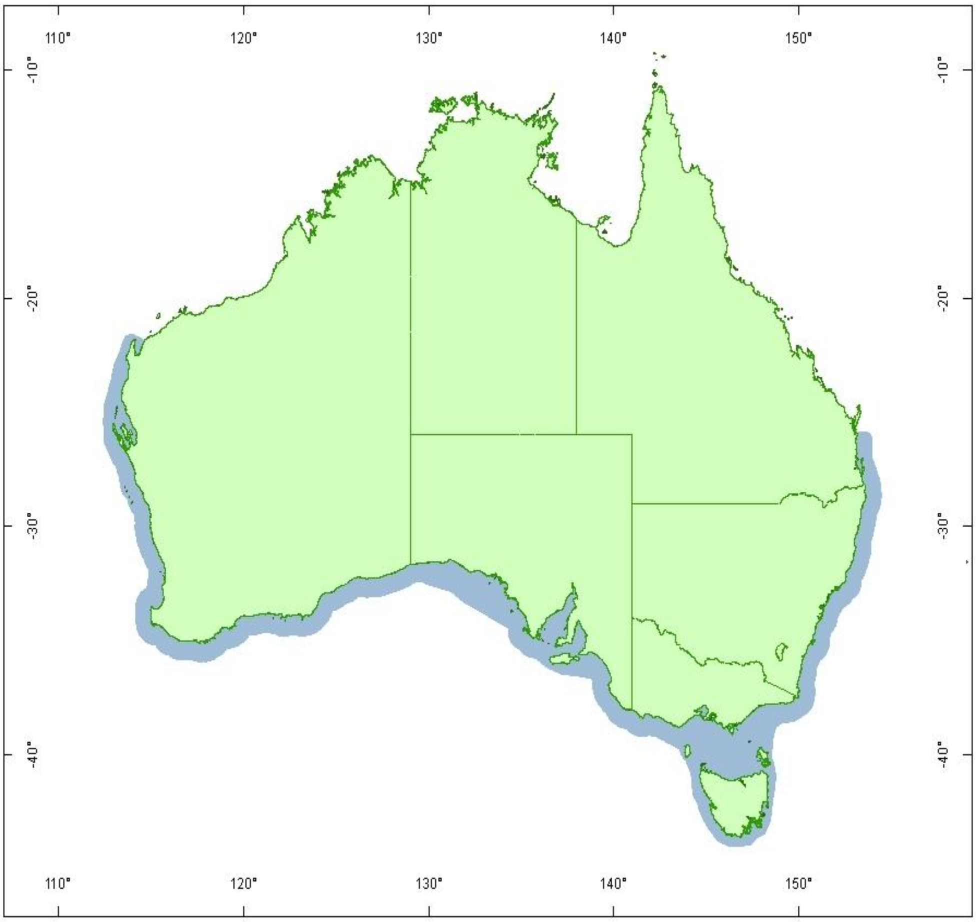

Figure 12.15: Distribution of yellowtail scad (*Trachurus novaezealandiae*) in Australian waters.

Redbait

E. nitidus is a surface and mid-water schooling species over the continental shelf distributed from South Africa, southern Indian Ocean, Southern Australia and New Zealand. In Australia, they are found from northern NSW (south of 30°S), Victoria, Tasmania, SA and WA. They appear to school by size and are found at larger sizes with increasing depth (Wellsford and Lyle 2003). Redbait form mixed schools with jack mackerel off the east coast of Tasmania (Williams and Pullen 1993). The preferred spawning habitat for redbait appears to be at the continental shelf break, where the seafloor depths are 125–325 m (Niera et al. 2008). There is no information on its stock structure in Australia, although marked differences in size and age at maturity coupled with variability in the timing of spawning between fish sampled from eastern and south-western Tasmania suggest some population structuring between eastern and western Tasmania.

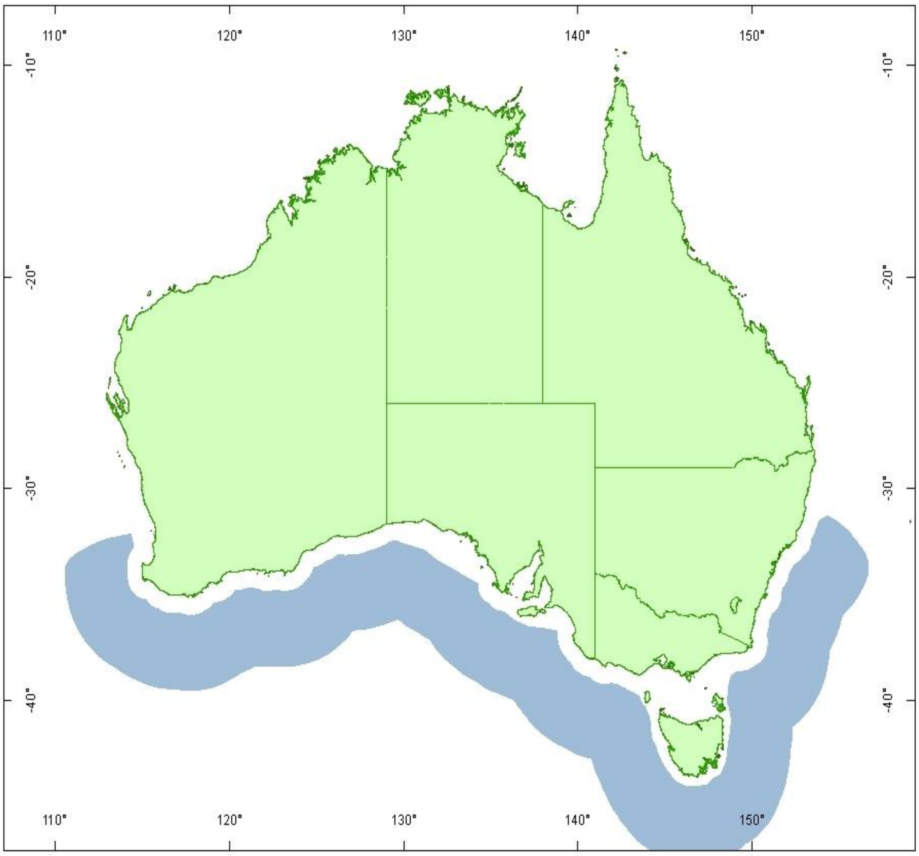

Figure 12.16: Distribution map of redbait (*Emmelichthys nitidus*) in Australian waters.

Key points:

- In SE Australian waters, small pelagic species occupy the following ecosystems, some of which are associated with important water current systems:
    - Eastern Australian Current (EAC) – sardines, yellowtail scad, redbait, blue mackerel
    - Flinders Current – sardines, anchovies, blue mackerel
    - Shallow embayments, gulfs – anchovies, sandy sprats, blue sprats
    - Cold temperate Tasmanian waters – jack mackerel.
- Many of these species occur beyond the SE Australian region and even within the region, they have complex stock structures. However, for some of the species there appears to be some delineation between eastern (NSW and eastern Tasmania) and southern (Victoria, SA) fish:
    - Sardines and yellowtail scad – complex structuring throughout SE Australia, with the possibility of overlapping distributions of stocks
    - Anchovies – eastern (NSW) and southern (Victoria and SA) Australian populations
    - Blue mackerel – eastern (NSW – Tasmania) and southern (SA) Australian populations
    - Redbait – circumstantial evidence for eastern (NSW – Tasmania) and western (Tasmania – SA) Australian populations
    - No information on stock structure for blue and sandy sprats.

12.2.3. Predators and prey

This section reviews the position of each species in the relevant ecosystem of SE Australian waters.

Australian sardine

The predators of Australian sardine include larger pelagic fish: barracouta (Blackburn 1957), Australian salmon (juveniles and adults; Hoedt and Dimmlich 1994; Cappo 1987) snook (Hoedt and Dimmlich 1994) southern bluefin tuna (Ward et al. 2006), marine mammals (NZ fur seals; Page et al. 2005), seabirds (crested terns; McLeay et al. 2009). The diet of barracouta was examined throughout its whole range in southern Australia by Blackburn (1957), who found that sardines were more common in the diets of fish found in SA and NSW waters, compared with those from Victorian (Bass Strait) and Tasmanian waters. This probably reflected the variation in relative abundance of sardine in each of these areas.

In Eastern Great Australian Bight waters, the diet of sardines was dominated by krill and unidentified small crustaceans, with fish eggs and larvae contributing <10% of the total prey biomass (Ward et al. 2008). There is no information on their diets elsewhere in SE Australian waters.

Australian anchovy

Anchovies are preyed on by seabirds, including terns (McLeay et al. 2009), gannets (Bunce 2001) and little penguins (Montague and Cullen 1988; Ward et al. 2008), marine mammals (Page et al. 2005) and larger pelagic fish (e.g. Australian salmon; Hoedt and Dimmlich 1994 and barracouta; Blackburn 1957). Blackburn (1957) found that anchovies were more common in the diet of barracouta caught in Victorian and Tasmanian waters compared with NSW and SA waters.

The diet of anchovies in the eastern Great Australian Bigh consists mainly of krill, unidentified small crustaceans and fish larvae (Ward et al. 2008). No information is available on their diet in the remainder of SE Australian waters.

Blue sprat

They are preyed on by larger pelagic species, seabirds, including crested tern chicks (McLeay et al. 2009), and marine mammals.

The diet of blue sprats is uncertain.

Sandy sprat

In Victorian waters, sandy sprats are preyed on by larger pelagic species (e.g. Australian salmon; Hoedt and Dimmlich 1994, and barracouta; Blackburn 1957), and some demersal species (e.g. sand and yank flathead) (Parry et al. 1995).

Blue mackerel

Off the SA coast, marine mammals (NZ fur seals) are known to prey on a range of small to large to medium-sized pelagic fish species, including southern bluefin tuna (Ward et al. 2008), blue mackerel (Page et al. 2005; Ward et al. 2008). In Port Phillip Bay, Bunce and Norman (2000) reported that Australian gannet consumed blue mackerel in small quantities and in SA, bottlenose dolphins are known to eat blue mackerel (Kemper and Gibbs 2001, cited in Goldsworthy et al. 2003).

The diet of blue mackerel off SE Australia consisted of more than a third as unidentified fish (Bulman et al. 2000), followed by pelagic zooplankton with minor components consisting of benthic animals (polychaetes and gastropods). In the eastern Great Australian Bight, clupeoid fish larvae and krill made up the dominant food items during late summer – autumn (Ward et al. 2008).

Jack mackerel

Larger pelagic fish (barracouta, southern bluefin tuna and albacore) and Australian fur seals are reported predators of jack mackerel in Tasmanian waters (Williams and Pullen 1986; Gales and Pemberton 1994). Similarly, off the SA coast, jack mackerel were the third to fifth most important fish species preyed on by Australian and NZ fur seals (Page et al. 2005). In the eastern Great Australian Bight, southern bluefin tuna were significant predators on jack mackerel (Ward et al. 2008).

The location, fish size and season appear to be important determinants of the diet of jack mackerel; however, generally, they feed on planktonic organisms and mesopelagic fish. In the Great Australian Bight, small jack mackerel feed on copepods in inshore waters, and as they grew to larger sizes, occurring in the more offshore waters their diet changed to euphausids (Shuntov 1969). Recent investigation of their diet in the eastern Great Australian Bight also noted the high importance of krill (Ward et al. 2008).

There is also a strong relationship between krill production and jack mackerel feeding behaviour off the east coast of Tasmania (Young et al. 1993; Williams and Pullen 1993). During the early to mid 1980s, the summer schools of jack mackerel gorged themselves on euphausiids (*Nyctyphanes australis*) (Williams and Pullen 1993), and at the shelf break, light fish (Sternoptychidae) and lantern fish (Myctophidae) were important components of their diet (Webb 1976, quoted in Williams and Pullen 1986). In the summer of 1988–89, La Niñna conditions provided strong intrusion of the low productivity EAC water across the shelf, resulting in low krill biomass (Young et al. 1993), and no surface schooling behaviour of feeding jack mackerel in that year (Williams and Pullen 1993). The consequences in terms of climate change are discussed later in this report.

Yellowtail scad

Predators of yellowtail scad include yellowfin tuna (Diplock (1990) cited in Glaister and Diplock 1993).

In SE Australian waters, little research on the diet of *T. novaezealandiae* has been undertaken (Bullman, 2001); however, in NZ, they are found to prey mainly in midwater on planktonic crustacean larvae as well as pelagic amphipods and isopods, and to a lesser extent on pelagic fish such as anchovies (Godfrieux 1970).

Redbait

Predators of redbait include the following fish species: Rays bream (*Brama brama*) (Blaber and Bulman 1986), angel shark (*Squatina australis*), silver dory (*Zenopus nebulosus*), John Dory (*Zeus faber*) and barracouta (*Thyrsites atun*) (Bulman et al 2000) and southern bluefin tuna (Young et al. 1997). The diet of some oceanic birds including shy albatross (*Thalassarche cauta*) (Hedd and Gales 2001) and Australasian Gannet (*Sula serrator*) (Brothers et al. 1993) included redbait, as did that of the marine mammals, Australian fur seals (*Arctocaphalus pusillus*) in Tasmanian and eastern Bass Strait waters, especially during winter months (Gales and Pemberton 1994). This also appears the case for New Zealand (*Arctocephalus forsteri*) and Australian fur seals off the South Australian coast (Page et al. 2005).

In SE Australian waters, the diet of redbait is closely associated with their generally oceanic pelagic distribution. Calanoid copepods, ascidians (salps), euphausids and mesopelagic fish (lanternfish) comprise their major food items (Bax and Williams 2000; McLeod 2005). Ontogenetic variation in their diet was found with relatively low numbers of euphausids in smaller redbait and larger proportions in larger fish (McLeod 2005). Importantly, McLeod (2005) correlated seasonal variation in diets of redbait off eastern Tasmania with sea surface temperature and productivity. In summer and autumn, EAC water which is associated with a higher abundance of copepods, moves onto the Tasmanian shelf accounting for an observed predation by redbait on copepods, while in winter, sub-Antarctic water which is related to an increase in krill (Harris et al. 1991) results in increased predation on krill (McLeod 2005). In the eastern Great Australian Bight during summer–autumn, redbait fed mainly on krill, unidentified small crustaceans and pteropods (Ward et al. 2008).

Key points:

- Generally, the group of small pelagic fish species provide a significant proportion of the diet of species higher in the pelagic food chain. Our greatest understanding of the position of small pelagic fish species within the food chain exists for those occurring off Tasmania and southern mainland Australia (Victoria and SA).
- Larger pelagic fish species (salmon, snook, barracouta, SBT, albacore), sea birds (crested terns, little penguins, gannets) and marine mammals (fur seals and dolphins) are generalist but significant predators of small pelagic species; with a tendency for the smaller sea birds (e.g. little penguins, crested terns) to focus their diet on the smaller pelagic fish species.
- There is some evidence that some pelagic species (sandy sprat and redbait) are preyed on by some demersal fish species (flathead, dories and angel sharks), which probably infers that sandy sprat and redbait occupy the whole of the water column.
- All the pelagic fish species reviewed here show some dependence on krill (euphausiids) in their diets, with other zooplankton (small crustaceans) being the second most important prey item.
- For several species (jack mackerel, blue mackerel and redbait), the proportion of euphasiids in their diet increases with increasing size of fish, which is probably a function of the more offshore distribution of larger fish.

12.2.4. Recruitment

For small pelagic species in Australian waters, the most successful method to determine recruitment variability has been through regular surveys to measure egg and larval abundances. Other ways include variation in CPUEs and the age structure of the population; however, there are serious uncertainties as to their usefulness as recruitment indicators. Generally, the fisheries for these schooling species are carried out by a relatively small number of operators using purse seine nets or mid water trawls, and do not necessarily sample the entire population. As such, their catch rate data and the age composition of catch samples may be misleading.

Australian sardines

The SA sardine population has been regularly monitored since 1995, and recently, variation in egg abundances have been linked to upwelling events off the west coasts of KI and SA (Ward et al. 2006). Also, egg and larval densities collected in 1999 were higher than those in 2000 reflects the recovery of the population from the mass mortality event in October–November 1998 (Ward et al. 2001).

The age structure of catches of Australian sardines is available from the SA and Victorian fisheries during the mid 1990s (Jackson et al. 1998). Near the commencement of the South Australian sardine fishery, two- and three-year-old fish dominated the catches in Coffin Bay waters, whereas in Spencer Gulf, the age composition shifted from mainly two- and three-year-old fish in 1995 to one- and two-year-old fish during 1996 and then returning to two and three year olds in 1997 (Jackson et al. 1998). The age structure of catches in Spencer Gulf between 1995 and 2006 suggest mainly two- and three-year-old fish, except in 1998, when one-year-old fish were the main age group (Ward et al. 2008). Catch per unit effort data for the SA fishery shows increasing trends since the development of the fishery; however, the steadily rising carrying capacity of vessels taking sardines, together with the setting of TACCs negates the use of these data to interpret recruitment.

In the Port Phillip Bay fishery, consistently younger fish (0 and 1 year olds) were caught during 1994–97 (Jackson et al. 1998; Neira et al. 1999) and at Lakes Entrance, one- and two-year-old fish dominated the catch in 1995. In both the SA and Victorian fisheries, it is considered that age compositions of the catches do not represent the age structure of the populations, and therefore, it is problematic to use such information to understand if there is variability in recruitment for this species.

There is no information on ages of sardines caught in the NSW fishery (Scandol et al. 2008).

Australian anchovies

Egg and larval surveys on anchovies off SA indicate considerable year to year variation in recruitment (Dimmlich et al. 2009). Due to variable upwelling conditions, population size of anchovies may be more variable than in the relatively stable gulf waters, which harbour a reserve of younger fish (Dimmlich et al. 2009).

In Victoria and SA, the age structure of anchovies is strongly determined by their spatial distribution, with the average size and age of fish increasing with increasing distance from the coast (reviewed in Dimmlich and Ward 2006). As the fisheries in SE Australian waters are confined to relatively small areas and mainly for juveniles, ongoing monitoring of year class strengths in these fisheries (NSW and Port Phillip Bay, Victoria) may not be as cost effective as egg and larval sampling programs to measure recruitment variation. Recent long-term sampling of anchovy eggs and larvae in Port Phillip Bay suggest variations in year class strength (Acevedo et al. 2009); however, there is no information on any correlation with environmental variables for this population.

Blue sprats

Blue sprats are a short lived (<1 year) sub-tropical species (Rogers et al. 2003) which spawns in the SA gulfs during summer months, when SSTs are between 19 and 26°C. There is no information on variability in annual abundances throughout the SE Australian region; however, variation in summer water temperatures during spawning may influence recruitment success.

Sandy sprats

In the NSW commercial fishery, the majority of fish are 1–3 years of age; however, little is known about temporal variation in recruitment to this fishery (Scandol et al. 2008). In SA gulf waters, sandy sprats are between 0.5 and 4 years of age; however, there is no information on year class strength (Rogers and Ward 2007).

Research on sandy sprat fisheries elsewhere in Australia suggests strong relationships between environmental variability and recruitment success. In the commercial sandy sprat fishery along the south west coast of WA, which consistently comprises mainly one-year-old fish, there is a strong positive correlation between annual catches and the strength of the Leeuwin Current in the previous year (Gaughan et al. 1996).

Blue mackerel

A 12-month sampling program on blue mackerel off the northern and southern NSW coast, show that fish in both areas begin to recruit to the respective fisheries as 0^+ fish, but are mainly caught as one- and two-year-old fish (Stewart and Ferrell 2001). The presence of young age groups of fish in these two fisheries may simply be a function of the fisheries being inshore, where smaller fish predominate for this species (e.g. Shuntov 1969; Stevens and Hausfeld 1984). More spatially widespread sampling in deeper waters of older fish may assist in determining whether temporal recruitment variation exists. However, as older blue mackerel are relatively difficult to age (Rogers et al. 2007), the regular annual sampling of young fish from the inshore purse seiners may provide a more cost-effective means to determine whether this variation exists.

Egg and larval sampling of blue mackerel off the NSW and SA coasts have recently been used to determine the spawning biomass of blue mackerel populations in these two areas (Ward et al. 2009); however, the distributions and relative abundances of eggs have not yet been related to environmental variation.

Jack mackerel

Lyle et al. (2000) reviewed the age composition of jack mackerel in the east Tasmanian fishery throughout the fishing years 1985–86 – 1994–95, noting a decrease in older fish over this period; however, it was not possible to separate the reasons for the change, which included:

- Impact of fishing on the size structure of the population
- Changes in size of fish which are targeted in the fishery
- Changes in population age structure due to recruitment variability
- Inter-and intra-annual changes in the behaviour of jack mackerel schools
- A combination of one or more of these factors.

Yellowtail scad

There is limited information for this species on recruitment and its spatial and temporal variation in SE Australian waters. A single year sampling program of yellowtail scad in northern and southern NSW waters indicate that fish in both areas begin to recruit to the inshore purse seine fisheries at the age of one year, but with differing peaks in recruitment for northern NSW fish at two years and at three years of age for southern NSW fish (Stewart and Ferrell 2001). This suggested variation in recruitment may just be a function of yellowtail scad being sampled in different ways in the two areas. In northern NSW, they were sampled from the inshore purse seine fishery which targeted the species, whereas they were sampled as a by-product in the blue mackerel fishery in southern NSW. More extensive temporal sampling in both regions is required to confirm whether this variation is real.

Redbait

Welsford and Lyle (2003) tracked the annual size composition of redbait taken in the purse seine fishery off eastern Tasmania between 1984–85 and 1993–94, and suggested the passage a strong year class entering the fishery in 1988–89; however, the authors questioned how representative the samples taken in the fishery, compared with the overall population.

Surveys of the egg and larval distributions and abundance off SE Australia (southern NSW to SW Tasmania) showed that spawning area confined to the EAC waters from the mid NSW coast to south-eastern Tasmania, and along the edge of the shelf (Neira et al. 2008). Peak spawning occurred during spring months which coincided with peak phytoplankton production in these areas.

Key points:

- It is notoriously difficult to measure recruitment for small pelagic species, as the fisheries for schooling species preclude the use of fishery catch and effort data. Also, age composition data of fish caught in the fishery may not be representative of the entire population.
- For most of the species in SE Australian waters, the age composition data from the fisheries is so sporadic as not to give a time series or fluctuations in year class strengths.
- Time series on egg and larval abundances, based on spatially extensive surveys are probably the most cost-effective ways in demonstrating recruitment variations for sardines off SA, anchovies in PPB and SA, redbait off eastern Tasmania and blue mackerel in southern Australia.
- More research is required to link productivity variations with recruitment.

12.3. Current impacts of climate change

The effects of climate change on the small pelagic fish species of SE Australian waters are considered through alterations to the location and/or strength of the key currents occurring in this region or rises in water temperature. For eastern Australia, there is now increasing evidence that the extension of the Eastern Australian Current (EEAC) has moved further south (Ridgeway 2007). In southern Australian waters, SE winds of increasing strength have produced the strongest upwelling of the westward directed Flinders Current over the last decade (Nieblas et al. 2009). Also, the wind-induced eastward directed surface currents (including the Leeuwin Current), which enter the western part of the SE Australian region during winter/spring, are influenced by ENSO / La Niña meteorological events (Li and Clarke 2004) and with the predicted increase in frequency of ENSO events, it is likely that the frequency of strong currents will lessen. Finally, in the shallow embayments of SE Australia, the effects of increasing surface water temperatures through climate change on the small pelagic species are discussed.

Australian sardine

The increase in the strength of upwelling off the eastern Great Australian Bight in the past decade (Nieblas et al. 2009) could have enhanced the recovery of the sardine population in SA after the two major sardine mortality events of 1995 and 1998, with egg and larval densities in this region now at their highest (Ward et al. 2008).

Off the east coast of Australia, sardines migrate northwards to spawn during winter–spring months (southern Queensland)(Ward and Staunton-Smith 2002). The southward extension of the East Australian Current due to climate change could advect eggs and larvae further south than what is currently occurring, and where larval growth and survival may be higher (Uehara et al. 2005). However, there is, as yet, little evidence that large numbers of sardines occur as far south as Tasmanian waters.

Outside the SE Australian region, the northern most range in distribution of sardines off the south-west coast of WA appears to have moved south as a response to increasing strength of the Leeuwin Current due to climate change (Gaughan et al. 2004).

Australian anchovy

Preliminary long term monitoring of the egg and larval abundances of anchovies in Port Phillip Bay, Victoria (Acerevo et al. 2008), suggest that abundances are influenced by environmental variables. Further research is required to investigate whether these environmental variables are influenced by climate change.

Also, being a short-lived, fast-growing species ensures that anchovies can rapidly adapt to varying environmental conditions, as seen in the rapid increase in anchovy production in SA shelf waters, and the time of the major sardine mortality events in 1995 and 1998 (Ward et al. 2001).

Blue sprat

The abundance of this species in the embayments of SE Australia is likely to be enhanced by rising summer water temperatures due to climate change; however, as there is no dedicated fishery for this species in these waters, evidence that this has occurred would need to be sought from other means, for example, shifts in the species compositions of seabird diets (Bunce and Norman 2000; McLeay et al. 2009).

Sandy sprat

Evidence outside the SE Australian region indicates a positive relationship between sandy sprat catches off the west coast of WA and the strength of the Leeuwin Current (Gaughan et al. 1996). With the strength of the Leeuwin Current predicted to increase with climate change (Gaughan et al. 2004), the sandy sprat population size off WA may increase.

Both the NSW and Victorian fisheries for this species experience fluctuations in catches (see Figure 12.3); however, no attempts have been made to link these fluctuations with environmental variables such as strength of EEAC or environmental conditions in PPB, respectively.

Blue mackerel

In SE Australian waters, the timing of spawning coincides with the southward movement of the EAC off NSW (winter–spring) and the Flinders Current along the southern Australian coast, and therefore, any shifts or changes in strength or upwelling due to climate change could influence the distribution and or abundance of this species in the two respective areas. Catches have increased in recent years (see Figure 12.4); however, it is unknown whether population abundances have also increased during this period.

Jack mackerel

Of all the SE Australian small pelagic species, jack mackerel is the one with the strongest evidence that climate change can affect the distribution and abundance of these species. During the early 1990s, climate-induced low westerly wind stress off Tasmania led to incursions of the Eastern Australian Current, reducing biological productivity off the eastern Tasmanian coast, and thereby reducing the production of krill (Harris et al. 1992). Highest catches in the purse seine fishery for jack mackerel in these waters occurred in years when jack mackerel fed on surface swarms of krill (Williams and Pullen 1993). Since then, this species continued to be caught in smaller numbers, and mainly as by-product in the mid-water trawl fishery targeting redbait. However, the apparent decline in the jack mackerel abundance could have been exacerbated by the effects of fishing (Lyle et al. 2000).

Yellowtail scad

Highest abundances of yellowtail scad appear to be in the northern NSW waters, and with the southward extension of the East Australian Current due to climate change, it is possible that its abundance may increase further south. However, the difficulty in distinguishing this species from jack mackerel, not only as eggs and larvae by scientists, but also as juveniles and adults by fishers, makes any future study on the effects of climate change on this species very problematic.

Redbait

This species is recognised as an East Australian Current (EAC) species, and its apparent increase in population off Tasmania is seen in the light of the extension of the EAC into these waters (Hobday et al. 2009). Although, at the respective heights of their abundances, the main spawning areas for redbait and jack mackerel are the same (shelf edge), the peak spawning time for redbait occurs during spring (October), several months earlier than that for jack mackerel (January–Feburary). It is therefore likely that this places redbait at a competitive advantage over jack mackerel.

Key points:

- There is general agreement that changes in the fishery catch off eastern Tasmania from jack mackerel to redbait are consistent with the southward shift in distribution of warm temperate species down the east coast of Australia.
- The ability to distinguish between jack mackerel and yellowtail scad larvae by researchers and juveniles and adults by fishers will add to evidence of the southward extension of the EAC.
- The increase in upwelling strength of the Flinders Current along southern Australia, through the incidence a stronger SE winds, may have favoured the rapid recovery of sardines after the two large mortality events during the 1990s.

12.4. Sensitivity to change

This section focuses on the biological characteristics of small pelagic species that are sensitive to climate change. These characteristics include physiological tolerances to spawning time and egg/larval development, feeding behaviour, whether the species are specialist or generalist feeders and the timing of life history events driven by temperature or day length.

Australian sardines

There is a positive relationship between egg hatching rate and water temperature for Australian sardines (White and Fletcher 1996), and so higher survival rates of eggs at higher temperatures would assist in enhanced survival of eggs for a particular year class.

Studies on the growth rate of sardine larvae in other SE Australian populations (NSW) and elsewhere (Japan and California) also found growth rates to be higher in waters downstream from upwelling areas than those found in the upwelled areas (Uehara et al. 2005). With increased strengths of upwelling linked to climate change, the higher growth rates of sardine larvae downstream from the upwelled areas in southern Australia may result in short times that larvae are vulnerable to predation, thereby potentially increasing population sizes.

Australian anchovies

No information is available on the relation between egg hatching rate and water temperature for Australian anchovies (Dimmlich and Ward 2004); however, research on other similar species elsewhere (*E. mordax*, Lo 1985, and *E. encrasicolus*, Melia et al. 2002) suggest a positive relationship. Therefore, any rises in temperature in shallow embayments during summer in southern Australia, caused by climate change could decrease predation rates on anchovy eggs and thus enhance survival of eggs and larvae produced from a particular year class.

Blue sprats

Peak spawning period for blue sprats in the SA gulfs occurs in November–February, coinciding with water temperatures ranging between 22 and 26°C (Rogers and Ward 2003). Spawning occurs as early as October, and so with increasing water temperatures due to climate change, it is possible that the peak spawning period may be extended for this species, thereby, enhancing population sizes for this species.

Sandy sprats

Sandy sprats spawn over a protracted period from spring to summer (September– February) in the SA gulfs, and the peak spawning time (November) coincides with increasing SST (Rogers and Ward 2007). There is the potential that any increase in SST during the earlier part of the spawning season due to climate change may extend the peak in the spawning season.

Blue mackerel

Development of blue mackerel eggs is temperature dependent (Neira et al. 2007) and as the spawning period for both the eastern and southern Australian populations covers relatively long periods (winter–spring and spring–autumn, respectively), the plasticity of their reproductive biology suggests that this species is adaptable to changes in water temperatures and therefore, climate change.

Jack mackerel

Jack mackerel is a specialist feeder, concentrating in euphausids (krill). The level of krill production and hence, the schooling, and feeding behaviour of jack mackerel on off the east coast of Tasmania is closely linked with the La Niña conditions (Harris et al. 1992; Williams and Pullen 1993; Young et al. 1993). The year of low krill production (1988–89) coincided with relatively low egg densities in the subsequent spawning year of 1989–90, caused by low fat concentrations (Jordan et al. 1995). The southerly extension of the EAC into Tasmanian waters will result in more lower productivity waters at the peak feeding season for jack mackerel, thereby resulting in lower egg production.

The spawning time for jack mackerel appears to be relatively rigid. In three consecutive years of egg and larval sampling, Jordan et al. (1995) found little difference in timing between peaks in egg production, despite large inter-annual variation in oceanographic conditions, suggesting that jack mackerel could be quite sensitive to climate change.

Yellowtail scad

Yellowtail scad spawn in the warmer East Australian Current (EAC) water mass (northern NSW and southern Queensland) (Rogers et al. 2007), and larvae are advected into cooler upwelled water supporting faster growth of post-larvae (Syahailatua 2005). Further southward extension of the EAC due to climate change, may extend the spawning area for this species further south.

Redbait

There is a positive relationship between egg hatching rate and temperature (13–16°C) (Neira et al. 2008). Therefore, at spawning time, rises in temperature could result in shorter periods when redbait eggs are vulnerable to predation, thereby increasing the reproductive success of respective year classes.

Key points:

- For most of the species reviewed here, there is a positive relationship between egg hatching rates and water temperatures, over the range of temperatures that the respective species occurs; however, their temperature tolerances are unknown.
- For sardines, enhanced growth rates of larvae occur downstream from upwelling events.
- The level of fat production, and hence reproductive capacity of jack mackerel, is sensitive to the level of krill production, which, in turn appears to be controlled by the productivity of sub-Antarctic waters off the east coast of Tasmania.
- The spawning time for jack mackerel appears to be relativity rigid, despite inter-annual differences in oceanographic conditions.

12.5. Resilience to change

This section reviews the available information for small pelagic species relating to their physiological and behavioural plasticity, their genetic diversity and adaptation to evolutionary scales, their dispersal capacity and spatial population structure.

Australian sardines

Egg development rates increase with increasing temperatures (<16–21°C); however, in the eastern Great Australian Bight waters, peak egg production currently exists at the lower temperature range (Ward et al. 2008). The physiological tolerances of egg hatching rates and larval growth rates for this species are unknown, but the southward contraction in distribution of sardines down the west coast of WA (Gaughan et al. 2004) suggests that sardine have a relatively low resilience to climate change.

Reproductive success for this species may in fact be dependent on productivity of the water mass associated with the Flinders Current. With the recent observed increase in strength of upwelled water in southern Australia (Nieblas et al. 2009), sardine production in this area, may, in fact increase with climate change.

Australian anchovies

There is insufficient information on which environmental variables are linked to anchovy egg and larval abundance (Acerevo et al. 2008).

Blue sprats

This inshore species, which possesses sub-tropical growth and reproductive characteristics (Rogers et al. 2003) has the potential to be highly resilient to increasing water temperatures in the shallow embayments of southern Australia; however, its upper temperature tolerance levels are currently unknown. As the fertile eggs of this species are possibly demersal, but the key habitat on which they are laid is unknown (Rogers, pers. comm.), it is uncertain what is the effect of increased water temperature on the benthic habitat where the fertilised eggs are laid.

Sandy sprats

Although the spawning period for sandy sprats is wide ranging (October–February), peak spawning occurs in November, when SSTs are beginning to rise (Rogers and Ward 2007). As they are found in generally inshore waters, and with increasing water temperatures occurring mainly here, there is the potential for them to be relatively resilient to climate change.

Blue mackerel

If there is a critical temperature range that blue mackerel spawn over, with increasing water temperatures the centre of blue mackerel spawning areas (currently in southern Queensland and northern NSW) during winter–spring, may shift southwards. If this is the case, blue mackerel can be considered to be relatively resilient to climate change.

Jack mackerel

This species is more commonly associated with cooler temperate waters, and highest population sizes appear to be related to high krill production in these waters (Young et al. 1993). The southward shift of the EAC, resulting in higher summer water temperatures off the east coast shelf of Tasmania have shown to be detrimental to jack mackerel production, suggesting that this species may have low resilience to climate change.

Yellowtail scad

In contrast to the closely related jack mackerel, this species is associated with the EAC, and will therefore be more resilient to climate change than the former species.

Redbait

Redbait has been recognised as a species associated with the warm water EAC (Hobday et al. 2009), and it is therefore a species that is potentially resilient to climate change.

Variations in diet of redbait appears to be highly correlated with sea surface temperature, and during summer-autumn their diet consists mainly of copepods, characteristic of shelf EAC waters (McLeod 2005). During winter and spring, when colder sub-Antarctic water intrudes up the east coast of Tasmania, euphausids make up the bulk of their diet. In contrast to that for jack mackerel, the adaptability of redbait to alter their diet, ensures that they are adaptable to temperature induced climate change.

Key points:

- Small pelagic species associated with the EAC probably have a high resilience to climate change as they are adapted to waters of relatively high temperature and low productivity.
- Redbait is a generalist plankton feeder associated with the EAC, and is able to shift its diet with changing water temperature, therefore demonstrating its relatively high resilience to climate change.
- Anchovies are capable of occupying a range of ecosystems in SE Australia, including shallow embayments, the SA gulfs and the offshore upwelled waters of the eastern GAB.
- Species associated with shallow embayments are probably the most resilient to climate change. Blue sprats have sub-tropical life history characteristics.

12.6. Ecosystem Level Interactions

Australian sardine

Australian sardines are preyed upon by larger pelagic fish species, seabirds and marine mammals and it is expected that these predators (e.g. SBT – see Ward et al. 2006) will also be affected by climate change. Many of these species are generalist pelagic feeders (e.g. gannets, (Bunce and Norman 2000; crested terns, McLeay et al. 2009). However, with the potential for sardine production to increase with increased upwelling in the eastern Great Australian Bight, it is possible that these predators may increasingly aggregate to feed on sardines in these regions.

Australian anchovy

A number of the seabird species, including Australasian gannets, that prey on anchovies are generalist feeders and switch their diet preferences depending on the relative abundances of different surface fish species (including anchovies and sardines) (Bunce and Norman 2000). However, McLeay et al. (2009) found that adult crested terns concentrated their feeding patterns on high quality food such as clupeoid species, including sardines, anchovies and blue sprats to feed their chicks. These food sources would therefore enhance chick growth and survival (McLeay et al. 2009). Different clupeoid species occurring in their diets also varied spatially and may reflect differences in relative abundances of these clupeoid species in different areas, therefore suggesting that crested terns may be satisfactory indicator species for the relative abundance of clupeiod species.

Blue sprat

Similar comments to those for anchovy.

Sandy sprat

Similar comments to those for anchovy

Blue mackerel

Australasian gannets (*Morus serrator*) are reported predators of blue mackerel in Port Phillip Bay (Bunce 2001).

Jack mackerel

Small pelagic fish species, including jack mackerel were important components in the diet of New Zealand and Australian fur seals off the Tasmanian coast during the late 1980s and early 1990s (Gales and Pemberton 1994).

Yellowtail scad

No information available.

Redbait

Redbait was the most common fish prey in the diets of New Zealand and Australian fur seals off Tasmania (Gales and Pemberton 1994) and South Australia (Page et al. 2005). The redbait fishery off Tasmania is currently harvesting only as high as 12% of the spawning biomass (Neira et al. 2008), which is sufficiently low to ensure no adverse effects on fur seal populations. Therefore, any increase in redbait population size due to climate change is likely to have positive effect on fur seal populations. However, this scenario could be balanced by the reported increase in fur seal populations around the SE Australia, where food web modelling suggest a decline in redbait biomass, due to greater predation mortality (Goldsworthy et al. 2003).

Key points:

- The small pelagic species in SE Australia are at intermediate trophic positions in each respective pelagic ecosystem and they underpin populations of larger pelagic fish, seabirds and some marine mammals.
- Some of these predators are generalist feeders (e.g. gannets, adult crested terns), with the ability to shift their diet composition of small pelagic species according to spatial and temporal variation in relative abundances of prey.
- However, the need to consume highly nutritious food, such as sardines, at key stages in their life history (e.g. crested tern chicks) is believed to be beneficial for the survival of chicks, and so any substantial changes to the population sizes of sardines could influence the population of crested terns.
- The interaction between redbait biomass (as controlled by oceanographic conditions and hence climate change), and fur seals numbers has been demonstrated through food web modelling.

12.7. Additional multiple stressors

Effects of fishing: The apparent decrease in the population size of jack mackerel off the east coast of Tasmania during the late 1980s and early 1990s was probably a combination of high fishing pressure and climate induced changes in population structure (Lyle et al. 2000). Since the early 2000s, the sardine, blue mackerel and redbait fisheries in SE Australia have now been managed by TACCs, based on harvested levels of less than 20% of the estimated spawning biomass (see fisheries summaries in this report).

Mortality events: The two large mortality events on sardines throughout Australia in 1995 and 1998, apparently caused by a novel virus (Whittington, 1998), resulted in 70% of the adult sardine population dying (Ward et al. 2001). However, recovery in the population off South Australia was relatively rapid, due to the favourable upwelling conditions (Ward et al. 2006).

12.8. Critical gaps and levels of uncertainty

- We are currently unable to distinguish between jack mackerel and yellowtail scad eggs.
- There is a need for long-term data on egg and larval abundances, or age structure representative of entire population for each species. The best long-term data set is for sardines.
- Although there is some information on the relationship between water temperatures and the egg hatching rates, there is limited information on growth rates of larvae in relation to water temperature. Information on temperature tolerance ranges for egg and larval survival for most of the species.
- Much of our current understanding has been dependent on information gleaned from short term funded projects, and there should be greater emphasis on longer term funded projects.

Table 12.3: Summary of small pelagics species assessment, which also indicates level of certainty of the associated information. Level of certainty is divided into high (H) = strong clear evidence, backed by several studies with solid datasets with little confounding interactions; medium (M) = evidence supported by one or more studies, conclusions may be partially ambiguous or confounded; low (L) = anecdotal evidence, limited data and/or predicted conclusions based on theoretical knowledge.

Life history stage	Multiple stressors	Distribution	Habitat	Predators and prey	Current impacts	Predicted impacts	Ecosystem interactions	Data gaps
Eggs, larvae	Unknown		All pelagic – inshore and/or offshore (H), except blue sprat eggs, demersal (L)	Predators: unknown for eggs and larvae Prey (larvae): phytoplankton (sardines; M), unknown for other species	Unknown	Egg hatching rates temperature dependent for all species (H)	Unknown	Jack mackerel and yellowtail scad eggs morphologically indistinguishable, blue sprat eggs suspected to be demersal, however, unknown whether eggs are habitat generalistic or specific. Unknown temperature tolerences for eggs and larvae for all species (L)
Juveniles			Juveniles for most species, generally more inshore than adults (H)	Predators: Seabirds (terns, gannets), pelagic teleosts (M) Prey: Zooplankton	Unknown	Similar comments to adults	Unknown	

Adults	1. For all species, except blue sprats, there are targeted commercial fisheries, which are managed either by TACC's (sardines, jack mackerel, blue mackerel and red bait) or licence limitation (anchovies and sandy sprats in NSW, Vic; and yellowtail scad in NSW). Current exploitation rates for all species assessed as sustainable (M, H). 2. Large mortality events for sardines, caused by novel virus (H)	See distribution maps	All pelagic – inshore and/or offshore (H)	Predators: Pelagic sharks, and teleosts, marine mammals (incl. fur seals, dolphins), Seabirds (incl. gannets, terns)(H) Prey: zooplankton (copepods, euphausiids) (H)	Most small pelagic species have high reliance to climate change, because they are generalist planktonic feeders, have inshore and offshore distributions (anchovies), or adapted to waters of high temperatures /low productivity (EAC) (M)	Potential for increased production of sardines in GAB, driven by increased upwelling (M); Rigid spawning time for jack mackerel influences level of fat production, hence, egg production in following season (L), Also jack mackerel adapted to cooler waters, compared with other small pelagic species, and probably has low resilience to change (M).	Modelling indicates higher production of small pelagic species (sardines, redbait) may result in higher population sizes of marine mammals (M), however, the higher small pelagic production may be balanced by increased aggregation of marine mammals at key upwelling areas (M)	Uncertain whether age composition from the respective fisheries are representative of the entire population (M).

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12.9. References

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13. Snapper *Chrysophrys auratus*

Invalid synonyms: *Chrysophrys guttulatus, Chrysophrys major, Chrysophrys unicolour, Labrus auratus, Pagrosomus auratus, Pagrosomus major, Pagrus arthurius, Pagrus auratus, Pagrus chinensis, Pagrus guttulatus, Pagrus latus, Pagrus micropterus, Pagrus rubber, Pagrus unicolour, Sciaena lata, Sparosomus unicolour, Sparus auratus*

Author: Neil Hutchinson

13.1. The fishery

Snapper is an important commercial and recreational species in all states in south-eastern Australia and while several stocks exist in Australian water, there is some overlap between the distributions of individual populations (Kailola et al. 1993; Fowler 2000) (Figure 13.1). For example, while there are distinct stocks to the east and west of Wilsons Promontory, Victoria and a division of stocks between Victoria and South Australia (SA) (Fowler 2000) there is little genetic differentiation between the populations.

Victoria

Snapper recruit to the Victorian fishery at three years of age (~27 cm TL), with large adults caught commercially mainly with long lines, while juveniles and smaller adults are caught mainly with haul seine nets (Hamer and Jenkins 2007).

While a decline of ~75% was recorded in commercial Victorian snapper catches in the 1980s to 1990s from ~200–49 tonnes (Hamer and Jenkins 2007), snapper is currently the fourth highest valued commercial finfish species in Victoria with a total catch of 113 t per $806,000 in 2007–08. Snapper is also one of the most popular recreational species making up 75% of the overall catch in the state (Hutchinson et al. 2010), with recreational catches in 2003 of 332.4 t (Henry and Lyle 2003). Port Phillip Bay catches make up 80% of the commercial and 60% of the recreational catch (DPI 2008).

Since the 1990s, the commercial catch has doubled, but is still considerably lower than catches in the 1970s (Hutchinson et al. 2010), due in part to decreases in commercial fishing effort during the 1990s (Coutin et al. 2003). The recreational catch in Victoria mainly includes smaller and younger fish than the commercial fishery and is more directly affected by episodic recruitment (Coutin et al. 2003).

Recreational catches are also high in other states: 116,967 kg (New South Wales), 309,031 kg (Queensland), 370,554 kg (SA), 292,554 kg (Western Australia), 950 kg (Tasmania) (Henry and Lyle 2003).

South Australia

The state of South Australia now makes the most significant contribution to the national catch of snapper (Anon 2009), having exceeded the catch of Western Australia (WA) for the first time in 2006–07. In 2005–06, South Australia's contribution to the national catch was 29.8%, which increased to 36.5% in 2006–07 and to 41.3% in 2007–08. In 2008–09, the statewide commercial catch was 780 t with an estimated landed value of $5.6 million (Knight and Tsolos 2010). The commercial catch is predominantly taken with handlines and longlines since fishing for snapper with haul nets was prohibited in 1993 (Fowler et al. 2010). Snapper are captured throughout all of South Australia's coastal waters; however, historically Spencer Gulf has contributed the bulk of the catches. Nevertheless, its significance has decreased in recent years as the contributions of regional fisheries in Gulf St Vincent and the south-east of the state have increased considerably.

Snapper is also a favourite target species of the recreational sector with many fishers chasing the large 'trophy' fish. In 2007–08, the estimated recreational catch was 177.7 t (Jones 2009), which accounted for 19.3% of the total catch in that year. Recreational fishers are restricted to rod and line fishing and their catches are restricted by a minimum size limit of 38 cm TL, and bag and boat limits that vary regionally.

Tasmania

Snapper is highly valued as a recreational species although only relatively low numbers are caught by fishers in Tasmanian waters.

Commonwealth

Snapper is a by-product species in the Commonwealth with an average annual catch over the last five years of 125 t. Snapper is managed in the Commonwealth under offshore constitutional arrangements with the state governments.

Key points:

- Snapper is an important commercial and recreational species.
- In 2008–09, combined commercial catch was 1247 tonnes.

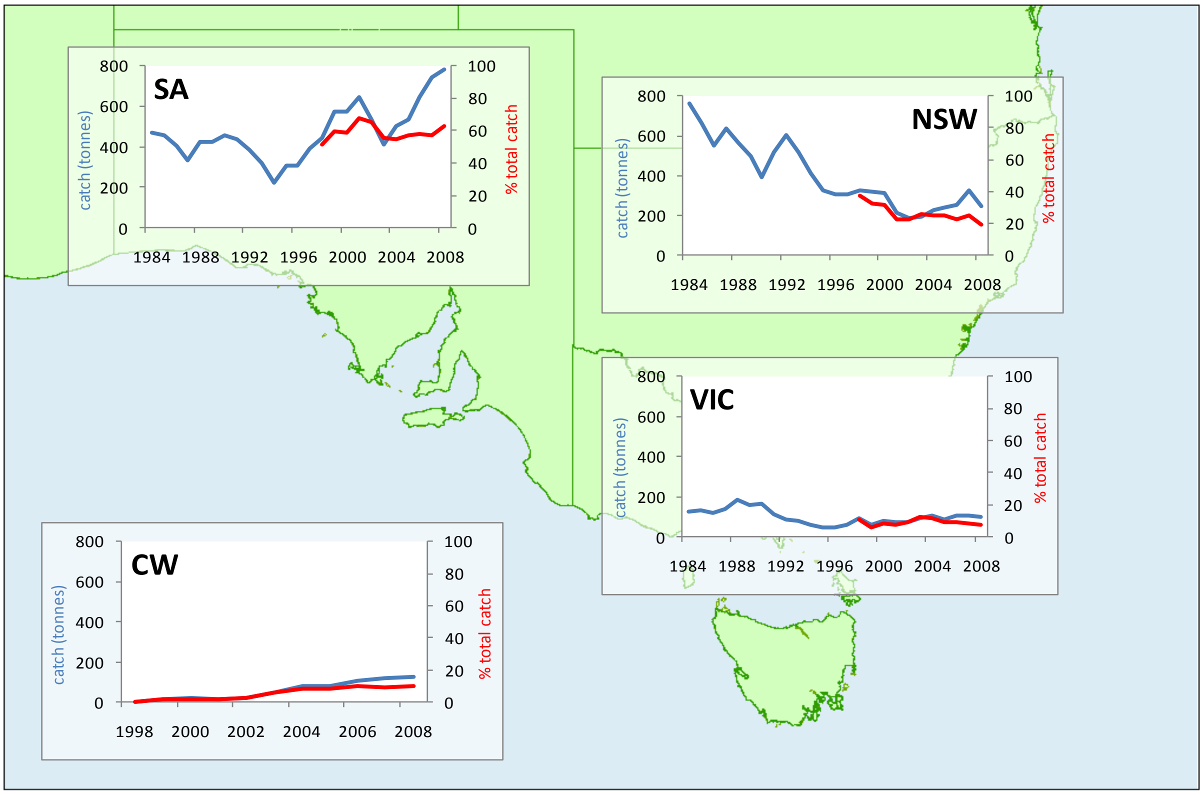

Figure 13.1: Commercial catch (tonnes) and contribution by each jurisdiction to total catch in south-east Australia (%) by year for Commonwealth, Victoria, NSW and SA.

13.2. Life history

13.2.1. Life cycle, age and growth

Snapper are a long-lived demersal/semi-pelagic species which can live up to at least 40 years in Australia (Hamer and Jenkins 2007) and have been recorded to live at least 60 years in New Zealand (Francis et al. 1992), with adults reaching up to 1.3 m (20 kg) (Gomon et al. 2008).

Snapper are serial spawners (Crossland 1977a; b; Fowler 2000) that reach sexual maturity at 3–5 yrs (20–30 cm fork length (FL)) (Francis and Pankhurst 1988) and can spawn repetitively during extended periods of up to 3–4 months (Aquaculture SA 2003), spawning daily in some areas (Fowler 2000). They spawn in coastal waters as well as in semi-enclosed, sheltered bays and gulfs throughout their range (Figure 13.2).

Adults form spawning aggregations at depths of <50 m (Kailola et al. 1993) and spawning is generally thought to occur once surface water temperatures reach ~18°C, although this varies throughout the species range; for example, in Shark Bay (WA) spawning occurs at temperatures of ~21°C and in Japan occurs between 15 and 22°C (Sanders 1975; Aquaculture SA 2003). It should be noted that although the Japanese population and the population found in southern Australia are thought to be different species (Tabata and Taniguchi 2000), physiologically they are almost identical and in the remainder of this report no distinction will be made between them. The timing of spawning therefore varies considerably within the species range with spawning in southern areas of Australia from October to March, with peaks in December (Coutin et al. 2003) and in northern areas from May/June to August (Kailola et al. 1993). Spawning occurs at dawn and during the evening/night (Aquaculture SA 2003), close to the water surface (Sanders 1975; MacDonald 1982) over a period of 30–60 minutes (Sanders 1975). Spherical eggs, approximately 0.7 – 1 mm in size are produced (Neira 1998; Aquaculture SA 2003) which are buoyant and drift for several days with currents prior to hatching (Kailola et al. 1993; Coutin 2000). Hatching occurs ~1–2 days after fertilisation depending on water temperature (Cassie 1955; Fowler 2000; Aquaculture SA 2003) and the planktonic larvae develop over <20–30 days (Fowler and Jennings 2003). Juveniles become demersal at ~ 1 month (Tanaka 1985; Fowler 2000) and individuals <1 year (<15 cm) tend to become closely associated with soft sediments.

After 12 months of age they are often found associated with soft sediments, reefs, algae and seagrass (Kailola et al. 1993; Gillanders 2002a; Fowler and Jennings 2003; Hamer and Jenkins 2007). Movement patterns of older juveniles and adults vary throughout the species range and with size; although in Victoria and NSW they tend to move from sheltered bays to coastal and offshore waters. In SA, settlement of new recruits occurs into muddy areas in northern Spencer Gulf.

Eventually, as they grow and develop the juvenile fish aggregate and become associated with structure on the sea bed. Eventually some fish of several years of age may undertake significant movements, leaving the vicinity of the nursery areas and moving to other regional waters (Fowler et al. 2005).

Evidence suggests that all fish initially develop as females, some of which undergo sex inversion at the juvenile stage in their second to fourth year, resulting in a certain degree of functional gonochrism in populations (Francis and Pankhurst 1988; Aquaculture SA 2003). In South Australia, estimates of batch fecundity vary linearly with fish size and weight, although with considerable variation between years (Saunders 2009). Estimates of batch fecundity range from 12,750 eggs for a 293 cm caudal fork length (CFL) fish to 1,100,282 eggs for one that was 922 cm CFL (Fowler unpublished data). Only a small proportion of eggs develop into hydrated oocytes (Coutin 2000); e.g., 35cm females produce ~10,000 oocytes while 60 cm individuals produce ~100,000 (Crossland 1977a; Coutin 2000). Increases in batch fecundity are also apparent with age; e.g., at seven years, fish in Victoria produce ~153,000 hydrated oocytes while at 14 years they produce ~469,000 (Coutin et al. 2003). Studies on cultured individuals, however, suggest that older fish may undergo senescence, producing eggs that are less viable in comparison with younger fish and may become reproductively inactive at ~15 years (Fowler 2000).

Growth rates of the species vary considerably both between states and at small within-state scales (Sanders and Powell 1979; Jackson 2007), potentially due to differences in habitat type, prey availability and other environmental factors such as temperature (Francis and Winstanley 1989; Aquaculture SA 2003; Jackson 2007). Studies in Shark Bay have found significant variation at fine spatial scales in the maximum age, growth, age at maturity and spawning time of snapper (Jackson 2007) and such differences can also be seen between states, with the onset of maturity at ~28 cm in SA (Kailola et al. 1993), three years in NSW (~30 cm FL) and four years in Victoria (~27 cm TL) with 50% maturity in Victoria at 42 cm (TL) (MacDonald 1982).

In South Australia, there is considerable variation in the estimates of size at age between different regions. Growth rates tend to be fastest in the northern gulfs. However, in the southern regions the catches include considerable numbers of relatively old, stunted fish that are small for their age. These include fish that are only marginally over the minimum legal size, but which are ten years of age or greater (Fowler unpublished data).

Victoria

In Victoria, snapper are generally sexual mature by ~5 years (42.2 cm) (Coutin et al. 2003) and while the degree to which snapper spawn in coastal areas of Victoria is unknown, it is likely to be more common in the eastern stock because adult snapper are largely restricted to coastal waters in this region.

Snapper move into bays to spawn during spring and summer when water temperatures increase and are known to aggregate in specific areas, such as eastern Port Phillip Bay where planktonic larvae have been collected (Jenkins 1986; Acevedo et al. 2008; Acevedo et al. 2009). The eastern stock appears to spawn during summer, and adults from the western stock move into Port Phillip Bay from coastal areas from October–December, and the majority are thought to leave again from April–June, although some may become resident either inside the bay or in coastal areas (Hamer and Jenkins 2007). Studies of otolith microchemistry indicate that the western stock is mostly replenished from spawning and juvenile recruitment within Port Phillip Bay, while the eastern stock is replenished from spawning in coastal waters off eastern Victorian and NSW (Hamer and Jenkins 2007). The East Australian Current is also likely to be important in supplying larvae spawned in NSW waters to nursery areas in east Victorian estuaries (Hamer and Jenkins 2007).

New South Wales

Snapper are known to migrate from Victorian estuaries to NSW, but the importance of this cross border migration to replenishment of the NSW fishery is unclear (Coutin et al. 2003).

South Australia

Between mid to late November and early February, snapper in northern Spencer Gulf form large spawning aggregations, and once water temperature reaches approximately 18°C spawning commences (Saunders 2009). This process may be delayed in more southern regions. Mature fish with active gonads can be caught throughout all of South Australia's coastal waters, suggesting that all regions; i.e. inside and outside the gulfs, contribute to egg production.

There are anecdotal reports of large schools of snapper that move up through the gulfs in October and November to join spawning aggregations. However, the proportional contribution of such fish to the numbers at the aggregations relative to local fish that have only moved a short distance to the aggregation site is unknown.

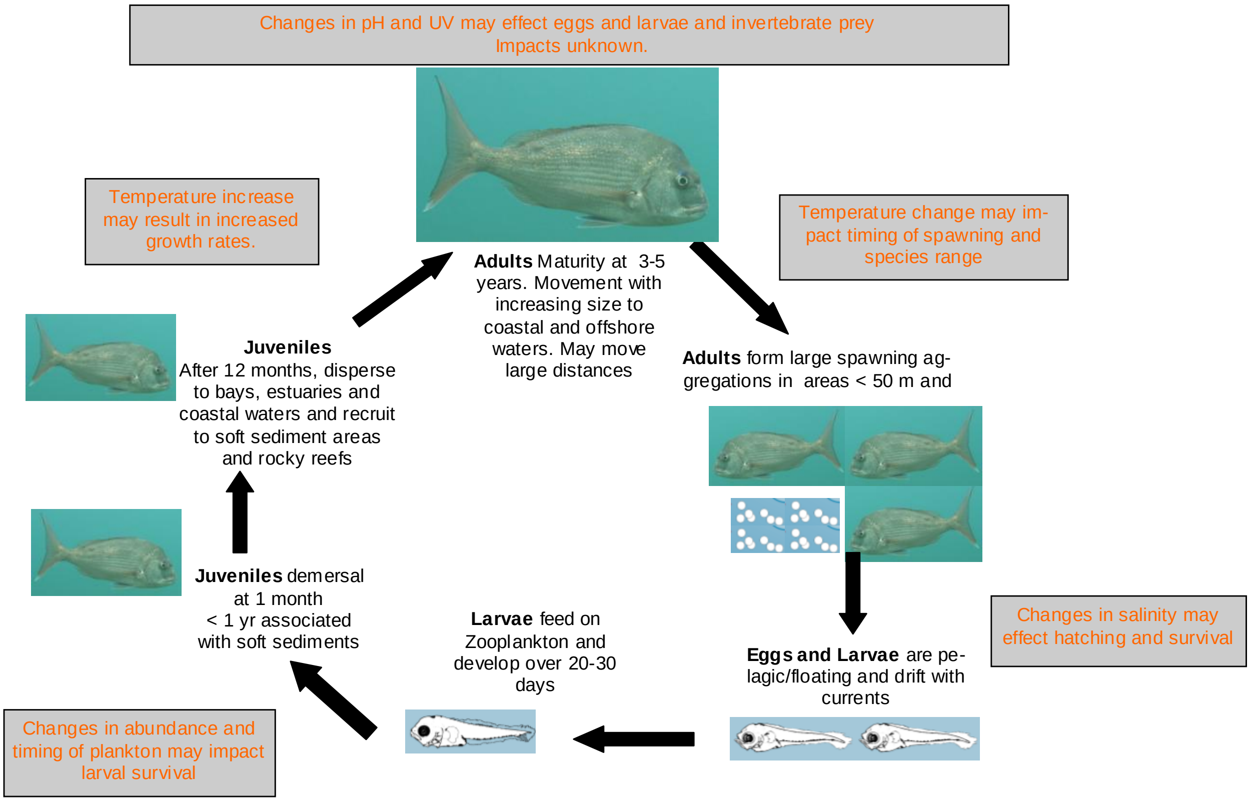

Figure 13.2: Summary of life cycle (this section), and points of exposure to relevant climate change drivers or known impacts (subsequent sections).

13.2.2. Distribution, habitat and environmental preferences

In Australia, snapper are found from Hinchinbrook Island (Queensland) to Barrow Island (WA) and also occur off the northern coast of Tasmania (Kailola et al. 1993) (Figure 13.3). The species is also found throughout the Indo-Pacific from New Zealand to Japan, and in the waters of several countries including the Philippines, India and Indonesia (Paulin 1990; Kailola et al. 1993).

Snapper is a demersal species distributed from shallow bays and inlets to the edge of the continental shelf (Kailola et al. 1993). Juveniles are demersal and are associated with bare soft sediments, reefs and macroalgae within bays. Adults are also demersal and can also be found associated with these types of habitat both within bays and in coastal areas (Hutchinson et al. 2010). Snapper are found at depths down to 200 m (MacDonald 1982), but in some areas are most common at depths < 50 m (Paul 1976; Francis 1993).

Zero-age (i.e. less than one year) fish in Japan, New Zealand and northern Spencer Gulf in SA have been shown to be strongly associated with fine sediments in areas with low current regimes, redistributing themselves at older juveniles (Fowler 2000), and distributions in WA have been found to be closely correlated with latitude and depth (Jackson et al. 2007). Juveniles have been shown to occur in high densities in association with soft sediments, and are most abundant where small surface features exist, such as depressions, burrows and small rocks (Thrush et al. 2002). Older juveniles are also commonly found in association with rocky reefs (Kingett and Choat 1981).

While early research found no relationship between the distribution of juvenile snapper in relation to complex habitats (Azeta et al. 1980; Kingett and Choat 1981; Sudo et al. 1983; Omori 1984; Kiso 1985), the distribution of juveniles associated with sediments is known to vary temporally at spatial scales <1 km (Francis 1995), and it has been suggested that they may prefer muddy substratum over mixed sediment substrata (Francis 1995). Patterns of distribution are, however, not governed solely by micro-habitat type. Small-scale distribution patterns and the behaviour of juveniles can be influenced by a combination of the distribution of predators and habitat type, with higher use of complex habitats that provide shelter when predators are in the area (Ross et al. 2007). Juveniles may occur over soft sediments adjacent to reefs because these areas allow them to access food resources found in sediments as well as areas that provide refuge from potential predators (Ross et al. 2007).

Snapper show distinct patterns of movement over diurnal and tidal periods (Hartill et al. 2003). For example, snapper of ~17–38 cm TL have been shown to move from deep channels to shallow areas at night (Hartill et al. 2003) when activity levels are known to be low (Hartill et al. 2003; Morrison and Carbines 2006). Snapper can show high levels of site fidelity over the short term in areas characterised by soft sediments or rocky reefs (Willis et al. 2001; Hartill et al. 2003).

Victoria

Victoria has distinct western and eastern stocks which are geographically divided around Wilsons Promontory (Sanders 1974; Coutin 2000). The western stock tends to spawn within bays, particularly Port Phillip Bay, while the eastern stock spawns in coastal areas (Hamer and Jenkins 2007; Hutchinson et al. 2010), and while some snapper <2 years old in coastal areas of western Victoria appear to originate from coastal waters, age classes of three years and older are dominated by those originating from Port Phillip Bay (PPB), indicative of high rates of emigration of juvenile snapper out of PPB to populate coastal waters (Hamer and Jenkins 2007). Various tagging studies have shown that snapper from PPB may move large distances; e.g., to Kingston (SA), between PPB and Western Port and that there is a high degree of movement between the bay and coastal waters (Coutin et al. 2003), while individuals tagged and released at Mallacoota have been shown to move to southern Queensland (Sanders 1974).

Major nursery grounds in Port Phillip Bay where juveniles 0-age to age 1 are usually found in depths of 10–20 m include Point Wilson, Hobsons Bay, and the eastern side of the bay between Beaumaris and Mornington (Hamer and Jenkins 2004). Areas outside the bay where 0-age snapper have been found include Corner Inlet/Nooramunga, Gippsland Lakes, the Snowy River estuary, Mallacoota Inlet and Western Port Bay (Hamer and Jenkins 2004). The occurrence of 0-age life stages in coastal waters remains poorly known (Hamer and Jenkins 2007). As they grow, juveniles from Port Phillip Bay disperse into coastal areas where they are common on inshore coastal reefs, returning as adults to spawn (Hamer et al. 2006). The proportion of adults from coastal waters that migrate into Port Phillip Bay during the spring/summer to spawn is unknown.

South Australia

Our understanding of the movement behaviour of snapper in South Australian waters is incomplete, but nevertheless so far suggests that it is quite complex. Tagging studies done in the 1970s and 1980s identified two types of movement (Jones 1981; 1984). Some fish were recaptured close to where they were tagged, even several years later and were identified as 'residents'. Another smaller number of fish were recaptured up to several hundred kilometres from their tag sites and were called 'migrants'. These were characterised more by smaller fish than large ones. The life history model, based on these types of fish, suggests that the majority of fish remain resident in their regions of residence, whilst a lower proportion is migratory (McGlennon and Jones 1997). The latter are thought to leave the nursery areas in the northern gulfs, move southwards, leave the gulfs and then migrate to the continental shelf. From there, it is suggested they make annual spawning migrations over a number of years back into the gulfs until they eventually cease this migratory existence and become permanent residents in the northern gulfs. Thus, this life history model suggests that migratory fish form a mixed-age population on the continental shelf that is derived originally from age-related migration from different regions.

There is another complexity to the issue of fish movement; i.e. where do fish that inhabit the different regions originate from as 0+ fish. Some data, based on otolith chemistry analysis, suggest that all fish in the South Australian fishery originated from only one or two nursery areas from where they dispersed to different regions at the ages of 3–5 years (Fowler et al. 2005). They then became residents of the regions to which they had dispersed, after which there was minimal subsequent movement. The otolith chemistry study suggests that the SA population of snapper is a single, large stock, in which the individuals have a common origin, but through age-related emigration ultimately disperse and supplement the sparser populations in regional state waters.

Western Australia

Snapper tend to be restricted to specific areas and several separate populations exist in Shark Bay (Johnson et al. 1986; Moran et al. 1999) (Kailola et al. 1993; Moran et al. 2003) and adjacent areas including Eastern Gulf, Denham Sound and Freycinet (Jackson 2007). Such patterns of restricted movement have also been noted elsewhere in the species range (Parsons et al. 2003; Sumpton et al. 2003). Analysis of egg and larval data in conjunction with hydrodynamic modelling indicate that eggs and larvae are retained in local eddies that occur in relation to spawning areas in Shark Bay (Jackson 2007). This information, together with that provided from tagging and otolith chemistry studies, show that movement of juveniles and adults is limited (Jackson 2007). There are, however, individuals that make annual spawning migrations from deep coastal areas to the inner bay (Moran et al. 2003). A thorough examination of the distribution of eggs and spawning individuals was undertaken in Cockburn Sound (Wakefield 2006), showing that the spawning period was extended in comparison to populations closer to Perth, and both males and females reached sexual maturity at a smaller size in the Cockburn Sound.

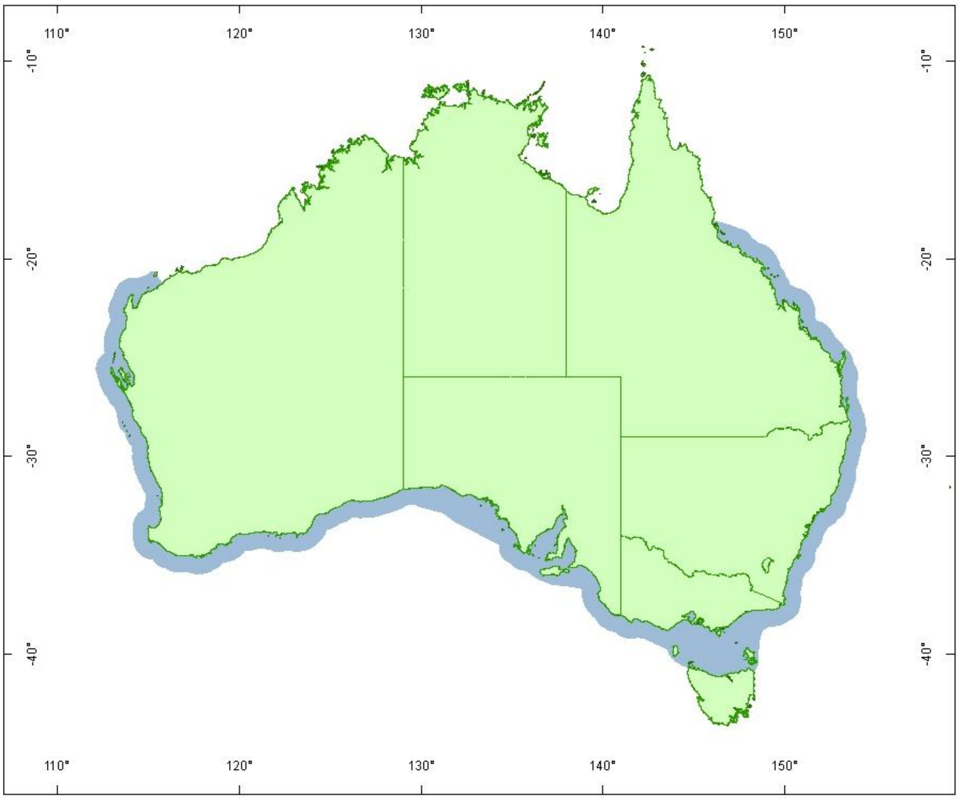

Figure 13.3: Map detailing distribution of snapper.

13.2.3. *Predators and prey*

Predators

Predators of snapper potentially include John Dory (*Zeus faber*), kingfish (*Seriola lalandi*), Australian salmon (*Arripis trutta*), scorpionfish (*Scorpaena papillosa*), sharks (e.g. *Carcharhinus brachyurus, C. obscurus*) and seals and dolphins that are known to associated with spawning aggregations or habitats where snapper are found (Kailola et al. 1993; Coutin 2000; Ross et al. 2007).

Prey

The mouth of **larvae** opens after 2–3 days (Sanders 1975) at which point they start to feed on phytoplankton (including diatoms and Dinoflagellates) and a range of zooplankton.

Juveniles feed on grapsid crabs, isopods, ostracods, amphipods, polychaete worms, small fish and molluscs (Kingett and Choat 1981; Kailola et al. 1993; Langlois et al. 2006). The distribution of juveniles has been found to be more heavily dependent on the distribution and abundance of food than topographic habitat complexity (Kingett and Choat 1981). In Japan, juveniles may follow a gradient of copepod abundance to nursery grounds where they their diet begins to include amphipods (Tanaka 1985).

Large juveniles and adults are generalist predators (MacDonald 1982) that feed on a variety of prey depending on the habitat where they occur which may include rocky reefs and soft sediments; e.g., (Colman 1972; Choat and Kingett 1982). For example, those associated with reefs and soft sediments in Port Phillip Bay (Victoria) have a diet that includes molluscs, crustaceans and small fish (Winstanley 1983; Parry et al. 1995), while in South Australia, juveniles and small adults feed on western king prawns and larger adults on blue swimmer crabs, mussels etc. (Kailola et al. 1993). The species is also known to feed on sea urchins present in urchin barrens (Shears and Russell 2002). Snapper feed predominantly during daylight hours, with peak feeding activity during early morning and late afternoon (MacDonald 1982). There are no apparent differences in diet between males and females.

13.2.4. Recruitment

Bays and estuaries provide important habitat for snapper from the larval settlement phase and act as nurseries for juveniles during the first two years (Gillanders 2002b; Thrush et al. 2002; Sumpton and Jackson 2005); for example, in Victoria 0+ snapper are found in Port Phillip Bay, Western Port Bay, Gippsland Lakes, Corner Inlet, Snowy Estuary and Mallacoota Inlet (Hamer and Jenkins 2004).

Recruitment levels have been shown to correspond with temperature in some parts of the species range (Fowler and Jennings 2003). For example, in New Zealand, strong year classes correspond to warm years and weak classes to cooler years (Francis 1993; Francis et al. 1997; Zeldis et al. 2005), although this may be linked to variability in prey at these times with availability affected by currents (Zeldis et al. 2005). Juvenile recruitment in Port Phillip Bay also varies strongly between years, by as much as 10-fold (Hamer and Jenkins 2004; Hamer and Jenkins 2007) and recruitment variability may be linked with temperatures during the spawning season (Coutin 2000; Hamer and Jenkins 2004) where there is a positive relationship between higher water temperatures and high recruitment the following year. Recent work, however, has shown that relationships between recruitment and water temperature tend to break-down over time (A. Fowler pers. comm., Jenkins 2010).

In South Australia, recruitment rates are highly temporally variable but spatially consistent. A recruitment survey undertaken in northern Spencer Gulf every year between 2000 and 2010 has demonstrated that the same areas consistently produce the highest catches of 0+ snapper. These are located along the north-western coast of the gulf, in areas that support a flat, muddy substratum. Recruitment rates varied between years by approximately 100 times (Fowler and Jennings 2003; Saunders 2009; Fowler et al. 2010). There is no relationship between the average summer water temperature and recruitment rates, suggesting that recruitment is not simply the direct consequence of the influence of water temperature on the physiological development and survival of the eggs and larvae.

Key points:

- Bays and estuaries provide important spawning and nursery habitats.
- Recruitment is highly variable from year to year.
- Environmental influences on recruitment variation likely to vary regionally and are poorly known.

13.3. Current impacts of climate change

Current impacts of climate change are largely unknown for this species and while a range of potential climate drivers may currently be of risk, high levels of uncertainty are associated with these risks, particularly in the impacts of climate change on the larval stages of this species.

Snapper have increased in abundance in the north and east coasts of Tasmania and populations appear to be shifting further south (Last et al. unpublished data), which is believed to be a function of increases in water temperature along the east coast of Tasmania.

Key points:

- Little is known about current impacts.
- Snapper appears to be increasing in abundance and range in Tasmania.

13.4. Sensitivity to change

Spawning and larval periods vary with water temperature (Francis 1994) and successful hatching and larval development can be influenced by temperature and salinity.

Water temperature influences the timing of egg hatching, e.g., eggs hatch after four days at 18°C, three days at 21°C and can hatch at temperatures up to 31°C (Coutin 2000). This species has been successfully cultured in Japan for several decades (Sanders 1975) and more recently in Australia (Fielder et al. 2001; Aquaculture SA 2003). Snapper culture has been carried out in water temperatures of 13–28°C, with optimum growth at 20–28°C. At <20°C food consumption declines and stops at <10°C, with mortality at <4°C (Sanders 1975; Aquaculture SA 2003). While increased water temperatures result in enhanced growth, feeding becomes less frequent and fish health deteriorates at > 29°C (Aquaculture SA 2003).

Laboratory studies on the similar species found in Japan have found that while hatching can occur from ~14–31°C, the highest hatching rates occur from 14.5 – 21°C and optimal temperatures for larval survival are ~19–25°C (Apostolopoulos 1976; Mihelakakis and Yoshimatsu 1998). Viable larvae have been found to occur in salinities of 12–48 ppt with hatching occurring from ~ 10–50 ppt (Mihelakakis and Yoshimatsu 1998).

While this species can withstand oxygen concentrations as low as 1.5 ppm, feeding rates decrease at <3.5 ppm (Aquaculture SA 2003). In addition, juvenile snapper are sensitive to potassium concentrations, and a reduction of potassium from 21 ppt as found in coastal seawater can be detrimental to development and growth (Fielder et al. 2001).

Snapper eggs only float in water that has a specific gravity of >1.023 (MacDonald 1982); i.e., they sink where salinities are less than ~30 ppt (Mihelakakis and Yoshimatsu 1998).

In South Australia, recruitment is highly variable between years, which is presumably related to egg and larval survivorship. Whilst most successful recruitment has resulted from spawning that occurred when water temperatures were between 22 and 24°C, there were many days when the water temperature was within this range and spawning did occur, but it did not lead to successful recruitment (Fowler and Jennings 2003; Saunders 2009). That there are physical environmental conditions that are associated with successful spawning suggests the involvement of physiological tolerances for the eggs and larvae. Nevertheless, there must also be other factors, as yet unidentified, which determine whether spawning will lead to successful recruitment of 0+ fish.

Key points:

- Snapper is able to tolerate a relatively wide range of physical conditions at different life stages.
- Egg development and larval survival is dependent on salinity and oxygen concentrations.

13.5. Resilience to change

Snapper occur over a relatively wide latitudinal range and the species is therefore able to survive over a relatively wide temperature range as well as exhibiting a wide salinity tolerance. Predicted increases in temperature are therefore unlikely to affect the species in much of its range, but may open up new habitat in the south of its range, such as southern Tasmania.

- As this species spawns at night and its larval stage is short, exposure to potential increases in UV are likely to be limited and higher water temperatures may lead to faster growth and increased recruitment

- Predicted increases in storm surges, sea level, desiccation etc. may lead to loss of vegetation in areas and an increase in soft-sediment areas that are preferred by the species. Conversely, loss of vegetation would reduce primary production from benthic plants and could negatively affect snapper feeding.

- Storm surges may increase levels of primary productivity, which would be beneficial to the larval stages of the species that consume plankton. Althernatively though, lower overall rainfall may lead to reduced levels of primary productivity in SE Australia (Jenkins 2010).

Key points:

- Snapper is relatively long lived and highly fecund.
- It has a wide geographical range and is therefore likely to adapt well to changes in conditions.
- Snapper is a generalist; it is likely to be able to adapt to changes in prey species.
- The range of the species may expand with climate change.

13.6. Ecosystem level interactions

Snapper are known to feed on sea urchins (as do lobsters) from urchin barriers and can therefore have a top-down effect on community structure that may be impacted by overfishing (Shears and Russell 2002).

Since ~1990, deep areas of Port Phillip Bay, Victoria where snapper settle have been impacted by the introduction of pest species and further threatened by pollution (Hamer et al. 2005b) and there may be some additive impact of these factors and the high exploitation rates of juveniles in the bay (Hamer et al. 2005b). Furthermore, detailed understanding of trophic dependencies of snapper of across all life stages is clearly lacking at a regional or stock scale. In areas where both key spawning aggregations and juvenile nursery areas co-occur, such as Port Phillip Bay, ecosystem changes pose significant risks to long-term fisheries productivity.

Key points:

- Snapper can have a top-down effect on community structure.
- A range of factors including overfishing of prey species, pollution, climate change and exotic species may impact key food sources for snapper.
- Research on snapper ecology and trophic dependencies should be focussed on critical areas where spawning aggregations and juvenile nursery areas occur.

13.7. Additional (multiple) stressors

This fish forms large predictable spawning aggregations and is therefore sensitive to overfishing on aggregations (Mackie et al. 2009).

Key point:

- Sensitive to overfishing on spawning aggregations

13.8. Critical data gaps and level of uncertainty

- While areas where spawning aggregations form have been identified for some populations, information on key environmental and habitat conditions required for successful egg production and spawning is generally limited. The role of variable environmental conditions or the availability of food in influencing individual egg production is unknown. Poor adult condition leading into and during the spawning season could impact on overall egg production levels and subsequent juvenile recruitment. The influence of environmental conditions on production of zooplankton prey for larvae is also poorly understood (Jenkins 2010).
- While research on otolith chemistry in Victoria (Hamer et al. 2005a) has demonstrated significant movement of juveniles and young adults out of bays to populate coastal waters over a broad scale, a greater understanding of the migratory dynamics of adults of this species between key bays, gulfs and coastal waters is required. The lack of knowledge of movement and migration patterns of the species in some areas hampers the ability to understand causes of local population fluctuations. Furthermore, poor understanding of the proportions of coastal snapper that participate in heavily fished annual spawning aggregations within bays and gulfs is important for improving sustainable management of spawning aggregation fisheries.
- Variability in recruitment largely drives the population dynamics for this species. However, as yet there remains only a poor understanding of why recruitment varies so much from year to year. Although it is likely that water temperature is involved to some extent, there are also other influences that may be associated with the physical environmental characteristics that are not yet understood.
- Snapper is increasing in abundance in Tasmania and populations appear to be shifting southward. It will be important to examine the potential effects of this relatively new species on the existing ecosystem and reef-based fisheries. To understand how they may compete with existing species it would be essential to determine the source of snapper (i.e. Victoria or Tasmania), their habitat utilidation, and diet.

Key points:

- There is a lack of knowledge of key habitat, environmental and food conditions essential for maximising spawning output and larval survival.
- There is limited knowledge of adult migratory dynamics between bays and gulfs and coastal waters for some populations.

Table 13.1: Summary of snapper species profile, which also indicates level of certainty of the associated information. Level of certainty is divided into high (H) = strong clear evidence, backed by several studies with solid datasets with little confounding interactions; medium (M) = evidence supported by one or more studies, conclusions may be partially ambiguous or confounded; low (L) = anecdotal evidence, limited data and/or predicted conclusions based on theoretical knowledge.

Life history stage	Multiple stressors	Distribution	Habitat	Predators and prey	Current impacts	Predicted impacts	Ecosystem interactions	Data gaps
Eggs	Salinity, temperature and oxygen concentrations (H)	See map 1 (L)	Surface waters (H)		Little known	Changes in temperature etc may increase the southerly range of the species (L)	Top-down effects on community structure, e.g., feed on sea urchins (M), Introduced species may affect habitat structure (L)	Habitat conditions essential for spawning and larval survival Movement patterns of all life-stages in some areas
Larvae			Pelagic (H)	Predators: other fish, benthic predators (L) Prey: Plankton (M)				
Juveniles		See map 2 (H)	Estuaries, bays, inlets, open coast, soft sediment, rocky reef (H)	Predators: Large fish, seals etc (H) Prey: Ontogenetic shift from small sediment associated invertebrates, e.g., molluscs, crustaceans, polychaetes, small fish to larger prey of similar types associated with reefs and sediments (H)				
Pre-spawning adult	Exploited, 1247 tonnes caught commercially each year, fishery is stable (H)							
Post-spawning adult								

13.9. References

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14. Southern bluefin tuna *Thunnus maccoyii*

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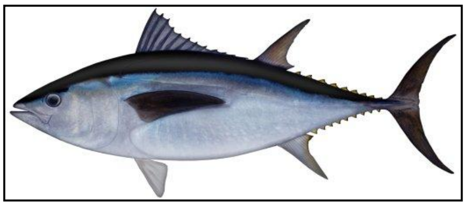

14.1. The fishery

Southern bluefin tuna (SBT) is a highly migratory species fished throughout its range. It is targeted by fishing fleets from a number of nations, both on the high seas and within the exclusive economic zones of Australia, New Zealand and Indonesia. Japan, Australia, New Zealand, the Republic of Korea, the Fishing Entity of Taiwan, South Africa and Indonesia account for the large majority of the catch. From 1985 the three main nations fishing for SBT, Japan, Australia and New Zealand, began to apply quotas. In 1994, these voluntary arrangements were formalised with the signing of the Convention for the Conservation of Southern Bluefin Tuna (CCSBT). Since then the CCSBT has managed the fishery internationally. Australia is a founding member of the CCSBT and is active in this Regional Fishery Management Organisation. Australia's international obligations under the convention are implemented through the *Southern Bluefin Tuna Management Plan 1995*.

At its sixteenth annual meeting in 2009, the CCSBT agreed that the status of the SBT stock was of concern and that a meaningful reduction in the total allowable catch (TAC) was necessary in order to recover the stock and work toward reaching an interim rebuilding target reference point of 20% of the original spawning stock.

The Southern Bluefin Tuna Fishery (SBTF) in Australia is managed through a system of output controls in the form of individually transferable quotas which are allocated as statutory fishing rights (SFRs) under the Southern Bluefin Tuna Management Plan 1995. Prior to the commencement of each season (1 December to 30 November) AFMA determines a total allowable catch (TAC) of SBT for the domestic fishery based upon Australia's national allocation from the CCSBT. Each SFR entitles the holder to receive an equal portion of the TAC set by AFMA for this period.

The AFMA Commission met on 30 October 2009 and agreed to set a single total TAC of 8030 tonnes for the next two years, and industry subsequently advised AFMA that it would target to catch a maximum 4015 tonnes in 2009–10.

Australian operators predominantly use purse seine nets to target surface schools of SBT. Fish are often located with fish-spotting aircraft, or from a crow's nest aboard a purse seine or pole vessel. Because specific schools of fish are targeted, the purse seine method is generally size and species selective. The vast majority of SBT caught in purse seines are taken from the Great Australian Bight, with fish targeted between the ages of one and four years, but predominantly two- to three-year-old fish. These juvenile SBT are subsequently towed back to sea pontoons off Port Lincoln and then grown out and harvested largely for the sashimi tuna market in Japan. The high prices obtained for SBT encourage targeted fishing, even when stock levels and catch rates are very low. Approximately 96% of Australia's total catch of SBT is taken by purse seiners operating in conjunction with the SBT farming sector.

SBT are also partly taken incidentally by pelagic longline vessels operating in the Eastern Tuna and Billfish Fishery (ETBF) and the Western Tuna and Billfish Fishery (WTBF), with this representing approximately 4% of the total catch by Australia. In 2009 some fish were taken by poling and purse seine on the east coast.

Juvenile SBT are targeted in the Great Australian Bight by Australian purse seiners, which predominantly take two- to three-year-old fish with small numbers of one- and four-year-old fish. Throughout the rest of its range, SBT is targeted by pelagic longliners, including domestic longliners operating along Australia's east coast. Longliners harvest all ages, from juveniles about three years old (~100 cm fork length; 20 kg whole weight) through to adults (12+ years old).

Catch rates have been relatively stable over the last 10 years, with approximately 5000 t caught each year by the Commonwealth (Figure 14.1). Approximate Australian dollar values for the SBT fishery (financial years) were 2006–07 \$42.4 million, 2007–08 \$44.6 million, 2008–09 \$45.3 million. Total gross value of production including the value added by ranching was (calendar years) 2007: \$142.3million and 2008: \$186.7million.

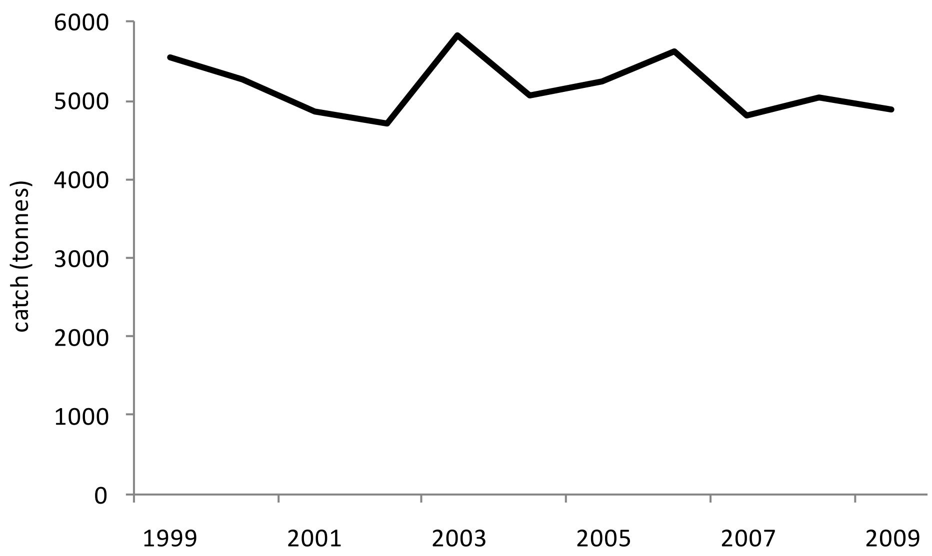

Figure 14.1: Commercial catch (tonnes) of wild SBT by year for the Commonwealth.

Key points:

- 96% of SBT catch is from the Great Australian Bight in conjunction with the SBT farming sector.
- In 2008–09 the combined wild catch was 5240 tonnes.
- SBT farming considerably increases the value of this catch.

14.2. Life history

14.2.1. *Life cycle, age and growth*

Southern bluefin tuna (SBT) constitutes a single, highly migratory stock that migrates throughout the temperate, southern oceans. Very young fish (aged 1–4 years) move from the single known spawning ground, in the north-east Indian Ocean (10–20°S, 105–120°E), into the Australian Fishing Zone and southwards along the Western Australian coast. It is not known how often mature fish spawn. SBT are broadcast spawners. The spawning season lasts from September to April.

SBT mature somewhere between eight and 14 years of age and live to over 40 years. The mean size at maturity is estimated to be around 150–160 cm (Campbell, 1994). Mature fish can reach 200 cm and can weigh 200 kg. Two-year-old fish range from 46 to 56 cm, eight-year-olds 125 to 137 cm and 14-year-olds 157 to 175 cm. SBT appear to grow faster during summer and early autumn, probably in response to warmer surface waters. The number of 0.5 – 1 mm diameter eggs produced in a spawning period has been estimated to be 14–15 million for a 158 cm female.

SBT larvae are restricted to the mixed layer during both the day and night when there is a strong thermocline. Larvae are not restricted to the mixed layer when the thermocline is weak, but they are rarely found below 35 m (Davis et al. 1990).

It is thought that rapid growth occurs in the late larval-juvenile stage, rather than the early larval stage. The pattern of growth in juveniles changes during their transition from juveniles to sub-adults.

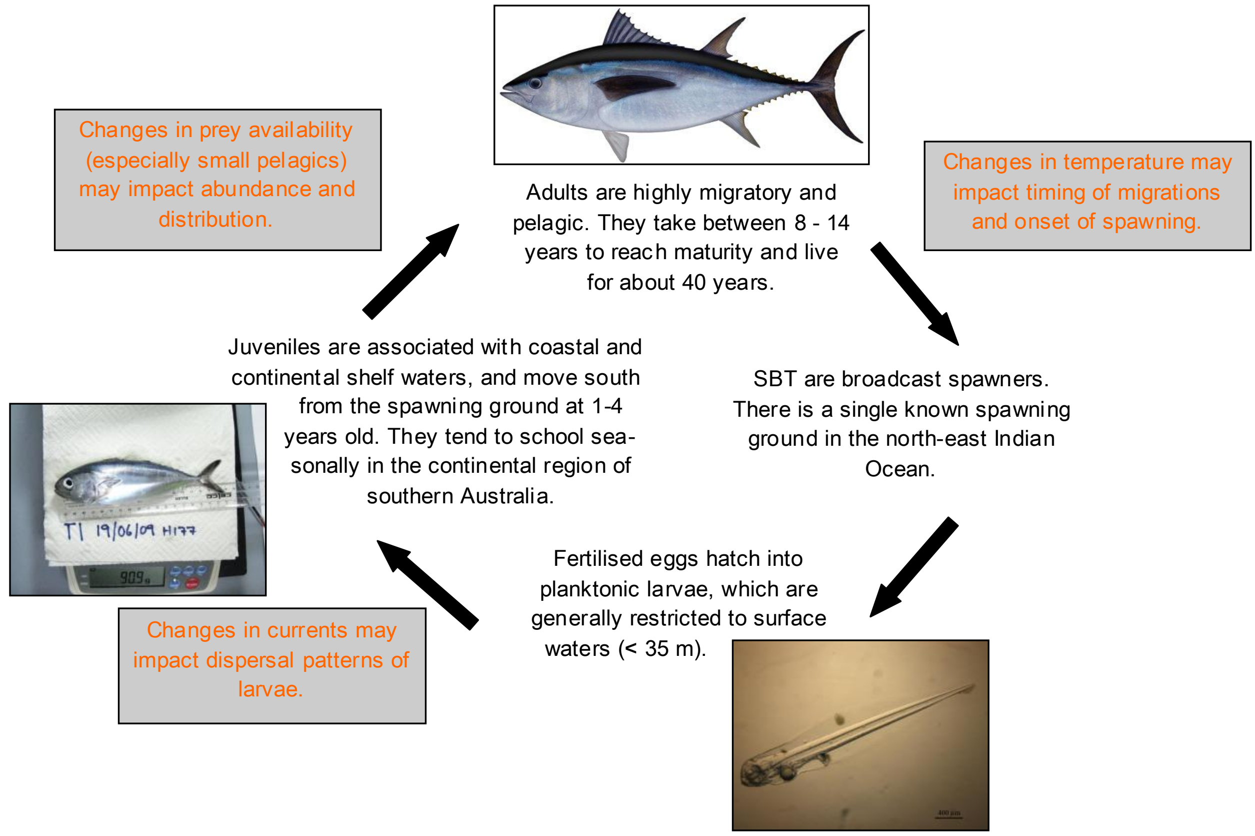

Figure 14.2: Summary of life cycle of SBT (this section), and points of exposure to relevant climate change drivers or known impacts (subsequent sections). Images of larva and juvenile: Emily Mantilla (Seafood CRC, Clean Seas Tuna Ltd).

14.2.2. *Distribution, habitat and environmental preferences*

The distribution of SBT is thought to be circum-global between 30° and 50° S, although they spawn further north, between 10° and 20°S. In Australia waters, SBT range from northern NSW, south around the continent to north-western Australia (Figure 14.3). They are a highly migratory pelagic fish. Young fish are generally closely associated with coastal and continental shelf waters. Surface-schooling juveniles are found seasonally in the continental-shelf region of southern Australia. The fraction of the juvenile stock that migrates into this area is not known, but some immature fish move south and west into pelagic waters from three years of age.

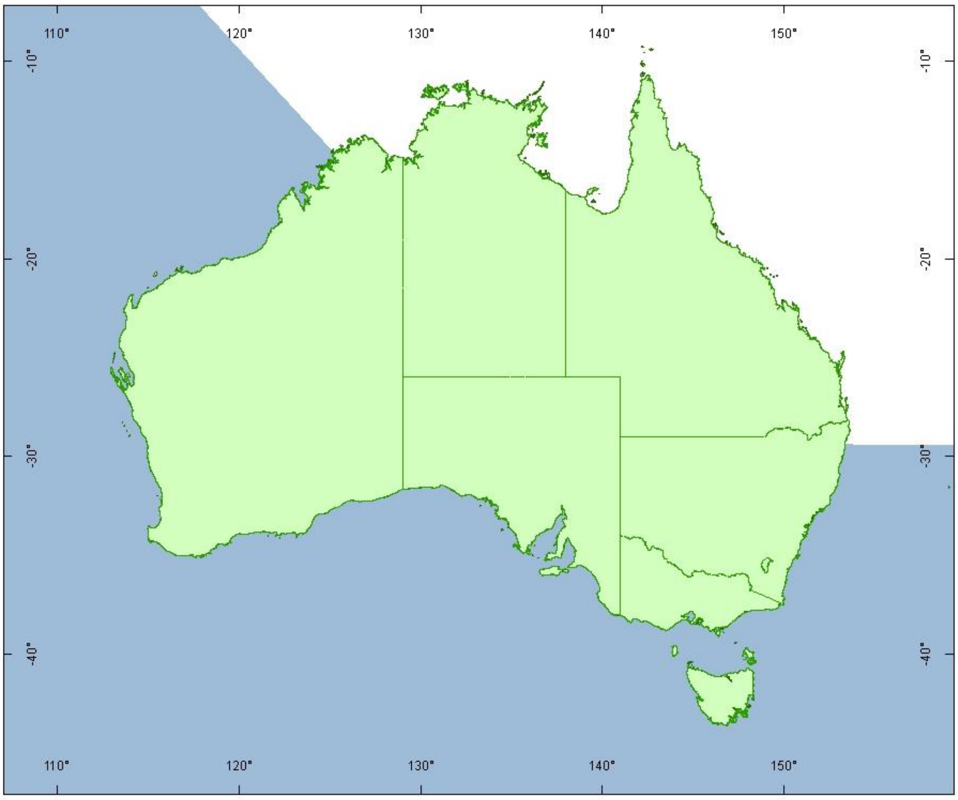

Figure 14.3: Map detailing distribution of southern bluefin tuna.

14.2.3. Predators and prey

Juvenile and adult SBT are opportunistic feeders, chiefly of cephalopods, crustaceans, fish (especially anchovies, pilchards and mackerel) and salps. Smaller SBT feed mainly on crustaceans and adults feed mainly on fish. Possible predators include sharks, other tunas and fish, seabirds and killer whales.

Crustacea (copepod nauplii, calanoids, cyclopoids and cladocerans) are the main prey items of SBT larvae. SBT larvae have been observed to affect the abundance of zooplankton biomass, suggesting food may be limiting.

14.2.4. Recruitment

Juveniles move south away from the single known spawning ground, in the north-east Indian Ocean. Juveniles are resident along the shelf in the summer and migrate south during the winter. Juveniles are capable of very extensive movements; e.g. from South Australian waters to east of South Africa within a few months.

Key points:

- SBT are a highly migratory pelagic fish.
- Surface-schooling juveniles are found seasonally in the continental-shelf region of southern Australia and in coastal waters.
- SBT are distributed throughout southern Australia and in spawning grounds of the north-west coast of Western Australia.
- The single known spawning ground is in the north-east Indian Ocean.

14.3. Current impacts of climate change

No increase in productivity has been observed in tropical Australia and no major changes in productivity are predicted for tropical Australia under most climate change scenarios. The impact of climate change on the winter SBT feeding grounds in the Southern Ocean may be more dramatic than those in temperate coastal Australia waters.

Key point:

- No evidence of current impacts on SBT

14.4. Sensitivity to change

Changes to water temperature are likely to have the greatest impact on distribution of SBT, with a likely southward movement of suitable habitat as temperatures warm on the east and west coasts. SBT are restricted to the cooler waters south of the East Australian Current and range further north when the current contracts up the New South Wales coast (Hobday et al. 2009).

Variation in the availability of prey (sardines and anchovies) may affect the distribution and abundance of SBT. Increased strength of south-easterly winds during summer and autumn is likely to increase seasonal upwelling along southern coast between the head of the Great Australia Bight (GAB) and western Victoria. Upwelling regions in southern Australia are important foraging grounds for SBT. If upwelling becomes more intense, this could lead to an increase in the production of small pelagic fishes. Increased pelagic productivity and sardine abundance off southern Australia could be beneficial for the southern bluefin tuna that aggregate each year in feeding grounds of the central GAB.

Key point:

- Changes to water temperature could result in changes to SBT distribution.

14.5. Resilience to change

SBT are a highly migratory pelagic species and hence theoretically have the capacity to move to different areas if conditions change and hence alter their distribution to maintain an optimal environment.

Key point:

- SBT are highly migratory and pelagic, potentially increasing the species' resilience to changing environmental conditions.

14.6. Ecosystem level interactions

Variation in the availability of prey (sardines and anchovies) may affect the distribution and abundance of SBT. Increased strength of south-easterly winds during summer and autumn is likely to increase seasonal upwelling along southern coast between the head of the Great Australia Bight (GAB) and western Victoria. Upwelling regions in southern Australia are important foraging grounds for SBT. If upwelling becomes more intense, this could lead to an increase in the production of small pelagic fishes. Increased pelagic productivity and sardine abundance off southern Australia could be beneficial for the SBT that aggregate each year in feeding grounds of the central GAB.

Key point:

- Increased upwelling could result in greater prey availability between the head of the Great Australia Bight (GAB) and western Victoria.

14.7. Additional (multiple) stressors

SBT are heavily exploited in Australian and international waters which may place additional stress on the population, and decrease resilience to environmental perturbations. SBT are thought to be at very low biomass levels, compared to historical population levels, with little indication of rebuilding. SBT is classified as being overfished.

Key point:

- SBT are heavily exploited in Australian and international waters.

14.8. Critical data gaps and level of uncertainty

It is not known how often mature fish spawn. It is not known what fraction of the juvenile population moves continental-shelf region of southern Australia.

SBT larvae are hard to catch and difficult to identify.

Key points:

- No information on spawning frequency of mature fish.
- Unknown what proportion of juvenile population schools in the continental shelf region of Southern Australia.

Table 14.1: Summary of southern bluefin tuna species profile, which also indicates level of certainty of the associated information. Level of certainty is divided into high (H) = strong clear evidence, backed by several studies with solid datasets with little confounding interactions; medium (M) = evidence supported by one or more studies, conclusions may be partially ambiguous or confounded; low (L) = anecdotal evidence, limited data and/or predicted conclusions based on theoretical knowledge.

Life history stage	Multiple stressors	Distribution	Habitat	Predators and prey	Current impacts	Predicted impacts	Ecosystem interactions	Data gaps
Eggs	Unknown	Single known spawning ground, in the north-east Indian Ocean (H)	Pelagic, offshore (M)		Unknown			Population size estimate Spawning frequency for adults Proportion of juveniles moving to southern Australian waters
Larvae				Prey: crustaceans				
Juveniles		Circum global distribution (H)	Surface-schooling juveniles are found seasonally in the continental-shelf region of southern Australia (M)	Predators: sharks, other tunas and fish, seabirds and killer whales (H) Prey: cephalopods, crustaceans, fish and salps (H)		Southward contraction of range (L) Possible impacts on winter feeding grounds (L)	Prey variability could be important (L)	
Adults	Exploited, 5000 t caught each year in the Commonwealth		Pelagic, offshore (H)					

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15. Southern calamari *Sepioteuthis australis*

Authors: Natalie Moltschaniwskyj, Michael Steer, Gretta Pecl, Zoe Doubleday

15.1. The fishery

The southern calamari is the most common squid species in southern Australian coastal waters and over the past three decades has contributed to multi-species marine fisheries in all southern Australian states, particularly South Australia and Tasmania. They are typically taken by commercial fishers in most shallow coastal bays using a variety of techniques. Most of the catch is landed using hand jigs and haul nets; however, purse seines, beach seines, gill nets, dab nets and spears are also used (Steer et al. 2007; Zeigler and Lyle 2009;). Trawlers targeting prawns in South Australia and demersal fish in New South Wales also incidentally catch calamari and are permitted sell it as by-product. Currently, calamari is sold on local and national markets and there has been little international export interest (ABARE 2009). Calamari are also a popular target for recreational fishers, a significant proportion of which fish from jetties, breakwaters and other shore-based platforms. In Tasmania, for example, approximately 44.6 tonnes were caught by recreational fishers in 2007–08 which accounted for 30% of the state's total catch (commercial and recreational) (Lyle et al. 2009).

Calamari catch typically peaks during spring and summer and coincides with the seasonal peak in spawning activity. Although calamari spawn throughout the year, they form large spawning aggregations during the warmer months which are subsequently targeted by both commercial and recreational fishers. Such targeted fishing practices have the capacity to compromise the sustainability of the resource and, as such, have resulted in strategic spatial and temporal closures of the fishery in Tasmania (Moltschaniwskyj et al. 2002). These closures allow spawning to occur uninterrupted and ensure a proportion of the population successfully spawns prior to being harvested (Moltschaniwskyj et al. 2002). Other state fisheries rely on other input controls, such as spatial and temporal gear restrictions. These measures are, however, more generic to their respective multi-species fisheries rather than being specific to calamari. South Australia has recently developed a means of forecasting recruitment strength in the inshore calamari fishery through quantifying the capture of sub-adults in the offshore prawn trawl fishery (Steer et al. 2007). This index, however, is yet to be integrated into the ongoing management of the resource.

Over the last 10 years, catch rates for both Victorian and Tasmanian fisheries have been relatively stable, with about 50–100 t harvested per year, while NSW catches have declined (Figure 15.1). With the exception of peaks in catch in 2000–01 and 2004–05,catch rates in SA have been relatively stable, with approximately 300–400 t caught per year since the early 1990s.

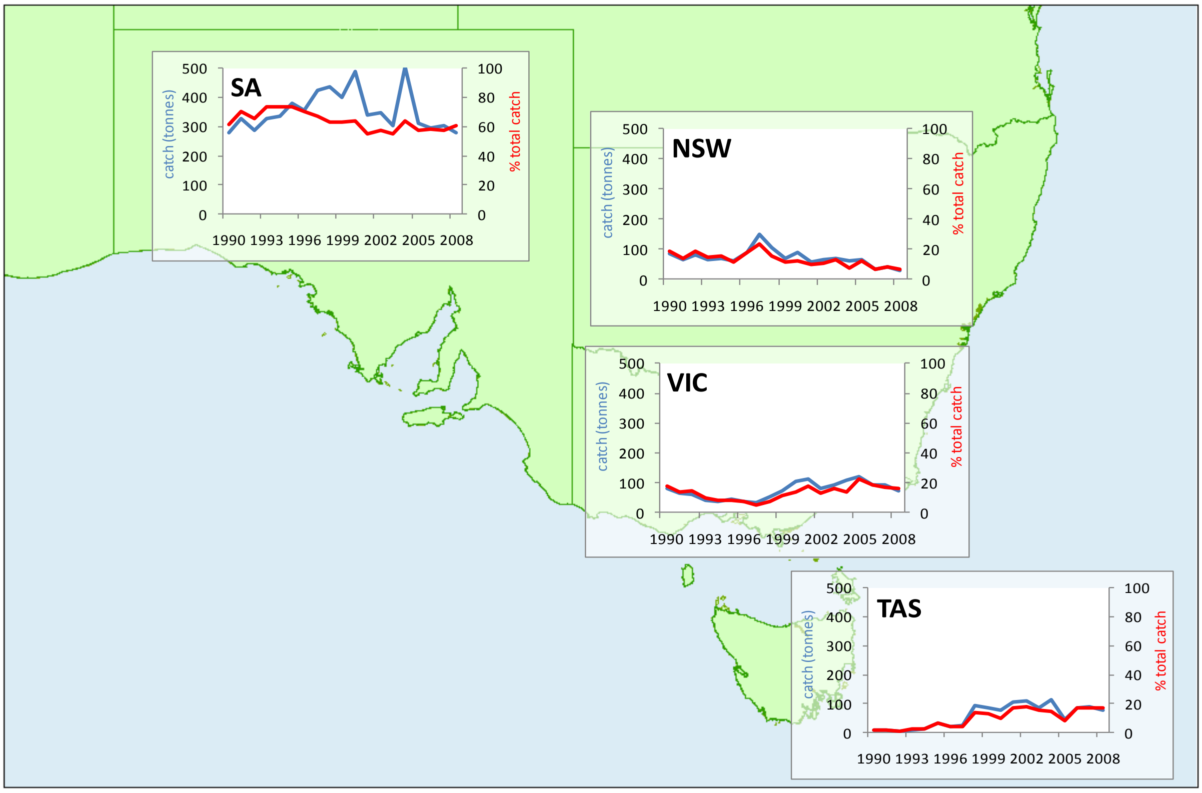

Figure 15.1: Commercial catch (tonnes) and contribution by each jurisdiction to total catch in south-east Australia (%) by year for South Australia, Victoria, New South Wales and Tasmania.

Key points:

- The largest commercial landings of calamari are in South Australia.
- Most catch is landed as a result of targeted fishing activity of spawning aggregations
- Important recreational fishery.
- Evidence of landings getting smaller over 2005–09 in some states.

15.2. Life history

15.2.1. *Life cycle, age and growth*

The calamari life cycle is rapid (approximately 12 months) and relatively simple (Figure 15.2). The sexes are separate and although courtship and mating is behaviourally complex and can last hours, the transfer of sperm from the male to the female is rapid (<2 seconds). Females store sperm within specialised membranes within their arm crown for extended periods and will mate multiple times with numerous males before fertilising and depositing the eggs. Females preferentially spawn in shallow, well protected bays, and attach their eggs to seagrasses and seaweeds (predominantly *Amphibolus antarctica*). Longitudinally aligned eggs (3–10) are encased within numerous mucous layers producing a relatively robust, finger-like egg strand. Each female deposits a series of egg strands over a period of hours, individually attaching each strand to a common holdfast, to form a discrete egg mass. Multiple females can contribute to an egg mass, increasing the size and density of the masses. Females spend as much as three months of their adult life in the spawning areas and will contribute to multiple egg masses throughout this period (Pecl el al. 2006).

Southern calamari do not have a true larval phase, instead they undergo direct embryonic development within well protected egg capsules to hatch as structurally and functionally adept 'miniature adults'. Embryo development is lengthy, taking 6–8 weeks, and upon hatching the juvenile is capable of inking, changing colour, hunting and avoiding predators. Embryos hatch at night and actively swim to the surface, reducing the risk of predation by visual predators. During the juvenile and sub-adult phase, individuals move to deeper waters to feed and grow, before moving back inshore to reproduce.

Growth rates of southern calamari are rapid and the pattern of growth is non-asymptotic, with individuals able to increase their body weight by as much as 8% per day. The recorded maximum ages are 275 days for males and 263 days for females (Pecl et al. 2004. Growth rates differ between the sexes, with males generally growing faster and attaining larger sizes. Growth rates are very variable and likely to respond to variation in temperature (Pecl et al. 2004), food availability, population density, and maturation. Females become reproductively mature as early as 117 days, 0.12 kg and 147 mm and males at 92 days, 0.06 kg and 104 mm mantle length (Pecl 2001).

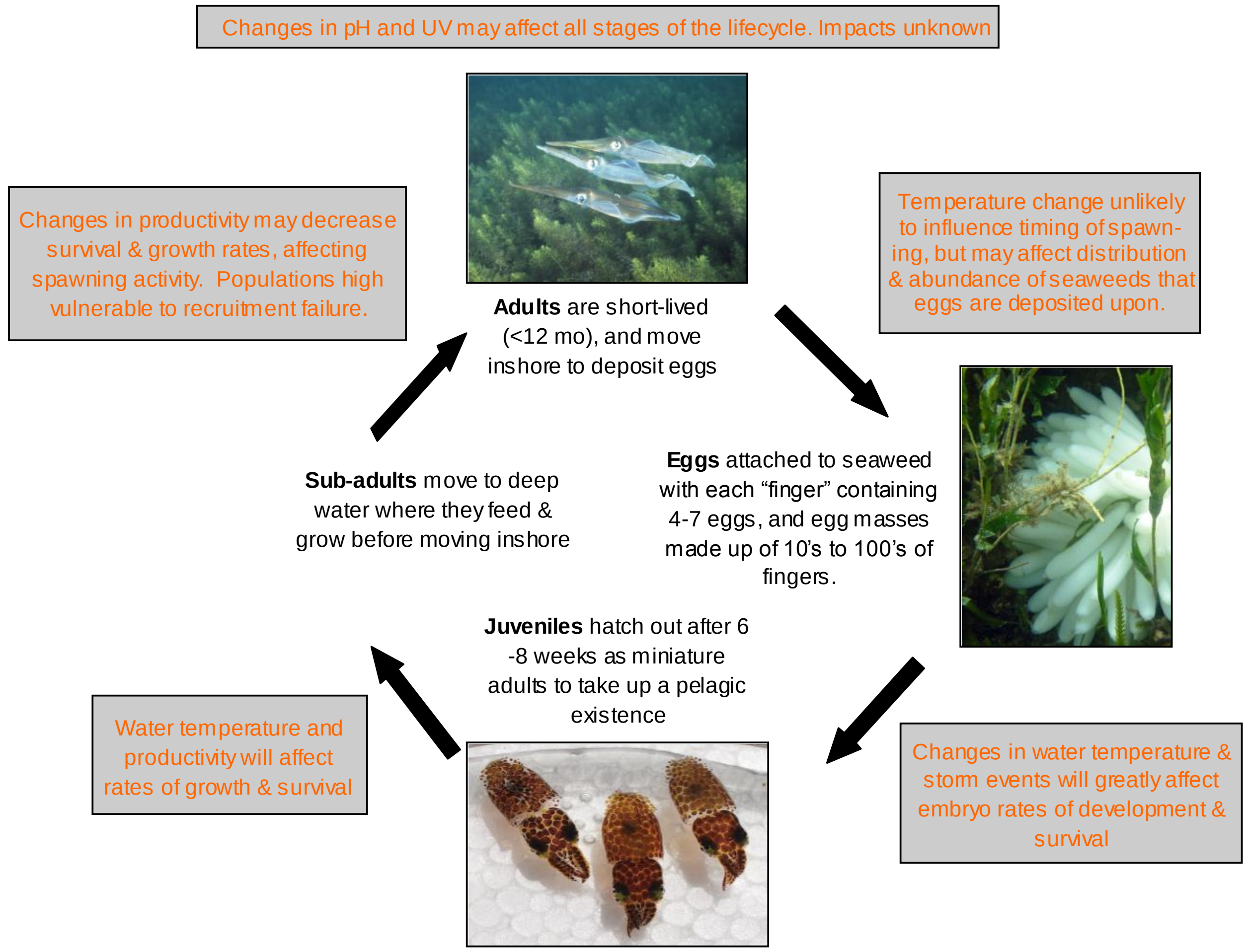

Figure 15.2: Summary of life cycle (this section), and points of exposure to relevant climate change drivers or known impacts (subsequent sections). (Photos provided by Troy Jantzen, Caroline Fisher, Natalie Moltschaniwskyj)

15.2.2. Distribution, habitat and environmental preferences

Southern calamari is endemic to southern Australia and northern New Zealand waters. In Australia it ranges from Dampier in Western Australia to Moreton Bay in Queensland, including Tasmania. It is an inshore species inhabiting coastal waters and bays usually in depths <70 m (Wistanley et al. 1983). Like most cephalopod species, southern calamari have limited capacity to tolerate low salinity conditions. The formation of statoliths (hard structures associated with balance and orientation) is sensitive to seawater composition and the absence of chemicals such as strontium can result in abnormal statolith formation leading to mortality (Hanlon et al. 1989).

Most egg deposition that has been observed and quantified occurs on the seagrass *Amphibolis tasmanica*, with relatively little use of other seagrass and macro-algae (e.g. *Posidonia* and *Sargassum*) as deposition substrate. Such a preference suggests that changes in the distribution and abundance of *A. tasmanica* may influence the spatial patterns of spawning and spawning behaviour (Moltschaniwskyj and Steer 2004). Calamari tend to form smaller, more ephemeral, spawning aggregations when *A. tasmanica* is widespread (e.g. Gulf St Vincent in South Australia; Steer et al. 2007) compared with the strongly aggregative behaviour where *A. tasmanica* forms discrete patches (e.g. east coast Tasmania; Moltschaniwskyj and Pecl 2003). Therefore, changes in spawning behaviour driven by spawning substrate may influence population distribution.

The distribution and abundance of adult calamari in South Australia's Gulf St Vincent conform to a seasonal, systematic pattern, where aggregations of spawning adults move anti-clockwise around the gulf, moving from the south-eastern corner of the gulf in spring to the western boundary in winter (Triantafillos 2001). Seasonal patterns in the prevailing winds and consequently water clarity have been suggested to drive this anti-clockwise progression as calamari are presumed to require clear water to successfully engage in their highly visual reproductive behaviour (Triantafillos 2001; Jantzen and Havenhand 2003). Retrospective investigation of wind strength and direction with calamari abundance (i.e. estimates of CPUE) within both Gulf St Vincent and the adjacent Spencer Gulf indicated that catches were generally low when winds have been strong and onshore, which are likely to create turbid conditions in shallow, inshore, waters (Steer et al. 2007).

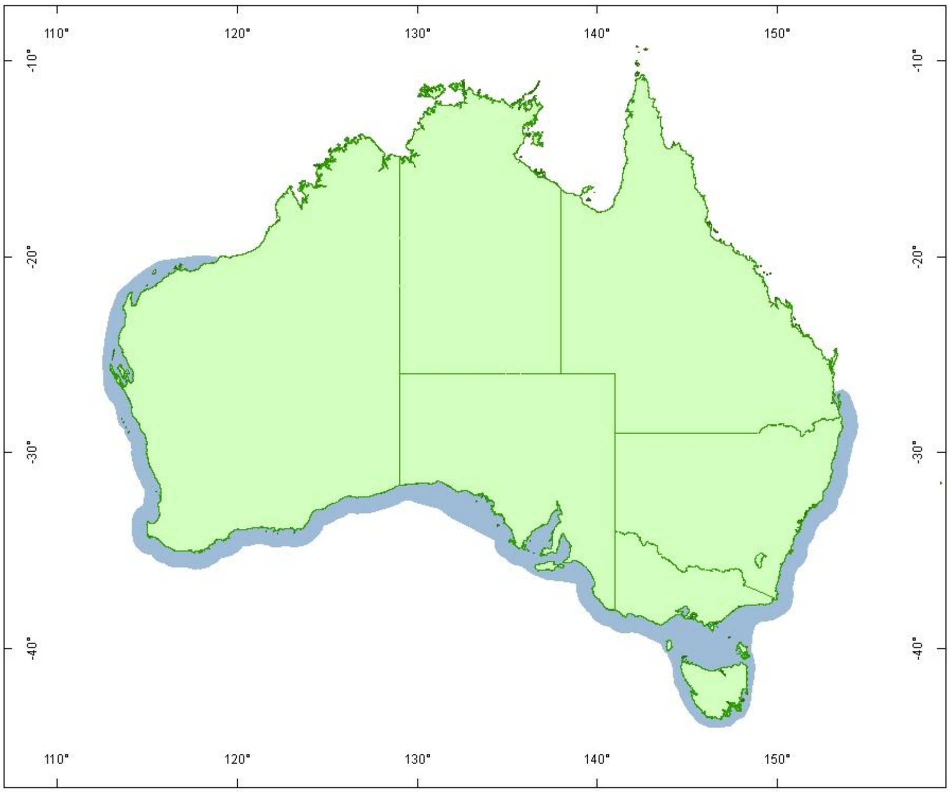

Figure 15.3: Distribution of southern calamari.

15.2.3. Predators and prey

Southern calamari, like many cephalopods, play a pivotal role in the ecosystem, as they play a large role both as predators and as prey. They are important prey items for marine mammals and seabirds, and predators of finfish and crustaceans.

Cephalopods are voracious generalist carnivores that are capable of capturing and consuming a broad size range of prey with their suckered arms and tentacles. This is in marked contrast to many fish species where the size of their prey is relatively narrow and limited to the gape of their mouths. A macroscopic analysis of the gut contents of 87 calamari collected as by-product from South Australia's commercial prawn trawlers indicated that fish were the dominant prey (63%), followed by crustaceans (27%) and cephalopods (9%) (Steer et al. 2005). Of those species that could be identified, the most frequently occurring were from the families Penaeidae (prawns), Platycephalidae (flathead), Carangidae (trevally), Engraulidae (anchovies) and Octopodidae (octopus).

15.2.4. Recruitment

The approximate annual life-span of southern calamari coupled with seasonal peaks in spawning activity means that the there is little generational overlap. Consequently, recruitment from one season to the next is highly variable and sensitive to the relative success of the previous spawning population. A spawning failure during the peak season, through either natural or anthropogenic factors, will significantly compromise subsequent recruitment. Catches of sub-adults as a by-catch of the prawn trawl fishery provide a useful index of recruitment in SA (Steer et al. 2007). However, for populations in other states there are no early indicators of population size or reproductive potential. There is evidence from statolith trace-element analysis that the east coast spawning sites of Tasmania are an important source of recruits for the broader east and south-east regions of the state (Pecl et al. in review).

Although, spawning failure during the peak season has the capacity to compromise the overall population, calamari have evolved a bet-hedging strategy to ensure that there is a constant supply of recuits by spawning at relatively consistent levels throughout the 'off season' (Jackson and Pecl 2004). This is quite literally a strategy where calamari do not 'put all their eggs into the one basket' but rather spread their mortality risk through space and time (Moltschaniwskyj and Steer 2004). This ensures that there will always be some individuals that experience favourable conditions and will be able to successfully reproduce. The timing, magnitude and success of recruitment resulting from the continual conveyor-belt of micro-cohorts will, however, still be contingent on the underlying variation in biological traits, such as relative growth rates, final body size, and fecundity.

Key points:

- Changes in the spatial patterns of seagrass species used as spawning substrates could affect spawning behaviour
- Changes in distribution and abundance would have a major affect on marine mammals that prey on southern calamari
- Changes in distribution and abundance could impact on inshore marine communities
- Difficult to estimate recruitment

15.3. Current impacts of climate change

Consistent declines in commercial catches in all states except for South Australia are evident, but the cause of decline is unclear. Changes in spawning activity on inshore seagrass habitats on the east coast of Tasmania over the past 10 years are coincident with the increase in water temperatures in this region. There is no evidence that southern calamari are undergoing range expansions, or that range extensions of other species have impacted on southern calamari. As seagrass and macroalgae are important spawning substrates for the southern calamari, there is the potential that changes in the spatial patterns of spawning may occur in concert with changes in these species.

Given that the size and structure of southern calamari populations fluctuates annually and it appears that environment is likely the underlying governing factor (Pecl et al. 2004), it is possible that the relative frequency of peaks and troughs in catch may change as a function of changes in water temperature, productivity, and storm frequency. Changes in temperature will affect survival, size at hatching and final size. A potential and quantified source of mortality for the embryos is dislodgement of eggs masses from the seagrass; losses of up to 54% of existing egg masses were lost following a storm (Moltschaniwskyj and Pecl 2003). The predicted increase in intensity and frequency of storm events associated with climate change may potentially increase the loss of eggs from the spawning grounds.

Embryonic development is very sensitive to water temperatures and monthly changes of 4°C typically experienced during a Tasmanian spring can result in development, taking 64% longer at cooler temperatures (Steer et al 2002). Furthermore, experimental manipulation of temperature resulted in a 13% increase in survival with a 3°C reduction in water temperature (Steer et al 2003). Exposure of embryos to periods of reduced salinity due to run-off has the capacity to reduce the growth rates of embryos by 40–50% (Villanueva et al. 2007). Such impacts of growth during the embryo phase will affect size at hatching with strong evidence of size-selective mortality determining adult population structure (Steer et al. 2003b).

Key point:

- There are declines in catch in most states but case is unclear.
- Changes in seagrass distribution would likely have a major effect on spawning.
- Massive egg losses can occur during storm events.

15.4. Sensitivity to change

Given the documented sensitivity of southern calamari life history characteristics to temperature including growth rates of adults, survival, body size, and fecundity, within the species' short-life span, it is expected that population characteristics will respond quickly to climate change. The influence of temperature on life-history processes of calamari is most evident during the early life-history stage. This is because the relative growth rate during the early development and juvenile stages are the most rapid and subtle changes to the growth trajectory early on will amplify throughout the rest of the lifespan (Pecl et al. 2004).

Although temperature has a direct affect on the duration of embryo development rates, it also affects the relative size of the hatchlings. Warmer temperatures accelerate embryo development and result in smaller hatchlings whereas cooler temperatures have the reciprocal effect (Steer et al. 2003a). These differences essentially provide the foundation to the relative success of the flow-on life-history processes. For example, hatchling size determines the relative chances of survival, as it has been found that natural mortality rates for calamari are size-mediated (Steer et al. 2003b). Furthermore, the resultant adult body size, arising from the initial early growth trajectory, may have reproductive ramifications, such as altered fecundity, reproductive potential, and sexual selection. Currently, the thermal tolerance of embryo development is unknown, but given any marked long-term, temperature changes in the current spawning areas, it is likely that calamari will seek more favourable environments and spawn in alternative areas.

Key points:

- Life history characteristics of southern calamari are highly responsive to temperature.
- A rapid response is expected because of short life span.

15.5. Resilience to change

The developing embryos may be the most vulnerable to short-term environmental changes as they are confined within sessile egg masses whereas the mobility of the juveniles and adults means that animals can move to areas where conditions can be tolerated. Furthermore, given the species' short life span and environmental plasticity in growth and reproduction, it is expected that southern calamari will be resilient and adaptable to thermal changes. However, this will depend on whether the populations can access sufficient, good quality, live protein sources. Warmer temperatures typically accelerate metabolic rates, and in turn individuals will be more energetically demanding and therefore any decline in the availability of food sources such as crustaceans and fish may be the most significant limiting factor (Pecl and Jackson 2008).

Key points:

- Mobility of juveniles and adults will allow populations to occupy preferred areas.
- Flexible life history characteristics should allow resilience to thermal changes.

15.6. Ecosystem level interactions

As most squid species are regarded as trophic opportunists (Pecl and Jackson 2008), including cannibalistic behaviour (Ibáñez and Key 2010), it is expected that southern calamari will respond quickly and positively to changes in community structure and species composition. This also means that changes in target prey could result changes in predator–prey relationships and unpredictable effects on inshore communities.

Reductions in calamari population size and/or distribution have the potential to affect predator populations, in particular local seals, dolphins and large teleosts. Given that squid are often viewed as an adaptable species that has life-history characteristics that should protect it from substantial and episodic, reductions in population size, there has been little consideration of the flow-on trophic impacts on higher order predators.

Key points:

- Southern calamari are potentially resilient to loss of prey items due to lack of prey specialisation.
- Changes in southern calamari distribution and abundance will affect teleost and marine mammal predators.

15.7. Additional (multiple) stressors

Fishing of both sub-adults and adults adds a level of mortality over an unknown and most probably highly variable amount of natural mortality. There is no evidence that fishing methods are sex-selective (Hibberd and Pecl 2007).

Key point:

- Exploitation may exacerbate impacts of climate change.

15.8. Critical data gaps and level of uncertainty

The short-life span and uncertainty about the processes affecting juveniles and sub-adults have resulted in a degree of uncertainty about the size of adult populations prior to them arriving onto the spawning grounds. Using the numbers of sub-adults caught as a by-catch in the South Australian prawn trawl industry provides a relative, but not absolute, measure of population size. This means that there may be only as much as two months' warning that populations are being affected by major environmental changes. The duration of this warning is obviously too short to detect any long-term changes in the environment, but may be useful in assessing the ramifications of short-term, pulse, climatic fluctuations.

There is anecdotal evidence that southern calamari use deep-water habitats as spawning sites; this may be positive with respect to uncertainty around changes in inshore habitats, but little is known about the successful development of the eggs and their recruitment potential. Furthermore, the magnitude of the effects of climate change on deepwater habitats is unclear.

Key points:

- The use of deep water habitats for spawning is unknown.
- Absolute size of adult population is unknown and hard to measure.
- Mortality rates of juveniles and sub-adults are unknown.

Table 15.1. Summary of southern calamari species profile, which also indicates level of certainty of the associated information. Level of certainty is divided into high (H) = strong clear evidence, backed by several studies with solid datasets with little confounding interactions; medium (M) = evidence supported by one or more studies, conclusions may be partially ambiguous or confounded; low (L) = anecdotal evidence, limited data and/or predicted conclusions based on theoretical knowledge.

Life history stage	Multiple stressors	Distribution	Habitat	Predators and prey	Current impacts	Predicted impacts	Ecosystem interactions	Data gaps
Eggs and embryos	Temperature and salinity effects quantified (H)	See Fig 1 (H)	Shallow seagrass and reef (M)	None (H)	Development rates and survival affected by temperature and salinity (H); loss due to storms (H)	Shorter development, but smaller at hatching (H)	None (H)	Population size Mortality rates of juveniles and subadults The use of deepwater habitats for spawning Capacity for population to recover following poor recruitment
Juveniles	Unknown		Unknown	Unknown	Unknown	Smaller animals increased mortality, small adults (H)	Unknown	
Pre-spawning adult	Caught as by-catch in trawl industry (H)		Deeper water >20m (M)	Unknown	Unknown		Reduction in prey; increase in predation	
Adults	Fished spawning aggregations ; fishing closures and permitting used; no landing controls (H)		Feed grounds in nearshore habitats (L); seagrass and reef habitats for spawning (M)	Carnivores (crustaceans, teleosts, and squid (M); preyed on by large teleosts and marine mammals (M)	Unknown	Fecundity reduced due to smaller body size and shorter life spans (H); changes in spatial pattern in spawning	Loss of spawning habitat (H); reduction in prey (M)	

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16. Southern garfish *Hyporhamphus melanochir*

Author: Tony Fowler

16.1. The fisheries

The southern garfish (*Hyporhamphus melanochir*) is a medium-sized, schooling pelagic species of halfbeak or garfish that is an important fishery species throughout the bays and inlets of southern Australia. Its schooling and pelagic nature make it particularly vulnerable to net fishing. Average annual production across SE Australia has been 466 tonnes over the past three years worth $3 million annually. However, there is not an even distribution of production across the three states as fishery production for garfish has consistently been highest in South Australia (SA) (Figure 16.1). In this state, the two main gears used by commercial fishers to target southern garfish are haul nets and dab nets, of which the former accounts for approximately 90% of the total catch (McGarvey et al. 2009). In Tasmania, garfish are also fished commercially using two types of gear. They are taken almost exclusively by beach seine on the north-east coast, but mainly by dip nets off the south-east and east coasts (Ziegler and Lyle 2009). In Victoria, they are taken by haul nets in Port Phillip Bay, Western Port and Corner Inlet (Knuckey et al. 2002).

In each state, the species is also targeted by recreational fishers. SA has generally produced the highest recreational catch, which over the past decade has accounted for approximately 20% of the total statewide catch (Table 16.1). Line fishing has been the dominant recreational fishing gear type (88.4% of the catch), whilst dab nets accounted for the remaining 11.6% (Jones 2009). In Victoria, the recreational catch also makes a considerable contribution to the total catch, whereas in Tasmania its proportional contribution is considerably less significant (Table 16.1).

Table 16.1. Comparison of southern garfish catches by the recreational and commercial sectors for South Australia, Victoria and Tasmania (Jones 2009, McGarvey et al. 2009, Henry and Lyle 2003, Lyle et al. 2009).

State	Year	Recreational catch (t)	Commercial catch (t)	% of total by recreational
SA	2000/01	124.6	496.9	20
	2007/08	74.8	290.1	20.5
Vic	2000/01	25.5	119	17.6
Tas	2000/01	2.3	81.4	2.7
	2007/08	2.0	51.0	3.7

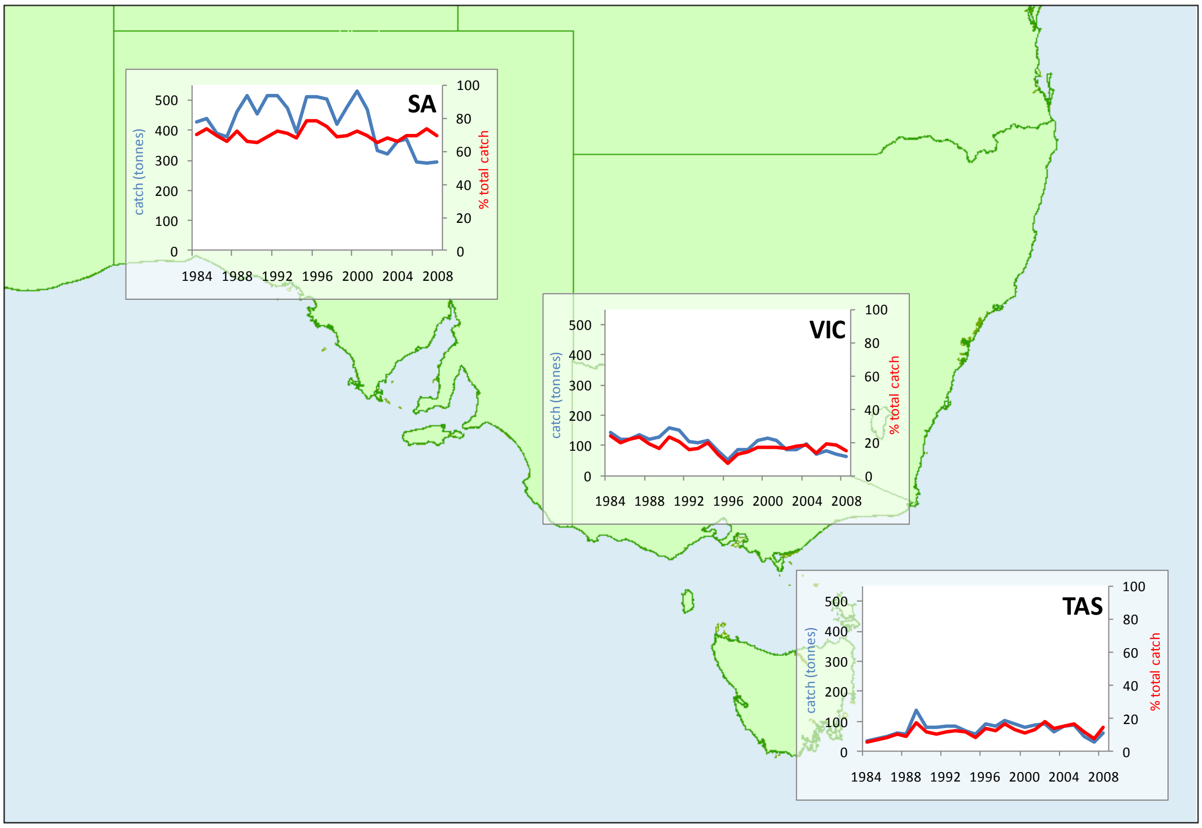

Figure 16.1. Commercial catch of southern garfish (tonnes) and contribution by each jurisdiction to total catch in south-east Australia (%) by year for South Australia, Victoria, and Tasmania.

Key points:

- Southern garfish are harvested by commercial and recreational fishing sectors in SA, Victoria and Tasmania.
- They are vulnerable to net fishing because of their schooling nature.
- The average total commercial catch has declined to 466 t per year, worth $3 million.

16.2. Life history

16.2.1. Life cycle, age and growth

Adult southern garfish are serial batch spawners that have asynchronous oocyte development (Ye et al. 2002c). Adult garfish have low batch fecundity, as consequence of the large size of the individual oocytes. In SA, the mean estimate of batch fecundity was 960 oocytes (Ye et al. 2002c), which is extremely low for a finfish species. Also, there is an extended spawning season from October to March. Southern garfish produce exceptionally large eggs that are up to 3 mm in diameter. The eggs have numerous filaments over their surface, which appear to function by attaching the eggs to drift algae or seagrass blades (Figure 16.2). During development, the eggs are presumably attached, and appear to be negatively buoyant (Jordan et al. 1998). Nevertheless focused searches for eggs attached to the blades of seagrasses in the northern gulfs of SA have failed to find any eggs. So far, eggs have only been found associated with filamentous drift algae in Great Oyster Bay in Tasmania and seagrass and algae in one Kangaroo Island bay. After a relatively long development time (28–30 days at 14–16.5 °C) the larvae hatch at 6–9 mm in length, are well developed and pelagic (Jordan et al. 1998). Larval sampling in Gulf St Vincent found that abundances were highest in the northern parts of the gulf waters proximal to the extensive, dense seagrass beds over which the adults are caught (Noell 2002). Prevailing winds from the south-west and south-east may have helped to entrain the larvae in this region. The larval duration and the spatial relationship between spawning grounds, larval transport and distribution patterns remain unknown.

There is a validated ageing protocol for adult southern garfish that uses the transverse sections of otoliths, which means that the age of individual fish can be determined in years (Ye et al. 2002a). Several studies have indicated that this species is capable of living up to 10 years of age (Jones 1990, Ye et al. 2002b). Yet, the age structures of the fished populations that occupy the most productive fishing areas in SA are dominated by only 1+ and 2+ fish, with fish of three years of age and older now comprising minor parts of the population (Fowler et al. 2008, McGarvey et al. 2009, Fowler and Ling in press). This has been the case at least since the 1990s (Ye et al. 2002b). Comparison of these modern age structures with those developed during the 1950s suggest that the populations are now significantly truncated in size and age (Fowler and Ling in press), due to the high rate at which the populations have been exploited over a long period of time (McGarvey et al. 2009). Similar apparently truncated age structures were found for the Victorian populations during the 1990s (Ye et al. 2002b).

In SA, growth varies between the sexes and spatially (Ye et al. 2002a). The von Bertalanffy growth parameters determined for samples collected throughout numerous regions of SA during the 1990s are presented in Table 16.2. Based on these growth parameters, it would take the average male approximately 27 months and the average female 24 months to reach the legal minimum length of 23 cm TL. Nevertheless, there was considerable variation around the general growth curve and many fast growing individuals reached the legal minimum length (LML) in approximately 12 months.

Table 16.2: Estimates of von Bertalanffy growth parameters based on all samples collected from South Australian waters during the 1990s (Ye et al. 2002b).

	L_{inf}	K	t_0
Males	280.6	0.063	-0.1
Females	296.8	0.0564	-2.3

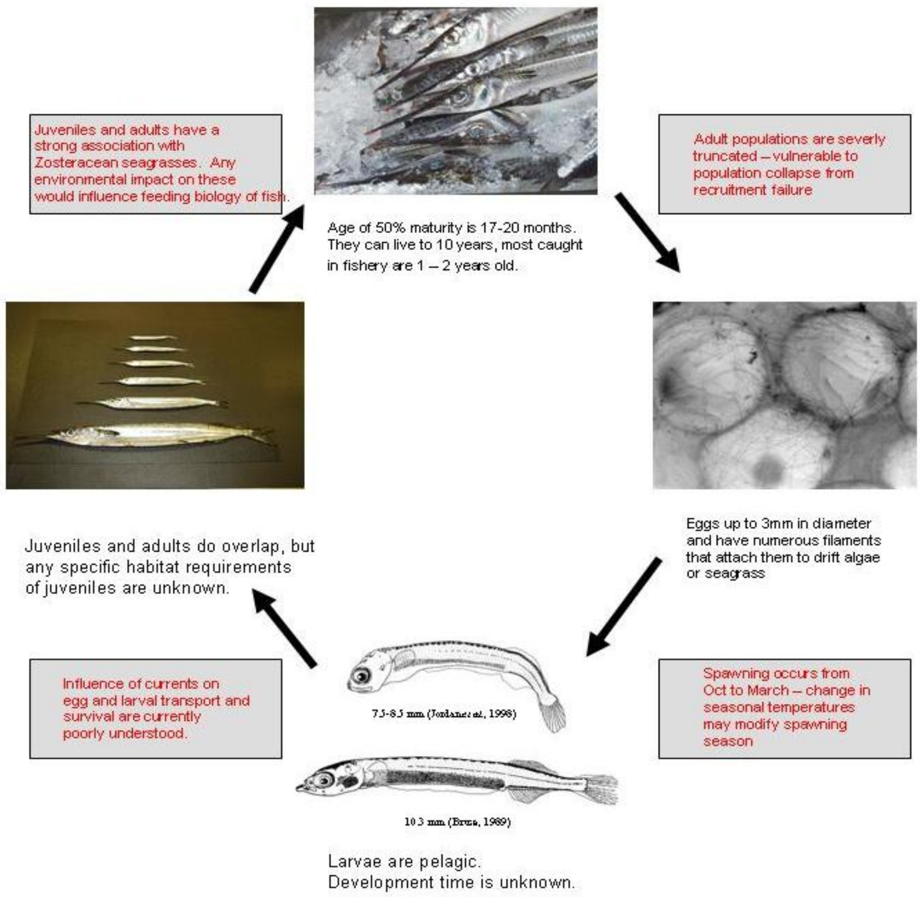

Figure 16.2: Summary of southern garfish life cycle (this section), and points of exposure to relevant climate change drivers or known impacts (subsequent sections).

16.2.2. Distribution and habitat

The southern garfish is distributed southwards from near Shark Bay in Western Australia, along the southern coast of the mainland and up the east coast as far as Eden in southern New South Wales, as well as the coastal waters surrounding Tasmania (Kailola et al. 1993, Noell and Ye 2008) (Figure 16.3). Throughout this distribution the adults occur in sheltered bays and shallow, inshore, marine waters to depths of approximately 20 m, often located above seagrass beds. The areas of high fishery catches in SA are characterised by relatively low wave-energy habitats (Middleton and Bye 2007), that support extensive wetland systems that involve mangroves, saltmarshes and large, tidal mudflats with extensive meadows of the intertidal seagrass *Zostera muelleri* (Edyvane 2000). These areas also include extensive sub-tidal seagrass meadows of species such as *Posidonia sinuosa*, *P. angustifolia*, *Amphibolis antarctica* and *Heterozostera tasmanica*. The eggs have been found attached to drift algae and seagrass, but no eggs have yet been found associated with attached demersal substrata. Abundances of small larvae were found to be highest in the northern South Australian gulfs, close to the seagrass beds with which the adults are associated (Noell 2002). The advection of eggs and larvae and the dispersion of juveniles and pre-recruit fish with respect to the spawning grounds is poorly understood.

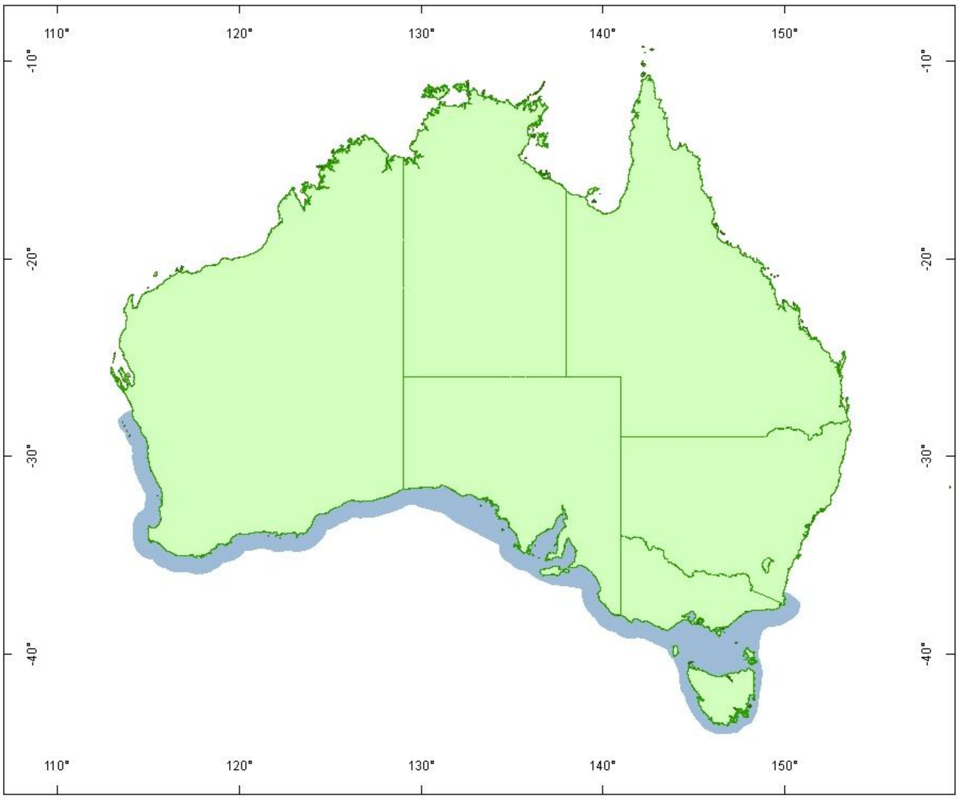

Figure 16.3: Distribution of southern garfish.

16.2.3. Predators and prey

The high density of southern garfish in nearshore waters that support extensive beds of seagrasses from the Zosteraceae family may be related to their diet. Several studies have determined that leaves of the seagrasses *Z. muelleri* and *H. tasmanica* are consumed almost exclusively throughout the day (Robertson and Klumpp 1983, Klumpp and Nichols 1983, Earl 2007). However, at night there is a switch in the diet to the consumption of hyperbenthic invertebrates. The adult fish primarily consume amphipods, which is augmented by the consumption of ostracods, cumaceans, polychaetes and even insects that land on the surface of the water (Robertson and Klumpp 1983, Earl 2007). The southern garfish is thought to be preyed upon by Australian herring (*Arripis georgianus*) and Australian salmon (*Arripis truttaceus*) (Thomson 1957, cited in Kailola et al. 1993), as well as coastal water birds (Kailola et al. 1993). However, a relatively comprehensive study of piscivory in the seagrass beds of Port Phillip Bay did not find any evidence of predation on Southern garfish (Hindell et al. 2000).

16.2.4. Recruitment

There is no direct sampling of 0+ or juvenile southern garfish that would provide an index of year class strength. However, in SA estimates of recruitment to the populations in Spencer Gulf and Gulf St Vincent are provided by the fishery stock assessment model 'GarEst' (McGarvey and Feenstra 2004, McGarvey et al. 2009). The calculations are based on population age structures as well as commercial catches. Here 'recruitment' is defined as the number of garfish spawned in each summer that survive to reach one year of age. For both gulfs, recruitment strength alternated between years, being relatively higher in the years of 2002, 2004 and 2006. There was considerable synchrony between gulfs in the patterns of recruitment variation suggesting the influence of a large-scale environmental phenomenon. In Spencer Gulf there has been a trend of lower recruitment over the past seven years. Annual variation in recruitment tends to be higher in Gulf St Vincent than Spencer Gulf.

Key points:

- Southern garfish have very large eggs and low batch fecundity. The planktonic larval stage lasts for about 1 month.
- They have a strong association with Zosteracean seagrass beds.
- Populations are significantly truncated in size and age due to long-term heavy exploitation.
- Limited capability for movement by individual fish would limit recovery of local sub-populations if they became depleted.

16.3. Current impacts of climate change

At present there is no evidence for direct effects of climate change on the populations of southern garfish. During the 2000s, changes in fishery catches and catch rates were observed both in SA and Tasmania. In SA, the recent changes were likely to be directly attributable to the high level of exploitation and the fact that the populations are now severely truncated with respect to size and age (McGarvey et al. 2009). In Tasmania, commercial catches fell considerably from 89 t in 2005–06 to 50 t in 2006–07 and 30 t in 2007–08, with decreases evident for both beach seine and dip net fishing methods. Catches on the south-east coast have decreased constantly since 2001–02. The reasons for these declines in the Tasmanian fishery are unclear. Nevertheless, separating the effects of climate change and fishery exploitation for this species would currently be difficult.

Key points:

- There is no direct evidence of the effects of climate change on southern garfish.
- However, populations may be under considerable stress because of heavy exploitation.

16.4. Sensitivity to change

In SA, the current annual exploitation rate is approximately 70%, and the populations are significantly truncated as a consequence of heavy long-term exploitation (McGarvey et al. 2009). Very few fish currently survive past the age of two years of age, even though the estimated longevity is 10 years. Recruitment to the populations is dependent on egg production by the relatively small and young one- and two-year-old fish, compared to in the past when older fish would have contributed (Fowler and Ling in press). As such, there is no 'storage effect' in these populations, whereby adults survive long enough to provide egg production to overcome prolonged periods that are unsuitable for egg and larval survivorship. As such, these populations are highly vulnerable to environmental change that might result in poor recruitment even over just a few consecutive years. This could lead to population crashes and collapsed fisheries.

A recent South Australian study indicated that individual garfish have limited scope for movement. The study considered stock structure through the analysis of otolith chemistry (Steer et al. 2009), and found that fish of two years of age, collected from places that were only tens of kilometres apart, demonstrated differences in otolith chemistry that were consistent with fish forming relatively discrete sub-populations at even small spatial scales. This suggests that if a local sub-population was to undergo significant decline and fishery collapse, there would be little scope for movement of individuals into that area from elsewhere to assist in the recovery of that local sub-population.

Key points:

- Populations are severely truncated due to long-term heavy exploitation, which means there are few old fish in the population to provide egg production if recruitment failed for several consecutive years.
- Movement of adults is limited at relatively small spatial scales, which would limit capacity for recovery after a population crash.

16.5. Resilience to change

To date, the populations of southern garfish in SA have been remarkably resilient. They have withstood high levels of exploitation for many years and have managed to persist despite having severely truncated size and age structures. The reasons for this persistence are not immediately obvious but may be related to their reproductive mode that has ensured relatively consistent recruitment through years, despite the reduced number, size and age of fish involved in reproductive activity. Unfortunately, the reproductive biology of adult garfish and the early life history of their progeny are extremely poorly understood. As such, the resilience of these populations to environmental change based on their own life history characteristics remains purely speculative.

Key point:

- Populations have been resilient to date, despite over-exploitation.

16.6. Ecosystem-level effects

The southern garfish has a strong association with seagrasses of the family Zosteraceae, which constitute a major component of their diet. Abundances are highest in relatively protected areas that support extensive beds of inter-tidal and sub-tidal seagrass meadows. As such, any environmental changes that were detrimental to the percentage cover or area of cover of such seagrass beds could also be detrimental to the life cycle and abundances of southern garfish.

Key point:

- Environmental impacts on Zosteracean seagrass beds would have a secondary effect on southern garfish populations.

16.7. Additional (multiple) stressors

It has been identified above that the populations of southern garfish in the gulfs of SA are over-exploited, based on their truncated populations. During the 1990s, the Victorian populations in Port Phillip Bay and Corner Inlet were also dominated by the 1+ and 2+ age classes; i.e. similar to the age structures in SA (Ye et al. 2002b). Furthermore, the catches from Port Phillip Bay have declined considerably since the 1980s and so may also be over-exploited. The Tasmanian population may now be demonstrating the same characteristics. Any loss of Zosteracean seagrass beds, which is essential habitat, would likely directly impact on the sustainability of populations of southern garfish.

Key point:

- Heavy rate of exploitation makes southern garfish vulnerable to recruitment failure through environmental change.

16.8. Critical gaps and level of uncertainty

Above it was speculated that the over-exploited and truncated populations of southern garfish, at least in SA, but possibly also in Tasmania and Victoria, would be particularly vulnerable to climate change. Since the populations now essentially consist of only a few year classes, the failure of recruitment over several consecutive years could devastate the populations resulting in fishery collapses. Nevertheless, this has not occurred so far, possibly related to the mode of reproduction and the early life history of the species that has ensured to date relatively reliable recruitment from year to year. The reproductive biology and early life history of this species are extremely poorly understood, thus representing an obvious critical gap in our understanding of the species.

A further gap in our understanding relates to the limited scope of movement of individual fish, as determined through the otolith chemistry study (Steer et al. 2009). The question based on this is: to what extent are sub-populations adapted to the local conditions where they live? As such, are ranges of physiological tolerance limited and different between places? There are likely to be different physiological tolerances between the South Australian and Tasmanian populations because egg development occurs at different temperature regimes. However, we do not know at what scale such physiological tolerances do vary. This will influence the sensitivity of local sub-populations to changes in physical environmental characteristics.

Key points:

- The reproductive biology and early life history of southern garfish is extremely poorly understood.
- The physiological tolerances for the different life history stages and the spatial scale at which they differ are also unknown.

Table 16.3: Summary of southern garfish species profile, which also indicates level of certainty of the associated information. Level of certainty is divided into high (H) = strong clear evidence, backed by several studies with solid datasets with little confounding interactions; medium (M) = evidence supported by one or more studies, conclusions may be partially ambiguous or confounded; low (L) = anecdotal evidence, limited data and/or predicted conclusions based on theoretical knowledge.

Life history stage	Multiple stressors	Distribution	Habitat	Predators and prey	Current impacts	Predicted impacts	Ecosystem interactions	Data gaps
Eggs		See Fig 3	Sheltered shallow waters in association with Zosteracean seagrass meadows (H)		Unknown		Strongly associated with seagrass beds. Any loss of seagrass due to climate change will impact garfish populations (L)	Reproductive biology and early life history is very poorly understood. Little known about differences in physiological tolerance among sub-populations.
Larvae								
Juveniles				Prey: seagrass, invertebrates (H) Predators: Australian salmon and herring, sea birds (M)				
Adult	Exploitation, considered over-exploited in SA					Populations are very truncated in SA due to exploitation, which makes them highly vulnerable to environmental change. Poor recruitment may lead to population crashes (L)		

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17. Southern rock lobster *Jasus edwardsii*

Authors: Zoe Doubleday, Adrian Linnane, Neil Hutchinson, Gretta Pecl, Caleb Gardner, Stewart Frusher

17.1. The fishery

Southern rock lobster (SRL) is one of the most valuable wild fishery resources in the south-east Australia region, and is harvested in Tasmania, South Australia and Victoria (Figure 17.1). The SRL fishery has been a vital component of the Tasmanian fishing industry for over 150 years. It is the state's second highest value fishing industry, estimated to be worth $72 million in 2008-09 (Pecl et al. 2009). The present commercial catch is taken from all around the state and involves the annual harvest of around 1.6 million animals (Haddon and Gardner 2009). The fishery is managed as a single zone, although the state is divided into eight stock assessment areas for more detailed regional biological assessment of the stock. SRL fishing is a popular recreational activity in Tasmania and the number of licences has rapidly increased. During the 2006–07 season approximately 16,583 pot, 8717 dive, and 5210 ring licenses were issued to recreational fishers (Lyle 2008).

In South Australia, SRL is the state's most valuable fisheries resource, with an annual landed value of ~$91 million (Knight and Tsolos 2009). The fishery is divided into two regions for management purposes: a northern zone (NZ) and a southern zone (SZ). Each fishery is further dived into marine fishing areas (MFAs) for statistical analyses. The total estimated harvest in 2008–09 was 1810 t representing approximately 2 million animals (Linnane et al. 2009a; 2009b). SRL fishing is also an important recreational activity in SA. The most recent survey of recreational fishers indicated that during 2007–08 about 48,000 animals were taken representing a combined weight of 60 t (Jones 2009).

In Victoria, the SRL fishery is currently divided into eastern and western zones, with the division just west of Apollo Bay. The landed catch in 2006–07 was 330 t in the western zone and 53 t in the eastern zone, slightly less than the total allowable catch (TAC) for the year. The TAC was reduced in the western zone to 320 t in 2008–09 because of declining catch rates (DPI 2008).

Key points:

- SRL is harvested in Tasmania, SA and Victoria, and comprises the second highest and highest valued fishery for Tas and SA respectively.
- In 2007–08 total commercial catch was 4190 t.
- SRL is an important recreational species.

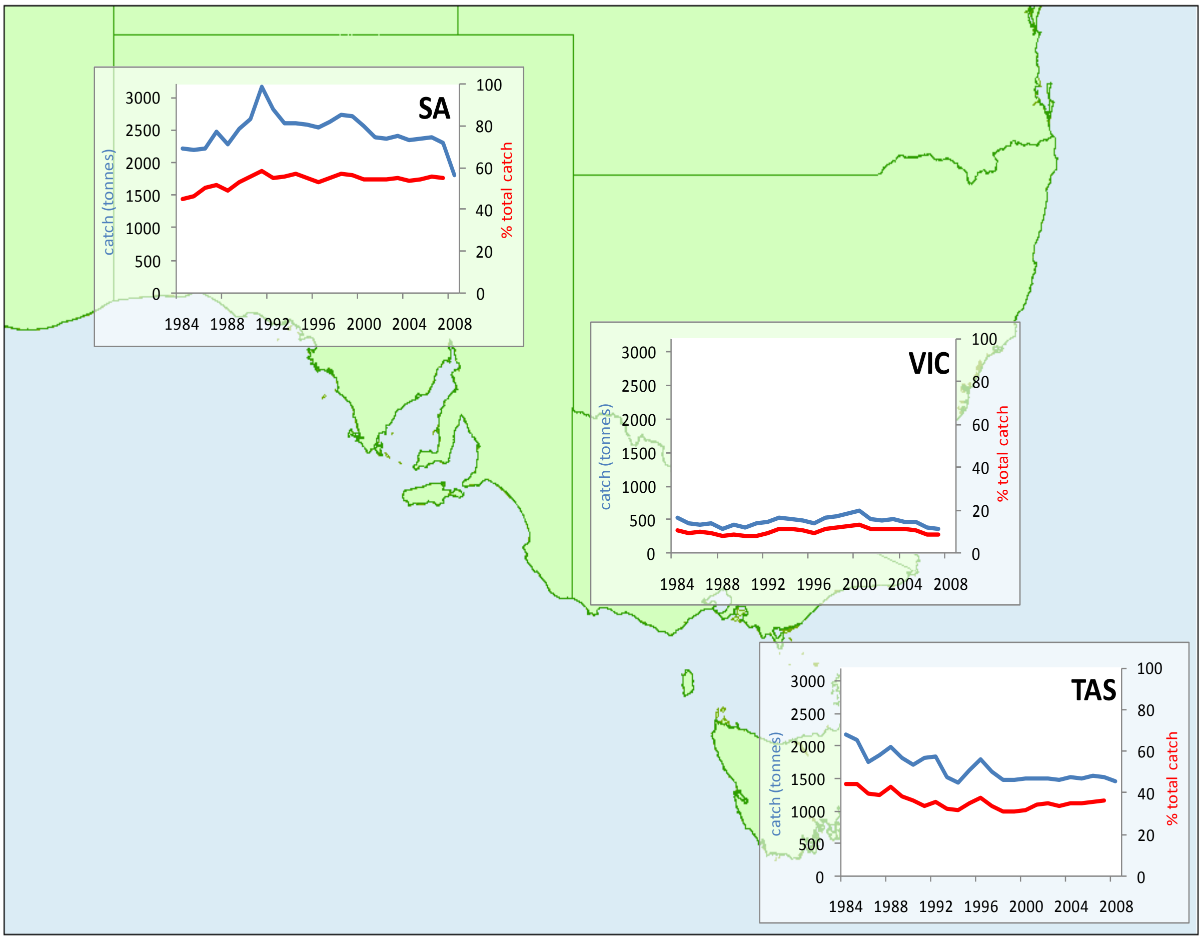

Figure 17.1: Commercial catch of SRL (tonnes) and contribution by each jurisdiction to total catch in south-east Australia (%) by year for South Australia, Victoria, and Tasmania. Tas data sourced from (Haddon and Gardner 2009).

17.2. Life history

17.2.1. Life cycle, age and growth

The following life cycle information has been derived from Pecl et al. (2009) and Hutchinson et al. (2010). The fertilisation of SRL eggs occurs externally, from April to July, where they are then carried under the tail of the female for 3–6 months (Figure 17.2). Up to one million eggs develop under the tail of a female before being released into the sea. Eggs hatch into larvae (phyllosoma), usually between September and October, with an oceanic phase estimated to last 9–24 months. Phyllosoma undergo 11 developmental stages, and at the end of their larval phase and when adjacent to the continental shelf, phyllosomas moult to the last larval stage known as the puerulus and swim towards coastal reefs where they settle as a 25 mm lobster and begin the benthic phase of their life cycle. SRL grow by periodically shedding their complete exoskeleton in a process called moulting. The number of moults that a lobster undertakes annually is dependent on its size and maturity, but frequency declines with age. After reaching sexual maturity, lobster normally undertake one moult each year and growth of female lobsters is often reduced because of the high demand on energy reserves for egg production. In Tasmania and SA, SRL growth rates vary spatially with slow growth in cooler southern regions and faster growth in warmer northern regions (Punt and Kennedy 1997; McGarvey et al. 1999). This ultimately impacts on size of maturity which can differ greatly depending on the region (Gardner et al. 2006; Linnane et al. 2008).

17.2.2. Distribution, habitat and environmental preferences

SRL are distributed from southern NSW (approximately Eden), around Tasmania and across SA into southern WA (Figure 17.3). They are also found in New Zealand waters. Little is known about the oceanic larval phase, although samples of phyllosoma collected during oceanic plankton research surveys show higher abundance in cooler waters just south of the sub-tropical convergence (Tasman front) – the region where the nutrient-poor warm East Australian Current (EAC) meets the nutrient-rich cooler Southern Ocean waters (Bruce et al. 2000). Adults and juveniles inhabit a variety of rocky reef habitats at a range of depths, from rockpools to reefs up to 200 m deep. Holes and crevices are important for survival for small early post-settlement juveniles (Booth 2001). SRL are active at night, during the day they are cryptic and hide in rock crevices and tagging studies indicate movements of up to 100 kilometres (Hutchinson et al. 2010).

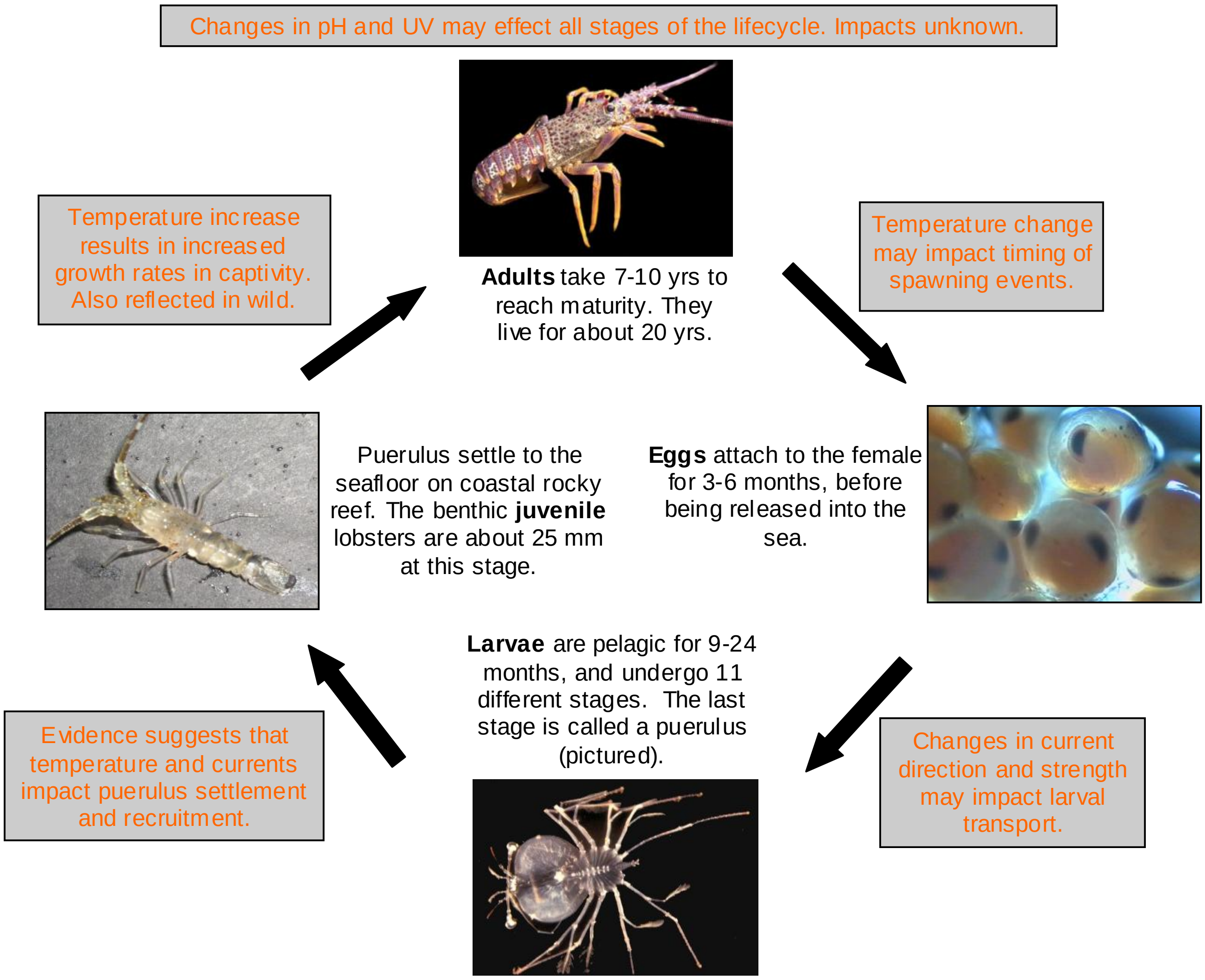

Figure 17.2: Summary of southern rock lobster life cycle (this section), and points of exposure to relevant climate change drivers or known impacts (subsequent sections). Image adapted from Pecl et al. (2009).

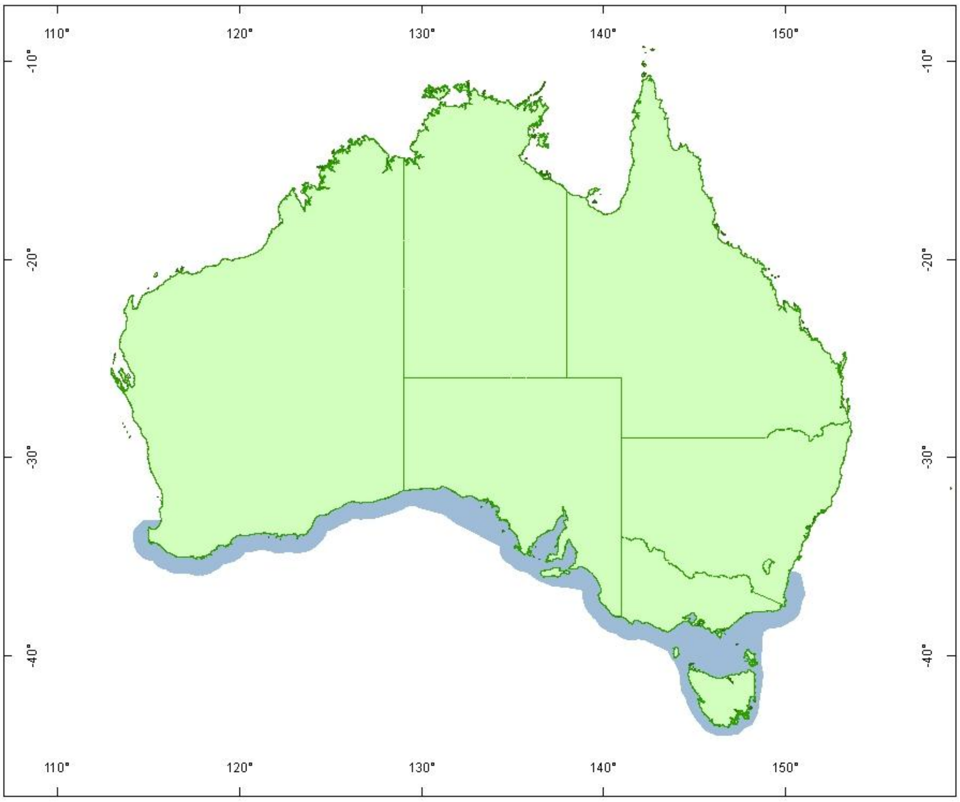

Figure 17.3: Distribution of southern rock lobster.

17.2.3. *Predators and prey*

There is very little information on diet of adult, juvenile or larval lobsters in general, although adults are known to be omnivorous and their diet includes ascidians, urchins and molluscs (Guest et al. unpublished data). Major predators of both adult and juvenile SRL include octopus, gummy sharks, and a variety of fish (Hutchinson et al. 2010).

17.2.4. *Recruitment*

The patterns in puerulus settlement and the correlations with SST in Tasmania support the hypothesis of Bruce et al. (2000) that the position of the sub-tropical convergence (STC), where the EAC meets cooler Southern Ocean water, is important for east coast puerulus recruitment. Modelling of lobster larvae transport suggests that regions from south-eastern South Australia to south-western Tasmania are important regions for supply of larvae to eastern Tasmania (Bruce et al. 2007). It has been hypothesised that the main winter peak observed at the puerulus settlement monitoring sites along eastern Tasmania is associated with the alignment of this water mass off the coast. While the south-eastern regions of South Australia were identified by Bruce et al. (2007) as a potential source of recruits, there was no correlation between projected settlement from the larval transport model and observed puerulus settlement on collectors throughout South Australian, Victorian and Tasmanian regions, suggesting that there are factors in addition to currents that affect puerulus recruitment. More recently, fisheries modelling suggest that large scale declines in recruitment patterns have occurred across the range of *J. edwardsi* in SE Australia (Linnane et al. in press). This has translated to poor fishery performance in almost all of the major fishing regions in South Australia, Victoria and Tasmania.

Key points:

- SRL are benthic, but have a very long pelagic larval phase, which is predominantly offshore.
- SRL are distributed throughout southern Australia in reef habitat.
- Modelling suggests that south-west Tasmania and SA are an important source of recruits, and that the position of the EAC is important for puerulus recruitment.
- There is evidence of recent large-scale spatial declines in recruitment patterns across SE Australia.

17.3. Current impacts of climate change

SRL growth rates vary spatially across SE Australia, with slow growth in cooler southern regions and faster growth in warmer northern regions. Associated with these spatial patterns in growth is a difference in the size at maturity. Growth of lobsters has been monitored in south-western Tasmania since 1995. This data show a long-term trend of increases in growth rate of around 0.4 mm (carapace length) extra each decade for both male and female lobsters at the size limit (Pecl et al. 2009). This may seem small but is significant with the long-term female growth rate only 0.5 mm per year at this size; in other words, the growth rate of females has almost doubled and the trend has the potential to almost double female contribution to catches in this region. In South Australia, growth rates tend to increase from south to north with slower growth in regions known to be influenced by annual coldwater upwelling events (McGarvey et al. 1999). Growth also tends to decrease with depth. A more recent analysis of temporal changes in growth suggests that in the Southern Zone of South Australia at least, growth tends to decreasing (Linnane et al. in press). The underlying causes remain largely unknown but it has been suggested that exceptionally strong upwelling events in the region in recent seasons may be a contributing factor.

Puerulus recruitment in eastern Tasmania has shown a gradual decline over the last 15 years, which has been correlated to sea surface temperature (SST) (Pecl et al. 2009). The data also suggest that puerulus abundance is shifting south. The reversal of the correlations between water temperature and puerulus settlement between northern and southern regions of the east coast of Tasmania can be explained by increasing water temperatures, indicating an increasing southern penetration of the EAC which drives this water mass away from the mid-east coast (negative correlation) towards southern Tasmania (positive correlation). Modelling of larval transport and observed changes in puerulus settlement in eastern and south-eastern Tasmania do support a hypothesis of declining recruitment with the predicted increase in the southward penetration of the EAC (Pecl et al. 2009). A delay in the timing of settlement in the more northerly regions of the east coast of Tasmania has also been observed. Model projections of SRL biomass indicate that there will be initial gains in biomass due to increased growth, but ultimately there will be a decline due to decreased recruitment, starting with the north-east regions. It should be noted, however, that declines in puerulus settlement have not been observed in either South Australia or Victoria with two of the highest settlements on record observed during 2005 and 2006 in both regions (Linnane et al. in press).

Key points:

- Growth rates are increasing in southern Tasmania but appear to be decreasing in South Australia.
- Evidence suggests that puerulus recruitment is declining in eastern Tasmania due to an increase in the southward penetration of the EAC.

17.4. Sensitivity to change

Controlled aquaculture experiments have shown that growth rate and moult increment in early stage phyllosoma larvae was greater at 18.2°C than at 14.3°C. Consumption of *Artemia nauplii* also escalated from 10.5 to 18.2°C, but not at higher temperatures, and almost all stage II phyllosoma died at 21.5°C (Bermudes and Ritar 2008). The effect of temperature on growth, feeding and metabolism of post-puerulus SRL found that there was no significant difference in the specific growth rates at 18, 20 or 22°C; however, growth decreased significantly at 24°C (Thomas et al. 2000). This is reflected in growth rates observed in the wild, with animals in cooler southern regions growing slower than their counterparts in warmer northern regions. Such growth patterns also influence differences in the size at maturity. Seasonally, fishers in Victoria report a drop in catch rates in February, coinciding with increased water temperature.

Key point:

- Controlled aquaria experiments showed that phyllosoma growth is faster at 18.2°C than 14.3°C; however, most stage II larvae died at 21.5°C. Growth rates are slower in the cooler southern regions in Tasmania.

17.5. Resilience to change

SRL have an extremely long pelagic larval phase, from 9 to 24 months, and thus a high dispersal capacity. The larvae spend most of their time offshore in oceanic environments.

Mitochondrial DNA analysis supports the apparent absence of genetic population subdivision of SLR throughout Australasia, including between Australia and New Zealand (a distance of approximately 2000 km) (Ovenden et al. 1992). Although changing current conditions may have a profound impact on larval transport patterns, due to their long larval stage, such dispersal capacity may prevent localised population effects due to climate change and may enable the species to shift distribution to maintain an optimal environment.

There is very little information on diet of adult, juvenile or larval lobsters in general, although adults are known to be omnivorous and consume a range of prey (Guest et al. unpub data).

Furthermore, translocation of SRL individuals in Tasmania, from deep-water to shallow-water inshore reefs, has demonstrated that SRL are resilient to change of habitat and show a wide degree of phenotypic plasticity (Green et al. 2010; Chandrapavan et al. 2010).

Key points:

- SRL have a high dispersal capacity, potentially increasing the species' resilience to changing environmental conditions.
- SRL is a generalist species, living in a wide range of reef habitat and consuming a wide range of prey.

17.6. Ecosystem level interactions

Lobsters are preyed upon by octopus, and there is a reasonable basis for expecting octopus populations to increase under climate change (Pecl and Jackson 2007). Ecosystem interactions between lobsters and *Octopus maorum* occur through octopus entering lobster pots to prey on the trapped lobsters. These interactions are reported in fishers' logbooks as lobster mortalities per pot lift due to octopus. Positive correlations between the number of lobsters killed by octopus and temperature, for each SRL assessment area, may suggest an increase in octopus abundance (Pecl et al. 2009).

The southward incursion of the urchin *Centrostephanus* from New South Wales and its successful establishment in Tasmanian waters is considered the result of larval transport, reflecting changes in the behaviour of the East Australian Current (EAC) (Ling et al. 2008). Once established, *Centrostephanus* denudes coastal reefs by overgrazing important habitat-forming seaweeds and invertebrate fauna and forming persistent barrens (Ling 2008). These barrens are likely to impact reef species through habitat reduction, including SRL, and have the potential to increase as a function of southern range expansion of the urchin. However, sea urchins are a food source for larger SRL and high densities of very large lobsters may be critical in preventing barren formation by controlling urchin numbers. This means that losses of larger SRL, due to overharvesting or reduced population recruitment, may have a substantial impact on the economic viability and sustainability of valuable commercial reef species in south eastern Australia, such as abalone.

Eastern rock lobster (*Jasus verreauxi*) are found in small numbers in north-east Tasmania, with larvae thought to be brought south via the EAC (Pecl et al. 2009). Numbers are expected to increase as conditions become more suitable for the warmer water species. Their behaviour and biology is quite different to SRL and an increase in abundance may lead to competition for resources with SRL.

In addition to the effect of temperature, growth is also likely to be affected by food availability and population density; although very little information is available on the impact of these parameters on growth (Pecl et al. 2009).

Key points:

- There is some evidence to suggest that octopus are increasing in abundance in Tasmania and that there are range extensions of another octopus species; octopus is a key predator of SRL
- The southward range expansion of the barren-forming *Centrostephanus* and ERL may impact SRL.

17.7. Additional (multiple) stressors

In Tasmania, SRL are heavily exploited which may place additional stress on the population, and decrease resilience to environmental perturbations. In the 1990s, concerns about stock decline emerged, resulting in the establishment of an individual transferable quota management system in 1998 (Bradshaw 2004). Since the introduction of the quota, stocks of SRL have increased markedly. Relative to the stock's lowest point in 1993–94, there has been significant rebuilding in terms of legal biomass, which has led to a rise in catch rates (Haddon and Gardner 2009). However, the geographic distribution of fishing effort has shifted more to the south-west region due to prolonged poor recruitment in the north (Haddon and Gardner 2009). It is unlikely the south will be able to sustain such fishing levels.

Expansion of sea urchin barrens and regional differences in stock abundance, recruitment and growth rates (which will only continue to change), cannot be effectively addressed under the current management regime (Pecl et al. 2009). Although fisheries management policies do not currently explicitly consider climate change, management is beginning to actively integrate the generally longer-term issues associated with climate change with the relatively shorter term responses to current stock trends.

Key point:

- Exploitation will likely have a strong influence on the impacts of climate change on SRL.

17.8. Critical data gaps and level of uncertainty

Information is only available on temporal aspects of recruitment and settlement and the relationship to temperature, with very limited information on the source of recruits. Spatial variation in important population parameters is likely to be highly variable to some extent reflecting variation in habitat complexity and food availability. Differentiating between local and regional effects on uncertainty among acquired data can be problematic, but is nevertheless essential for developing an understanding of broader scale responses to perturbations. There also remains considerable uncertainty regarding the drivers for puerulus settlement for SRL throughout its distribution. An improved understanding of the regional growth of rock lobster and response to temperature is required, as changes in the number of lobsters entering the legal-sized stock each year can be caused by either changes in abundance of undersize lobster or changes in growth rate. The impacts of ocean acidification and UV are also unknown and these may be significant.

Key points:

- Limited information on the source of recruits and drivers of puerulus settlement.
- Impacts of ocean acidification and increasing UV are unknown.

Table 17.1: Summary of southern rock lobster species profile, which also indicates level of certainty of the associated information. Level of certainty is divided into high (H) = strong clear evidence, backed by several studies with solid datasets with little confounding interactions; medium (M) = evidence supported by one or more studies, conclusions may be partially ambiguous or confounded; low (L) = anecdotal evidence, limited data and/or predicted conclusions based on theoretical knowledge.

Life history stage	Multiple stressors	Distribution	Habitat	Predators and prey	Current impacts	Predicted impacts	Ecosystem interactions	Data gaps
Eggs	Unknown	See Figure 4 (H)	Pelagic, offshore (M)	Unknown		Continued decline in recruitment (M) Growth rates to reach a maximum and then start to decline (L) Decline in biomass (M)		Source of recruitment Impact of currents on recruitment Impact of decreasing pH Effect of increasing UV
Larvae					Increased growth rates (M) Decline in recruitment (M)			
Juveniles			Rocky reefs, from 0-200 m (H)	Predators: octopus, reef fish (H) Prey: range of molluscs, urchins (L)			Increase in octopus predation (L) Loss of habitat, *Centrostephanus* (H) Increase in eastern rock lobster abundance and competition for resources (L)	
Pre-spawning adult								
Post-spawning adult	Exploited, # t caught each year, fishery is stable (H)							

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18. Spanner crab *Ranina ranina*

Author: Philip Gibbs

18.1. The fishery

Spanner crabs (*Ranina ranina*) are a tropical species and a shared stock with Queensland, where the majority (~90%) of the total fishery of ~1150 tonnes in 2009, exists. In New South Wales (NSW) virtually all spanner crabs are caught in the Ocean Trap and Line Fishery by specifically endorsed fishers using spanner crab nets (also known as dillies) with the majority of the catch being taken north of Yamba. Spanner crabs in NSW are at the southern limit of their range and are likely to be impacted by anthropogenic climate change and a southern extension of the East Australian Current (EAC).

There are no concerning trends evident in catch rates of legal-sized crabs from Queensland, but the fishery-dependant catch rates from NSW have declined since 2003–04 and are now back to where they were in 1984–85. However, total catch in NSW remains at about 100 tonnes compared to the peek catches in the mid 1980s to mid 1990s ranging between 250 and 450 tonnes (Anon 2006).

Both jurisdictions have regulations that prohibit the harvesting of berried crabs (females carrying maturing ova). In NSW there is a minimum legal length of 9.3 cm carapace length and a recreational bag limit of 10 spanner crabs. Sampling of spanner crabs in both NSW and Queensland has indicated that the commercial catch consists predominantly of males.

The annual recreational harvest of spanner crab in NSW is not documented but anecdotal evidence suggests it is likely to be less than one tonne.

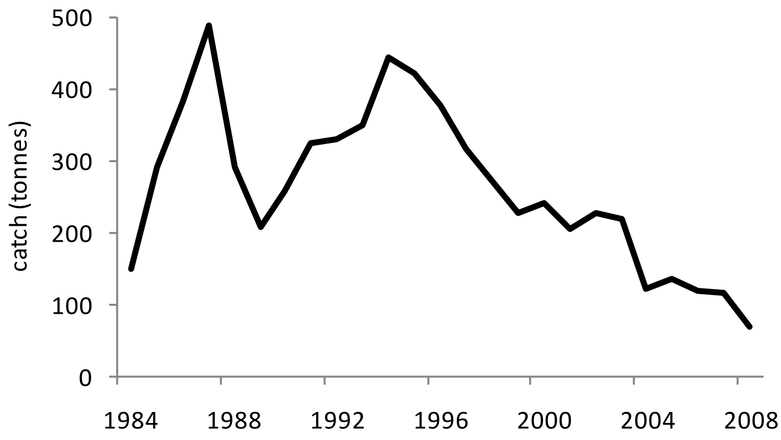

Figure 18.1: Commercial catch (tonnes) by year for NSW.

Key point:

- The spanner crab fishery is based in Queensland and the species is at its southern limit in northern NSW.

18.2. Life history

18.2.1. *Life cycle, age and growth*

Virtually all the life cycle information for spanner crabs is based on Queensland data. Female crabs mature at about two years of age which is equivalent to 7 – 7.5 cm carapace length (CL) or about 100 g in weight (Figure 18.2). Spawning occurs during the warmer months of the year (October to February). Mature crabs can mate at any stage within their moult cycle (Brown 1986) and females store their partners' sperm until the eggs are extruded. The female often buries herself to incubate and protect the egg sponges. During one season a large female spanner crab will produce at least two batches of eggs, with each egg mass containing an average of 120,000 eggs per batch. Fertilised eggs remain attached to the female for approximately four to five weeks before hatching (Brown 1986).

As with other crustaceans, growth occurs through moulting. This involves the shedding of the hard shell, and then swelling of soft body tissues to expand the new soft shell before it hardens. Attempts to estimate the individual growth rate and longevity of this species have yielded inconsistent results, and at this stage these population parameters remain uncertain.

Growth estimates based on spanner crabs sampled in NSW suggest that males reach a maximum size of 14 cm CL and females reach a maximum size >11 cm CL. Growth to these maximum lengths is thought to take approximately 10 years.

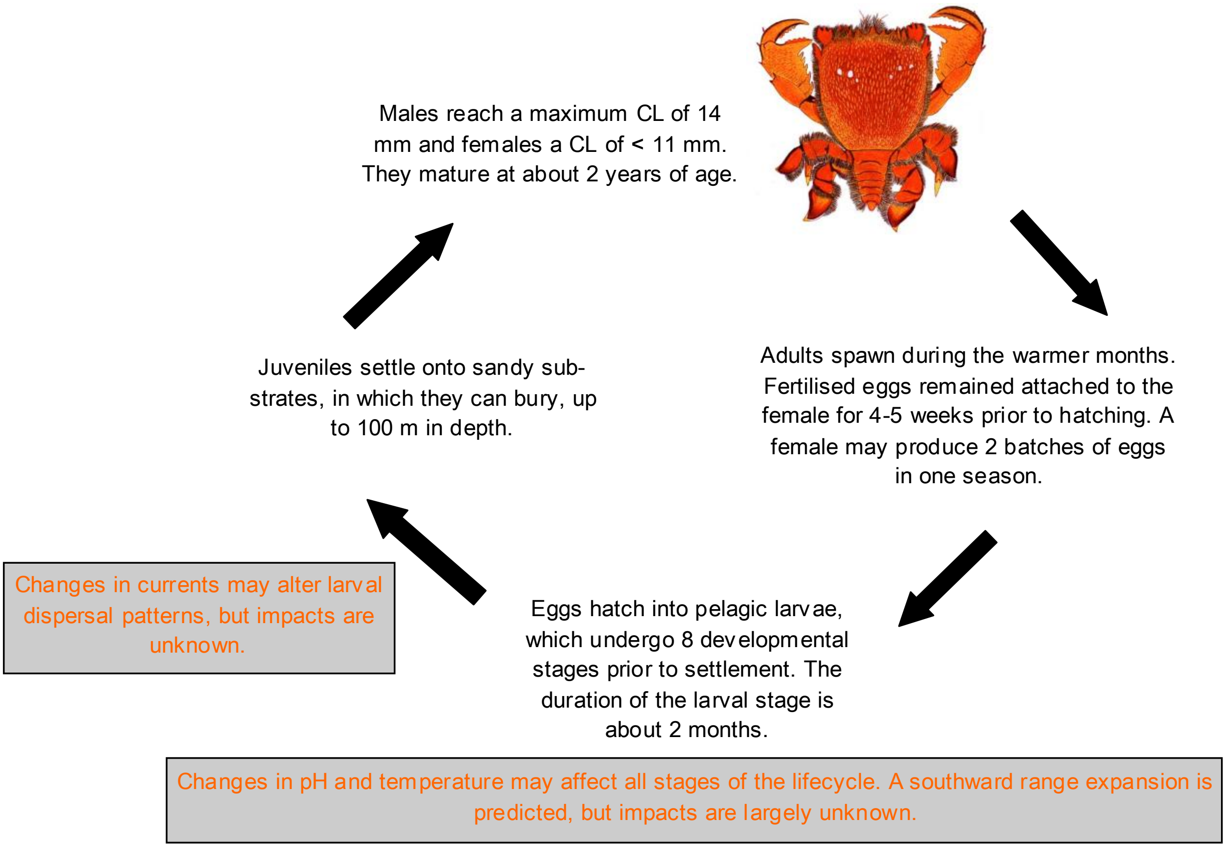

Figure 18.2: Summary of spanner crab life cycle (this section), and points of exposure to relevant climate change drivers or known impacts (subsequent sections). Image: Bernard Yau.

18.2.2. Distribution, habitat and environmental preferences

Spanner crabs (*Ranina ranina*) are distributed throughout the Indo-Pacific region in coastal waters, to a depth of 100 m, on sandy substrates in which they bury. On the east coast of Australia, spanner crabs are distributed from Yeppoon in Queensland to Nowra in NSW and, on the west coast, from Quinn rocks (north of Perth) to the Houtman Abrolhos and Geraldton in WA (Kailola et al 1993).

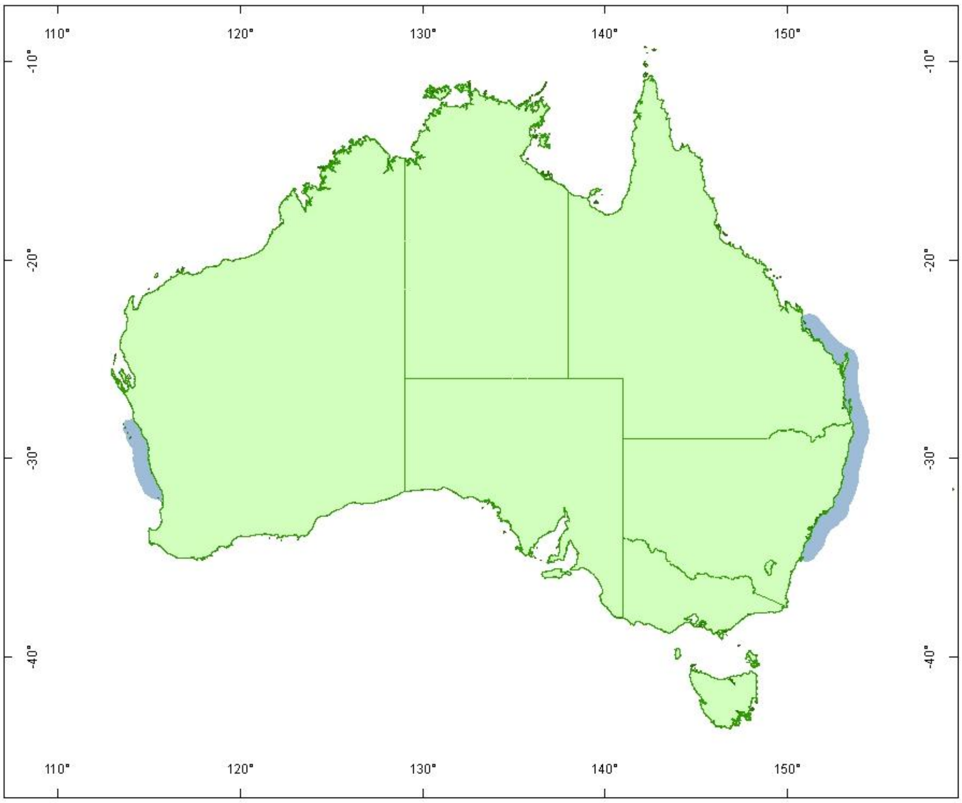

Figure 18.3: Distribution of spanner crabs.

18.2.3. Predators and prey

Spanner crabs are opportunistic feeders with their diet consisting of urchins, bivalve molluscs, crustaceans, polychaete worms, and fish. Predators of spanner crabs are a variety of large fish especially rays and sharks.

18.2.4. Recruitment

Spanner crabs metamorphose through eight larval stages during the first two months of their life. Larvae eventually settle and enter the final transformation into the recognisable spanner crab form (Brown 1986).

Key points:

- Spanner crabs mature at two years of age and live to a maximum of 10 years.
- The species is a benthic opportunistic feeder living in nearshore sandy habitats.

18.3. Current impacts of climate change

There is insufficient information on the biology and population dynamics of spanner crabs to comment on the current impact of climate change on this species. However, future recruitment and distributional changes are predicted as the EAC moves south.

Key point:

- Spanner crabs are predicted to move south with the changes predicted for the EAC under a range of climate change scenarios.

18.4. Sensitivity to change

Unable to comment.

18.5. Resilience to change

Unable to comment.

18.6. Ecosystem level interactions

The importance of spanner crabs within the nearshore ecosystems is uncertain.

18.7. Additional (multiple) stressors

Unable to comment.

18.8. Critical data gaps and level of uncertainty

A much better understanding of the biology and distribution of the species especially at the southern range limit on the east coast is fundamental to an understanding of the effects of climate change on this species

Table 18.1: Summary of spanner crab species profile, which also indicates level of certainty of the associated information. Level of certainty is divided into high (H) = strong clear evidence, backed by several studies with solid datasets with little confounding interactions; medium (M) = evidence supported by one or more studies, conclusions may be partially ambiguous or confounded; low (L) = anecdotal evidence, limited data and/or predicted conclusions based on theoretical knowledge.

<table>
<tr><th>Life history stage</th><th>Multiple stressors</th><th>Distribution</th><th>Habitat</th><th>Predators and prey</th><th>Current impacts</th><th>Predicted impacts</th><th>Ecosystem interactions</th><th>Data gaps</th></tr>
<tr><td>Eggs</td><td rowspan="4">Unknown</td><td rowspan="5">See Figure 4 (H)</td><td rowspan="2">Offshore (H)</td><td rowspan="2"></td><td></td><td rowspan="5">Southern extension of the range in association with the EAC (H)</td><td rowspan="2"></td><td rowspan="5">Improved understanding of the species biology on the current southern limit of the species range</td></tr>
<tr><td>Larvae</td><td rowspan="4">Unknown (H)</td></tr>
<tr><td>Juveniles</td><td rowspan="3">Offshore (H)</td><td rowspan="3">Opportunistic omnivores (H)

Prey for large fish and rays (H)</td><td rowspan="3">Unknown</td></tr>
<tr><td>Pre-spawning adult</td></tr>
<tr><td>Post-spawning adult</td><td>Commercial Harvest (H)</td></tr>
</table>

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19. Striped marlin *Kajikia audax*

Author: Lisa Cocking

19.1. The fishery

Striped marlin is a highly migratory pelagic billfish species which is commercially harvested worldwide within its distributional range in the Indian and Pacific oceans. Striped are caught on the east and west coasts of Australia and their range is generally limited by ocean temperatures. Tagging data shows the species is capable of large migrations (3000 nm); however 80% of recaptures of tagged fish occur within 500 nm of the release point (Bromhead et al 2004).

Molecular heterogeneity indicate that the Pacific Ocean has at least four genetically distinct stocks which correspond to spawning grounds (Figure 19.1), one being the stock off the east coast of Australia (McDowell and Graves 2008). McDowell and Graves (2008) also showed genetic stability was present in this stock. This is supported by tag recapture data where individuals are generally caught within several hundred nautical miles of release. Further, Ortiz et al (2003) found no tag recaptures of marlins released in the south-western Pacific have been recorded as recaptured in the eastern Pacific and vice versa. There may be some mixing between the Pacific and Indian Ocean stocks under optimal conditions (Bromhead et al 2004).

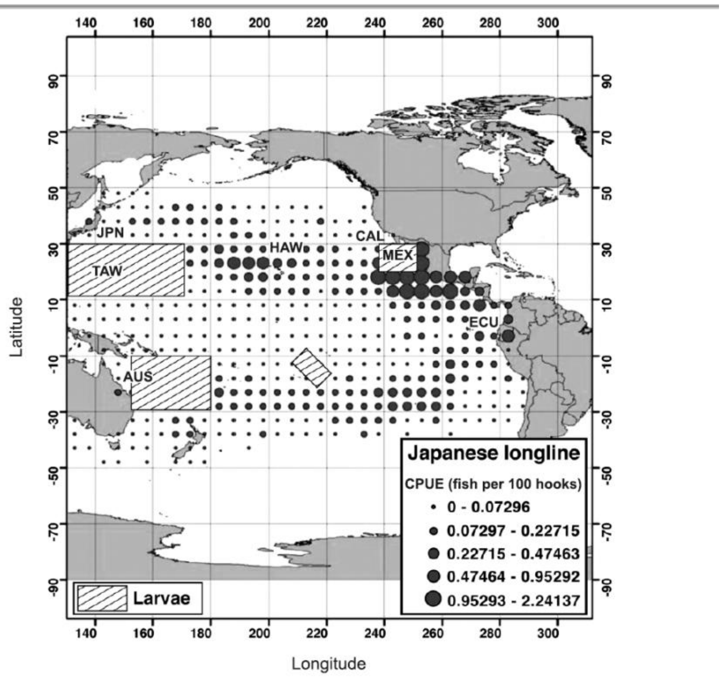

Figure 19.1: Striped marlin spawning grounds (based on the presence of larvae in the figure) represent the areas of discrete genetic stocks (source: Mc Dowell and Graves 2008).

Striped marlin are commercially harvested through the pelagic longline and minor line (handline, troll, rod and reel) fishing methods. Within Australia, striped marlin are a primary species taken in the Eastern Tuna and Billfish Fishery (ETBF) with incidental catches also occurring in the Western Tuna and Billfish Fishery. Over the last five years the catch of striped marlin in the ETBF has varied between around 360 and 440 tonnes (AFMA catch data), and in 2006–07, the take of striped marlin in the ETBF was 413 t (AFMA catch data) with a GVP of $2.40 million (ABARE-BRS 2010).

Of the striped marlin caught in the area of the ETBF, approximately 30– 40%is caught and landed in the south east ports. The remainder of the catch is landed in Queensland. Figure 19.2 shows the catches of striped marlin in south-eastern Australia between 1999 and 2009. The lower levels of catch in this figure compared to the catch levels discussed above are a result of the figure only including south east catches.

Historically, Japanese longliners were responsible for taking the majority of striped marlin catches in Australian waters. The catches in the south-western Pacifc Ocean (SWPO) peaked in 1972 at 1642 tonnes; however, they have rarely been recorded above 1000 tonnes since this time. This reflects the restriction to Japanese longliners and other foreign vessels in Australia which commenced in 1982 when the 200 nm exclusive economic zone was agreed to at the third meeting of the United Nations Convention on the Law of the Sea. Australia began limiting Japanese catch throughout the 1980s and 1990s until all non-Australian fishing vessels were completely excluded in 1997.

The ETBF is managed under the *Eastern Tuna and Billfish Management Plan 2005* through the allocation of Statutory Fishing Rights (SFRs) in the form of effort units. Operators are limited to setting a certain amount of gear and are restricted in the gear they can use. The fishery is moving to an individual transferrable quota (ITQ) system in March 2011, for which a commercial quota will be set on striped marlin.

There is also an important recreational fishery for this species which started on the southern New South Wales (NSW) coast in the 1930s. NSW tag and release data show that approximately 1500–2000 tonnes (Bromhead et al. 2004) of striped marlin are tagged and released each year. Further, the New Zealand recreational fishery catches an estimated 1000–1500 tonnes of striped marlin each year of which approximately 60% are tagged and released (Holdsworth and Saul 2003). Despite this data, it is uncertain how much is caught recreationally, as the above data are provided through the tournament monitoring programs only and don't include other recreationally caught fishes. Fisheries managers are yet to determine an appropriate way to collect information on the total recreational catches. Further, there is uncertainty of the post-capture mortality rates for this species (estimated at 0–24% from tag and release programs in the US; Holts and Bedford, 1990). It seems that it may vary with handling techniques (Bromhead et al 2004). As such, it is uncertain how significant the total recreational catch is.

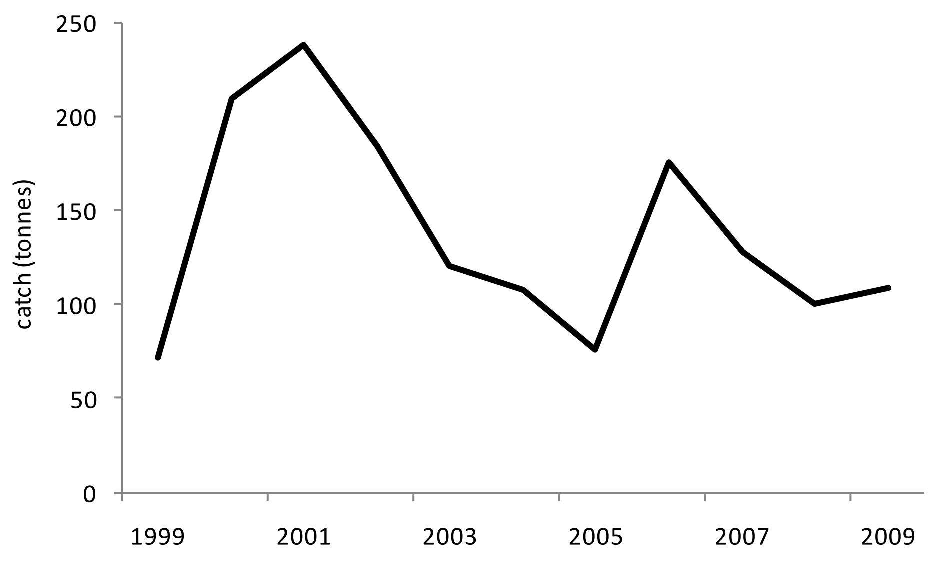

Figure 19.2. Commercial catch (tonnes) of striped marlin by year for south-eastern Australia. (Note: the striped marlin commercial fishery is managed by the Commonwealth. State recreational catches are not included in this figure.)

Key points:

- The commercial striped marlin fishery is managed under Commonwealth jurisdiction.
- Striped marlin is an important recreational species in SE Australia, predominantly NSW and Queensland.
- Recreational catch is unknown, but striped marlin is an important recreational species.
- In 2006–07 the total commercial catch was 267 tonnes with a GVP of $1.27.

19.2. Life history

19.2.1. Life cycle, age and growth

See Table 19.1 and Figure 19.3 for a summary of spawning information for striped marlin.

Striped marlin are broadcast spawners where females release batches of several hundred thousand mature oocytes into the water column which are externally fertilised by males (Ueyanagi and Wares 1975). Mature eggs are around 1.5 mm in diameter after they hydrate and expand 12–24 hours before spawning (Pers comm. R Kopf 2010).

Females are capable of spawning every 24 to 48 hours during a 90-day spawning period with a mean batch fecundity of approximately 3 million oocytes. Fecundity varies with size; however, a 100 kg female may produce between 12 million (based on four spawning events during a season) and 90 million hydrated oocytes (based on 30 spawning events over a season; Kopf 2010). Males have continual production of spermatozoa throughout a season (Bromhead et al. 2004).

Fertilised eggs hatch within one week and fish grow at a rate of 5–8 mm per day for the first six months. The transition from larva to post-larva (yolk sac reabsorbtion) occurs within the first couple of weeks. Gonads develop (juvenile photo) before six months of age but spawning doesn't typically occur until 2–3 years old. Little is known about the larval stage; however, larvae are probably active swimmers where prevailing ocean currents influence distribution of eggs and larvae (Kopf 2010).

Ninety five per cent of striped marlin mature between 1.9 and 3 years for females and 1.4 and 2 years for males. Kopf (2010) determined that although the size at which 50% of individuals were mature was recorded as 200 cm for females and 190 cm for males, the majority of mature striped marlin in their study were over 230 cm.

Kopf (2010) also found that there appeared to be a distinct lack of smaller female striped marlin in the SE Australia region around 220 cm. This may be due to small length classes of females residing in areas that are unknown and currently under-sampled.

In south-eastern Australia spawning and larval hatching generally occurs during late spring and the early summer months, peaking in November and December (Nakamura 1983; Kopf 2010). Spawning generally occurs in the South Coral Sea between 15° and 30° South (Figure 19.1; Kopf 2010; Bromhead et al. 2004). Samples of post-spawning females off the coast of New Zealand and south-eastern Australia in April suggest that limited additional spawning activity occurs later than January; however, it is uncertain where or when (Kopf 2010).

During the spawning season adults tend to migrate north, while juveniles appear to remain around the underwater ranges and seamounts (Kopf 2010). Striped marlin are generally a solitary species except when spawning and feeding (Holland 2003). Spawning events are often indicated by increased commercial catches of Striped Marlin (Kopf 2010).

Table 19.1: Life history parameters of striped marlin.

Life history parameter	Description
Longevity	Females: **8 years;** males: **7 years**
Age at Maturity (50%)	**Age:** females ~1.9 years; males ~1.4 years
Size at Maturity (50%)	**Size:** females ~2m; males ~1.9m
Maximum Size	**Females:** ~261cm lower jaw fork length (LJFL) and **Males:** ~249cm LJFL
Recruitment into the fishery	**Length:** ~1.9-2m LJFL **Age:** ~1.7-2.2 yrs. **Weight:** ~40kg trunked (the average weight of Striped Marlin caught by Australian longliners is ~90 kg whole weight)
Spawning season	October through January in the southern hemisphere. Concentrated spawning activity takes place during November–December in sparsely aggregated spawning grounds in the south Coral Sea between 15° and 30° S.
Fecundity	Females have been found to spawn between 4 and 60 times within a season, up to every 24-48 hours. Most recent work suggests spawning every three days however it is unknown if this occurs throughout the whole season. Batch fecundity is estimated at 3 million oocytes. Males have continual production of spermatozoa throughout the spawning period.
Growth	3.1mm per day for 1st year, 1.5mm/ day after 1 year. Males and females attain 75-80% of max body length during first two years.

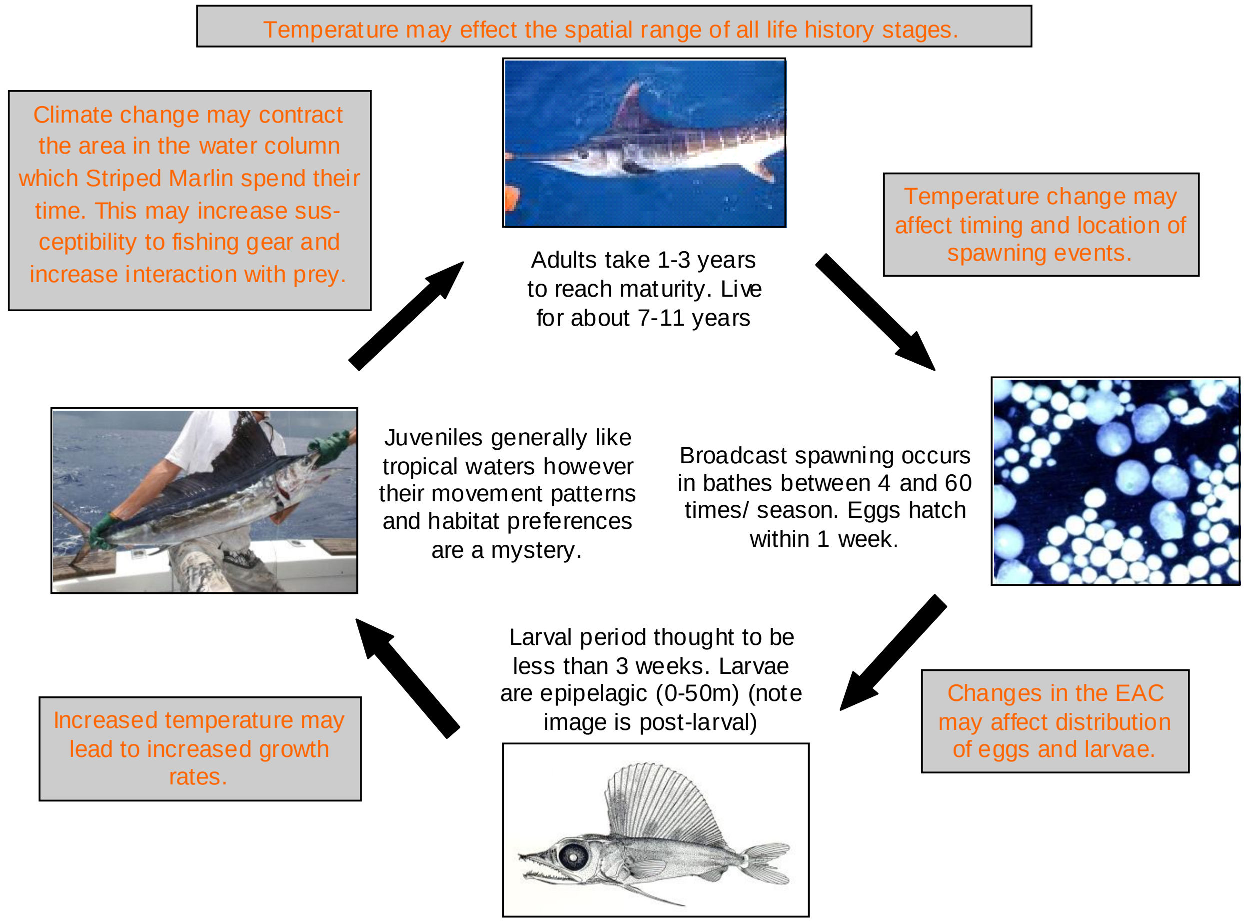

Figure 19.3: Potential effects of global warming on the life cycle stages of striped marlin.

19.2.2. *Distribution, habitat and environmental preferences*

Striped marlin are found on the east and west coasts of Australia (Figure 19.4). Molecular heterogeneity indicates the stock on the east coast of Australia is genetically distinct (McDowell and Graves 2008). Fishery boundaries of the south-west Pacific Ocean stock for stock assessment purposes include the area from the equator to 40°S and from 140°E to 130°W.

Archival satellite tagging data indicates striped marlin generally occur in <200 m depth, spend 75% of their time in the mixed layer of the ocean and 72% in the top 5 m (Sippel et al 2007, Holts and Bedford 1990). Striped marlin abundance increases with distance from the continental shelf and are usually only seen close to shore when there are deep drop-offs (Kopf 2010).

Spawning and feeding grounds in SE Australia are fairly distinct, with spawning generally occurring in the warmer tropical areas between 10°S and 30°S (Figure 19.1) and feeding in subtropical/temperate waters. Striped marlin in eastern Australia generally prefer temperatures less than 25°C, with 80% of their time being spent in waters ranging from 20.1 to 24 °C (Sippel et al 2007).

Spawning tends to occur in warm waters generally between 24 and 29 °C (Kopf 2010), often on the continental shelf in close proximity to sea mounts (Figure 19.1; Kopf 2010). This indicates spawning occurs in the warmest waters physiologically tolerated by the species and it is assumed that warmer temperatures maximise larval growth rates (Kopf 2010). Mature resting females and recovering females are commonly found in SE Australia and New Zealand, specifically in the fourth quarter of the year (Kopf 2010; Bromhead et al 2004).

Little is known about the larval stage; however, larvae are probably active swimmers where prevailing ocean currents influence distribution of eggs and larvae (Kopf 2010). Some larvae have been recorded in shallower waters and associated sea mounts. This may be due to better protection from predators and more available food sources (Nishikawa et al 1985).

Juvenile striped marlin are rarely encountered, but those that are appear to be restricted mainly to tropical waters. Their movement patterns and habitat preferences remain a mystery. It is possible they do migrate as juveniles as they have been reported on the continental shelf, near sea mounts, and in the open ocean off the coast of Queensland, Fiji, and French Polynesia (Kopf 2010).

Striped marlin depth may also be limited by temperature differences between the surface and depth. Studies show that they don’t like to descend to waters more than 5–8°C colder than the surface layer where they spend most of their time, regardless of the actual sea surface temperature (Holts and Bedford 1990 and Brill et al. 1993).

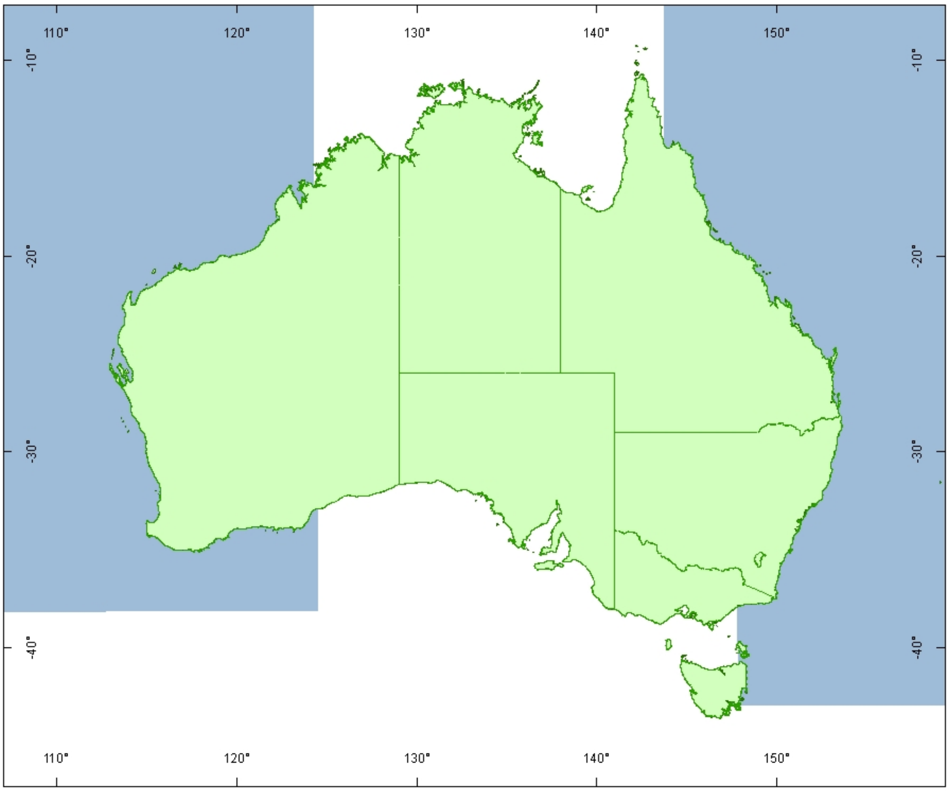

Figure 19.4: Distribution of striped marlin around Australia.

19.2.3. Predators and prey

Adult striped marlin are opportunistic generalist feeders that prey on species that inhabit the surface layers of the pelagic ecosystem (Bromhead et al 2004). In Australia, squid make up a large component of the diet as do lancetfish, clupeids and sauries. Studies suggest that trophic competition with other pelagic species is reduced due to the specific targeting that occurs for each species (Hunt and McKinnell 2006). There is some trophic competition between striped marlin and other pelagic species; however, evidence shows that striped marlin generally target species in the surface layer to mid-water depth, while the predatory behaviour of some other pelagic species means they target more in the mesopelagic layer (Hunt et al. 2006; Bromhead et al. 2004). Larvae and juvenile striped marlin have been found to consume phytoplankton (Wells and Rooker 2009) as well as small copepods and fish (Lipskaya and Gorbunova 1977).

There are likely few predators able to prey upon a full grown adult marlin except some of the large pelagic sharks and the toothed whales, especially the false killer whale. However, there are many predators of the earlier life stages including tunas, other pelagic fish such as dolphin fish, and marlin (Bromhead et al 2004).

19.2.4. Recruitment

Analysis of striped marlin data from the pelagic database (housed in Tasmania) for southern Queensland as well as information from Kopf (2010) indicates that striped marlin off eastern Australia have a single annual spawning cycle with spawning generally occurring continually between around September to December and with the resulting cohort recruiting the fishery around 10 months later when they weight around 11 kg. This annual spawning cycle is likely to be dependent on environmental triggers such as water temperatures.

Size at recruitment for striped marlin is somewhat complex. Although there are records of striped marlin caught in the ETBF with processed weights less than 10 kg, they generally have weights greater than 40 kg (trunked). The processed-to-whole weight relationship presently remains unknown for striped marlin landed in the ETBF; however R. Campbell (pers comm., August 2010) provided the following two estimates:

1. Using a conversion factor of 0.726 based on observer samples for headed and gutted swordfish landed in New Zealand the corresponding processed-weight-to-age relationships are shown in Figure 19.4. From this figure, fish with a processed weight of 40 kg are found to be around 2.2 years of age and can be taken as an approximate age-at-recruitment of striped marlin to the ETBF. The corresponding lower-jaw-to-fork length is around 2.0 m.

2. Using the relation Whole-weight=1.1788*(Trunked Weight)$^{0.9984}$ provided by R. Kopf (pers. comm. March 2009), fish with a processed weight of 40 kg are found to be around 1.7 years of age and can be taken as an approximate age-at-recruitment of striped marlin to the ETBF. The corresponding lower-jaw-to-fork length (LJFL) is around 1.9 m.

It remains unknown how the trunked weights used by R. Kopf relate to the manner in which striped marlin are landed in the ETBF (generally headed and gutted) and so some uncertainty remains as to which of the two estimates above is more accurate.

This size and weight at recruitment for the ETBF is substantially larger than the average recruitment for other western Pacific striped marlin fisheries where length of 86 cm LJFL and whole weight of 4.2 kg is recorded. These other fisheries include many artisanal fleets in archipelagic waters and are areas where smaller striped marlin occur. The average weight of striped marlin caught by Australian longliners is ~90 kg whole weight.

Key points:

- Striped marlin have an annual single spawning season which is continuous from the months of September to December.
- Striped marlin are epipelagic occurring mainly around the continental shelf from 0–200 m depth (predominantly <40 m).
- Sexual maturity generally occurs between 1.9 and 3 years.
- Spawning typically occurs in warm waters (24–29°C between 10°S and 30°S).
- Opportunistic generalist feeders, preying on small fish and cephalopods.
- Recruitment into the fishery is estimated at 40 kg trunked weight, 1.9 – 2m LJFL and 1.7 – 2.2 years.

19.3. Current impacts of climate change

There is little information documenting current effects of climate change on striped marlin specifically. However, information on other pelagic species has shown that they are most likely to be affected by changes in ocean temperatures, currents and nutrient upwelling (Griffiths et al 2010) which will likely affect patterns in recruitment, growth rates, distribution, abundance and predator-prey relationships.

Off the east coast of Australia, striped marlin prefer 24–25°C water (SST) and areas bordering the EAC. Oceanographic evidence shows that the EAC has moved further south over the past 60 years with changes to ocean temperature and salinity (Ridgeway 2007; Hobday et al 2008). The southern extent of the EAC is expected to further move around 180 km over the next 30 years (Mcgllorm 2008). This will likely change the distributional range of the striped marlin and other pelagic species, including tropical tuna, whose southward distributional range is generally limited by the extent of the EAC warm water eddies (Mcgllorm 2010). It will also likely affect spawning grounds and recruitment, as striped marlin generally spawn in the warm waters bordering the EAC. This may mean that some of the striped marlin stock moves out of Australian jurisdiction and into New Zealand waters, affecting the Australian fleet’s access to this species.

Key points:

- Evidence over the last 60 years has seen an increase in the extent of the EAC southward and increasing temperatures of the east coast of Tasmania.
- Models have shown that the greatest effects of climate change on pelagic species is likely to be ocean temperature and changes to the EAC.

19.4. Sensitivity to change

If the EAC continues to move southward and sea temperatures continue to increase, it is possible the striped marlin stock will move southward to maintain habitat in its optimal temperature range. Similarly, the area and time of spawning may change with changes to temperature. This could cause an expansion of the stock; however, considering the upper temperature limits of the species (~29°C SST) the whole stock is more likely to shift in a southerly direction. As the stock is under Commonwealth jurisdiction, movement should have minimal effect on management. It may, however, affect fleet management and home ports, having an economic impact on fisheries. Further, if southward movement of the stock is extreme, a portion of the stock may move into New Zealand jurisdiction, which may affect Australian operators' abilities to catch the stock. There are already records of some mature resting and recovering females in this region.

Research in the Gulf of Mexico indicates that the amount of available habitat in the water column may also reduce with increased ocean stratification which is predicted to occur with climate change (Prince and Goodyear 2006). It is uncertain if this will also occur in the SWPO; however, effects would likely increase fishes susceptibility to surface fishing gear, as striped marlin generally spend ~75%of their time in the mixed layer (Bromhead et al 2004). This change may also increase interactions with prey as they share the same preference for area of the water column which may be restricted in size (Prince and Goodyear 2006).

Finally, if southern waters begin to warm, there is a possibility that there may be increased mixing between stocks via the southern ocean between the SWPO and east Indian Ocean stocks.

Key points:

- Evidence suggests that pelagic species may shift their range southward with changes in temperature.
- Spawning grounds and times may change with temperature changes.
- Contracted depth range due to stratification may increase susceptibility to surface gear.
- Interactions with prey may increase due to contracted depth range

19.5. Resilience to change

Striped marlin are a migratory species and have the ability to change their distribution with changes in water temperature. This will offer some protection to the species; however, changes may affect the economic viability of the Australian striped marlin fishery if the fishery contracts within Australian jurisdiction.

Striped marlin's generalist feeding behaviour will also allow them to adapt somewhat to changes in prey availability.

Despite the relatively rapid growth rate, early maturity, and high fecundity of striped marlin, there is some uncertainty over the resilience of the species to fishing pressure and thus climate change in the SWPO.

Key points:

- Striped marlin are highly migratory giving them the ability to change distribution to stay in optimal habitat.
- Generalist feeding behaviour may make them more adaptable to changes in prey.

19.6. Ecosystem level interactions

High level trophic species such as striped marlin have a generalist diverse diet and make up only a small portion of the biomass (<1%). As such, they are predicted to have minimal effect on the trophic food chain, as increases or decreases in striped marlin are predicted to be balanced by other pelagic predators (Griffiths et al. 2010). However it is considered they may be affected by changes in the food chain at lower trophic levels. Past La Niña events (warming) have been linked to the disappearance of krill (Young et al. 1993), a species that is at the base of Tasmanian shelf food chains; thus reductions in abundance of krill are likely to affect krill-dependant food chains such as cephalopods and in turn pelagic fishes.

Pecl and Jackson (2008) found that warmer water temperatures cause squid to hatch out smaller and earlier, undergo faster growth over shorter life spans and mature younger and at a smaller size. They also found that individual squid required more food per unit body size, require more oxygen for faster metabolisms and have a reduced capacity to cope without food. Squid are an important part of the pelagic food chain and a major food source for striped marlin. As such, changes in squid abundance may affect striped marlin. That said, it is possible squid will move their distributional range similarly to striped marlin to allow maintain optimal temperatures ranges.

Key points:

- Striped marlin abundance may have minimal effect on low trophic levels, as they are thought to be easily replaced by other pelagic species.
- Changes to lower levels in the food chain are predicted with climate change (krill) which may affect the food chain for striped marlin.

19.7. Additional (multiple) stressors

The first, and most recent, assessment on striped marlin was undertaken in 2006 by the Bureau of Rural Sciences (BRS) and the SPC (Griffiths et al. 2010). Stock assessment inputs had some uncertainty around natural mortality and growth. The report records the status of the striped marlin stock as unknown as to whether it is overfished or if overfishing is occurring. The status report indicated that it is plausible that current fishing mortality equalled or exceeded F_{MSY}.

If the stock moves south, it is uncertain of the effects of sub-surface topography, as larvae and spawning individuals currently reside in these areas. Larvae are thought to have better availability of prey and protection from these sites. If new topography isn't present if the stock shifts southward, this may affect growth and mortality rates.

The other significant stressor on the striped marlin stock is the uncertainty in the recreational catches as discussed above. Without a certain estimate of catch, this information cannot be included into stock assessments and catch limits for the species.

Key points:

- Stock status is uncertain as per 2008 BRS Status Report.
- Growth and mortality rates may be affected if new sub-surface topography can't be found with distributional changes.
- Levels of mortality from recreational fishing are unknown.

19.8. Critical data gaps and level of uncertainty

There is little known about the larval and juvenile stages of striped marlin. Further, there has been found to be a distinct lack of juveniles and smaller females (~220 cm size) in the SWPO region. With uncertainty of the location of these life stages, it isn't possible to determine the effect of climate change.

Further information is required about the importance of sub-surface habitat such as sea mounts as spawning grounds and protective areas for larvae. This gap makes it difficult to fully know the effects that changing distribution may have on the stock. There is also little information on the effect of ocean acidification and UV on pelagic species. The most likely effect would be to the trophic chain and a possible UV effect on eggs.

Despite the relatively rapid growth rate, early maturity, and high fecundity of striped marlin, there is some uncertainty over the resilience of the species to fishing pressure in the SWPO.

There are also significant knowledge gaps in recreational catch figures and the post release survival rates of the species. With catches of at least 1500 tonnes estimated, this is not an insignificant catch of striped marlin by the recreational sector. More work should be undertaken to produce more accurate estimates of total catch and mortality. This will allow sensitivity to climate change to be more appropriately considered.

Key points:

- There is limited information on the larval and juvenile stages.
- Impacts of ocean acidification and increasing UV are uncertain.
- The distribution of smaller females in the SWPO region is unknown.
- Total mortality from recreational fishery uncertain.

Table 19.2: Summary of striped marlin species profile, which also indicates level of certainty of the associated information. Level of certainty is divided into high (H) = strong clear evidence, backed by several studies with solid datasets with little confounding interactions; medium (M) = evidence supported by one or more studies, conclusions may be partially ambiguous or confounded; low (L) = anecdotal evidence, limited data and/or predicted conclusions based on theoretical knowledge.

Life history stage	Multiple stressors	Distribution	Habitat	Predators and prey	Current impacts	Predicted impacts	Ecosystem interactions	Data gaps
Eggs	Unknown.	See figure 1 – spawning area (M).	Pelagic (M).	Predators: Pelagic fish such as Dolphinfish (L).	Unknown. Little current research.	Distribution may be effected through changes EAC (M).	Unknown.	Effect of UV on Striped Marlin eggs.
Larvae		Little is known about larval distribution. Some recorded in shallower waters around seamounts. (M)	Pelagic (M)	Predators: Pelagic fish such as Dolphinfish. Prey: plankton and small/ larval copepods and fish (M).	Unknown. Little current research.	Distribution may be effected through changes EAC (M).	May be effected by changes to food sources at lower trophic levels (L).	Little is known about larval stage (M).
Juveniles		Little is known of distribution of juveniles in SE Australia stock (L).	Pelagic (L).	Predators: toothed whales, large pelagic sharks. Prey: plankton and small/ larval copepods and fish (M).	Unknown. Little current research.	Increased temperature may increase growth rates. This may be minimal as species is likely to shift (L).	May be effected by changes to food sources at lower trophic. levels (L).	Little known about this stage (M).

Adult	Exploited, 267 tonnes caught in 2008, fishery status is uncertain (M). Effect of recreational fishing catch unknown (M).			Predators: toothed whales, large pelagic sharks (M). Prey: cephalopods and fish (H).	Unknown. Little current research.	Distribution may be effected through changes EAC currents and water temperature. Most likely cause economic effects to Australian fleet rather than risk to stock (H). If mixed layer contacts (due to winds/ currents etc) where Striped Marlin reside, susceptibility to fishing may increase (L).	May be effected by changes to food sources at lower trophic levels such as squid (L).	Importance of sub-surface topography. Total recreational catches uncertain.

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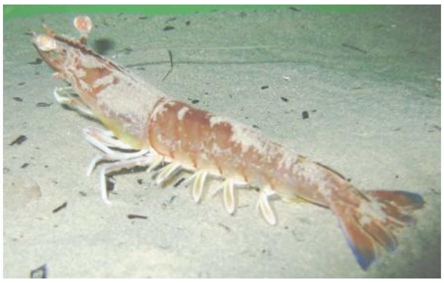
20. Western king prawn *Penaeus latisulcatus*

Author: Cameron Dixon



20.1. The fishery

The South Australian prawn fishery is a single species fishery that targets the western king prawn (*Penaeus (Melicertus) latisulcatus*) (WKP). In 2008–09 it was South Australia's (SA) second highest value wild fishing industry, with 2188 tonnes harvested estimated to be worth $34.2 million (Figure 20.1). It is a limited entry fishery, currently with 52 licence holders separated into three regions: Gulf St Vincent, Spencer Gulf and West Coast (Figure 20.2). Prawns are harvested at night using demersal, otter-trawl, double-rig gear (Figures 20.3 and 20.4). Considerable technological advancements have been made in the fishery including the use of 'crab bags' to exclude mega-fauna by-catch, 'hoppers' for efficient sorting of the catch and rapid return of by-catch to the water, and 'graders' to sort the prawns into marketable size categories (Figures 20.3 and 20.4). Many vessels in the prawn fleet are 'factory vessels' that process the catch on-board.

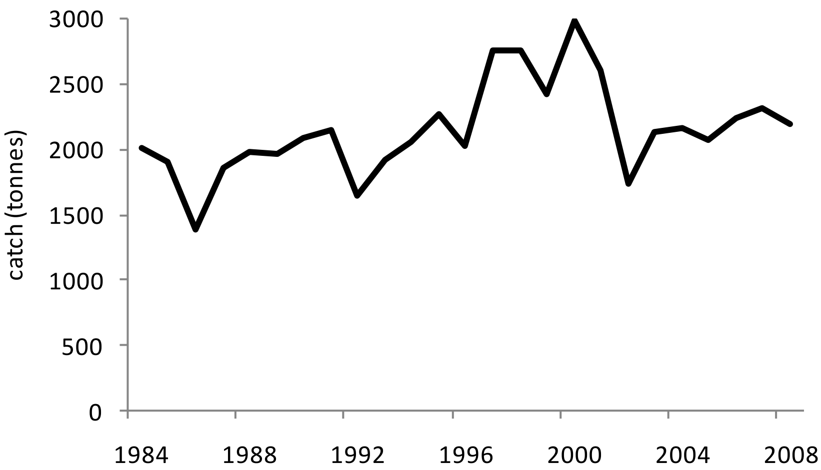


Figure 20.1: Commercial catch of western king prawn (tonnes) by year for SA.

Trawling activities are banned during daylight hours and must be conducted in waters >10 m depth. Effective effort (fishing power) is restricted by gear restrictions including vessel size and power, type and number of trawl nets towed, maximum headline length and minimum mesh sizes. Effort is restricted both spatially and temporally throughout the fishing year by closures. These closure lines, also referred to as 'harvest strategies', are determined separately for each fishing month on the basis of data collected during fishery-independent and fishery-dependent surveys. Harvest strategies are determined collaboratively between government and industry. For the Spencer Gulf and Gulf St Vincent fisheries there are generally six fishing periods within each fishing year. Each fishing period lasts a maximum of 18 nights from the last to first quarters of the moon in November, December, March, April, May and June. In contrast, the oceanic West Coast Prawn Fishery harvests the majority of its catch during winter months. Fishing is generally conducted during March, April, June to September, November and December.

The three regions from which prawns are harvested are managed separately by Primary Industries and Resources South Australia (PIRSA) under the framework provided by the *Fisheries Management Act 2007*. General regulations for SA's prawn fisheries (commercial and recreational) are described in the Fisheries (General) Regulations 2000, with specific regulations located in the Scheme of Management (Prawn Fisheries) Regulations 2006. These three documents provide the statutory framework for management of the fishery.

Significant recreational catches of *P. latisulcatus* are precluded by current fisheries regulations that require recreational prawn catches to be taken from waters >10 m in depth using hand held nets. Levels of indigenous and illegal fishing are considered negligible (Anon 2003).

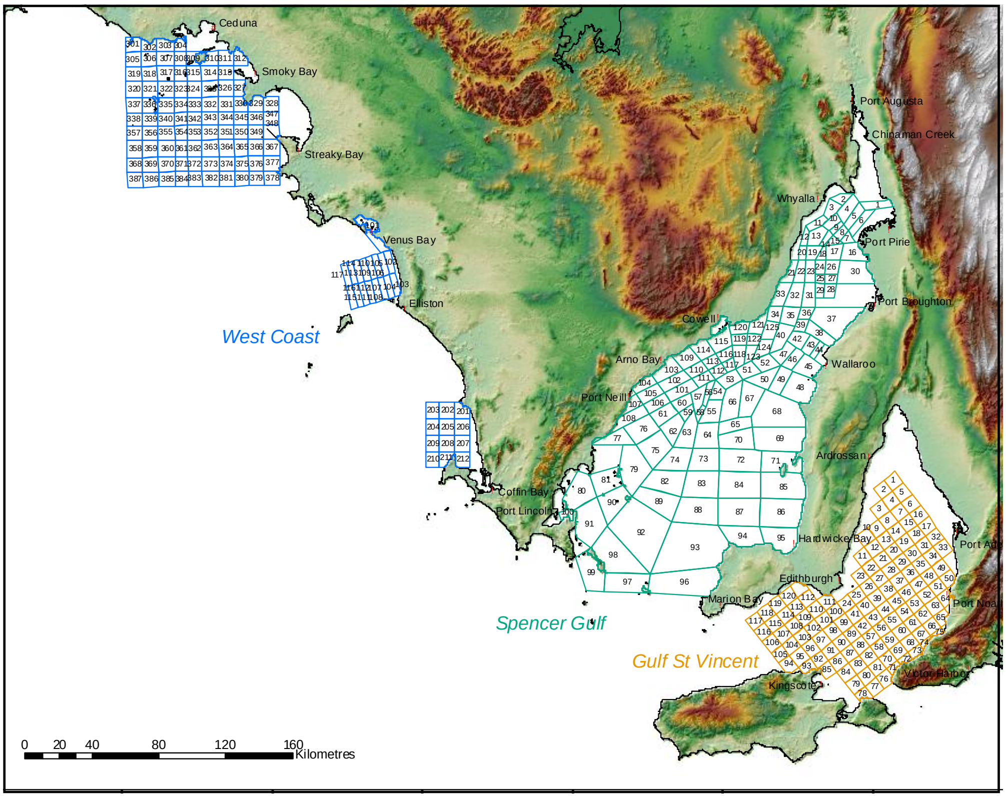


Figure 20.2: Location of South Australia's three commercial prawn fisheries.

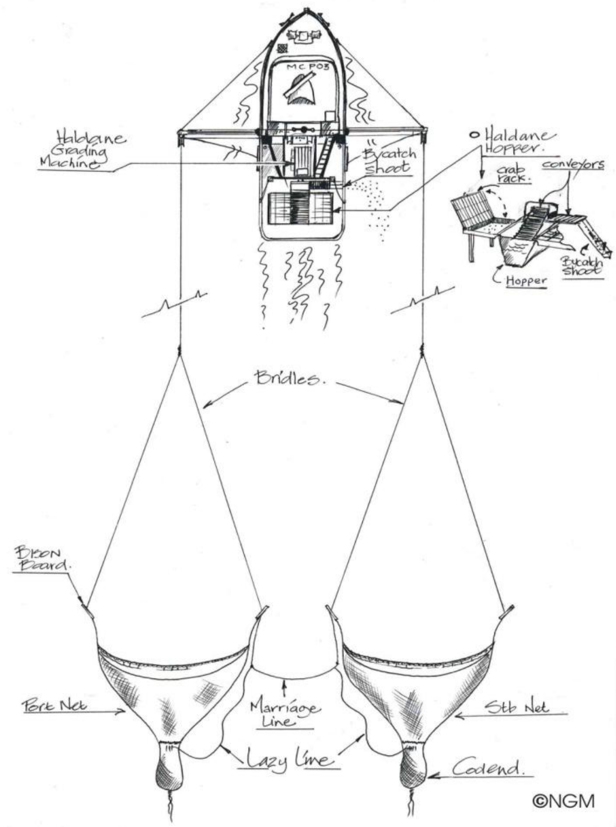


Figure 20.3: Double rig trawl gear and location of hopper sorting and prawn grading systems used in the Spencer Gulf Prawn Fishery.

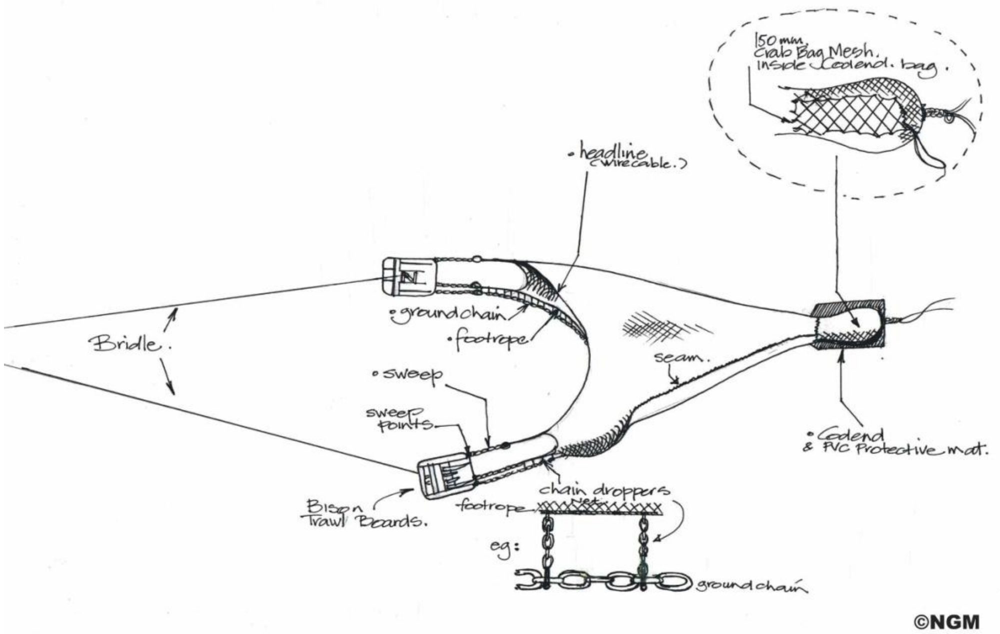


Figure 20.4: Trawl net configuration showing trawl boards, head rope, ground chain and cod end with crab bag.

Key points:

- South Australia's three prawn fisheries targets the western king prawn, *Penaeus (Melicertus) latisulcatus* and collectively are South Australia's second most valuable wild fishing industry ($34.2 million in 2008–09).
- Considerable technological advancements have been made including the development of 'hoppers', 'crab bags' and 'graders'.
- Fishing effort is restricted through a series of temporal and spatial fishing closures termed 'harvest strategies'.

20.2. Life history

20.2.1. Life cycle, age and growth

Adult WKP aggregate, mature, mate and spawn in deep water (>10 m) between October and April, with the main spawning period between November and February. *P. latisulcatus* has an offshore adult life and an inshore juvenile phase (Figure 20.5). The length of the larval stage depends on water temperature, with faster development in warmer water (Hudinaga 1942). SARDI unpublished data from FRDC project 2008/011 'Prawn and crab harvest optimisation: a biophysical management tool' demonstrate that the larval period varies from 15 days at 25° C to 34 days at 17° C (Table 20.1). This was determined by spawning wild-caught female prawns from Spencer Gulf and raising larvae at different temperature regimes under laboratory conditions. It had previously been suggested that the larval period of *P. latisulcatus* in Spencer Gulf could exceed 40 days, where water temperatures over the main spawning and larval period range from 19 to 25° C (after Shokita 1984, cited in Carrick 2003). Prawn larvae are generally dispersed by wind-driven and tidal currents (Carrick 2003). Latitude, water temperature and salinity all influence the distribution and abundance of larvae (Carrick 2003). Larval densities vary significantly among years, probably due to differences in environmental conditions and spawning stock status. Prawns undergo a series of moults to increase their size incrementally. The shedding of hard body parts during moulting means that the age of individuals cannot be reliably determined. The inability to directly age prawns has increased the reliance on tag-recapture and cohort analysis for the determination of growth rate.

Table 20.1: *P. latisulcatus*, larval duration reared at four different water temperatures (SARDI unpub. data).

Temperature	17°C	20°C	22.5°C	25°C
Larval duration	34 days	22 days	17 days	15 days

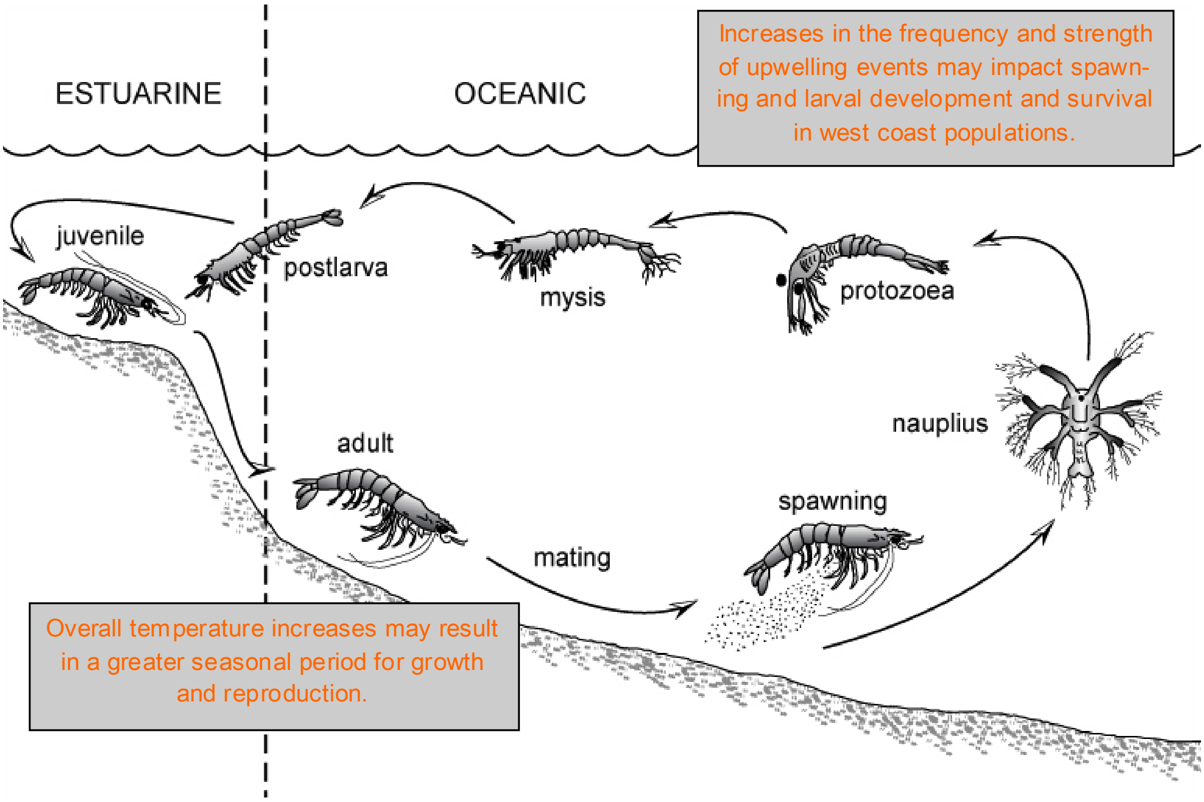


Figure 20.5: Summary of life cycle (this section), and points of exposure to relevant climate change drivers or known impacts (subsequent sections).

Male WKP grow slower and attain a smaller maximum size than females (Table 20.2). Maximum growth rates occur during late summer and autumn, and growth is negligible from July to December. Growth estimates from Spencer Gulf are compared to those estimated from GSV and the West Coast Fishery in Table 20.2. Kangas and Jackson (1997) estimated growth rates from 464 tag-recaptures in GSV while in the West Coast Prawn Fishery growth was estimated from 510 tag-recaptures as well as from length-frequency cohort analyses (Wallner 1985).

Seasonal growth and differences between genders were evident in each fishery. Prawns in Spencer Gulf attained a similar size to GSV prawns, although a slower growth rate was evident for male prawns in GSV. Also, prawns in both gulfs attain a greater size and growth rate than their west coast counterparts. Whilst this may be an artefact of the uncertainty associated with west coast prawn growth estimates (Dixon and Roberts 2006), growth may be slower due to the cooler summer water temperatures of the West Coast's oceanic environment.

Table 20.2: Sex-specific growth parameters for *P. latisulcatus* estimated from tag-recapture and cohort analysis in the West Coast (Wallner 1985) and from tag-recapture in Spencer Gulf (Carrick 2003) and Gulf St Vincent (Kangas and Jackson 1997).

Fishery	Method	Sex	Growth parameters	
			K (yr^{-1})	L_∞ (mm)
West Coast	Cohort	Male	0.73	44.1
		Female	0.88	53.9
West Coast	Tag	Male	0.83	39.4
		Female	0.36	60.4
Spencer Gulf	Tag	Male	0.86	46.1
		Female	0.61	64.0
GSV	Tag	Male	0.62	47.2
		Female	0.54	65.3

Key points:

- The main spawning period for western king prawns in South Australia is November to February.
- The duration of the larval stage depends on water temperature; 15 days at 25°C and 34 days at 17°C.
- Prawns undergo a series of moults to increase their size incrementally.
- Males grow slower and attain smaller maximum sizes than females. Maximum growth rates occur during late summer and autumn, and growth is negligible during winter and spring.

20.2.2. *Distribution and habitat*

P. latisulcatus, is distributed throughout the Indo-west Pacific (Grey et al. 1983). Its distribution in SA is unique, as it is at its lowest temperature range, restricted to waters of Spencer Gulf and Gulf St Vincent and along the west coast including the commercially fished areas of Ceduna, Venus Bay and Coffin Bay (Figure 20.6).

The western king prawn is a benthic species that prefers sandy areas to seagrass or vegetated habitats (Tanner and Deakin 2001). Both juvenile and adult prawns show a strong diel behavioural pattern of daytime burial and nocturnal activity (Rasheed and Bull 1992; Primavera and Lebata 2000). Strong lunar and seasonal differences in activity are also exhibited, where prawn activity (and catchability) is greater during the dark phase of the lunar cycle and during warmer months. The distribution and abundance of *P. latisulcatus* within gulfs and estuaries is affected by salinity and the presence of sandy substrate (Potter *et al*. 1991). Higher abundances are associated with salinities above 30‰ (Potter et al. 1991). Juvenile *P. latisulcatus* are more efficient osmoregulators than adults, tolerating greater variation in salinity.

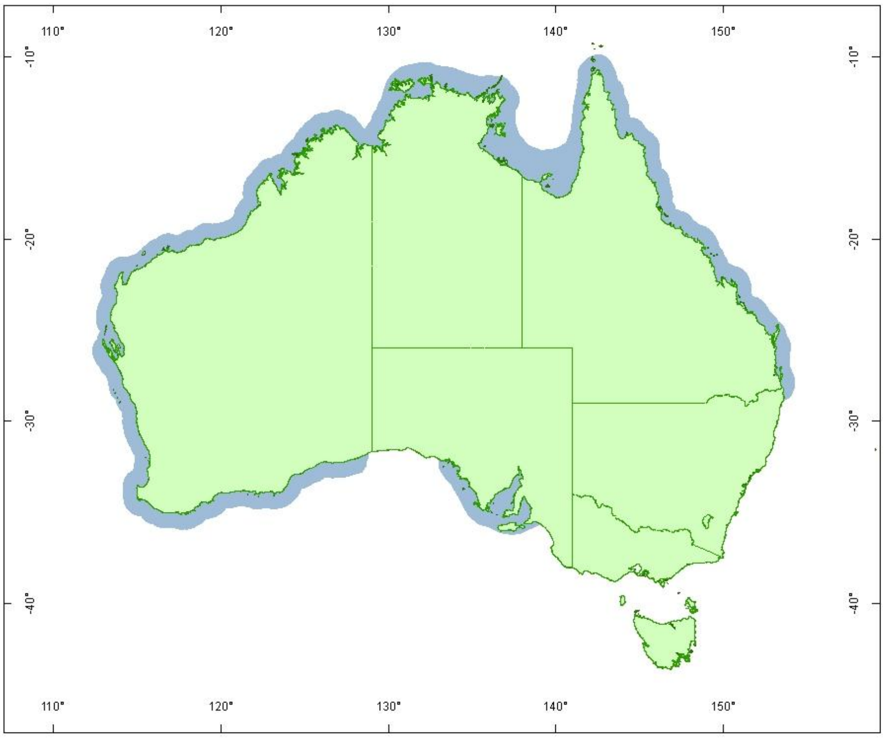


Figure 20.6: Distribution of western king prawn.

Key points:

- Western king prawns are distributed throughout the Indo-west Pacific but are found at their lowest temperature in South Australia.
- They are a benthic species that prefer sandy or muddy substrates.
- Activity is influenced by daylight, lunar phase and water temperature.

20.2.3. Predators and prey

There is little information on the diet of WKP in SA. In general they are known to be scavengers, herbivores or detritus feeders, and are important in recycling organic matter. In a study of the by-catch species of the Spencer Gulf Prawn Fishery (Currie et al. 2009), *P. latisulcatus* was the second most abundant species captured, and the third highest in terms of biomass. As a highly abundant primary consumer, it is therefore reasonable to assume that *P. latisulcatus* is a very important component of the tropho-dynamics of the Spencer Gulf community. Of 132 fish species collected in the by-catch study, over half of all fish species examined from Spencer Gulf contained some combination of crabs, prawns and amphipods (Currie and Sorokin 2010).

Key points:

- Western king prawns are scavengers that are important in recycling organic matter.
- Their high abundance and low trophic order suggest that they are a particularly important component of the tropho-dynamics of South Australia's gulf systems.

20.2.4. *Recruitment*

The recruitment processes for the two gulf fisheries are well understood. Post-larvae settle in inshore nursery areas when 2–3 mm carapace length and can remain there for up to 10 months, depending on the time of settlement (Carrick et al. 1996). The post-larvae produced from early spawning events settle in nursery areas during December or January where they grow rapidly before emigrating to deeper water in May or June. Alternatively, post-larvae produced from spawning after January settle in nurseries from March and then grow slowly. They 'over-winter' in the nursery areas before recruiting to the trawl grounds in February of the following year (Carrick 2003). The effect of over-wintering on adult growth and survival are unquantified.

Key points:

- Recruitment of western king prawns to the two gulf fisheries are well understood.
- Recruitment to the West Coast fishery is highly variable and poorly understood. Recent studies suggest that recruitment success is highly dependent upon oceanic conditions.

20.3. Current impacts of climate change

The intuitive response to the current and potential impacts of climate change for *P. latisulcatus* in SA is deemed positive, particularly for the favourable climatic change of increased water temperate. However, there is some uncertainty regarding the impact of climate change on the oceanographic patterns of water movement that are critical to larval advection and adult movement. The impact of climate change on ocean systems is particularly important for the West Coast Prawn Fishery, which has a fluctuating catch history that likely reflects variation in recruitment. There is some evidence to suggest that recruitment to the West Coast Fishery is negatively affected by upwelling events associated with El Niño years (Carrick 2007). It also appears that these upwelling events have become more frequent and severe in recent years, a likely result of climate change. A current FRDC project (FRDC 2008/011) is being conducted that incorporates biological and hydrodynamic models for Spencer Gulf with the aim of improving the understanding of the stock/recruitment relationship for the prawn and blue crab fisheries. One of the aims of the project is to provide insight into the effects of increases in water temperature on larval advection and settlement for both species. A source of uncertainty for prawn species, particularly in the two gulf systems, is the effect of climate change on seagrass habitats. Although it is known that prawns feed on detritus, the importance of seagrass for prawns in South Australia is poorly understood.

Key points:

- The intuitive effect of climate change is deemed to be positive for the two gulf prawn fisheries due to increases in water temperature that increase the duration of the growing season. The major uncertainty is the indirect effect of possible loss of seagrass habitat.
- The current effects of climate change on the West Coast prawn fishery are believed to be negative, as recent increases in strength and frequency of upwelling events associated with more frequent El Niño events may have increased variability in recruitment to the fishery.

20.4. Sensitivity to change

The primary sensitivity to climate change is likely to occur for the West Coast Prawn Fishery if the frequency and strength of upwelling events increases during the spawning and larval advection period. There are three likely sources of sensitivity to an influx of cold water from upwelling events. First, normal reproductive capacity (i.e. the production of gametes) may be adversely affected as prawns are likely to remain buried in the substrate to avoid these conditions and thus will not obtain the nutrients needed for gamete production. Second, spawning activity may be directly affected in the same manner. Finally, larval development would be affected, with the possibility of mass larval mortality if the upwelling events reached the upper levels of the water column.

Key points:

- For the West Coast fishery, further increases in the strength and frequency of upwelling events associated El Niños are likely to increase the probability of recruitment failure to the fishery through several possible pathways:
    - Cold water upwellings may affect the reproductive capacity of the population.
    - Cold water upwellings may affect the spawning behaviour of the population.
    - Cold water upwellings may increase larval mortality.
    - El Niño events can influence tidal strength and direction which may in turn influence larval advection pathways to nursery habitats.

20.5. Resilience to change

As WKP in SA are at the southern extent of their range, increases in water temperature are likely to be favourable. This may result in a greater period of growth and reproduction, which is seasonal in SA, unlike most other regions that are in tropical environments (Figure 20.6).

Higher abundances of prawns are associated with salinities above 30 ‰ (Potter et al. 1991). SA's gulf environments are inverse-estuaries, meaning that they are hyper-saline environments. In the northernmost reaches of Spencer Gulf the salinity at depth can reach 49‰ (Nunes and Lennon 1986), while the salinity in the tidal flats associated with juvenile habitats can reach 55‰ (Carrick 1982). Although the upper salinity tolerance is unknown for adult western king prawns, they do occur at high abundance in the upper reaches of Spencer Gulf. Thus, whilst there is some uncertainty on the effects of increases in salinity associated with climate change, it is likely that adult prawns would be quite robust to this change. If sensitivities were evident, they would likely occur in the northern most reaches of Spencer Gulf first. Juvenile *P. latisulcatus* are more efficient osmoregulators than adults, and can tolerate greater variation in salinity. Thus they are likely to be more resilient to change than adults.

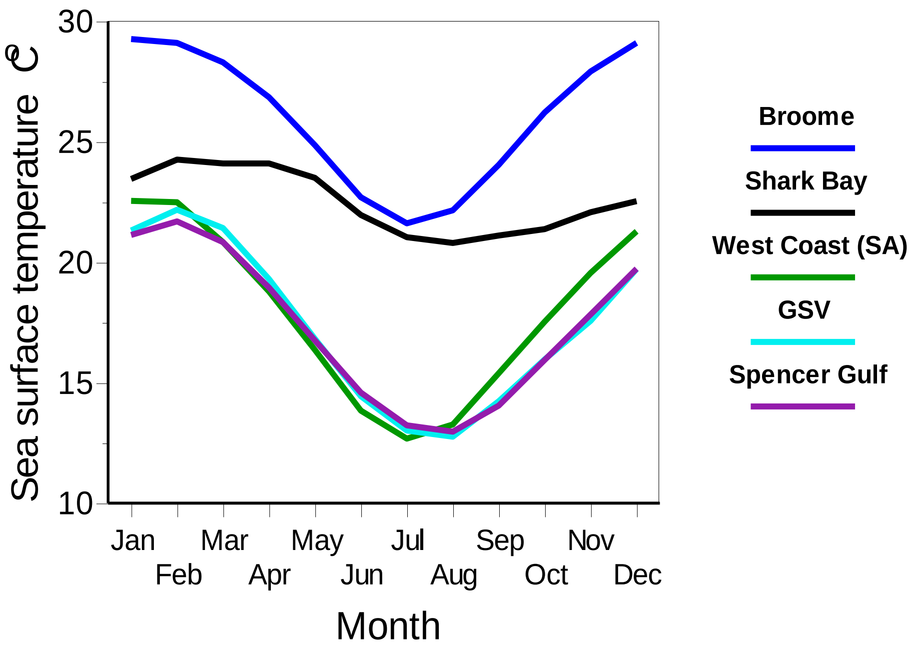


Figure 20.6: Comparison of mean monthly sea surface temperature (SST, °C) for the Australian prawn fisheries that target *P. latisulcatus*.

Key points:

- As western king prawns are at their southernmost distribution in South Australia, they are likely to be resilient to increases in water temperature.
- It is likely that western king prawns would also be resilient to increases in salinity associated with climate change.

20.6. Ecosystem levels effects

Under an assumption of no substantial change in the biomass of prawns as a result of increases in water temperature and salinity for the two gulf systems, potential ecosystem effects may result from changes in the abundance of predator communities or changes in the distribution and abundance of seagrass habitats. The biomass that supports the West Coast Prawn Fishery has fluctuated substantially throughout the fishery's history, including two periods of stock collapse. Thus, while a repeated stock collapse would undoubtedly create ecosystem shifts, such shifts have already been experienced within these communities. There was no evidence of obvious ecosystem changes during previous stock collapses.

Key point:

- Assuming no change in prawn biomass, likely ecosystem level effects are limited to changes in the abundance of predators and/or seagrass habitats.

20.7. Additional stressors

Exploitation

SA's two gulf prawn fisheries are managed sustainably under stringent harvest strategy criteria established in formalised Management Plans (Dixon and Sloan 2007a,b). The Spencer Gulf Prawn Fishery has a long history of stable catches (>40 years) and sound research including fishery-independent surveys. In contrast, the Gulf St Vincent has suffered two periods of significant stock decline. However, in 2004 the fishery embarked on a strategy for stock recovery underpinned by consistent fishery-independent surveys. This strategy has led to considerable increases in both biomass and commercial catch (Roberts et al 2009). The West Coast Prawn Fishery has a history of stock collapse and recovery. While exploitation rates do influence the sustainability of the fishery, PIRSA Fisheries have defined the fishery as 'environmentally limited' to acknowledge the impact of the environment on recruitment variability. This variability does make the fishery highly sensitive to levels of exploitation.

Pollution and habitat degradation

A number of anthropogenic factors may cause environmental degradation, resulting in negative effect on marine species (Highsmith et al. 1996; Hooten and Highsmith 1996; Stekoll et al. 1996; Carman et al. 2000; Huntingford et al. 2006) (Table 20.3). Environmental stressors can substantially increase the risks associated with spread of disease and pests, and push species towards their physiological thresholds. These are limiting factors in marine animal populations, although generally overlooked in fisheries management (Harvell et al.

2004). These issues are of particular relevance to the sustainability of fisheries located within SA's semi-enclosed and isolated gulf systems, although this area of research is limited for these regions.

Inter-tidal sand/mud flats, associated shallow water environments (including seagrass meadows) and mangrove forests in SA's gulfs are important juvenile nursery habitats for a number of commercially and recreationally important species. These coastal habitats are highly susceptible to anthropogenic coastal impacts such as oil spills, acid sulphate soil disturbance from coastal development, heavy metals, wastewater and stormwater discharge. In upper Spencer Gulf, several key industrial complexes have discharged large amounts of heavy metals and nutrient rich water into the coastal environment for decades (Harbison 1984; Tiller et al. 1989; Ross et al. 2003; Corbin and Wade 2004.). Trace metals subsequently enter the food web, and may have lasting effects on the physiology, reproduction and survival of local marine organisms (Ward 1982). Further, coastal discharges can negatively affect seagrasses (Ward 1987; Bryars 2003), with losses previously reported in the region (Seddon et al. 2000). While oil spills from shipping within SA's gulfs are rare events, when they do occur the consequences can be catastrophic and directly affect economically important species (Wardrop et al. 1993; Roberts et al. 2005).

Acid sulphate soils exist along SA's coastline, and may be disturbed by coastal developments and dispersed and augmented by rainfall (SA Coast Protection Board 2003). In Gulf St Vincent, acid sulfate discharge has been identified as a major cause of habitat degradation, including mangrove dieback at St Kilda and contaminated tidal flats in the Barker Inlet (Edyvane 1999; SA Coast Protection Board 2003). Disturbance of these soils have previously been attributed to massive mortalities of fish, crustaceans, shellfish and other organisms, affecting both coastal aquaculture and fisheries (Russell and Helmke 2002; SA Coast Protection Board 2003). Resultant acidic waters enhance the breakdown of metal-bearing sediments, and increase trace metal concentrations in the environment. Stock collapse of the Australian bass (*Macquaria novemaculeata*) in NSW, due to recruitment failure, has been partially attributed to acid sulfate discharge (Harris 1989).

Table 20.3: Environmental degradation, as a result of human activities, identified by Huntingford et al. (2006) that potentially compromise fish health and welfare.

Activity	Examples of potential effects on welfare
Environmental degradation	• Reduced availability of natural food. • Introduction of exotic species into existing fish communities. • Habitat modification, creating (*e.g.*) sub-optimal hydrological regimes. • Loss of or displacement from natural habitats. • Reduced population densities (or crowding) and abnormal social experiences. • Disturbance through tourism. • Acute and chronic exposure to pollutants and litter.

Key points:

- Prawn fisheries are highly sensitive to exploitation rates. South Australia's three prawn fisheries have very different catch histories that reflect either different approaches to exploitation or the different environments prawns inhabit.
    - Spencer Gulf has a stable catch history based on sound management practices that are underpinned by a long history of research surveys.
    - Gulf St Vincent has suffered periods of increasing and declining catch. Recently the introduction of harvest strategies developed from consistent research surveys has facilitated the beginning of stock recovery.
    - The west coast fishery is environmentally limited due to the highly variable nature of recruitment to the fishery.
- All three fisheries are susceptible to environmental degradation, especially in their nursery habitats. This is particularly the case for the two gulf fisheries where heavy industry and urban runoff are critical factors that may affect the productivity of western king prawn populations.

20.8. Critical data gaps and level of uncertainty

There is little known about the diet of WKP in SA. Although prawns feed on detritus, the importance of seagrass for prawns in SA is poorly understood. It is uncertain, therefore, what impact changes in seagrass habitat will have on prawn populations. There is some uncertainty regarding the impact of climate change on the oceanographic patterns of water movement that are critical to larval advection and adult movement. The upper salinity tolerance of adult WKPs is unknown, therefore there is also some uncertainty in regard to the potential impacts of salinity increases in SA's hyper-saline gulf environments.

Key points:

- Critical uncertainties include:
    - the importance of seagrass as a food source
    - the effect of climate change on oceanographic patterns, particularly for the west coast
    - the potential impacts of increases in salinity, particularly in the upper reaches of each gulf.

Table 20.4: Summary of western king prawn species assessment, which also indicates level of certainty of the associated information. Level of certainty is divided into high (H) = strong clear evidence, backed by several studies with solid datasets with little confounding interactions; medium (M) = evidence supported by one or more studies, conclusions may be partially ambiguous or confounded; low (L) = anecdotal evidence, limited data and/or predicted conclusions based on theoretical knowledge.

Life history stage	Multiple stressors	Distribution	Habitat	Predators and prey	Current impacts	Predicted impacts	Ecosystem interactions	Data gaps
Eggs		See Fig 6			Recruitment in West Coast Fishery is negatively affected by upwelling events. Upwelling events are becoming more frequent. (M)	Continued increases in the strength and frequency of upwelling may impact reproductive capacity and larval survival (M). Temperature increases may result in a greater period for growth and reproduction (L).		
Larvae			Pelagic					Diet The importance of seagrass habitats Salinity tolerance of adults Future changes in oceanographic conditions (ie. upwelling) which may impact WKPs
Juveniles	Shallow water habitats are highly vulnerable to pollution		Sandy habitats, in shallow inshore waters (H)	WKPs are scavengers, feeding on detritus and plankton (L) Predators: various fishes (L)				
Adults	Exploitation		Sandy habitats, in deeper offshore waters (H)				Changes in seagrass distribution may impact population (i.e. seagrass maybe a potential food source) (L)	

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21. Yellowtail kingfish *Serolia lalandi*

Authors: Philip Gibbs, Keith Jones

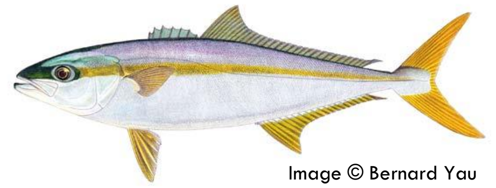
Image © Bernard Yau

21.1. The fishery

21.1.1. Commercial

Yellowtail kingfish is an important commercial and recreational species. In New South Wales (NSW) the Ocean Trap and Line Fishery contributes about 99% of the total catch in the commercial sector. The commercial harvest of kingfish decreased from around 600 tonnes in the mid to late 1980s to around 100 t in the late 1990s (Figure 21.1). A 60 cm minimum legal length (MLL) was imposed for kingfish in NSW waters in 1990, and kingfish traps were banned in 1996. The peak period of capture is December to May with line methods being the main capture method. In September 2007 the MLL for yellowtail kingfish in NSW was increased from 60 cm to 65 cm total length. Commercial landings have fluctuated between 85 and 160 t in recent years. Length-based monitoring of commercial catches shows little change in the size composition of recent landings, except that caused by the change from 60 to 65 cm in the MLL.

Historically, in South Australia (SA), yellowtail kingfish had been caught commercially for many years by beach seine and later, modified hauling nets in inshore waters of the SA gulfs. Schools of kingfish were beach seined along the beaches south of Adelaide in Gulf St Vincent during the 1940s and 1950s, with landings of up to 800 kg occurring. Also, for many years, a net fishery for schooling kingfish occurred in upper Spencer Gulf in waters adjacent to Port Augusta. The fishery took place between July and December, with a small number of net fishers specialising in their capture, local processing and marketing. Reports of the annual harvest during the 1970s and early 1980s ranged between 1 and 15 tonnes, with large inter-annual variation. Close inspection of their catch and effort data suggest large variation in catch rates, suggesting variation in the availability of these fish to the net fishers. However, since the early 1980s, with netting bans in the northern Spencer Gulf where yellowtail kingfish schooled, in the rest of the state small quantities continue to be caught usually as a by-product by up to 15 commercial handline/rod fishers (486 kg, live wt, wharf value $ 2600 in 2008–09). For many of the years during the period 1984–85 – 2008–09, there were less than five fishers reporting catches of this species.

21.1.2. Recreational

The annual recreational harvest of yellowtail kingfish in NSW is likely to lie between 120 and 340 t. This estimate is based upon the results of the offsite National Recreational and Indigenous Fishing Survey (Henry and Lyle 2003; Steffe et al. 1996) and onsite surveys undertaken by Industry & Investment NSW.

Since September, 2005 a licence-managed charter boat fishery, with up to 106 licences, has operated for SA, interstate or overseas clients to catch (retain or release) a number of species, including yellowtail kingfish. In the last two years, 11–12 licence holders reported they had harvested this species. Retained catches are reported in numbers of fish, and the annual numbers are very low relative to all other species retained in this fishery. Harvest weights were more than double those of the commercial fishery in the same years. Released rates varied considerably from year to year, depending on whether fishing for the species is directed at catch/tag-and-release fishing or fishing for human consumption. For many years, yellowtail kingfish has been a popular species taken by sport fishers in the upper reaches of the SA gulfs, as well as SA offshore waters, sometimes for human consumption, but often for catch and release fishing. Estimates of the recreational catches of yellowtail kingfish by SA residents are available from large statewide recreational fishing surveys for two years (2000–01 and 2007–08; Jones 2009); however, for both years, the levels of precision around the estimates for yellowtail kingfish are poor (+/-95% confidence limits > than the estimates). The recreational fishery for yellowtail kingfish can therefore be described as a ‘rare event’ one, in comparison with the recreational fisheries for key species, such as King George whiting etc. An estimated approximate total catch of 9000 (± 10,000) and 5000 (± 4,500) yellowtail kingfish were caught in SA in 2000–01 and 2007–08, respectively (Jones 2009). Of these, 20–25% were released as part of catch and release fishing, and the harvested (retained) catch amounted to between 90 and 100 tonnes, live weight.

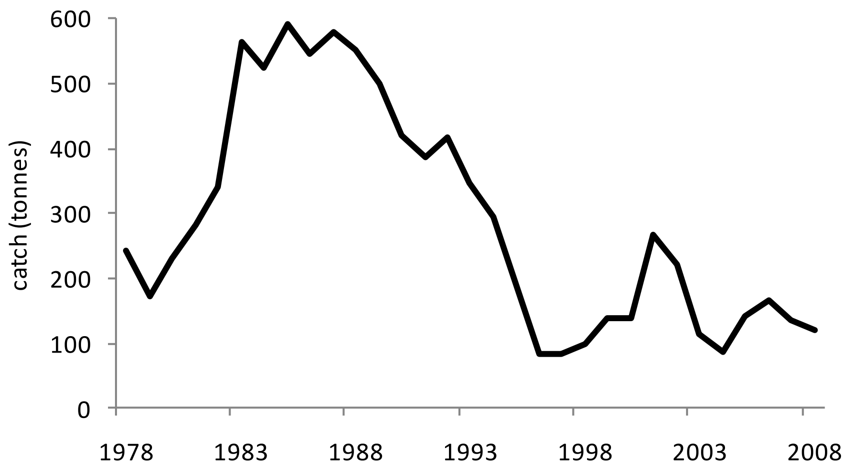

Figure 21.1: Commercial catch (tonnes) by year for NSW.

Key points:

- The species occurs across the south-east of Australia and is a significant harvested species in NSW and SA.
- Kingfish are an important recreational species in both states.

21.2. Life history

21.2.1. *Life cycle, age and growth*

Kingfish are spring–summer spawners with pelagic eggs that are about 1.4 mm in diameter. Larval kingfish hatch within 2–3 days at 4 mm in length. Schools of juvenile kingfish can be found in offshore waters around the continental shelf while solitary or small groups of adults can be found near rocky shores, reefs and islands. While it is reported that adults can reach about 190 cm in total length (TL) and can weigh up to 70 kg, it is thought that fish of this size are rare. Maximum age is thought to be in excess of 21 years. Tagging programs have shown widespread movements of kingfish from NSW to New Zealand (and vice versa) and many large scale movements (>500 km) along the NSW coast (Gillanders et al. 2001).

The estimated size at which 50% of females and males are sexually mature is around 83 cm and 47 cm fork length (FL) respectively. For males, this size at maturity occurs at an age of less than one year old. Growth is rapid, being nearly linear between 1 and 11 years old, with fish reaching the 65 cm minimum legal length (MLL) in NSW at around 2–3 years of age Gillanders et al. 1996, 1999a,b 2001).

Limited research has been directed at gaining an understanding of the life cycle of wild-caught yellowtail kingfish in SA. They are known to spawn in northern Spencer Gulf during August–October (McGlennon, 1997); however, it is unknown whether this is the only spawning area in this state. Nursery areas for wild populations of kingfish in SA are unknown. Since early 2001, juvenile fish, ranging from 25 to 60 cm (TL) have been reported in Spencer Gulf; however, these have all been identified as escapees from adjacent aquaculture sites (Fowler et al. 2003; Gillander and Joyce 2005).

Being a semi-pelagic species, the otoliths are relatively small, and difficult to age (Henry and Gillanders 1999). There have been no attempts to age wild caught fish from SA. Fish up to 1.4 m (40 kg live weight) are known to occur in SA.

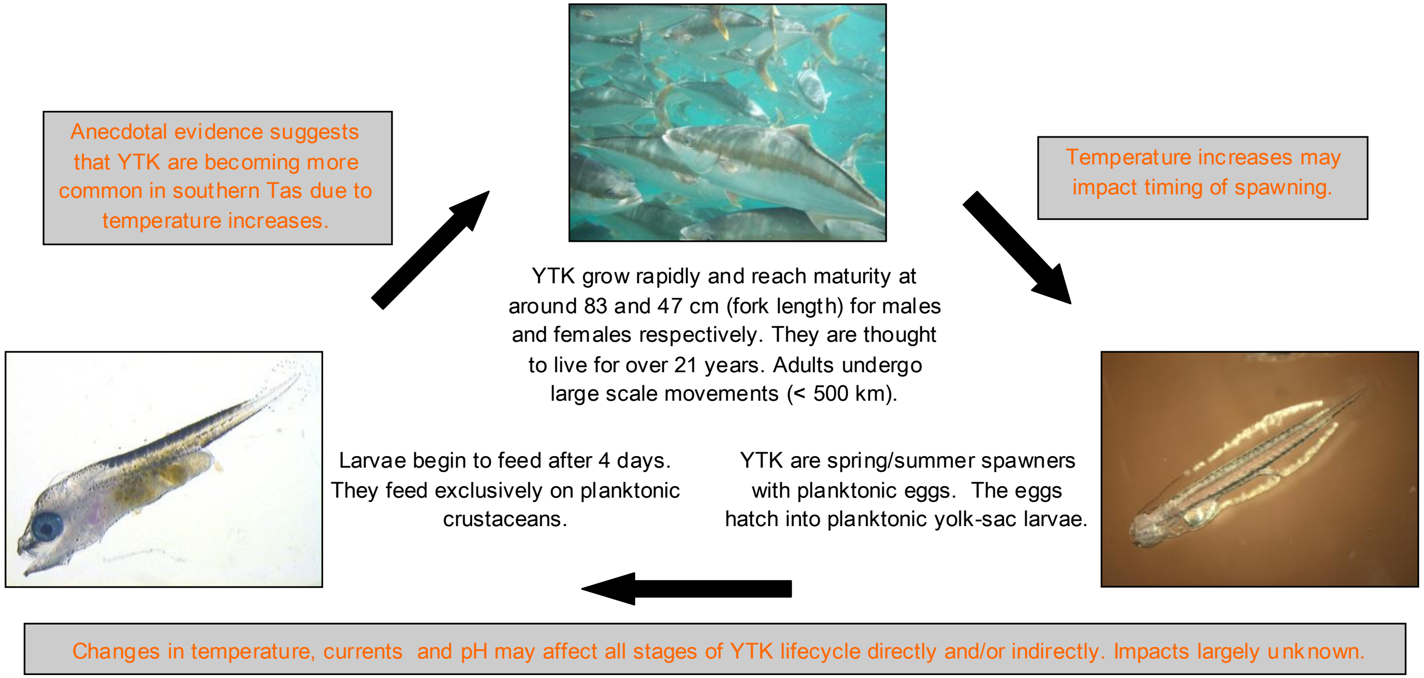

Figure 21.2: Summary of yellowtail kingfish life cycle (this section), and points of exposure to relevant climate change drivers or known impacts (subsequent sections). Image source: B Chen, D Stone and W Hutchinson (SARDI).

21.2.2. Distribution, habitat and environmental preferences

Yellowtail kingfish are distributed throughout temperate waters of the Pacific and Indian oceans. In Australian waters they are distributed from southern Queensland to central WA, including the east coast of Tasmania, and around Lord Howe and Norfolk islands (Figure 21.3). Movement in NSW is throughout the nearshore coastal waters (Gillanders et al. 1996).

Yellowtail kingfish are found throughout the central and western waters of SA, from sandy shallow within the northern gulfs and west coast waters, to the reefs associated with the offshore islands off the west coast of SA.

A limited tagging program in SA waters has been carried out since the early 1990s (Hutson et al. 2007), which suggests only localised movements, up to 150 km distant from the tagging sites, especially in the upper Spencer Gulf region. Micro-chemical analysis of otoliths of fish from this region also initially suggested a separate stock in this part of SA; however, the effect of strong environmental factors (i.e. high water temperatures and salinities), may confound this inference. The recent 2007–08 recreational fishing survey (Jones 2009) suggested some capture of fish during the rest of the year in this area, suggesting that some of the fish may remain in upper Spencer Gulf for the whole year (Jones, unpubl. results). The seasonality of movements in Spencer Gulf may also be confounded by the presence of escaped kingfish from sea cages located in western waters of Spencer Gulf (Fowler et al. 2003; Gillanders and Joyce 2005).

The results of these tagging experiments differ markedly from those found from kingfish tagged off the east coast of Australia, which show substantial movements; however, importantly, no fish tagged off the east coast were recaptured in SA waters, suggesting separate populations. This observation may have been a function of relatively light fishing effort for this species in this state, compared with the rest of SE Australia.

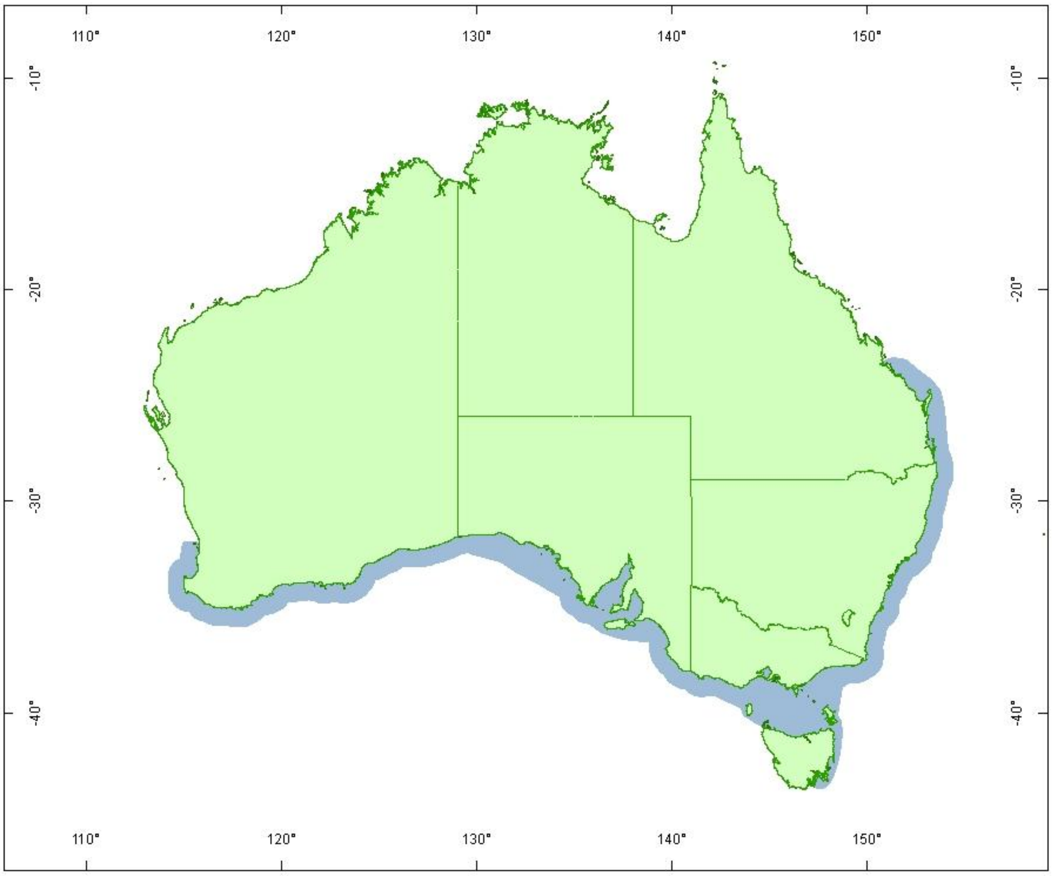

Figure 21.3: Distribution of yellowtail kingfish

21.2.3. Predators and prey

In NSW yellowtail kingfish are prey for a number of shark species and occasionally marine mammals especially dolphins. No known predators in SA and documented.

Kingfish are opportunistic daytime feeders with fish, squid and crustaceans forming a large part of their diet. There is a little more information on the diets of yellowtail king fish in SA. In upper Spencer Gulf, they are known to feed on King George whiting, garfish, western king prawns and trevally (McGlennon 1997). In northern Spencer Gulf, the escaped kingfish were not experienced feeders, and were found to consume only small remnants of vertebrate and invertebrate material, but also fed on plant material, which is not consistent with their known carnivorous diet (Fowler et al. 2003). The larger more offshore fish fed on small pelagic species, including redbait, Australian herring and krill (Euphasiids) (Fowler et al. 2003).

21.2.4. Recruitment

Anecdotal information suggests that currently, average size of fish passing through the recreational fishery in upper Spencer Gulf is steadily increasing over time, suggesting a strong year class passing through the population; however, as no age determination of these fish has been carried out, this remains speculative.

Key points:

- Kingfish are long lived (21 years), grow rapidly to a maximum size of 190 cm and reach sexual maturity at a young age.
- Kingfish adults undergo significant oceanic migrations.

21.3. Current impacts of climate change

There is insufficient information on the biology and population dynamics of yellowtail kingfish in NSW and SA to comment on the current impact of climate change on this species, in terms of the wild population. However, historical records and fisher observations suggest that kingfish is becoming more abundant in southern Tasmania, which corresponds to dramatic warming in the region (Last et al. in press; REDMAP, 2010). Possession limits for yellowtail kingfish have been recently introduced in Tasmania (DPIW, 2009), which also indicates that they are becoming an increasingly important recreational species in the state.

Key point:

- Kingfish occurrence in southern Tasmania is increasing and may be a result of climate-induced ocean warming

21.4. Sensitivity to change

Unable to comment.

21.5. Resilience to change

Unable to comment.

21.6. Ecosystem level interactions

The importance of yellowtail kingfish within the pelagic ecosystems is uncertain.

21.7. Additional (multiple) stressors

There is a relatively small commercial fishery for this species in both states. The recreational fishery is larger, with the harvest in both states exceeding the commercial harvest; however, the precision of the catch estimates are such that it is not possible comment on trends for this fishery, nor the SA charter boat fishery.

21.8. Critical data gaps and level of uncertainty

A much better understanding of the biology and distribution of the species across its distribution is fundamental to an understanding of the effects of climate change on this species.

Table 21.1: Summary of yellowtail kingfish species profile, which also indicates level of certainty of the associated information. Level of certainty is divided into high (H) = strong clear evidence, backed by several studies with solid datasets with little confounding interactions; medium (M) = evidence supported by one or more studies, conclusions may be partially ambiguous or confounded; low (L) = anecdotal evidence, limited data and/or predicted conclusions based on theoretical knowledge.

Life history stage	Multiple stressors	Distribution	Habitat	Predators and prey	Current impacts	Predicted impacts	Ecosystem interactions	Data gaps
Eggs	Unknown	See Figure (H)	Estuaries and Offshore (M)	Unknown	None (M)	Southern expansion of distributional range (M)	Unknown (H)	Improved understanding of the biology of the species across its geographical range.
Larvae	Significant harvest in the recreational fisheries of NSW and SA (M)				None (M)			
Juveniles			Estuaries and Offshore (M)	Prey for sharks and marine mammals (M)			Uncertain (M) but strong linkage to EAC.	
Pre-spawning adult								
Post-spawning adult	Significant harvest in the recreational fisheries of NSW and SA (M)							

21.9. References

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SECTION B: AQUACULTURE SPECIES

22. Abalone, blacklip, greenlip and tiger (hydrid), *Haliotis rubra & H. laevigata*

Authors: Xiaoxu Li, Steven Clarke, Zoe Doubleday, Neil Hutchinson

22.1. The industry

Abalone are marine gastropods with a flattened only slightly spiralled shell and a large edible muscular foot (Figure 22.1). Some ten out of the 100 abalone species in the world are considered a great delicacy by a number of Asian cultures (PIRSA Aquaculture 2000a). In Australia, the main species farmed are the greenlip abalone (Haliotis laevigata), the blacklip abalone (H. rubra), and the hybrid between these two species, the so called tiger abalone, which can also occur naturally in the wild. Greenlip abalone are farmed in South Australia (SA), Victoria and Tasmania. Blacklip and tiger abalone are farmed in Victoria and Tasmania. Tiger abalone grow more rapidly and are easier to handle than their blacklip and greenlip parents, with the 'skirt' of the foot of the tiger abalone being similar in colour to the Asian preferred Japanese abalone species H. discus hannai. The tiger abalone fetches the highest market price of these types of abalone. There have also been attempts to culture other abalone species in Australia, including the brownlip abalone (H. conicopora), staircase abalone (H. scalaris), Roe's abalone (H. roei) in West Australia (WA) and the tropical donkey-ear abalone (H. asinine) in Queensland (Freeman 2001).

Aquaculture of abalone began in the early 1980s near Port Lincoln, SA and then in Tasmania (Fleming 2000). Farming started in Victoria in the 1990s but had fast caught up with SA and Tasmania by the early 2000s. The development of abalone aquaculture in WA comprised sea-based trials initially in the late 1990s and then in land-based facilities in early 2000s. All abalone stocks farmed in Australia are hatchery produced. The success of abalone aquaculture in Australia in the last three decades is represented by the evolution and/or innovations of the farming techniques meeting the requirement of local species, local environments and local business conditions. In the early years the design of growout facilities was based on deep, rectangular tanks used in Asia and California, USA, which were designed for feeding abalone with live seaweed. The evolution of this system mainly occurred in SA for the growout of greenlip abalone, and led to several subsequent developments. The first was the development of shallow raceways, which offered a vast saving in water usage and were most suitable for the application of manufactured diets, which in Australia were initially developed and refined at the South Australian Research and Development Institute (SARDI). Vertical stacking of raceways also allowed efficient use of floor area (Fleming 2000). The second breakthrough in tank design was the development of a pipe and then maze system, which improved the water quality substantially. The third and present tank system to evolve, was the 'slab' tank (a very large shallow rectangular tank), the basis for growout at most modern land-based abalone farms in Australia. The slab tank not only retains the advantages of earlier systems, but further reduces the operating costs (i.e. labour by at least 50% Fleming 2000). Deep round or rectangular tanks with numerous shelters have also been developed specifically for blacklip abalone farming over the same time period, and these are now beginning to appear on some greenlip abalone farms for use at the weaning stage.

All land-based abalone farms are located near the sea shore in rural regions in Australia.

A few types of offshore growout facilities, such as barrels and different kinds of cages have also been tried in Australia. The establishment of the largest Australian offshore abalone farm near Elliston, SA is based on the novel technique – the 'moored floating sea-cage system', with cages that are about 40 m in diameter with uniquely designed habitat structures on the bottom of the net on which the abalone predominate. Abalone farmed in this system feed on macroalgae growing naturally on the cage nets, but when necessary can be supplementarily fed using collected beach cast macroalgae and/or manufactured feeds.

The time period required for abalone to grow from fertilised eggs to marketable size varies according to the environmental conditions at the site (particularly water temperature), food type and quantity, the market size targeted and market demand. For greenlip and blacklip abalone it normally takes 3– 4 years to grow to a market size larger than 70 mm total length, while for tiger abalone it takes shorter period. During growout, the abalone are generally graded once a year to achieve size uniformity and optimal stocking density in individual tanks.

Farmed abalone are mainly exported to Asian markets and a small amount are sold domestically. Three kinds of aquaculture product are produced; live, frozen (in shell or meat only) and processed (canned is by far the most common). The live product is usually sold by farmers directly to distributors in Asian countries. The processed or frozen product is prepared by local abalone processors who then sell to wholesalers in Asia. When abalone are sold live, which is challenging, special attention is given to ensure they are packed in a moist insulated and dark environment, without excess water and with enough oxygen for the long transportation time.

Key points:

- All species of farmed abalone are endemic to Australia. Their aquaculture was established in the 1980s in SA and Tasmania, the 1990s in Victoria, and the 2000s in WA.
- All farmed abalone stocks are hatchery produced.
- Land-based abalone growout systems dominate the current industry, although a few offshore cage systems are in use and interest in this type of ongrowing is increasing.
- Almost all Australian farmed abalone are sold to Asia, primarily, Japan, China, Chinese Taipei, Hong Kong and Singapore.

22.2. Production

Abalone aquaculture contributes significantly to the economy in SA, Victoria and Tasmania. In the 2007–08 financial year both production volume and farmgate value are at a similar level in each of these three states; about 170 tonnes worth $5.5 million (Figure 22.1, ABARE 2009). During the period from 2002–03 to 2007–08 production volume and value increased at a similar pace in each of these states and all have doubled over this time period (Figure 22.1; ABARE 2006, 2007, 2009). In SA, the industry employs about 43 full-time equivalent staff directly (Econsearch 2009) and the projections of abalone aquaculture production and employment over the period from 2008–09 to 2010–11, relative to 2007–08, are 100% and 13% respectively (Econsearch 2009. In Tasmania and Victoria it is anticipated that abalone aquaculture production will double and direct employment increase by one third within the next five years (Nick Savva, pers. comm.).

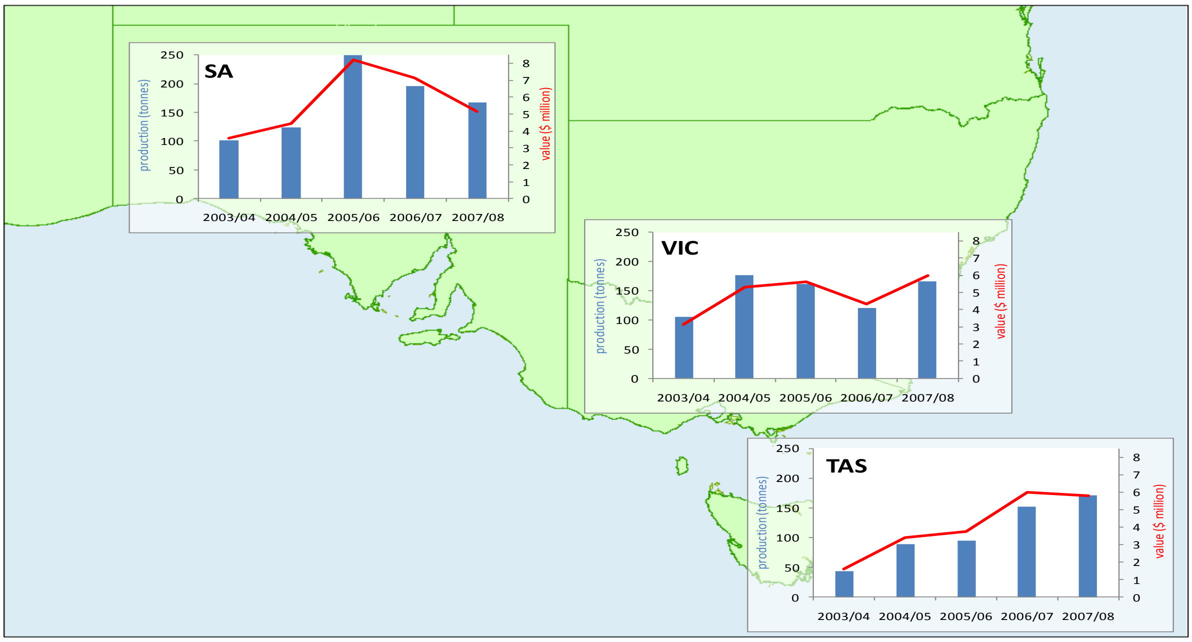

Figure 22.1: Abalone production (tonnes) and value ($, million) in SA, Victoria and Tasmania from 2003–04 to 2007–08 (ABARE 2006, 2007, 2009).

In SA there are 66 abalone farming licences issued (ABARE 2009) and only greenlip abalone is farmed. The four major areas with land-based systems are Streaky Bay, Louth Bay, Port Lincoln, and Kangaroo Island. The largest offshore abalone farm is near Elliston and uses floating sea-cages (Figure 22.2).

In Tasmania there are 15 abalone farming licence holders for sea-cage and land-based tank systems (ABARE 2009) and both greenlip and blacklip abalone and their hybrid – the tiger abalone – are grown. The main farming areas are Bicheno, Swansea, George Town, Dunalley and Flinders Island (Figure 22.2).

In Victoria there are 14 abalone aquaculture licences issued for flow-through systems (ABARE 2009) and these involve the culture of all three kinds of abalone: greenlip, blacklip and tiger. The main farming areas are Portland, Warrnambool, Port Philip Bay and Phillip Island.

In WA abalone production is low and based on the farming of greenlip abalone. The main farming areas are: Bremer Bay and Albany.

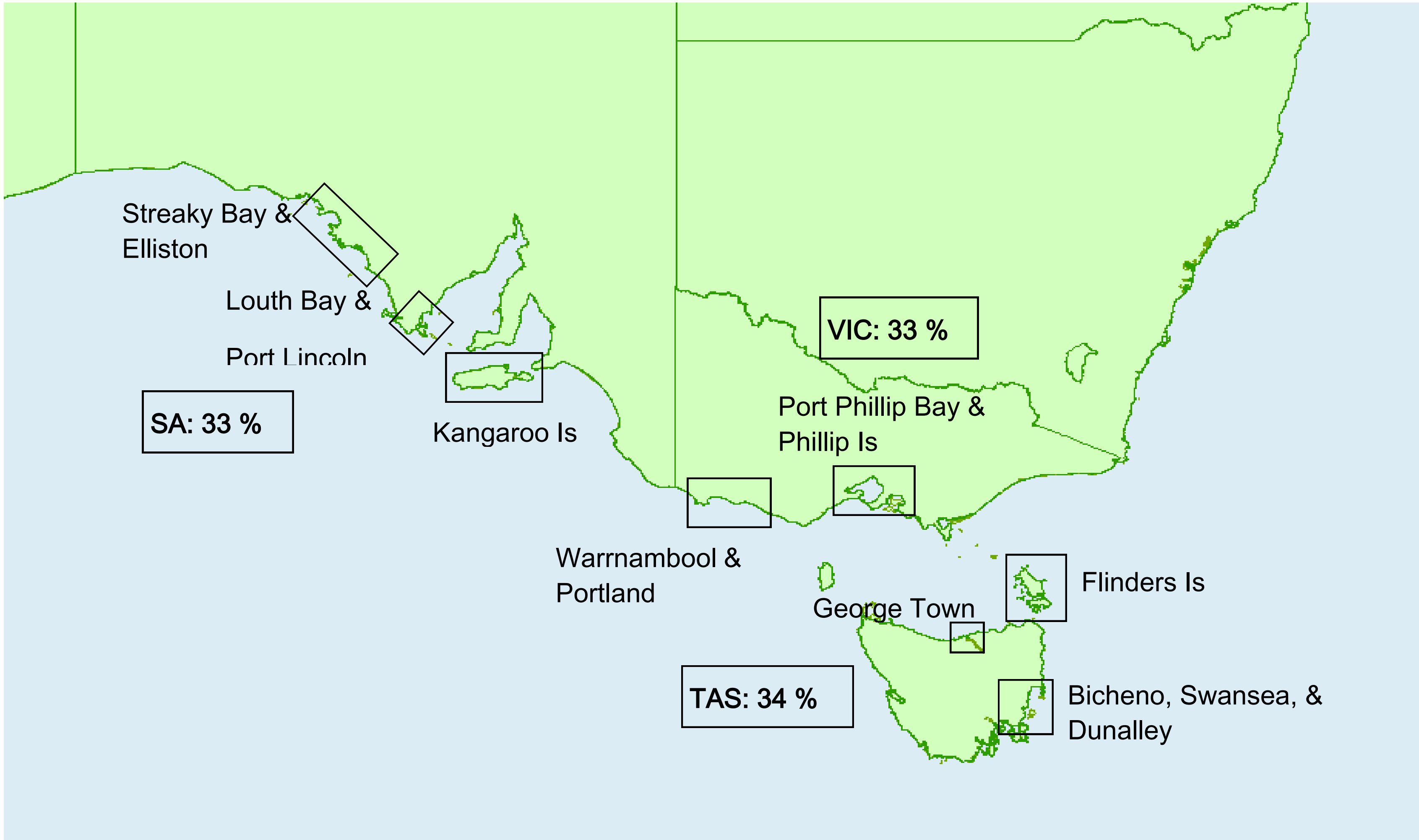

Figure 22.2: Location of abalone farms in SA, Tasmania and Victoria and the proportion (%) each state currently contributes towards total production (based on 2007–08 production).

Key points:

- SA and WA farm greenlip abalone only, while Tasmania and Victoria farm both greenlip and blacklip and their hybrid – the tiger abalone.
- In the last decade abalone production volume and value have about doubled in SA, Victoria and Tasmania; all states currently have similar size industries.
- In 2008–09, about 170 tonnes of abalone valued at $5.5 million was produced in SA, Victoria and Tasmania respectively.

22.3. Life history stages, stages in farming process and physiology

22.3.1. *Abalone life history*

Abalone mature as either a male or a female; both can easily be recognised by the animals' gonad colour. Males have a creamy white gonad whereas females have a light to dark green gonad. Abalone start to produce gametes as young as two years old (Li 2008) and release their gametes into the water column at spawning during the period from late spring to early summer in greenlip abalone or earlier in blacklip abalone. Eggs and sperm are released into the water with fertilised eggs developing and beginning to rotate within their membrane in 8 hours at 18°C for greenlip abalone and 17°C for blacklip abalone. They hatch into free swimming larvae (trochophore) within 18 hours and move towards the upper water layer. Approximately 10 hours later the trochophores develop into veliger larvae, which are each characterised by the presence of a small shell and other larval organs such as retractable vellum, cephalic tentacles and foot (Shepherd 1976). Once the veliger larvae start to test the substrate and develop the third tubercle on the cephalic tentacle, after 6– 7 days, they are ready for settlement. During this period the larvae loose their swimming capability due to the degeneration of the velum and they start to crawl over surfaces using the foot to select an appropriate habitat to live when they becomes a juvenile. This change from swimming to a bottom dwelling life style is called metamorphosis.

Abalone larvae do not feed during the larval period and live off the eggs yolk. After metamorphosis a mouth with a radula, tongue-like organ having rows of tiny teeth, develops, which allows the juvenile abalone to graze on bacteria, benthic diatoms and later to consume seaweeds. The development of an adult shell occurs at the same time (Figure 22.3).

In the wild, abalone larvae recruit onto crustose coralline algae, which not only provides a settlement substrate but also form the main food source during the first year of abalone life (Shepherd 1987). When young abalone (less than about 30 mm in total length) are cryptic, they only move out to search for food at night.

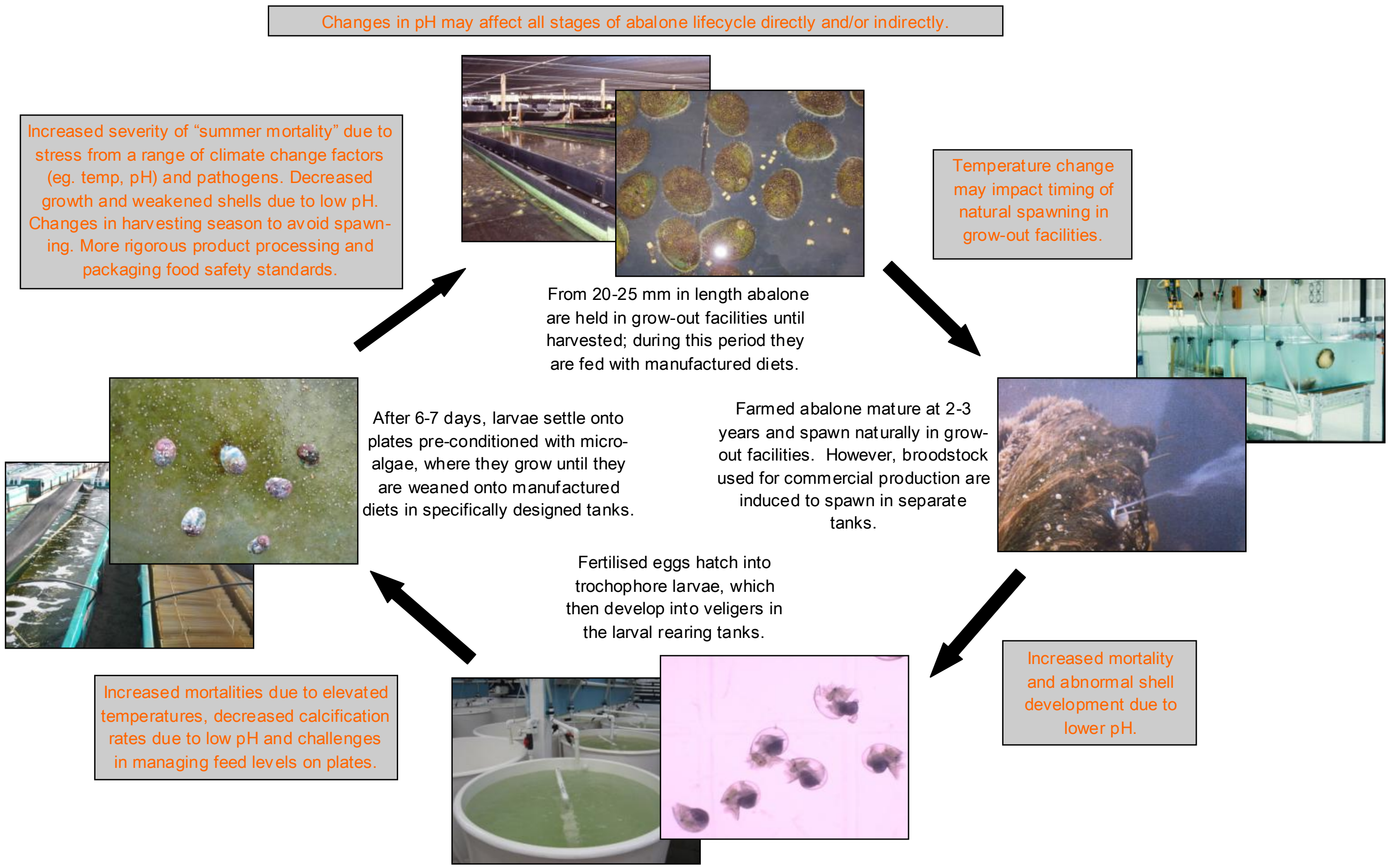

Figure 22.3: Key abalone life cycle stages in a landbased farming system (this section) and responses to or impacts from relevant climate change drivers (subsequent sections). Image source: X Li (SARDI), A Butterworth (SA Oyster Hatchery), B Smith (Southern Australian Seafoods Pty Ltd) and L Lyall (IMAS).

22.3.2. Abalone aquaculture

The abalone aquaculture business consists of four main stages: 1. Hatchery; 2. Nursery; 3. Growout; and 4. Market Supply. Currently there are two types of abalone farms: hatchery and growout based, and growout only (Fleming 2000). The former is vertically integrated and comprises all four stages, while the later involves only the last two stages. Most abalone farms in Australia are of the hatchery and growout type.

The hatchery activities include broodstock selection, conditioning and maintenance, spawning induction, fertilisation and intensive larval rearing in tanks. The nursery stage involves the preparation of the settlement system to ensure that a biofilm of microalgae has developed on the plates prior to the introduction of competent larvae for settlement. These settlement plates are mounted vertically in wire baskets. The biofilm quality and condition on the plates are maintained by turning the basket regularly or when required, controlling the light intensity using different grades of shade cloth and/or adding nutrients if needed. Some farmers seed the plates with selected cultured microalgal species whereas others just condition them with the naturally occurring microalgae. When the juveniles reach a length of 10–15 mm or when the microalgae on the plates are no longer enough to support abalone growth, the abalone are weaned onto manufactured diets in specifically designed tanks with numerous shelters. The system needs be cleaned regularly until the abalone are transferred into either land-based or offshore growout systems at 20–25 mm in length. The survival rate at the nursery stage (including settlement) is by far the lowest in the abalone aquaculture production process, between 3 and 10%.

Growout seeks to get abalone to market size over a 24–36 month period. During this period the abalone in land-based tank systems are fed and cleaned regularly. The feeding and cleaning frequencies are adjusted according to the season and abalone condition (size, spawning, etc). Abalone are typically graded once a year to maintain a uniformity in size as well as an optimal stocking density within tanks. When graded by a machine, abalone are anaesthetised first. For offshore cage systems, the maintenance regimes are highly variable according to the system used. The main activities are feeding, monitoring the performance of cages and abalone, maintaining an optimum density for the system and feed used, and removing predators.

Abalone are marketed according to their whole weight, and classified into extra large (>130 g), large (110–130 g), medium (90–110 g) and small (70–90 g). To provide live abalone to the market (which is challenging due to higher than desired mortalities), feeding is stopped for a few days prior to harvest to empty their digestive system. The harvested abalone are placed in a holding tank with high water exchange so that the quantity required for shipment can be packed in a short period and delivered straight away. No chemicals are allowed for the harvest process. Some farms have established the capacity to quickly freeze individual abalone in-shell. Most farmers transport their abalone to processing plants using ice, where they are typically cleaned, frozen, packaged and then distributed to wholesalers, retailers and/or restaurants.

The hatchery involves broodstock/gametes through to the larval stage competent for metamorphosis. The nursery involves the stages from metamorphosis to juveniles of 20–25 mm in length. Growout takes abalone from about 20–25 mm through to market size. The market supply stage involves only a short period of time, from harvest to selling to the live market, or being processed (frozen, canned or prepacked prepared dishes), stored and marketed. The processed products can be stored for an extended period.

The key environmental parameters in abalone hatcheries are highly controlled to provide the optimal conditions to promote or maintain gonad condition in broodstock, and growth in larvae. These include water temperature, feed quantity and quality (for broodstock only) and water quality (at least filtered). When abalone are moved into nursery and land-based growout systems, the environmental conditions that can be controlled are very limited due to the much greater flow rates of water. The main methods used are to adjust the water flow rate and tank cleaning frequency. When abalone are transferred into sea-cages, they are subjected to local environmental changes and predators. The methods used by farmers to improve production are maintaining appropriate stocking densities, optimising feeds and feeding, and managing predators, fouling and net integrity. Therefore, offshore farming site selection is a balance between having good water flow but not having too much wave generated disturbance so that farm husbandry and maintenance are not interrupted and the food provided remains available to the animals (Freeman 2000). Most farms harvest year-round to meet market requirements, but their largest orders are generally in the period just prior to Christmas, New Year and the Chinese New Year (which varies yearly but is always in January or February). Abalone harvesting from offshore farms is typically prior to spawning to ensure maximum product quality (Oulton 2009).

The optimal water temperatures for blacklip and greenlip abalone growth are 17°C and 18°C, respectively (Gilroy and Edwards 1998; Fleming 2000; Wang et al. 2006). However, these might change with size/age. In blacklip abalone, for example, the optimal temperature for growth decreases with an increase in size/age; 18.4°C for abalone of 4–5 months of age and 3–10 mm in length, compared to 14°C for animal of 18–19 months (or more) of age and 30–45 mm or longer in length (Heasman et al 2004). The peak settlement of competent blacklip abalone larvae occurs at 19°C, with a progressive decline to zero when temperature rises toward 26°C (Heasman et al 2004).

In general, abalone have remarkably conservative thermal responses (Gilroy and Edwards 1998). When lethal temperatures are reached, the difference between 0–100% mortality was recorded over a range of less than 1.0°C (Hines et al. 1980; Madigan et al. 2000). At 26°C greenlip abalone are unlikely to survive for an extended period.

Abalone require well oxygenated water. A detectable reduction (5%) in growth rate occurs at 96% oxygen saturation within an optimal water temperature range. Both growth and mortality are affected significantly when juvenile greenlip abalone are exposed to chronic low oxygen saturation of 73% and 63%, respectively (Harris et al 1999b). Reduction in growth rate and increase in mortality would be expected as water temperatures rise (Hutchinson and Vandepeer 2004).

Juvenile blacklip abalone have a more restricted optimal pH range than juvenile greenlip abalone, being 7.93 to 8.46 and 7.78 to 8.77, respectively (Burke et al. 1999). Significant mortalities occur at a pH less than 7.16 or greater than 9.01 (Burke et al. 1999).

Juvenile greenlip abalone are highly sensitive to ammonia, a detectable (5%) reduction in whole body weight at a free ammonia nitrogen (FAN; un-ionised) level of greater than 0.041 mg L^{-1} (Harris et al. 1998). Survival relative to the control (0.0006 mg FAN L^{-1}) significantly reduces at 0.188 mg FAN L^{-1} (Harris et al. 1998).

Both greenlip and blacklip abalone tolerate the salinity range between 25 and 40‰, with 35‰ being optimal (Burke et al. 1999; Fleming 2000). A margin of 2‰ outside of this range causes mortality (Burke et al. 1999, Edwards 2003).

Benzocaine, the anaesthetic used for moving stock, is found to cause reductions in subsequent growth rates in both greenlip and blacklip abalone (Burke et al. 1999).

Key points:

- Abalone have a complex life cycle, with no feeding being required at larval stages.
- Environmental conditions at both hatchery and market supply stages are highly controlled.
- For onshore farms, there is limited capability to control the environmental conditions at the nursery and growout stages as water flow volumes increase.
- Abalone farmed in offshore cages are subjected to local environmental conditions, which are essentially uncontrollable, as well as natural predators.
- The performance of abalone is affected by many environmental factors such as temperature, pH, salinity, ammonia, dissolved oxygen and anaesthetic treatments.

22.4. Likely current impacts of climate change

Significant abalone mortality over summer months is referred to as ‘summer mortality’ and affects abalone approaching harvest size (about three years old) more than juveniles. This event has been reported in many countries in the world (Sawabe et al. 2007; Travers et al. 2008; Cheng et al. 2008) and deaths of as high as 50% have been reported on some farms in Australia (Vandepeer 2006). Results from published studies indicate that abalone summer mortality in European abalone is influenced by both the physiological status of abalone (reproductive stress of host), and environmental parameters experienced (elevated temperatures and the presence of a Vibrio species) (Travers et al. 2008, 2009). Temperature promoting fatal bacterial diseases has also been confirmed in other abalone species including those farmed in Australia (Lee et al. 2001; Cheng et al. 2004; Vilchis et al. 2005; Bower 2006; Vandepeer 2006). Results from studies in other molluscan species suggest that other factors such as dissolved oxygen, physiological/metabolic disturbances, etc. can also cause summer mortalities (Berthelin et al. 2000; Li et al. 2007; Soletchnik et al. 2007; Li 2008, Li et al. 2009).

In South Australia the protozoan parasite, Perkinsus olseni is a potential threat to theabalone aquaculture industry. The pustules resultant from its infection reduces the market value of abalone (Lester and Hayward 2005). In severe cases this parasite results in abalone mortality (Fleming 2000). There has been a persistent reference in the literature to warmer water temperature being associated with P. olseni infections in abalone (Lester and Davies 1981; Oulton 2009).

Key points:

- 'Summer mortality' occurs repeatedly on some abalone farms, especially on those experiencing high summer water temperatures.
- In SA, *Vibrio* spp are commonly detectable but it is often unclear whether they were the primary cause of mortality or just developed in association with sub-optimal environmental conditions and/or increasing abalone stress.
- In SA the infection of abalone by the protozoan parasite, *Perkinsus olseni*, appears to be associated with warmer water temperature.

22.5. Potential impacts of climate change (direct and indirect)

Climate changes can affect the abalone aquaculture business by directly acting on the farm stock, farming infrastructure, and marketing (direct impacts), or on other factors such as natural feed abundance (e.g. macroalgae), predators or even the communities that provide and sustain abalone farm employees (indirect impacts).

22.5.1. Potential direct impacts

Abalone performance

Abalone larval shells are composed of substantial amounts of the unstable form of calcium carbonate and as such are susceptible to the calcium carbonate levels in the seawater in which they occur (Hofman Lab 2009). It has been predicted that in cold, high-latitude surface waters, calcium carbonate will become undersaturated by the year 2050 due to climate change (Miyazaki et al. 2010). Studies on other molluscs with similar form of calcium carbonate in their larval shells have shown that the development of this type of shell is very sensitive to pCO_2 increases. In Pacific oysters, for example, only 5% of fertilised eggs developed normal larval shells in the CO_2 treated group, as compared with 70% in the control group (Kurihara et al. 2007). If pCO_2 increases occur in an abalone hatchery it can be devastating because contamination from unhealthy larvae can quickly spread through the intensive larval rearing system and is difficult to manage.

Adult abalone shell consists of three layers, an outer periostacum, a middle layer of calcite (a form of calcium carbonate), and an inner layer of aragonite calcium carbonate (Leighton 2000). When exposed to high levels of pCO_2 the calcite mass of greenlip abalone and other molluscan shells starts to dissolve away (Gazeau et al. 2007; Oulton 2009).

Abalone are also sensitive to a lower pH (more acidic conditions), resulting in low growth rates and damage to many organs (Harris et al. 1999a).

Offshore farms have less capacity than land-based farms in mitigating high pCO_2 and/or low pH.

When hot weather is experienced for an extended period, land-based farms stop feeding their stock, and increase at the same time the water flow rates and cleaning frequency (if needed) to provide the best available environmental conditions, leading to higher energy consumptions and labour costs. In addition, any practices that could impose extra stresses to abalone are avoided. If this period is further extended or more severe hot weather is experienced due to climate change in the future, the abalone's performances could be further compromised or result in mortalities.

Increases in freshwater run-off into coastal areas as a result of sporadic events of high rainfall, predicted to increase, will lower salinity at least for short periods of time. Therefore it is likely that some abalone farms will have to occasionally deal with varying salinity levels. Several abalone culture sites in China have had to be abandoned because of fluctuating salinity (Department of Fisheries 2001).

Abalone farmed in offshore cages can not feed when the foot of the animal is clamped to the substrate in stormy conditions. Therefore, with increased storm frequency due to climate change abalone are less likely to feed as much, which is likely to reduce growth (Oulton 2009).

Farm infrastructure

Due to the requirement for water intake and discharge points, and the costs associated with pumping large volumes of water, land-based abalone farms are generally sited to have low pump head pressures and hence are located close to sea level. They are therefore likely to be impacted by sea level rise at some stage in the future (Oulton 2009).

Increases in air temperature may also require greater shading of onshore nursery and growout areas, and improved insulation of water intake pipes.

It is likely that in more wave-exposed areas there will need to be improvements made to better anchor and strengthen offshore farm infrastructure. The number of days that such infrastructure can be accessed for key operational tasks may also be reduced (e.g. cleaning infrastructure, removing predators, feeding).

Marketing

Some farmers prefer to harvest abalone stock prior to spawning to ensure product quality. If abalone spawn earlier due to climate change, they will also need to be harvested earlier as well. This may increase abalone product storage costs because the largest orders are normally in the period prior to Christmas, New Year and the Chinese New Year.

22.5.2. Potential indirect impacts

Abalone performance

Abalone summer mortalities are generally thought to result from opportunistic pathogens that infect abalone already weakened by a combination of internal and external stressors (Travers et al 2008, 2009). High temperature promoting fatal bacterial disease outbreaks has been confirmed to be a key factor for a few abalone species (Lee et al. 2001; Cheng et al. 2004; Vilchis et al. 2005; Bower 2006; Vandepeer 2006; Travers et al. 2009).

Higher temperatures in summer also increase the likelihood of the deterioration of manufactured abalone feed if it is not properly stored on-farm (Hutchinson and Vandepeer 2004). Reduction in growth due to the use of feed subjected to excessive heat has been observed (Maguire et al. 1996).

The supply of diatoms on abalone settlement plates can vary greatly with temperature, light intensity, and the level of nutrients (Heasman and Savva 2007). Often the naturally colonising species are not suitable as a food source for juvenile abalone and as a result may proliferate further, not only reducing the growth rate of both the preferred diatoms and juveniles but increasing juvenile mortality (Ebert and Houk 1984). Increased use of cultured diatom species to seed plates as well as management of plates may prove necessary, adding to abalone farm operational costs.

The availability and productivity of seaweeds used for abalone feed are likely to vary with climate change, although the net effect is unknown because changes are likely to be species specific and abalone can be fed a diverse range of taxa.

Some predators of abalone may also become more problematic with climate change, particularly in offshore farms where they are more difficult to manage, as recent research has suggested that high CO_2 and/or low pH may favour crustaceans (Oceanus 2010), with crabs being well known to predate on small abalone (Shepherd 1998; Griffiths and Gosselin 2008).

Farming infrastructure

Settlement and growth of barnacles and some seaweeds on farming infrastructure may be enhanced due to increased water temperature and pCO_2 based on some research of the effects of climate change on representative taxa of these types (Oceanus 2010). If this occurs, farm infrastructure will need to be cleaned more frequently.

Marketing

The period that abalone can survive live transportation is likely to be reduced due to increased pathogen loads at elevated temperatures so greater care and use of refrigeration will be necessary.

Social

Abalone farms are normally located in remote regions in Australia and frequently require part-time staff for labour intensive activities such as grading, harvesting, etc. at peak work periods. However, due to climate change impacts on other industry sectors many people might relocate to more climatically favourable locations resulting in shortages in local casual staff.

Key points:

- Climate change can affect abalone performance, farming infrastructure, animal husbandry practices and marketing, directly and indirectly.
- Reduced pH has been shown to significantly affect abalone growth rate.
- Fouling and predation might increase on offshore farms.
- New marketing strategies might be needed.
- Possible casual staff shortages in climatically extreme remote regions.

22.6. Critical data gaps and level of uncertainty

Abalone are farmed in 'fixed' land-based tanks and offshore generally in cages, and as such the performances of farmed abalone and thus abalone aquaculture businesses, are influenced by local (fine scale) environmental conditions. At this time, climate change modelling provides very limited or no information on climate change impacts at this scale. This increases the challenge for the abalone aquaculture industry, resource managers and policy makers to accurately assess and then establish effective methods to mitigate the potential negative impacts of climate change.

Metabolic/physiological and immunological processes are critical biological factors that determine the performance and health status of abalone. Knowledge of the effects of climate change on these processes is low for abalone. This limits the capability of climate change modellers to predict the impacts of climate change on abalone farming and thus the ability of this industry sector and its managers to develop suitable mitigation strategies.

The precise cause of abalone summer mortality is still challenging the science community. Its complex nature suggests that it might be very sensitive to climate change and might become more pronounced as a result of a range of factors increasing the stress levels on abalone in some farms.

The impacts of climate change on the susceptibility of abalone to abalone viral ganglioneuritis (AVG), and the spread of the virus is not well understood. Research is required to determine if increased water temperature may lead to changes in the impact or occurrence of the virus in both the wild and aquaculture. This in turn may influence practices related to the discharge of effluent from aquaculture.

Very limited information is available on the effects of increased seawater pCO_2 on the critical development stages of abalone such as fertilisation, early larval shell development, settlement, growth, gonad development etc. These stages are all critical to a successful abalone aquaculture business.

Very little is known about the impacts of climate change on interactions between abalone and other organisms affecting abalone performance and survival, such as mudworms (Lleonart 2001).

There remains uncertainty regarding the level of abalone genetic variation and the ability for selective breeding to cope with the speed and magnitude of the climate changes predicted, especially in parts of SA where many environmental parameters such as salinity and temperature are already close to the upper tolerance limits of greenlip abalone.

There is very limited information on the basic biology of tiger abalone.

Key points:

- There is limited information on fine scale climate change impacts on land-based abalone farms and offshore leases.
- There is limited information on impacts of climate change on critical abalone developmental stages and their physiology and immunology.
- Abalone summer mortality may become a greater issue.
- AVG occurrence and spread may be impacted by climate change.
- Genetic variations associated with environmental parameters driven by climate change are unknown and will determine the effectiveness of selective breeding as an adaptation strategy to climate change.
- There is limited information on basic biology of tiger abalone.

Table 22.1: Summary of abalone species profile, which also indicates level of certainty of the associated information. Level of certainty is divided into high (H) = strong clear evidence, backed by several studies with solid datasets with little confounding interactions; medium (M) = evidence supported by one or more studies, conclusions may be partially ambiguous or confounded; low (L) = anecdotal evidence, limited data and/or predicted conclusions based on theoretical knowledge.

Life history stage	Business stage	Farm activity	Current impacts	Predicted impacts	Data gaps
Broodstock	Hatchery	Broodstock conditioning and/or holding		Little to none as can be managed through changes in settings used in existing broodstock conditioning systems (M)	Reproduction physiology and spawning cues
Spawning and fertilisation		Spawning induction and fertilisation			
Larval development		Larval rearing		Increased larval mortality and abnormal shell development due to increased pCO2 and/or lower pH (M)	1. Climate change on larval physiology, developmental biology 2. The suitability of existing hatchery method for rearing 'weak' larvae
Settlement		Artificial settlement induction		Increased mortality (L)	1. Developmental physiology at metamorphosis 2. Settlement cues
Juvenile	Nursery	Juvenile rearing		Increased mortalities due to: 1. decreased calcification rates (M) 2. elevated temperatures (M) 3. challenges in managing plate preparation and feed levels (L)	1. Physiological studies required; particularly on the interaction between key factors 2. Mechanisms for evaluating and selecting suitable farm sites 3. Climate change modelling at relevant spatial and temporal scales and of all

					factors of interest to farmers
Adults	Growout	Adult rearing	'Summer mortalities' due to stress caused by a combination of factors (reproduction, high temperature, poor water quality, *Vibrio*) (H)	1. 'Summer mortalities' - increased severity and prolonged events (H) 2. Reduced working times on offshore cages (L) 3. Increased impact from disease because of greater stress from range of climate change factors (temp, pCO_2, pH) (H) 4. Decreased growth because of decreases in calcification rates at a high pCO2 and/or low pH (M) 5. Change in reproduction pattern (H) 6. Weakened abalone shells due to ocean acidification (M) 7. Increase in pathogen load (H)	As above plus: 4. Reproduction biology/physiology 5. Genetic capability to cope with the magnitude and speed of the predicted climate change
Postharvest	Market and marketing	Harvesting		1. Change in harvesting season to avoid spawning (M)	Climate change and physiological modelling at relevant spatial and temporal scales and of all factors of interest to farmers
		Processing		Highly restricted standards for transportation and processing (M)	Optimal conditions to control the proliferation of marine bacteria
		Packaging		Reduced shelf-live of live product due to high bacteria load (L)	

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23. Atlantic salmon *Salmo salar*

This species assessment has been largely adapted from the report cited below, reproduced in condensed format here so that information is presented consistently for all species considered in the current report.

Battaglene S., Carter C., Hobday A. J., Lyne V. and Nowak B., 2008. Scoping Study into Adaptation of the Tasmanian Salmonid Aquaculture Industry to Potential Impacts of Climate Change. National Agriculture & Climate Change Action Plan: Implementation Programme report 84p. Available for download at: http://www.tafi.org.au/index.php/site/publications/category/others/

Authors: Stephen Battaglene, Pheroze Jungalwalla, Barbara Nowak, Zoe Doubleday

23.1. The industry

Farming salmonids began in Tasmania in 1981 using rainbow trout and then Atlantic salmon in 1984 as a joint venture project between the state government, a Norwegian company and industry. Farming developed quickly due to the establishment of a large hatchery, the use of proven European hatchery technology, a high level of government involvement, excellent cage culture sites, and good water quality (Treadwell et al. 1991). The Tasmanian industry is a major regional employer of around 1200 people. There are currently four salmon farming companies, three with large vertically integrated businesses. The industry has experienced around 12% growth p.a. over the past few years, and plans to double production in the next ten years (Jungalwalla P, pers. comm.). Grow-out facilities are located in the south-east (Channel and Huon, Tasman Peninsula), west coast (Macquarie Harbour) and northern Tasmania (Tamar River) (Figure 23.1).

In Tasmania, salmonids are farmed towards their upper thermal limit and growth rates are extremely fast, with a production cycle taking around 30 months. There are four large freshwater recirculation hatcheries in Tasmania and several smaller flow-through hatcheries providing over eight million smolts per year. The *Marine Farming Planning Act 1995* provides a statutory planning process for the development of marine farming in state waters. This planning process delivers marine farming development plans that determine specific zones where marine farming leases are allocated. Most salmon farming zones are currently at or near maximum development with regard to their respective marine farming development plans and if the industry is to expand as planned, new zones will be required, perhaps in less sheltered waters. Leases are subject to strict conditions for pre and post farming environmental monitoring, input registers, predator control, health surveillance, and general farming conditions. The Tasmanian Salmonid Health Surveillance Program monitors all salmonid marine farming operators in a structured surveillance and monitoring program.

Key points:

- There are currently four salmon farming companies in Tasmania.
- The industry employs around 1200 people.
- In Tasmania, salmon are farmed towards their upper thermal limits, resulting in fast growth rates.

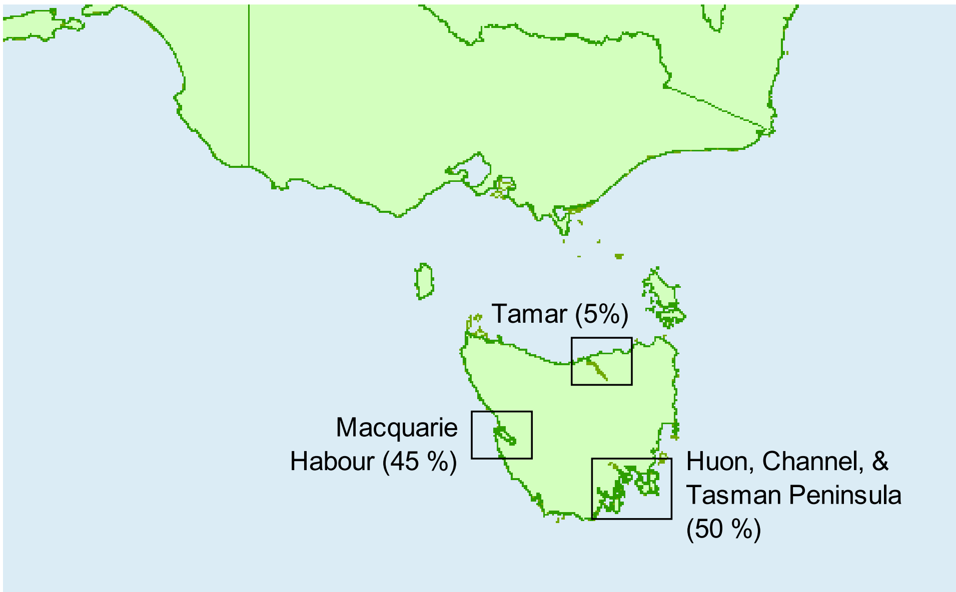

Figure 23.1: Key Atlantic salmon farming regions and the proportion each contributes to total production (%) in Tasmania. Figure adapted from Battaglene (2008).

23.2. Production

Farmed salmonids from Tasmania have emerged as a key seafood produce in Australia in terms of both volume and value. In 2008–09, this sector produced some 28,700 tonnes of salmonids, predominantly Atlantic salmon (90%), with an estimated farm gate value of $323 million. It is the largest aquaculture sector in Australia accounting for 37% of the total value of Australian aquaculture production and 15% of the total value of fishery production (ABARE 2010). Most of the salmon produced in Tasmania supplies the domestic market.

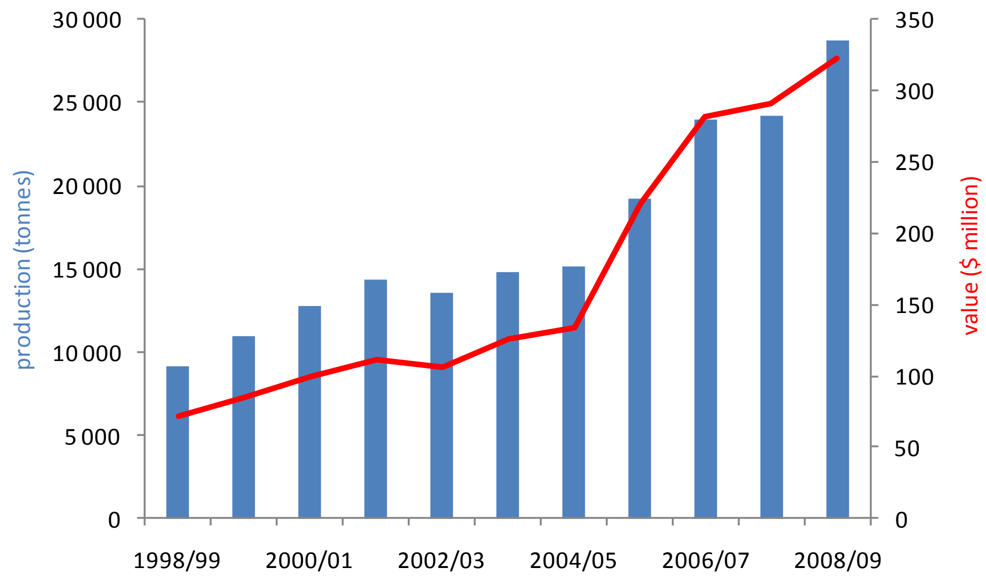

Figure 23.2: Production (tonnes) and value ($ million) of salmonids in Tasmania (ABARE 2008). Ninety per cent of salmonid production is based on Atlantic salmon.

Key point:

- Atlantic salmon is Australia's most valuable finfish species, with an estimated value of $323 m in 2008–09, and accounts for 62% of Tasmania's total gross value of fisheries production.

23.3. Life history stages and stages in the farming process

In late autumn each year, broodstock held in freshwater hatcheries are spawned. Eggs are collected, fertilised and laid out in special incubator trays in the hatchery building. The eggs are supplied with a constant flow of fresh, filtered and well oxygenated water at an appropriate temperature. The eggs start hatching some weeks later, with the larvae or alevins initially absorbing nutrients from a large yolk-sac attached to their bodies. When the young fish or fry are ready to eat for the first time, they are moved into small tanks and provided with a specially prepared food. As the fry grow they are graded for size, and transferred to progressively larger tanks. These juvenile salmon, called parr at this stage, continue to grow until they change physically and physiologically to become pre-adapted to seawater, at which stage they are called smolt. The freshwater phase, from hatching to smolt, takes on average 12 months during which time the fish have grown to an average of 80–100 g at which point they are transferred to seawater. Once transferred to seawater, healthy smolt typically experience an explosive growth rate, growing to 3–5 kg in the next 15 months. Salmon are typically harvested between 3 and 5 kg and must be harvested before the onset of sexual maturity, which degrades flesh quality. Salmon are marketed as fresh whole HOG (head-on, gutted) or value added portions (smoked, prepared meals, etc).

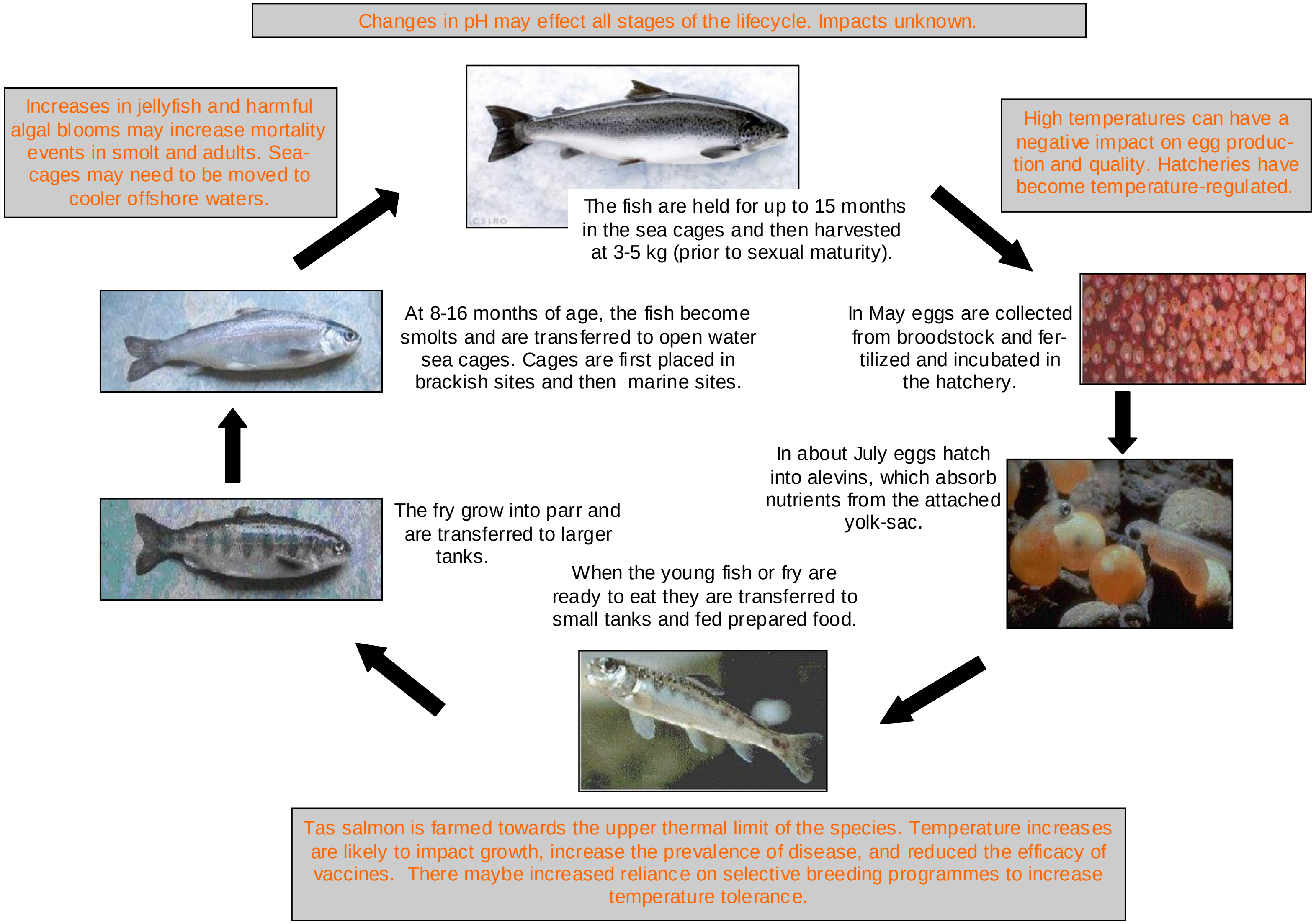

Figure 23.4: Life cycle of farmed Atlantic salmon and aquaculture process (this section) and responses to or impacts from relevant climate change drivers (sections 4 and 5). Adult image sourced from (Battaglene et al. 2008), all other images sourced from (The Marine Institute [Ireland] 2010).

Key points:

- Freshwater phase (alevins, fry, parr, smolt) takes 8–16 months.
- Smolt are transferred to sea cages, in brackish or fully marine sites.
- After a maximum of 15 months in grow-out, fish are harvested at 3–5 kg.

23.4. 4. Likely current impacts of climate change

The preferred temperature range for Atlantic salmon in sea cages is 16–18 °C. It has been suggested that 19°C is above the optimum temperature for growth and development of salmon in sea water. Although Atlantic salmon farmed in warmer climates can adapt to higher temperatures, summer temperatures experienced in some years have been known to affect salmon production in Tasmania. Overall, most Tasmanian salmon farms reported the maximum water temperature in winter to be 11°C and the maximum summer temperature as 18°C (at 5 m depth), which is a very favourable temperature profile compared to most other salmon farming regions of the world. However, in extreme conditions, water temperatures over 22°C do occur in summer months of some years.

Infectious disease outbreaks usually occur either due to the immunosuppression of the host due adverse environmental conditions or environmental factors being particularly beneficial for the pathogen, and thus can be both a direct and indirect impact of climate change. Temperature is the most important environmental factor involved in most disease outbreaks. Disease outbreaks on Tasmanian salmon farms (both hatcheries and marine grow-out) are currently more prevalent in warmer years. Additionally, if there is a disease outbreak and the temperature is greater the resulting mortality is greater. Increased temperature is a risk factor for most diseases currently affecting salmon industry, such as amoebic gill disease (AGD), rickettsia-like organism (RLO) infections, and marine flexibacteriosis, and more disease outbreaks occur in summer, even more during unusually warm years.

Harmful microalgae are influenced by changes in ocean temperature, nutrients and currents. The red-tide dinoflagellate *Noctiluca scintillans* has undergone a southward range expansion from NSW and is now a permanent overwintering species in southern Tasmania (Hallegraeff et al. 2008). This is likely to be due to increasing sea surface temperature (SST) in Tasmania and the strengthening of the East Australian Current. *Noctiluca* blooms have persisted in Tasmania since 1994 and were a significant problem for salmon farms in Nubeena (Tasman Peninsula) in 2002 (Hallegraeff et al. 2008), and are a significant and potentially increasing threat to salmon farms as temperatures continue to increase.

Key points:

- Currently, high summer temperatures in Tasmania can affect productivity and health of salmon, and cause an increase in disease outbreaks.
- The southward range expansion of *Noctiluca* in Tasmanian waters is a potential threat to salmon health.

23.5. Potential impacts of climate change (direct and indirect)

Looking at a worst case scenario, an average increase of 3°C in the surface water temperature in northern Tasmania could increase average temperatures up to 25°C in summer and to 14°C in winter. Whilst undoubtedly a generally alarming scenario from the Tasmanian salmonid farming industry's perspective, such predictions of average surface temperature do not provide adequate prediction of temperature profiles on a sufficiently fine spatial or temporal scale to elicit a clear mitigation response. (What will be peak temperatures in the bays/estuaries where salmonids are actually farmed? Given temperature profiles in most months of most years are very favourable for salmonid farming, how frequently and for what duration will temperatures remain above say 19°C?) The consideration of potential impacts should be viewed in this light.

23.5.1. Direct

Performance

Increases in infectious diseases as a function of climate change can be both a direct and indirect impact, but will be discussed in this section only. Continuing increases in water temperature will cause immunosuppression, which will make salmon more susceptible to some infectious diseases. While some pathogens may disappear due to too high water temperatures, other diseases will become more prevalent, such as marine flexibacteriosis. Furthermore, yersiniosis infections in marine environment (from carriers) occur more often at higher temperatures and thus will be more common if the water temperature is greater. Reduced rainfall in summer will have a synergistic effect on the outbreaks of AGD. It may also adversely affect the availability of freshwater for bathing. Changes in environmental factors often lead to the emergence of new pathogens and diseases. Many disease outbreaks occur for the first time during unusually high temperatures. For example, AGD which has been a health issue in the Tasmanian salmon industry for many years is increasingly being recorded in many other countries with increasing water temperature. Given Atlantic salmon are farmed in Tasmania at higher temperatures than elsewhere in the world it is difficult to predict what the potential new challenges will be. However, as water temperature continues to rise, the selective breeding program in Tasmania, which commenced in 2004, will become integral to maintain optimal growth rates and health though the selection of temperature tolerance.

While all vaccinations are currently undertaken at hatcheries, which are mainly temperature controlled and operating at optimum temperature, if fish become stressed and immunosupressed by high water temperature after transfer to sea cages, the efficacy of vaccination could be adversely affected. Most research conducted overseas on the effects of elevated temperatures on vaccination of salmonids has been done either at relatively low temperatures or on rainbow trout. Consequently the results may be misleading under Australian conditions.

Increasing ocean acidification is unlikely to have direct effect on salmon health but it is possible that it can contribute to disease outbreaks.

Farming infrastructure

A possible solution to temperature increases is to move the sea cages either south or offshore to colder waters. Suitable cage sites in southern Tasmania with lower temperature profiles are not available. More exposed offshore sites are available in state and also Commonwealth waters but would require new government zoning and the use of stronger cages, feeding systems, supply boats and infrastructure and may not offer any greater advantage with respect to lower water temperature profiles. Another possibility is for fish farming ships to be used but their development is still embryonic and operating them in the southern ocean would appear extremely difficult. True open ocean offshore sea cage technology is being developed overseas but is not currently used commercially in Australia. Intensive on-shore recirculation systems are now commercially in operation within Australia but on a scale that is not compatible with the volumes of salmon currently produced in sea cages. While technically feasible, salmon culture in recirculation systems is not widely practised in other parts of the world. However, the industry does increasingly rely on the technology for the hatchery production of smolts and all hatcheries are expected to become temperature-regulated to ensure the production of healthy smolt.

Market

Temperature increases may also affect the final product; studies on salmonids have shown that fish grown in warmer water have better physical flesh quality, but poorer colour. High temperatures have also been found to affect fatty acid composition in salmonids, with unsaturated fatty acids decreasing, in proportion to saturated fatty acids, with increasing temperature.

23.5.2. Indirect

Performance

Some species of jellyfish can cause significant problems for salmon farms, including suffocation and toxicity. It has been predicted that global warming may lead to further increases in jellyfish blooms worldwide (Mills 2001). Higher temperature could also increase the effects of jellyfish due to the potential for low oxygen concentrations in water and an increased toxicity of jellyfish toxins at higher temperatures. Harmful microalgae are influenced by changes in ocean temperature, nutrients and currents. Climate change may result in longer lasting 'bloom windows' for species already present in Tasmania (e.g. *Noctiluca*) and lead to the emergence of new species. Changes in environmental factors may also lead to the emergence of new pathogens and diseases (see Section 23.5.1 for more details).

Key points:

- Changes in temperature and pH may result in greater outbreaks of infectious diseases, such AGD, marine flexibacteriosis, and yersiniosis.
- Efficacy of vaccines maybe reduced.
- Sea cages may be moved offshore to cooler waters.
- There may be a potential increase in jellyfish and harmful microalgal blooms.

23.6. Critical data gaps and level of uncertainty

Little research has been done on the effects of higher temperature on Atlantic salmon health in Tasmania. Most of our knowledge of the effects of temperature on salmon health is based on information from the northern hemisphere, often investigating temperatures which are considered within the lower range in Tasmania. Furthermore, rainbow trout is more commonly used in research than Atlantic salmon. Other knowledge gaps identified include efficacy of existing vaccines at higher water temperature; effect of increased temperature on salmon immune response; effect of high temperature on pathogens currently affecting salmon farming; presence of organisms which could become pathogenic or affect salmon health in Tasmanian waters. Development of a vaccine against AGD and selective breeding for AGD-resistant stock should remain a high priority, as AGD is likely to become an increasing problem in the short-term. In relation to growth and nutrition, there appears to be very little information available about the impact of warmer waters on the nutrition of large production salmonids held in sea cages, with many studies focusing on juvenile stages. Temperature can also affect the final product and further research is required, there is a large body of literature on thermal acclimation and membrane fatty acid composition but it is difficult to integrate this into practical solutions.

Key points:

- Salmon is already farmed at high temperatures in Tasmania, and most studies are conducted on northern hemisphere stocks grown in cooler waters.
- Temperature has an effect on vaccine efficacy, immune response, and pathogens.

Table 23.1: Summary of Atlantic salmon species profile, which also indicates level of certainty of the associated information. Level of certainty is divided into high (H) = strong clear evidence, backed by several studies with solid datasets with little confounding interactions; medium (M) = evidence supported by one or more studies, conclusions may be partially ambiguous or confounded; low (L) = anecdotal evidence, limited data and/or predicted conclusions based on theoretical knowledge.

Life history stage	Business stage	Farm activity	Current impacts	Predicted impacts	Data gaps
Broodstock	Hatchery	Conditioning and/or holding		All Hatcheries/nurseries are expected to become temperature-regulated to ensure the production of healthy eggs and smolt	
Spawning & fertilisation		Fertilisation & incubation of eggs			
Larvae (alevins)		Larval rearing			
Juvenile development (fry and parr)	Nursery	Juvenile rearing, commencement of feeding, transfers to larger tanks			
Smolts	Growout	Transfer smolts to sea cages in brackish water	1. High summer temperatures currently effect salmon production and health (M) 2. Southward range-expansion of the harmful microalgae *Noctiluca* (M)	1. Further increases in infectious diseases due to increased stress and immuno-suppression (M) 2. Reduced efficacy of vaccines (L) 3. Ocean acidification may affect salmon health (L) 4. Sea-cages may need to be moved to cooler offshore waters (L) 5. Increased reliance on selective breeding programmes to increase temperature tolerance (M)	1. Most studies are conducted on northern hemisphere stocks grown in cooler waters. 2. Effect of temperature on vaccine efficacy, immune response, and pathogens. 3. Nutritional requirements at higher temperatures
Adults		Move sea cages to fully marine sites			

Post harvest	Market and marketing	Harvesting		Temperature increases may impact final product (L)	Further research is required in this area.
		Processing			
		Packaging			

23.7. References

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24. Blue mussel *Mytilus galloprovincialis*

Authors: Zoe Doubleday, Natalie Moltschaniwsky, Mark Gluis

24.1. The industry

The blue mussel (*Mytilus* sp) has a cosmopolitan distribution in temperate waters, and is found in the northern and southern hemispheres. For many years the Australian blue mussel was thought to be *Mytilus edulis*; however, taxonomic revision has identified the Australian and New Zealand mussel as *Mytilus galloprovincialis* (McDonald et al. 1991). The blue mussel is an important aquaculture species for West Australia (WA), South Australia (SA), Victoria and Tasmania.

Mussel farming in Australia uses the longline culture system (ABARE 2009), rather than the bottom culture system typically used in Europe. There are currently 14 licensed mussel farms in Tasmania, which are located on the mid-east coast (Spring Bay and Great Oyster Bay), Tasman Peninsula, and Huon and Channel regions (DPIPWE, unpub. data 2010) (Figure 24.1). The largest mussel farm, located at Spring Bay, produces spat from its own hatcheries, whilst the smaller farms rely on natural spatfall, which is collected in south-east Tasmania. There are 26 mussel licences in Victoria (ABARE 2009), which are primarily located in Port Phillip Bay. The Victorian farms depend on both natural spat fall and a recently established hatchery which has been developed through a joint industry–government partnership to provide seedstock for on-growing (Hutchinson et al. 2010). Spatfall in Port Phillip Bay is inconsistent and this has affected the productivity of the industry. Mussel farming began in SA in the mid-1990s and production has since grown steadily and is predicted to continue increasing. Key farming regions in SA are located in the Spencer Gulf, at Boston and Proper Bays adjacent Port Lincoln and also near Wallaroo. Spat are obtained exclusively from the wild in SA.

Key points:

- Blue mussels have a cosmopolitan distribution in temperate waters and are native to Australia.
- Mussels are cultured in WA, Tasmania, Victoria and SA using the longline system.
- Spat is collected from the wild, except for one farm in Tasmania which is hatchery based.

Figure 24.1: Blue mussel farming locations in SA, Tasmania and Victoria.

24.2. Production

Mussel production in Victoria has decreased significantly, from 1582 tonnes in 2001–02 to 521 t in 2007–08 (Figure 24.2). The decline in production is thought to be due to a decline in natural spatfall in Port Phillip Bay as a result of drought and lower nutrient input (Hutchinson et al. 2010). Production in SA has increased steadily over the last 10 years, with 1369 t produced in 2007–08 with a value of about $2.59 million. In 2007–08, Tasmania produced nearly half the amount of mussels as SA (746 t); however, the value of the Tasmanian mussels was slightly more ($2.61 million) than SA.

Key point:

- Mussel aquaculture contributes significantly to the economy in SA, Victoria and Tasmania, with a total production of 2636 t and value of $6.66 million in 2007–08.

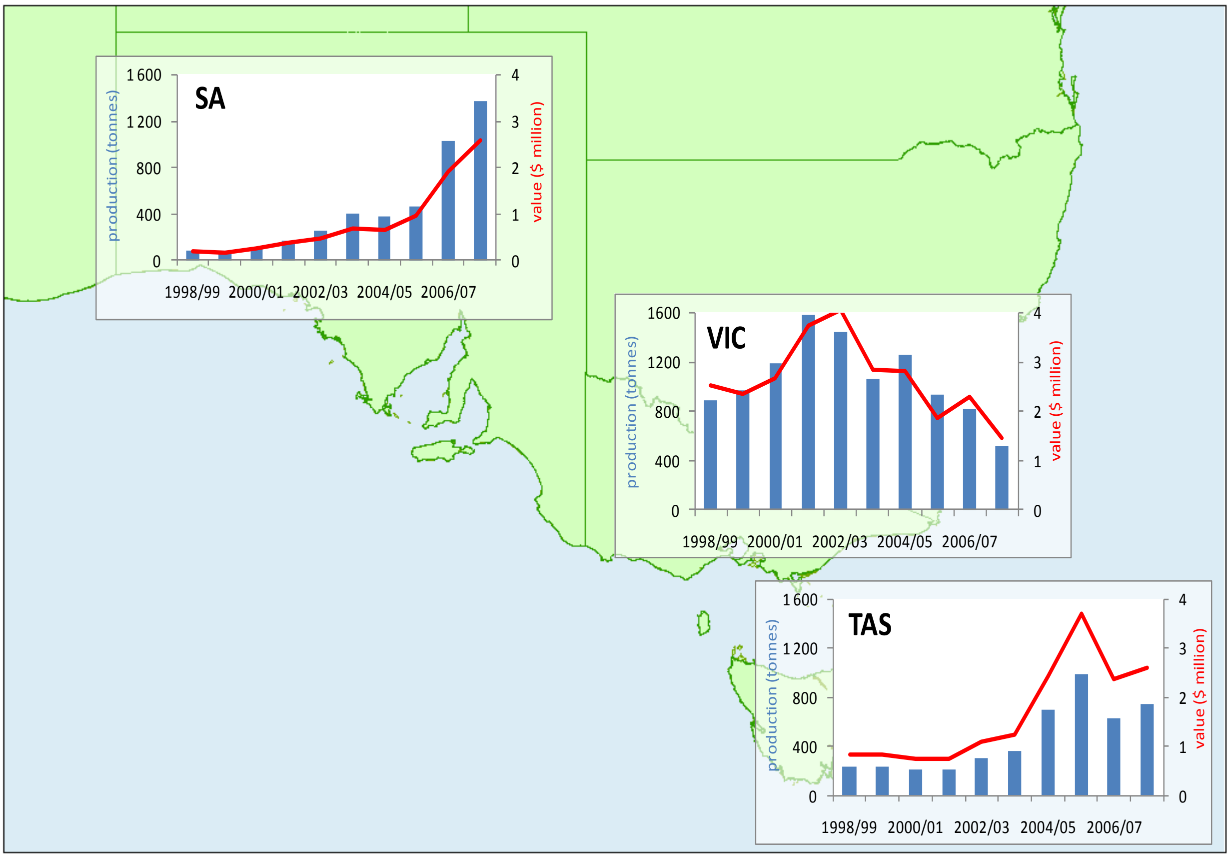

Figure 24.2: Blue mussel production (tonnes) and value ($ million) in SA, Victoria and Tasmania from 1998–99 to 2007–08 (ABARE 2008).

24.3. Life history stages and stages in the farming process

24.3.1. Life history

Mytilus sp. typically have a peak in spawning activity in late winter/early spring, followed by smaller spawning events over the summer. However, they are capable of adjusting their reproductive strategy according to environmental conditions which leads to annual variation in the timing of gametogenesis and spawning (Seed and Suchanek 1992). Although the exact drivers are unclear, the reproductive cycle of mussels is controlled by a complex interaction between external factors, such as temperature food and salinity, and endogenous factors, such as nutrient reserves, hormonal cycles and genotype (Seed and Suchanek 1992), making it difficult to predict spawning periods (Hutchinson et al. 2010). Mussels are broadcast spawners and are moderately fecund, with females producing millions of eggs (Lutz and Kennish 1992) (Figure 24.3). Eggs hatch into planktotrophic larvae, which have two developmental stages, trochophore larvae (24 hours) and veligers (14–21 days). Duration of the larval stage is dependent on temperature, salinity, and food availability. Immediately before settlement veligers become pediveligers during which time a suitable settlement substrate is sought; metamorphosis and settlement can be delayed until the pediveligers find a suitable substrate (Lutz and Kennish 1992). Once the larvae settle they secrete byssus threads to attach themselves to the substrate. Growth rates are variable, according to size, age, environmental conditions and genotype (Seed and Suchanek 1992), but can be rapid, with blue mussels typically reaching 32–92 mm in length at 12 months, and 53–110 mm after 18 months (Kailola et al. 1993). Mussels mature within two years and can live for about 25 years; however, they are harvested within 1–2 years. Mussels are filter feeders, and rely on phytoplankton, bacteria and organic matter for food (Hutchinson et al. 2010). They are preyed upon by fish, octopus, crabs and flatworms (Kailola et al. 1993); however, longline culturing methods reduced predation pressure from benthic species (Hutchinson et al. 2010).

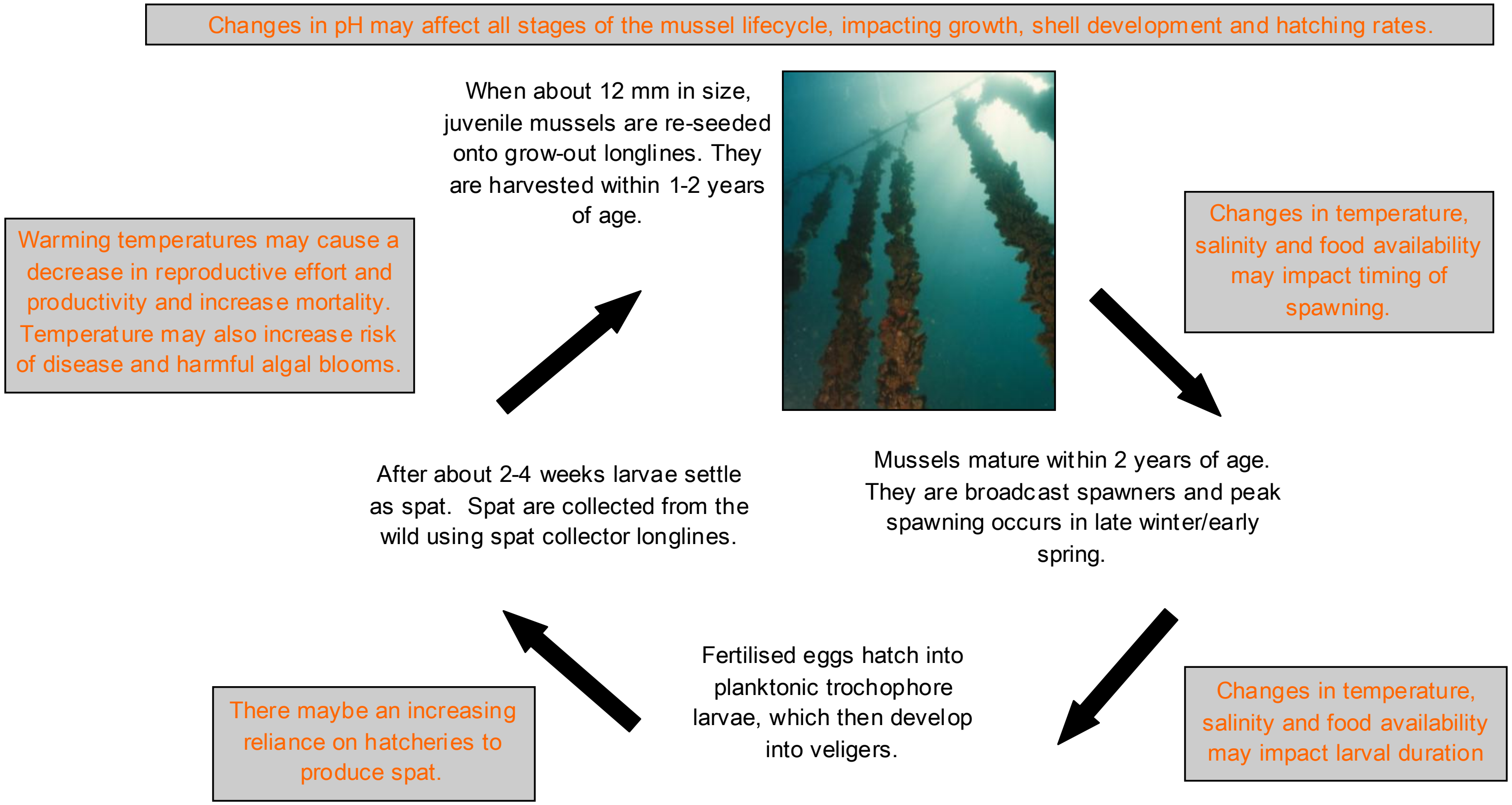

Figure 24.3: Life cycle of cultured blue mussels and aquaculture process (this section) and responses to or impacts from relevant climate change drivers (sections 24.4 and 24.5). Does not include the hatchery-based aquaculture of mussels. Image sourced from Xiaoxu Li (SARDI).

24.3.2. Aquaculture

Site selection is extremely important for bivalve mollusc culture, which are best cultured in areas with nutrient-rich water that can sustain healthy phytoplankton populations (Hutchinson et al. 2010). Significant water movement is also important, so the mussels can be supplied with a sufficient quantity of food. Currents at mussel farms typically range from 2–10 cm sec^{-1} (Hickman 1992). The culture sites should be relatively sheltered, to reduce stock loss from wind and wave action, and free from pollution and eutrophication (Hutchinson et al. 2010).

The longline culturing system involves a backbone rope (approximately 100 m in length) which is stretched horizontally 2–20 m below the water's surface and held in position by a system of anchors and buoys. The mussels are grown on either single (3–5 m) or continuous dropper lines (> 400 m) hung from the backbone. Longline systems are used for wild spat collection and for on-growing juvenile mussels to market size (PIRSA 2000). Once the juveniles have reached about 12 mm in size on the spat collection ropes, they are de-clumped, thinned-out and allowed to re-attach to the dropper line in a process called 'socking' (PIRSA 2000). A cotton sock retains the mussels on the dropper until they re-attach to the dropper using byssus threads, after which time the cotton sock rots away. Following this adjustment of densities, the mussels continue grow for a further 8–12 months. In Victoria, each dropper will produce between 15–30 kg of mussels over a production cycle, which is usually between 12 and 18 months (Hutchinson et al. 2010).

Most farms in Australia rely on natural spatfall for seed stock, and timing, in relation to the spawning period, is important when deploying spat collectors. Natural spawning of Port Philip Bay mussels occurs from June to September each year, with maximum product availability from July to January (Hutchinson et al. 2010). Limited data suggests that in SA mussels appear to be in peak spawning condition from June to September, with peak spawning occurring during August (PIRSA 2000). A study conducted in the 1980s in southern Tasmania found that major spawning events occurred also in late winter or early spring (at about or just above 10°C), however, spawning also occurs during summer and early autumn (Dix and Ferguson 1984). A similar pattern has been observed in WA, with spawning occurring in mid July, which also coincides with minimum winter water temperatures (~14°C) (Wilson and Hodkin 1967). However, in WA a second major spawning followed in September. Hatchery production allows for out-of-season reproductive conditioning of adults, and thus the resulting production of larvae and spat, by controlling the timing and the rate of gametogenesis (Fearman and Moltschaniwskyj 2010). Despite the benefits, mussel hatcheries are generally deemed economically unviable due to the low value of mussels compared with other shellfish and the ready availability of wild spat (PIRSA 2000; Galley et al. 2010). However, with increasing demand for mussels exceeding wild spat collection, often unreliable supply of spat, and the need for the aquaculture industry to develop sustainable practices it is likely that hatchery production, and the potential genetic advances it can bring, will become important (Galley et al. 2010).

Key points:

- Mussels are broadcast spawners, and larvae are planktonic for 2–4 weeks. Settled larvae or spat grow rapidly and mature within two years.
- In southern Australia, major spawning events are typically in late winter/early spring.
- Spat are mostly collected from the wild using spat collector ropes; however, there is one hatchery in Tasmania and one in Victoria.
- Juveniles are re-attached to grow-out ropes and harvested within two years of age.

24.4. Likely current impacts of climate change

There are no known studies documenting current impacts of climate change on blue mussels in Australia. However, the decline in natural spatfall in Victoria may be linked to climate change, with the decline thought to be the result of drought and lower nutrient input into Port Phillip Bay (Hutchinson et al. 2010).

Key point:

- There are no documented impacts of climate change. However, it is hypothesised that the decline in spat in Victoria is due to drought.

24.5. Potential climate change impacts (direct and indirect)

24.5.1. Direct

Performance

Mussels naturally reproduce during cooler winter months and warming temperatures in Australia may have serious implications for reproductive effort and mortality (Fearman and Moltschaniwskyj 2010). A laboratory study in Tasmania found that rates of gametogenesis in *M. galloprovincialis* were negatively correlated with temperature, with energy availability appearing to have limited the rate of maturation, which was particularly evident in mussels held at 19°C (Fearman and Moltschaniwskyj 2010). Although 19°C is greater than the thermal maximum typically experienced by mussels in Tasmania, mussels in SA also live in waters that reach 23–24°C. Another laboratory study in Greece found that *M. galloprovincialis* increased the duration of valve closure by about sixfold when held to 24°C rather than to 17°C (Anestis et al. 2007). Such behaviour caused metabolic depression and probably a shift from aerobic to anaerobic metabolism. Acclimation to temperatures greater than 24°C caused an increase in mortality. It seems that *M. galloprovincialis* in the Mediterranean lives close to its thermal limits and that a small degree of warming will cause stress responses at whole organism and molecular levels (Anestis et al. 2007).

Mussel larvae also are sensitive to moderate increases in temperature. The growth of *M. edulis* larvae increases with temperature, with growth rate increasing from 3.6 – 5.0 µm day^{-1} with a 3°C rise in culture temperature from 14–17 °C (Galley et al. 2010). However, no increases in growth were observed between 17 and 21°C, suggesting an optimum culture temperature of about 17°C for *M. edulis* larvae. An integrated model of ecosystem-scale carrying capacity in shellfish growing areas in Northern Ireland predicted the effect of water temperature increases of 1 and 4°C on aquaculture productivity. It was predicted that for *M. edulis* an increase of 1°C would lead to a reduction in productivity by about 50% and an increase of 4°C would result in a reduction of productivity by 70% (Ferreira et al. 2008). Climate change was also suggested to affect nutrient inputs due to alterations in the hydrological regime and land use of the catchment.

Mussels, like other $CaCO_3$-producing organisms, may be particularly sensitive to ocean acidification (due to increasing CO_2 levels). Decreased pH levels, predicted to occur at the end of this century, significantly affect the growth of planktonic *M. edulis* larvae (Gazeau et al. 2010). Although blue mussel larvae are able to develop a shell in seawater undersaturated with aragonite, decreases in hatching rates and shell growth could negatively impact on settlement success. Calcification rates of juvenile and adult *M. edulis* have also shown to decline linearly with increasing CO_2 (Gazeau et al. 2007). A second similar study on *M. edulis* found that there was reduced growth at a pH of 7.1, but growth at 7.4 and 7.6 was not significantly different from growth at the normal pH of seawater (8.1) (Berge et al. 2006).

Farming infrastructure

There may be an increased reliance or need for hatchery production due increased variability in production of wild spat. There are already a number of molluscan hatcheries in existence, and there may be little need to build new hatcheries; however, more research into hatchery methods that will allow all year production of mussels is required. Another key vulnerability is the increased risk of stock loss due to wind and wave action (Hutchinson et al. 2010). There may be a need in the future to improve and strengthen farm infrastructure against mechanical damage from storms.

Social

The increased use of hatcheries will likely require more labour and may result in the relocation of labour. Most mussel farms are owned by families in rural areas, so hatchery use may have a positive impact on small businesses and rural communities due to increased employment.

24.5.2. *Indirect*

Performance

Higher water temperatures increases the risk of mussel mortalities caused by bacterial and viral infections (Galley et al. 2010). A study in Greece found that temperature was positively related to the growth of a disease-causing protozoan in *M. galloprovincialis*, with such parasitism impairing mussel health and their resistance against other stressors, such as increasing water temperatures (Anestis et al. 2010).

Farming infrastructure

Suspended culturing systems are vulnerable to fouling by epifloral and epifaunal species (Hickman 1992). Ascidians, especially, can impact spat collection because they prevent spat from settling and grow over spat once settled. Fouling organisms may increase due to increases in water temperature, increasing the effort required to clean infrastructure and the mussels for market. There are no known studies which have linked climate change with increases in fouling species on mussel farms; however, the impact of ascidians on spat collection has increased in SA in recent years.

Marketing and social

Increases in harmful algal blooms (HABs) may pose particular problems for mussel aquaculture in the future in regards to human health, product marketability, and productivity (due to farm closures). The Huon Estuary in Tasmania is particularly susceptible to regular mono-specific blooms of the chain forming toxic dinoflagellate *Gymnodinium catenatum*, a species which causes paralytic shellfish poisoning (PSP) (Hallegraeff et al. 1995). The dinoflagellate can cause significant problems for the local shellfish farms (Clementson et al. 2004). Warming temperatures are predicted to cause longer-lasting bloom windows for *G. catenatum*; however, there are already early signs that this dinoflagellate is now persisting in Tasmania through warmer winter months (Hallegraeff et al. 2009).

The shelf life of fresh mussels may be reduced due to increased pathogen loads at elevated temperatures. Procedures for handling, transport, packaging and storage may have to be more stringent or improved.

Key points:

- There is considerable evidence from laboratory studies to suggest that small increases in water temperatures in southern Australia may have negative effects on mussel health and productivity.
- Laboratory studies also indicate that decreases in pH will have negative impacts on mussel growth and development.
- Parasites and disease may become a greater issue as mussels become stressed with increasing temperatures.
- There may be potential increases in HABs and fouling organisms.

24.6. Critical data gaps

Little is understood about the complex set of factors influencing the reproductive cycle, timing of spawning, and larval development in mussels. This will be important in determining any current or potential impacts of climate change on spat variability and availability in the wild. Impacts of increasing temperature and decreasing pH have only been tested in laboratory conditions, and predominantly based on *M. edulis* or European stocks of *M. galloprovincialis*. More studies are required that are based on Australian mussel stocks and relevant to environmental conditions in southern Australia. It will also be important in the future to examine the synergistic impacts of climate change drivers, such as temperature and pH. If a greater reliance on hatchery-produced spat is required, more research into mussel culture will also need to be addressed.

Key points:

- Further research is required into factors effecting wild spatfall.
- More studies are required which address climate change impacts on mussels in Australia.

Table 24.1. Summary of blue mussel species profile, which also indicates level of certainty of the associated information. Level of certainty is divided into high (H) = strong clear evidence, backed by several studies with solid datasets with little confounding interactions; medium (M) = evidence supported by one or more studies, conclusions may be partially ambiguous or confounded; low (L) = anecdotal evidence, limited data and/or predicted conclusions based on theoretical knowledge.

Life history stage	Business stage	Farm activity	Current impacts	Predicted impacts	Data gaps
Spawning and fertilisation (wild)	N/A	N/A	Variability in timing & extent in reproductive output (L)	Decrease in time period optimal for gonad development (M)	Little understood about the complex set of factors influencing reproductive cycle and timing of spawning
Spawning and fertilisation (hatchery)	Hatchery	Conditioning of broodstock and fertilisation		None: conditions can be modified to provide optimal environment	
Larvae and spat (wild)	Spat collection	Spat collection using longline method	Decline in wild spat in Vic (L)	1. Reduced time period suitable for larval and spat development each year (M) 2. Reduced growth and poor shell development due to lower pH (M)	Impacts of temperature and pH have only been tested in laboratory conditions.
Larvae and spat (hatchery)	Hatchery	Larval rearing and settlement induction		None: conditions can be modified to provide optimal environment	
Juveniles/Adults	Growout	Re-seed grow-out longlines		See 1 and 2 in 'larvae and spat (wild)' 3. Increases in fouling organisms (L) 4. Increases in HABs (M)	
Postharvest	Market and marketing	Harvesting		Increases in contaminated product due to HABs (L)	
		Processing		More restricted standards for	Optimal conditions to control the

				transportation and processing (L)	proliferation of marine bacteria
		Packaging		Reduced shelf-life due to higher bacteria loads (L)	Alternative packaging methods

24.7. References

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25. Pacific oyster *Crossostrea gigas*

Authors: Xiaoxu Li, Steven Clarke, Zoe Doubleday

25.1. The industry

The Pacific oyster *Crassostrea gigas*, also called the Pacific giant oyster or Japanese oyster, is a bivalve mollusc and endemic to the Pacific region in Asia. This species was introduced from Japan into four Australian states to trial its suitability for aquaculture between 1940 to 1970 (Medcof and Wolf 1975; Olsen 1994), resulting in survival of some oysters in Tasmania and a small population in Victoria. The oysters in South Australia (SA) and Western Australia (WA) died (Coleman and Hickman 1986).

The farming of Pacific oysters begun in Tasmania in the 1960s and it was then extended to SA in the 1970s (Clarke and Madigan, 2008). At that time the spat supply for both states was wild caught on sticks in Tasmania. The spat was then grown with the stick and tray system originally developed for Sydney rock oysters in NSW (Wilson 1970; Sumner 1980a, b; Grove-Jones 1986; Olsen 1994). The industry expanded rapidly in both states in the 1980s when the hatchery production of spat was developed in Tasmania (Olsen 1994). At the same time the industry also developed the basket and plastic tray systems for intertidal culture and the stacked plastic tray system for subtidal culture. The oyster industry in SA now uses spat produced both locally and from Tasmania, with the first SA oyster hatchery established in the 1990s (Olsen 1994). The oyster growers in SA have also invented the longline system for intertidal culture and this has now been adopted for Pacific oyster growout in NSW and Tasmania, as well as in some countries overseas.

Pacific oysters were illegally introduced into Port Stephens, New South Wales (NSW) in the 1980s (Holliday and Nell, 1985). However, their classification by the NSW Government from a noxious, feral species that should be destroyed to one that could be grown and marketed in the Port Stephens region occurred in 1991.

The time period required for Pacific oyster to grow to marketable size varies between farming regions and targeted market size; but it is normally between 1.5 and 2.5 years. During this period, oysters are regularly brought back to onshore sheds to be graded by hand or mechanical grader to achieve size uniformity and maintain optimal stocking densities. Some growers also move stocks between regions to improve product quality, such as shell hardiness in one region and meat/shell ratio in another.

Pacific oysters are sold by growers in three forms; fresh unopened (by far the most common), fresh opened, and frozen opened. The fresh unopened oysters are mainly sold to seafood processors where they are opened and packed in dozen or half dozen trays prior to provision to retailers or restaurants. During transport and storage these oysters are refrigerated. This 'half-shell' market is the premium and main market for the Pacific oyster industry in Australia.

Since the introduction of Pacific oysters in Australia, dense wild Pacific oyster populations have become established in some parts of Tasmania and NSW, totally covering some intertidal reefs. In SA, wild individuals have colonised some farming regions (Madigan and Clarke 1998; Sierp 2008).

Key points:

- Pacific oysters were first introduced from Japan to Australia in the 1940s and their aquaculture was established in the 1960s in Tasmania, 1970s in SA and 1990s in NSW.
- Pacific oysters in Australia are now mainly farmed in intertidal regions on racks or longlines with spat being produced by commercial hatcheries.
- Wild Pacific oyster populations have become established in Tasmania and NSW, while wild individuals have colonised some farming regions in SA.

25.2. Production

Pacific oyster aquaculture is now a major contributor to the economy in both SA and Tasmania. It is the second highest value aquaculture industry in both states, having an annual farm gate value of $30 and $19 million in 2007/08, respectively (Figure 25.1, ABARE 2009). From 1998–99 to 2007–08 the product volume remained relative stable while its value nearly doubled in Tasmania. In SA, on the other hand, both the annual volume farmed and its value have tripled over the same period (Figure 25.1). It is anticipated that the production value in SA will further increase by 14% in 2010–2011 (Econsearch 2009). Currently the industry directly employs 468 on-farm staff in SA, the most of any of the diverse aquaculture industries in the State (Econsearch 2009).

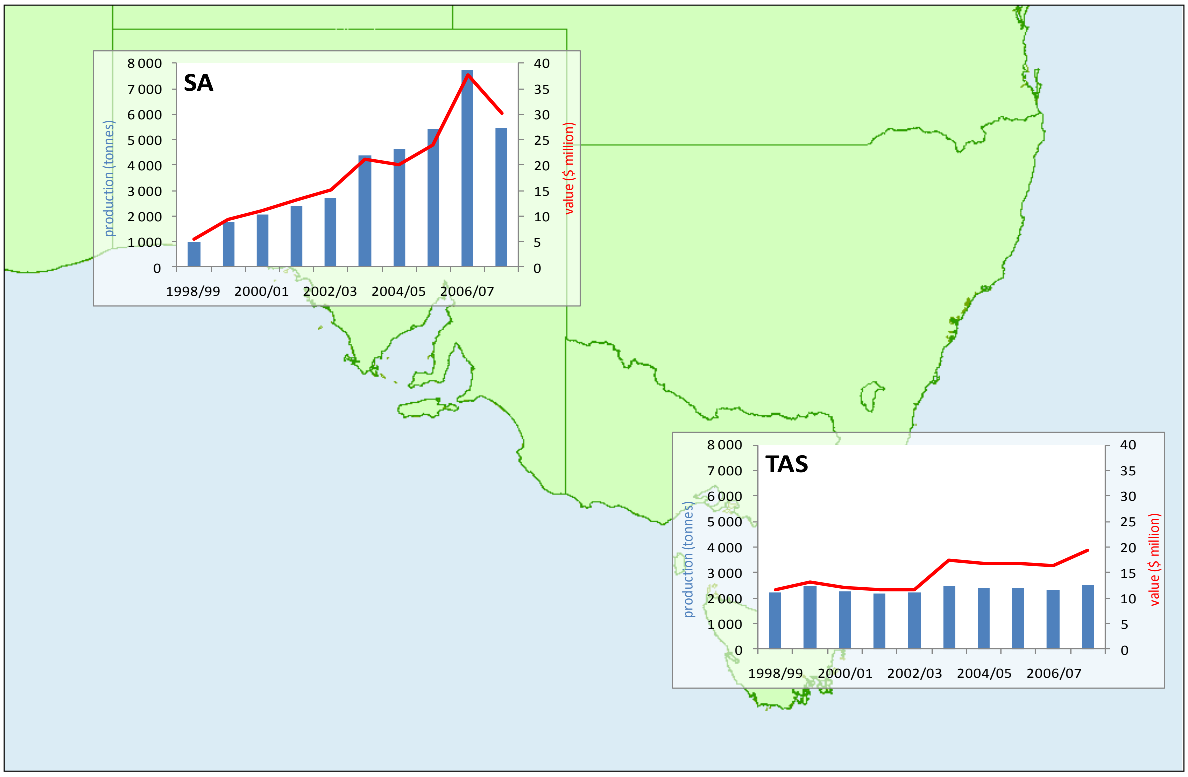

Figure 25.1. Pacific oyster production (tonnes) and value ($ million) in SA and Tasmania from 1998–99 to 2007–08 (ABARE 2008).

In SA there are 581 Pacific oyster farming licences issued (ABARE 2009) and this species is farmed in five major areas: Coffin Bay, Franklin Harbour, Murat Bay, Smoky Bay, Streaky Bay, the eastern side of Yorke Peninsula and the north eastern side of Kangaroo Island (Figure 25.2). In Tasmania there are 118 Pacific oyster farm licence holders (ABARE 2009) and they growout hatchery spat primarily in the Smithton, St Helen's, Great Oyster Bay, Norfolk Bay and D'Entrecasteaux Channel and Huon areas (Figure 25.2).

In NSW Pacific oysters are commercially farmed in the Port Stephens area, but the annual volume and value is much less than in SA and Tasmania, although total oyster production (mainly Sydney rock oysters) is substantial with a value of $39 million and volume of 4500 tonnes.

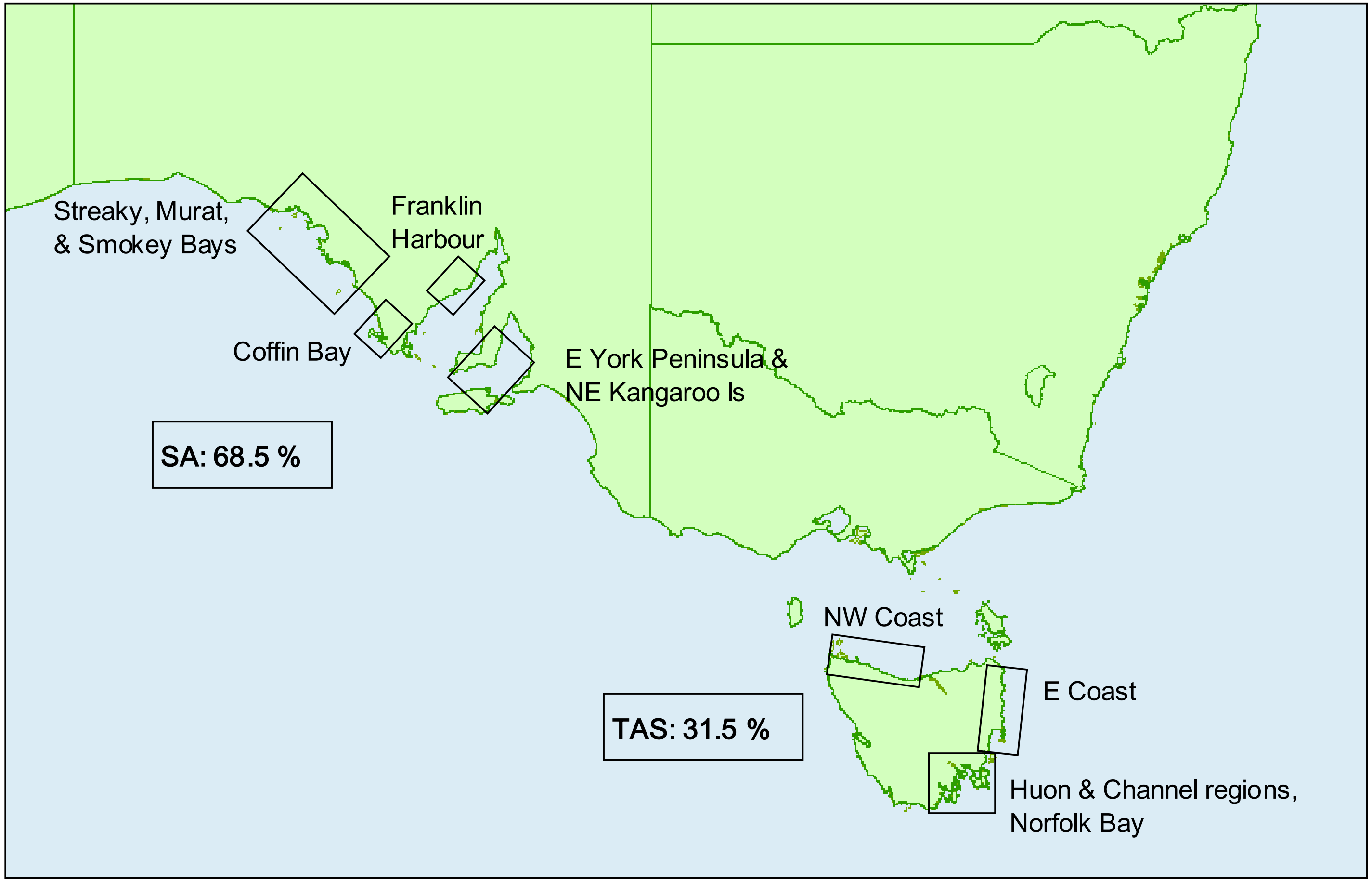

Figure 25.2: Farm locations of Pacific oyster in SA and Tasmania and the proportion (%) each state currently contributes to total production (based on 2007–08 production).

Key points:

- Pacific oysters are farmed in SA, Tasmania and in the Port Stephens area, NSW.
- Pacific oyster farming is the second highest value aquaculture industry in both SA and Tasmania, and the largest direct on-farm employer in the diverse SA aquaculture industry.
- In 2008–09, the total annual value and production of Pacific oysters was $30.1 million and 5448 tonnes in SA and $19.4 million and 2512 tonnes in Tasmania. Production of this species is much less in NSW.

25.3. Life history stages, stages in farming process and physiology

25.3.1. Pacific oyster life history

Pacific oysters start to produce gametes when about one year old. They change sex during their life, usually maturing as a male first and then change to female in subsequent spawning seasons (Li 2009). Their sex may also be affected by environmental conditions. The percentage of male oysters farmed in regions of low primary productivity is normally higher than in higher productivity regions. Pacific oysters release their gametes into the water column in one spawning during late spring and summer each year, although multiple spawning occur in some regions. When gametes from different sexes unite and produce fertilised eggs, they hatch into swimming larvae within 5 hours at 25°C and develop their first larval shells within 24 hours. At this stage most their larval organs have developed and the larvae are able to feed on microalgae. The second larval shells develop about one day later and grow with the further development of the larvae. When the eyes and foot of the larvae are fully developed in approximately three weeks, the larvae are ready for settlement. Pacific oyster larvae prefer to attach themself to a hard surface and are classified as spat when they have developed the basis of an adult shell. This change from a swimming to a bottom dwelling life style is called metamorphosis. Oysters remain attached for life; although aquaculurists frequently settle them on small pieces of substrate (e.g. shell) that facilitate their ongrowing as individual unattached oysters (Figure 25.3).

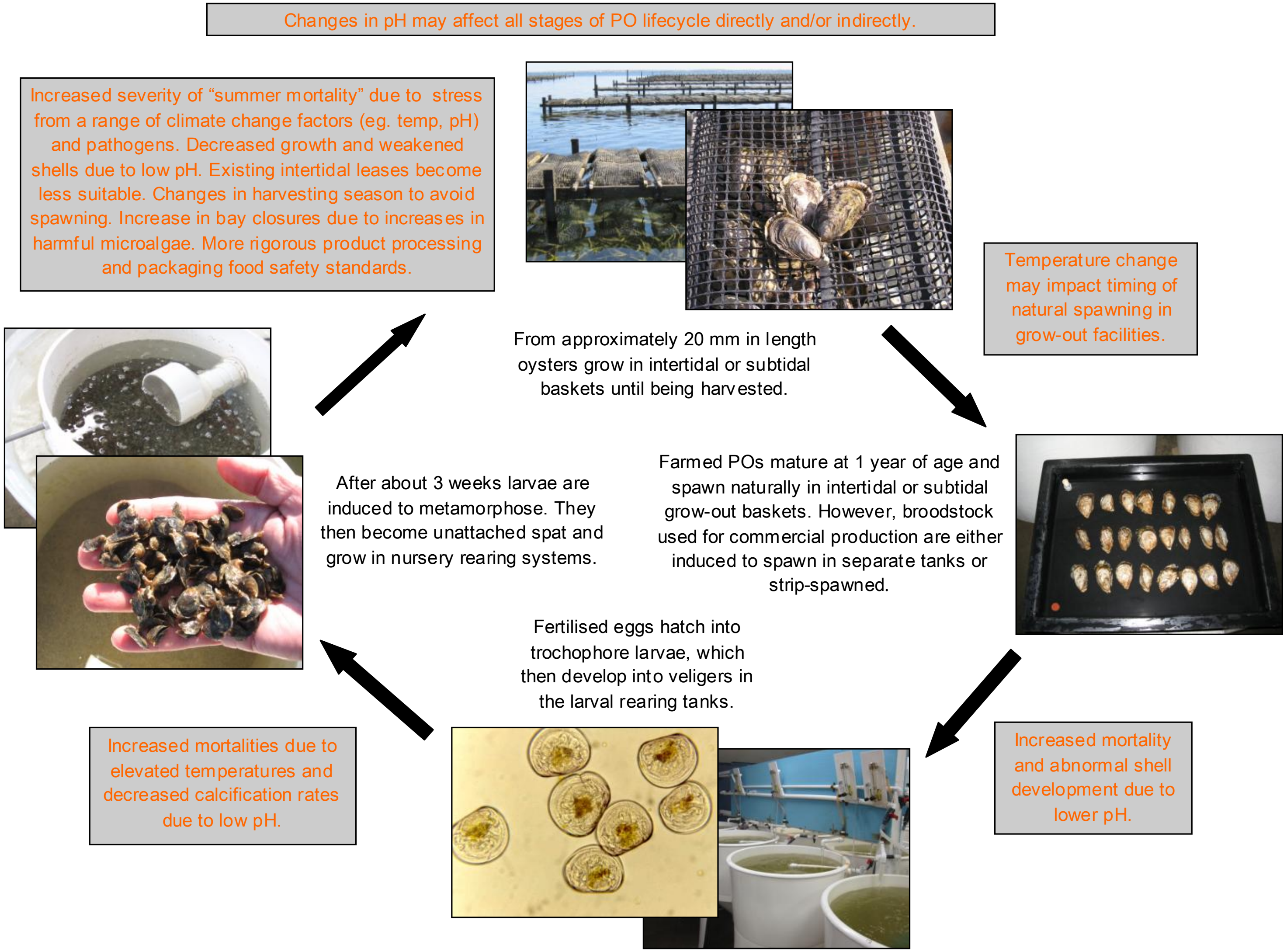

Figure 25.3. Key oyster life cycle stages (this section) and responses to or impacts from relevant climate change drivers (subsequent sections). Image source: X Li (SARDI), G Zippel (Zippel Enterprises Pty Ltd), and A Butterworth (SA Oyster Hatchery).

25.3.2. *Pacific oyster aquaculture*

The Pacific oyster aquaculture business consists of the following four main stages: 1. Hatchery; 2. Nursery; 3. Growout and 4. Market Supply. Some specialisation exists in this industry in each of these areas. Commercial hatcheries specialise in broodstock selection, conditioning and maintenance, spawning induction, fertilisation and intensive larval rearing in tanks, metamorphosis induction to produce cultchless spat (spat without settlement) and early stage spat maintenance in land-based facilities, or on subtidal leases. Hatcheries sell their spat to oyster growers who specialize in finishing oysters to market size over an 18–30 month period. Depending on the spat size at purchase, growers normally continue to grow the young oysters in spat trays until they are large enough to be put into baskets for growout on racks, or longlines. Therefore, the farming process at the oyster nursery stage often involves and is shared by hatcheries and growers. Growers are also responsible for the harvesting of their stock (the first step in the market supply chain) and grade them according to their shell height, typically into jumbo (>100 mm), large (85–100 mm), standard (70–85 mm), buffet (60–70 mm), and bistro (50–60 mm) size classes. Oysters are sold according to their size grade, meat quality (meat/shell ratio), shell shape and of course the market demand. Graded oysters are sent to seafood processors where they are processed into half-shell product, packed on trays and then distributed to retailers or restaurants as a fresh or frozen product. Graded oysters are also sent to retailers and restaurants directly where they are processed according to customers' demand.

Hatcheries therefore manage the oyster from the broodstock to spat stage; growers from the spat to market size stage, and marketers thereafter, typically only a very short period (less than 10 days).

The environmental conditions in oyster hatcheries are highly controlled to provide broodstock, larvae and spat the optimal conditions to promote ideal conditions for gonad development and produce the best conditions for growth and survival. The parameters considered of most importance include water temperature, feed (microalgae) quantity and quality, and water quality. When oysters are put out on leases either at the nursery or growout stage, they are subjected to local environmental conditions, as well as predators and pests, and at this stage farmers have much less control once their farm site has been decided. The methods used by growers to improve production and product quality are maintaining appropriate stocking densities and regularly (every 6 to 8 weeks from March to December), grading oysters to avoid larger oysters out-competing smaller ones for space and food. Grading also allows oysters and baskets to be 'cleaned' of fouling organisms (animals and plants) and sediment.

Pacific oysters are a filter feeding invertebrates. Their farming regions therefore require good quality water to provide sufficient food to promote growth and conditioning, as well as being free of pollution, pathogenic bacteria and toxic microalgae, which could cause public health concerns when the oyster are marketed. In Australia, oysters are mainly harvested prior to spawning when they are in peak condition around the Christmas – New Year high market demand period. After harvest, oysters will be maintained in refrigerated environments (about 4°C) during storage and transportation and be sold to consumers within a short period.

Pacific oysters have a very wide environmental tolerance, demonstrated in part by their success following translocation. Their introductions have been tried in around 55 countries globally for aquaculture, often due to a decline in abundance of the oyster species previously endemic to that region due to overfishing (Ruesink et al. 2005). They can grow at a water temperature range of 3–35°C and a salinity range of 10–42‰ (Shatkin et al 1997). The optimal salinity ranges for rearing Pacific oyster larvae and spat are 19–27‰ and 15–30‰ respectively (Nell and Holliday 1988). At a salinity of 41‰, a typical salinity level in some SA bays, the water temperature of 27°C is the upper limit for oyster growth given adequate food is available (Shpigel and Blaylock 1991). The optimal water temperatures for larval and adult growth are 25–30°C and 15–18°C respectively (Quayle 1969; His et al. 1989).

Triploid Pacific oysters are also farmed in Australia, mainly in Tasmania. They are commercially produced by crossing eggs from diploid females with sperm from tetraploid males. Their life cycle stages and the methods used for their aquaculture are the same as their diploid counterparts except that they are nearly sterile and normally do not spawn in the wild.

Key points:

- Pacific oysters have a complex life cycle and are sessile in the wild.
- Both diploid and triploid Pacific oysters are farmed in Australia.
- The environmental conditions at both the hatchery and market supply stages are highly controlled.
- During growout on intertidal farm leases, oysters are subjected to the local air and water environmental conditions as well as a range of natural predators and pests.

25.4. Likely current impacts of climate change

Pacific oyster 'summer mortality' refers to an 'abnormal' mortality episode when more than 30% of the population dies during the warm temperature season (Soletchnik et al. 2007). Summer mortality affects oysters of one year old or older and on both diploid and triploid stocks (Calvo et al. 1999). This event has been reported in many countries in the world (Beattie et al. 1980; Berthelin et al. 2000; Soletchnik et al. 2007; Li 2008) and re-occurs in some farming regions in Australia. Results from published studies indicate that summer mortality cannot be explained by a single factor, but rather by the combination of environmental and internal factors such as variations in temperature, salinity and dissolved oxygen, gametogenesis and spawning, physiological and/metabolic disturbances, and pathogens (Perdue et al. 1981; Berthelin et al. 2000; Cheney et al. 2000; Le Roux et al. 2002; Li et al. 2007; Song et al. 2007a, b; Soletchnik et al. 2007; Li 2008; Li et al. 2009). Most these parameters can be influenced directly and/or indirectly by climate change.

Flatworms, *Imogine mcgrathi* are a threat to oyster production (Jennings and Newman 1996), and can have devastating effects on oyster spat when it occurs in high numbers (O'Connor and Newman 2001). It appears that they become abundant in the periods of prolonged drought when estuarine salinities are relatively high (O'Connor and Newman 2001).

Key points:

- 'Summer mortality' occurs frequently in some Pacific oyster farming regions, although its linkage to climate change is unclear.
- The abundance of the flatworm species threatening oyster production in estuarine regions appears coupled with prolonged drought.

25.5. Potential impacts of climate change (direct and indirect)

Climate changes can affect the Pacific oyster aquaculture business by directly acting on the animal itself, on farming infrastructure, on farm husbandry practices, and/or marketing strategies (direct impacts). Alternatively, climate change can cause indirect effects by acting on associated organisms and the community on which oyster farmers are dependent (indirect impacts).

25.5.1. *Potential direct impacts*

Oyster performance

Oyster larval shells are built up from the unstable form of calcium carbonate and as such these are in balance with the calcium carbonate levels of the seawater in which oysters live. One of the predictions from climate change modelling is that the cold, high-latitude surface waters will become undersaturated by the year 2050 (Miyazaki et al. 2010), another that low pH upwelling waters may increasingly influence surface waters at some coastal locations (Feely et al. 2008). It has been hypothesised that both may negatively impact on bivalves.

Studies on Pacific oyster larvae have shown that their early development is very sensitive to pCO_2 increases; only 5% of fertilised eggs develop into normal D-shaped larvae in the CO_2 treated group as compared with 70% in controls, although no difference was observed between these two groups prior to this stage (Kurihara et al 2007). This can result in devastating consequences for an oyster hatchery because contamination from unhealthy larvae can quickly spread through the intensive larval rearing system and is difficult to manage.

When adults are exposed to CO_2-induced acidified seawater, Pacific oysters build less shell as CO_2 levels increase. The calcification rate in Pacific oysters decline linearly with increasing pCO_2 (Gazeau et al 2007).

With an increase in air and seawater temperatures, Pacific oysters may spawn earlier. Also, on hot days oysters are hung at a lower level to reduce the period they are exposed to air. Handling is also avoided to minimise any extra stress that could occur. If the higher air and water temperature period is extended due to climate change, the oyster's performances could be compromised. Exposure to high air temperatures coupled with reproductive activity may be a significant factor causing summer mortalities (Summer 1980a).

Farming infrastructure

With a predicted rise in sea level due to climate change, water depth at existing intertidal oyster farm sites will become deeper, which may lead to a need to modify the infrastructure in place (to cope with deeper water or in some cases a commensurate increase in wave action), and as such additional infrastructure costs. Existing husbandry practices may also need to be varied or new practices developed. If sea level changes increase significantly, some existing intertidal sites may become unsuitable for farming; and alternative intertidal sites may not be available. While Pacific oysters can be farmed subtidally, these practices are not well established in Australia and are best when done in association with intertidal farming.

Marketing strategy

If oysters spawn earlier due to climate change, they might become unmarketable during the Christmas – New Year period; the time of highest market demand in Australia. This is because spawned oysters become watery and have the lowest meat/shell ratio; in SA it generally takes about four months before they are marketable again.

25.5.2. Potential indirect impacts

Oyster performance

While bivalves have been shown to consume a wide range of particulate organic matter, marine phytoplankton is the major component of their diet. Marine phytoplankton can be quite sensitive to CO_2-related environmental changes (Fu et al. 2007), which can, in turn, affect oyster performance.

Pacific oyster mortalities are generally thought to result from opportunistic pathogens that infect oysters already weakened by a combination of stress and the high energetic costs associated with reproduction (Taris et al. 2009). Elevated temperature is known to be the strongest environmental predictor of the presence of marine pathogenic bacteria

(Zimmerman et al. 2007). Increased salinity, turbidity and chlorophyll have also been shown to increase bacterial numbers in some conditions (Zimmerman et al. 2007).

Farming infrastructure

Settlements and growth of fouling species such as barnacles on farming infrastructure may increase due to higher water temperature and pCO_2, requiring farmers to more frequently clean the infrastructure. The design of infrastructure may also need to be varied as climate change may result in predatory crustaceans becoming more prolific; research has shown that species such as American lobster (*Homarus americanus*) and the blue crab (*Callinectes sapidus*) grow a larger and heavier shell under higher CO_2 levels (Oceanus, 2010).

Marketing strategy

The Huon Estuary in Tasmania is particularly susceptible to regular mono-specific blooms of the chain-forming toxic dinoflagellate *Gymnodinium catenatum*, a species which causes paralytic shellfish poisoning (PSP) (Hallegraeff et al. 1995). The dinoflagellate can cause significant problems for the local shellfish farms (Clementson et al. 2004). Warming temperatures are predicted to cause longer-lasting bloom windows for *G. catenatum*, and there are already early signs that this dinoflagellate is now persisting in Tasmania through warmer winter months (Hallegraeff et al. 2009).

The shelf life of fresh oysters can be reduced due to increased pathogen loads at elevated temperatures. Susceptibility in-situ may increase, and procedures for handling, transport, packaging and storage may all have to be more stringent or improved.

Social

Oyster farming typically occurs adjacent to relatively remote rural communities. In SA townships such as Coffin Bay (population 650), Cowell (population 791), Denial Bay (356) and Smoky Bay (200) are very small. Oyster farming and other agriculture business are the major forms of employment within them. Climate change that results in increased aridity and higher air temperatures has the potential to negatively impact on the other agriculture business, with any decrease in population likely to cause labour shortage and have rapid flow-on effects that result in a loss of services, which in turn leads to further population loss.

Key points:

- Climate change is likely to affect oyster performance, farming infrastructure, farm husbandry practices, and marketing, both directly and indirectly.
- Research has already identified that some potential impacts of climate change can have serious consequences (e.g. lower pH and/or increased pCO_2 can significantly affect growth of adult oysters).
- New market strategies might be needed.

25.6. Critical data gaps and level of uncertainty

Pacific oysters are filter feeders and are farmed on 'fixed' infrastructure and leases, and as such the performance of farmed oysters and thus oyster aquaculture businesses are determined by local environmental conditions. However, very limited or no information on fine-scale climate change impacts is available, which is a challenge to oyster growers, resource managers and policy makers to establish effective methods to mitigate the potential negative impacts of climate change.

Metabolic/physiological and immunological processes are the critical biological events to maintain oysters' healthy status, performances, and harmoniousness with surrounding environments. Knowledge on the responses of these processes to climate changes is unknown in this species. This would limit the modelling capacities to predict climate change impacts on this species and develop mitigate strategies.

Pacific oyster summer mortality is still an open question challenging the science community. Its complex nature suggests that it might be very sensitive to climate changes.

Very little is known about the decline in calcification rates with increasing pCO_2 on shell hardiness or if the existing intertidal farming methods and market supply methods are suitable for 'weak shell' oysters. Very limited information is available on the effects of increased seawater pCO_2 on oyster early larval development, with no information on other critical development stages such as metamorphosis, gonad development and sex ratio. These are critical to a successful oyster aquaculture business, especially for hatcheries.

Very little is known about the impacts of climate change on interactions between oysters and predators or other organisms affecting oyster marketability such as mudworms and flatworms (Hone and Tonkin 1993).

There remains uncertainty regarding Pacific oyster genetic variation to cope with the speed and magnitude of the climate changes predicted, especially in SA where many environmental parameters such as salinity and temperature are close to the up limitations the Pacific oysters can tolerate.

Key points:

- There is limited information on fine-scale climate change impacts on oyster leases and the business (farm to market supply/value chain) of oyster farming.
- There is limited information on impacts of climate change on critical oyster developmental stages and their physiology and immunology, particularly the interaction of key factors.
- Impacts on oyster summer mortality might increase.
- Impacts of climate change on interactions between oysters and their predators and other organisms affecting their marketability are unknown.
- Genetic capability of Pacific oysters to mitigate climate changes in Australian water conditions is unknown.

Table 25.1: Summary of Pacific oyster species profile, which also indicates level of certainty of the associated information Level of certainty is divided into high (H) = strong clear evidence, backed by several studies with solid datasets with little confounding interactions; medium (M) = evidence supported by one or more studies, conclusions may be partially ambiguous or confounded; low (L) = anecdotal evidence, limited data and/or predicted conclusions based on theoretical knowledge.

Life history stage	Business stage	Farm activity	Current impacts	Predicted impacts	Information/data gaps
Broodstock	Hatchery	Broodstock conditioning and/or holding		Little to none as can be managed through changes in settings used in existing broodstock conditioning systems (M)	Reproduction physiology, effects of environmental change on sex ratio and spawning cues
Spawning and fertilisation		Spawning induction and fertilisation			
Larval development		Larval rearing		Increased larval mortality and abnormal shell development due to lower pH and/or increased pCO_2 (M)	1. Climate change on larval physiology, development at late development stages 2. The suitability of existing hatchery methods for rearing 'weak' larvae
Metamorphosis		Artificial settlement induction		Increased mortality (L)	1. Developmental physiology at metamorphosis 2. Biological bases of cultchless spat induction techniques
Spat	Nursery	Spat rearing		Increased mortalities due to lower pH and/or increased pCO_2 resulting in decreased calcification rates and elevated temperatures (M)	1. Physiological studies required; particularly with respect to interactions of key factors 2. Mechanisms for evaluating and selecting more suitable farm sites

					3. Climate change modelling at relevant spatial and temporal scales and of all factors of interest to farmers
Adults	Growout	Adult rearing	'Summer mortalities' due to stress caused by combination of factors (reproduction, high temperature, poor water quality, *Vibrio*) (H)	1. 'Summer mortalities' - increased severity and prolonged events (H) 2. Existing intertidal leases become less suitable for intertidal farming (M) 3. Increased impact from disease because of greater stress from a range of climate change factors (temp., pH, pCO_2) (H) 4. Decreased growth because of decreases in calcification rates at lower pH and/or increased pCO_2 (M) 5. Change in reproduction pattern (M) 6. Oyster shells are weakened due to ocean acidification (L) 7. Increase in pathogen load (L)	As above plus: 4. Reproduction biology/physiology 5. Suitability of existing intertidal farming methods for 'weak shell' oysters 6. Genetic capability to cope with the predicted magnitude and speed of climate change
Postharvest	Market and marketing	Harvesting		1. Change in harvesting season to avoid spawning (M) 2. Increase in bay closures due to increased incidences or length of time affected by harmful organisms (microalgae, bacteria, etc) (M)	Climate change and physiological modellings at relevant spatial and temporal scales of all factors of interest to famers
		Processing		More restricted standards for transportation and processing (M)	Optimal conditions to control the proliferation of marine bacteria

		Packaging		Reduced shelf-life due to higher bacteria loads (L)	As above plus: Alternative packaging methods

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26. Southern bluefin tuna *Thunnus maccoyii*

Authors: Steven Clarke, Xiaoxu Li, David Ellis

26.1. The industry

Southern bluefin tuna (*Thunnus maccoyii*)(SBT) is one of three iconic and much commercially sought tuna species, the others being the giant Atlantic bluefin tuna (*T. thunnus*) and the Pacific bluefin tuna (*T. orientalis*). This genus belongs to the family Scombridae that consists of 15 genera and about 50 tuna species, although Chow et al. (2006) questions whether the above three mentioned bluefin species should be considered separate. SBT, like the others, are fast swimming, deep diving, pelagic finfish with a streamline shaped body, very small smooth scales, predominately silver in body colour but with a blackish blue dorsal surface, and the potential to grow to a large size (Collette et al. 2001). SBT are also obligate ram ventilators, meaning that they would suffocate rapidly if prevented from swimming (Brill and Bushnell 2001) and maintain a body temperature elevated above that of the surrounding water (Block et al. 1993; Graham and Dickson 2000; Dickson and Graham 2004). Tuna are also opportunistic feeders and consume a wide range of prey often rapidly and in quantity as it is located; their elastic stomach wall and considerable capacity being well suited to this (van Barneveld et al. 1997).

Even though the distribution of SBT is circumpolar in southern temperate waters, 30–50°S, it is thought that only a single population exists, with the sole spawning ground between north-west Australia and south Java, Indonesia (10–20°S, 105–120°E) (Sund et al. 1981; Grewe et al. 1997; Safina 2001). After spawning occurs in these tropical Indian Ocean waters, the fertilised eggs hatch and the pelagic larvae drift southwards, with 1–2-year-old juveniles primarily in the waters of western Australia, and predominately 2–3-year-olds in the Great Australian Bight (GAB) off southern Australia, where sardines, a primary feed for SBT, are in abundance. As they grow older, the SBT move from south-western Australia, offshore into deeper water both west into the Indian Ocean and east across southern Australia to the waters offshore of Tasmania and New South Wales (NSW). SBT mature somewhere between eight and 14 years of age and live to 20–40 years (Kailola et al. 1993; Gunn et al. 2008). The mean size at maturity is estimated to be around 150–160 cm (Campbell 1994; Gunn et al. 2008). Mature fish can reach 200 cm and weigh 200 kg. SBT grow faster during summer and early autumn, probably in response to warmer surface waters. SBT are broadcast spawners and the spawning season lasts from September to April, possibly with two peaks in activity (Young 2001). The number of about 1 mm diameter eggs produced in a spawning period has been estimated to be 14–15 million for a 158 cm female (Young 2001).

SBT ranching, the on-growing of wild caught tuna, was initiated in around 1990 in South Australia by the Tuna Boat Owners Association of Australia, the Japanese Overseas Fishery

Cooperative Foundation and the South Australian Government, and was a planned initiative to address declining catches and a reduction of allowed quota of wild SBT, both responses to overfishing (Clarke et al. 1997; Carter et al. 1998). After a few years of research and development, commercial ranching began. Purse-seined schools of juvenile SBT are caught in the GAB in December–March and transferred into special tow cages, which when filled are slowly brought back to the ranching area in south-west Spencer Gulf, off Port Lincoln, South Australia. Here, some 1500–2000 SBT are transferred into each moored farm cage, which typically consists of one or two floating rings of 40–45 m diameter from which a net is suspended with a maximum wall depth of 10 m. SBT at transfer are typically about 17 kg in weight and are then held for 4–8 months until they are harvested, over which time their weights have doubled.

SBT propagation is also being attempted by one South Australian company, Clean Seas Tuna Ltd, which has a hatchery at Arno Bay, Eyre Peninsula, South Australia with growout sites located (from south to north in Spencer Gulf) in Boston Bay, Arno Bay and Fitzgerald Bay. At this time SBT spawning and larval production has been achieved repeatedly over a number of years, and the most successful outcome has been the production of massive amounts of larvae, with some being raised through in tanks to a few fish to 30–40 cm in length. Research and development as well as proof-of-concept trials continue, with much of the work undertaken within the framework of the Australian Seafood Cooperative Research Centre; key participants being SARDI, NSW Fisheries, University of the Sunshine Coast, Flinders University, NT Department of Primary Industry and Energy and Challenger TAFE.

Ranched SBT are predominantly exported to Japan, with fish delivered whole, either fresh chilled by air freight or more commonly deep frozen (-60°C) by ship. Some sale of loins also occurs which are usually vacuum packed and frozen.

Key points:

- Southern bluefin tuna have a single breeding ground between north-western Australia and Indonesia, despite the adults travelling circumpolar.
- Ranching of SBT was first established in the early 1990s in SA through collaboration between the Australian Tuna Boat Owners Association, the Japanese Overseas Fishery Cooperation Foundation and the South Australian Government.
- Almost all SBT produced is sold deep frozen or fresh chilled to Japan where it is widely used for sashimi.
- One SA company, Clean Seas Tuna Ltd, is pioneering the hatchery production of SBT.

26.2. Production

For many years the Australian southern bluefin tuna (SBT) quota has been 5265 tonnes, but following a recent meeting of the Commission for the Conservation of Southern Bluefin Tuna (CCSBT), the Australian Fisheries Management Authority (AFMA) Commission met on 30 October 2009 and agreed to set a single total allowable catch (TAC) of 8030 tonnes for the next two years, resulting in industry electing to catch a maximum 4015 tonnes in 2009–10 financial year. There are suggestions that further quota reductions may occur if a recovery is not detected in the fishery, with each of these quota reductions not only affecting the wild catch but the stock available for ranching. Hatchery produced SBT (Elizur et al. 2006) provides an opportunity for growout to become independent of quota limits.

Southern bluefin tuna ranching has and continues to contribute greatly to the economy in SA. In the 2007–08 financial year, for example, the combined production volume and farmgate value were 9757 tonnes and $187 million respectively (ABARE 2009; Figure 26.1). In SA, the industry is responsible for direct employment of 348 full-time equivalents (FTE) and through associated processing and transport activities another 58 FTE; flow on business activity generates a further 885 FTE to give total employment of 1,291 FTE (EconSearch 2010).

In SA there were 40 SBT farming licences issued (ABARE 2009). All farming is offshore of Port Lincoln, South Australia in the lower eastern region of Spencer Gulf (Figure 26.2). While the first farms began in Boston Bay, they soon moved seaward of Boston Island and are now often 10–20 km offshore.

The industry has been a strong believer in research and development, and has and continues to use this to increase their awareness of the biology of SBT and the environment in which the tuna are farmed, as well as maintain and enhance their international competitiveness and minimise environmental risks.

The industry undertakes an annual environmental monitoring program to address their license requirements as specified by the SA Government (PIRSA 2010).

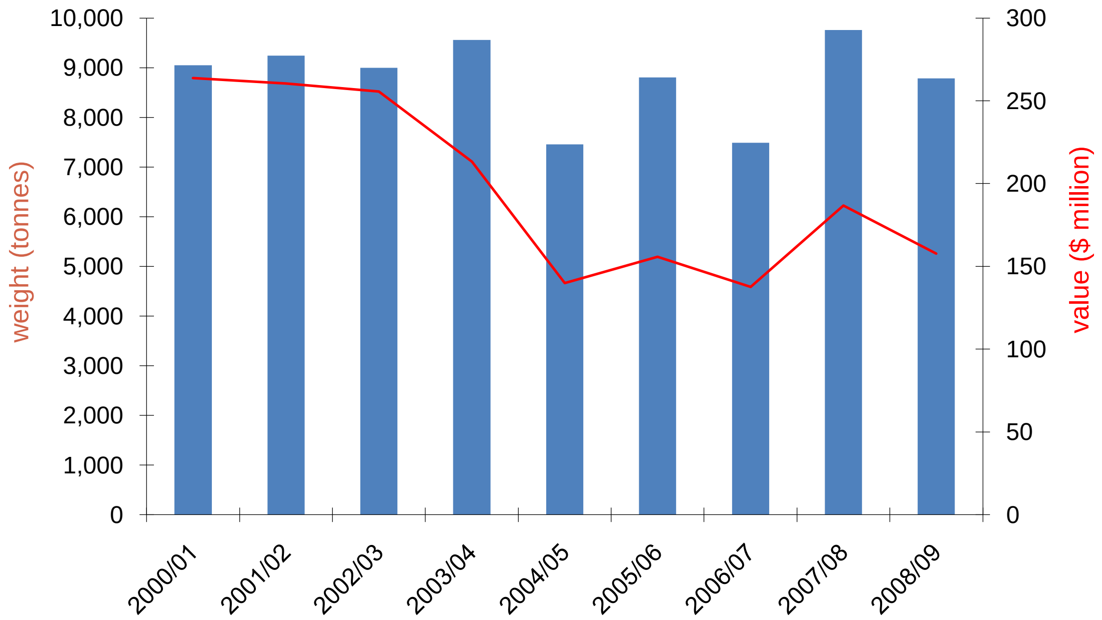

Figure 26.1: Southern bluefin tuna aquaculture production by weight (red bars) and value (blue line) (ABARE 2009; EconSearch 2010)

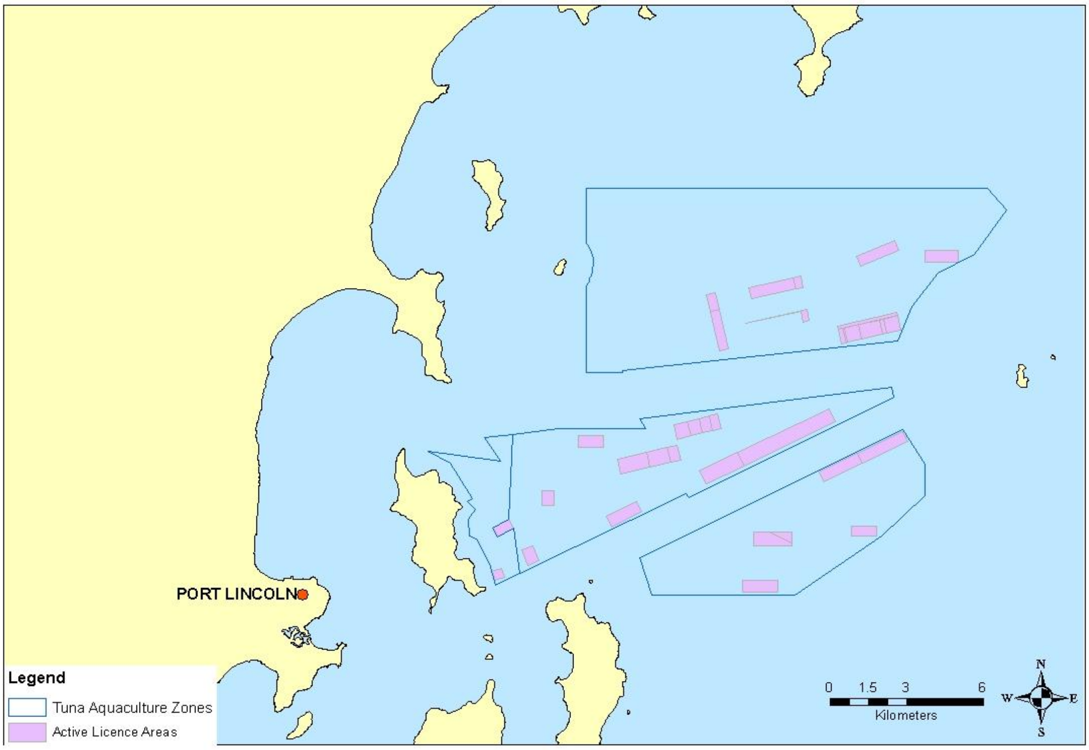

Figure 26.2: Southern bluefin tuna ranching locations in South Australia (pink leases within blue zones)

Key points:

- The catch of SBT from the wild is managed by quota, this restricting the tonnage available for ranching.
- SBT ranching is the third largest seafood industry in Australia and very important to the economy in SA, where is creates a substantial level of regional employment.
- In 2007–08, about 5000 tonnes of tuna was stocked into SA SBT farms and 9757 tonnes marketed, with the latter valued of $187 million.
- SBT is subject to fishery assessments and the current spawning biomass level indicates that the stock is exploited. Further research will be included at the CCSBT meeting in 2011 to determine new management strategies for recovery of the stock.

26.3. Life history stages, stages in farming process and physiology

26.3.1. *Southern bluefin tuna life history*

SBT have a simple life history with externally indistinguishable male and female broodstock (Schaefer 2001) producing gametes at multiple spawnings over summer months. This either occurs in the spawning ground between north-west Australia and south of Java, Indonesia or in specially constructed onshore environmentally controlled broodstock facilities. The ~1 mm floating fertilised eggs then hatch and develop into larvae similar to other finfish species, although their growth is faster and the period when they are dependent on live feeds, such as rotifers and copepods, shorter. The larvae continue to develop and by about 30 days post hatch have reached actively swimming juveniles of about 30 mm in length that are now focused on consuming larval fish of other species. These juveniles continue to grow rapidly through the first year, although instantaneous growth rates then begin to decline with age, with four year old fish slower than two and three year old ones (Ellis et al. 2009).

In the wild, first year fish are common off Western Australia and two- and three-year-old fish within the Great Australian Bight. Larger and older fish are found off Tasmania, New South Wales, southern West Australia and west into the Indian Ocean. Broodstock, typically 8–14 years of age return to the spawning grounds where they often occur in cooler water at a depth of 100–200 m before rising to warmer, near surface waters to spawn (Davis et al. 1990; Gunn et al. 2008; Hintze 1981).

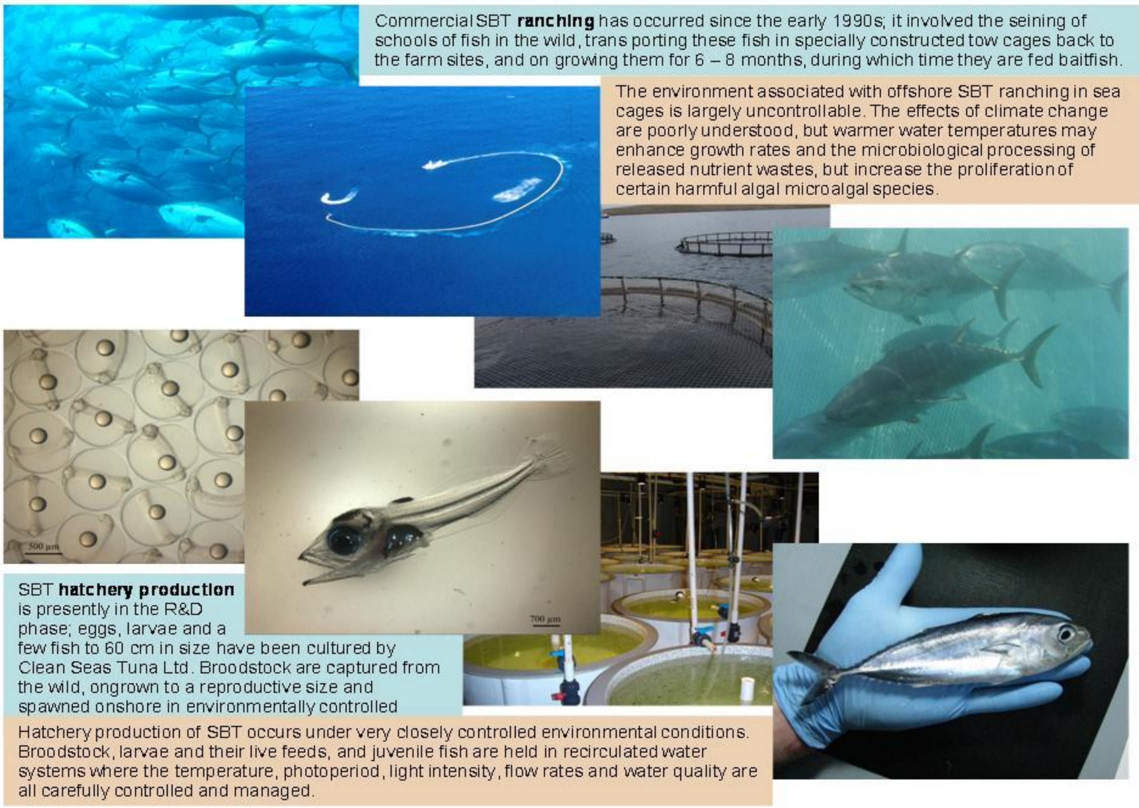

Figure 26.3: Key southern bluefin tuna life cycle stages (this section) and responses to or impacts from relevant climate change drivers (sections 26.4, 26.5).

26.3.2. Southern bluefin tuna aquaculture

The southern bluefin tuna aquaculture business consists of four main stages: 1. Hatchery; 2. Nursery; 3. Growout and 4. Market Supply. Currently there is only one type of SBT farm; growout (ranching), but Clean Seas Tuna Ltd is well on the way toward establishing a second type, that based on a hatchery and growout. Both types of farms may be further vertically integrated in that they may also hold a sardine fishing license and need to tow SBT to stock the growout sea cages. Sardines are an important feed for SBT.

The hatchery activities include broodstock selection, conditioning and maintenance, spawning induction and fertilisation, hatching, intensive larval rearing in tanks and production of live food for larvae prior to them being weaned onto artificial diets. All of these activities are at an early research and development phase and are the focus of a single company in a potentially competitive environment; therefore exact details cannot be provided. However, in general, mature SBT spawn multiple times over a spawning season. Fertilised eggs, which float, are collected daily from broodstock tanks holding small numbers of both male and female fish, which are difficult to differentiate externally (Schaefer 2001). These eggs are then transferred to hatching tanks with very low aeration and almost no water flow where after a few days the larvae hatch. When hatched, larvae are usually moved to larger tanks where aeration is increased so as to maintain larvae in suspension. Enriched rotifers are supplied when SBT larvae first feed and followed by enriched *Artemia*. The juveniles are then transferred into larger nursery tanks, where they are continuously monitored and graded. SBT show aggressive behaviour at very early developmental stages and are exceedingly fast swimmers by the time they reach 30–40 mm in length, suggesting the need to get them into the larger offshore sea cages as soon as possible. At this time larval mortalities are very high but some SBT have been reared in tanks through to a size of 30–40 cm.

Typically, ranching involves stocking about 1500–2000 juvenile SBT into each sea cage between late December and March each year. Growout seeks to get SBT to market size over about a six-month period. During this time the SBT are fed baitfish two times per day, six days per week with divers checking for mortalities, net integrity and for any sign of wasted feed at the same time; there is no grading of fish. A typical cage is 40–45 m in diameter with a wall depth of 10 m. Cage nets may be cleaned in-situ with high pressure hoses or other types of net cleaners, with the nets only being removed and taken ashore for a full clean and maintenance at the end of the ranching season. The sea cages in the growout area undergo a two-year fallowing period to allow the seafloor at the site time to recover (PIRSA 2002).

At harvest the SBT are brought close to the harvesting platform that hangs from the pontoon and links to the servicing vessel. The SBT are 'crowded' within the pontoon using a small scale purse seine net and divers are used to capture and deliver the fish to the harvesting platform or fish escalator. Here they are spiked, cored, have a fibreglass rod inserted down the central nervous cord and bled, all within seconds, so as to minimise stress and therefore maximising product quality. A depletion of muscle glycogen and a reduction in pH are well documented to cause a reduction in shelf life (e.g. Goodrick et al. 2002; Thomas 2007). Typically the SBT are then transported in an iced brine solution to the processing facilities either on a Japanese freezer vessel or onshore, where they are gilled, gutted and cleaned and either packed fresh chilled into cardboard 'coffins' with 'ice blocks' or deep frozen at -65°C. In both instances they are sold whole, with frozen product becoming the dominant form as supply has increased internationally, and demand and price decreased. Some fish are further processed into loins and vacuum packed and frozen.

The key environmental parameters in the SBT broodstock facilities, hatchery and nursery are highly controlled to provide the optimal conditions to promote or maintain gonad condition in broodstock, and optimise growth and survival in larvae, and juveniles. These include water temperature, light intensity and photoperiod, feed quantity and quality, water quality (dissolved oxygen and ammonia) and water flow/exchange rate. When SBT are transferred into sea cages, they then become subjected to local environmental conditions. The methods used by farmers to improve production include maintaining appropriate stocking densities; optimising feeds and feeding (Carter et al. 1999; 2010; Glencross et al. 2002a); and managing fouling and net integrity. Most farms harvest only from about May to August to match with optimal growth performance, product quality, market prices and requirements, recognising that tuna land at the Japanese markets from a large number of countries and market volumes need to be balanced to maintain satisfactory sale prices.

SBT are typically ranched in temperatures of 12–22°C, but their optima for production are unknown because of the complexity of undertaking physiological research with free-swimming 15–30 kg fish of about 1.0 m length. In Japan, Pacific northern bluefin tuna have much accelerated production at Okinawa as compared to just south of Tokyo and as such it is expected that SBT would demonstrate higher growth rates at more consistent temperatures around 20°C.

Little is known of the physiology of SBT because of the difficulty in working with a large fast-swimming fish that is typically held in large sea cages. However, a 250 cubic metre mesocosm respirometer for use at sea provided the first measurement of the routine metabolic rate of SBT (Fitzgibbon et al. 2008), the energetic consequence of the specific dynamic action in SBT (Fitzgibbon et al. 2007), as well as a range of other studies including the effects of hypoxia (Fitzgibbon et al. 2010). One interesting result was the suggestion that SBT have the ability to control thermal conductance and thus to physiologically regulate visceral temperature thereby enabling them to occur in colder waters than might otherwise be feasible.

Key points:

- SBT have a complex life cycle.
- The aquaculture industry is based on wild caught SBT that are ranched for 4–8 months before being marketed and over this time they typically double in weight (15–20 to 30–40 kg).
- Development of hatchery production of SBT is now occurring; larvae and fingerlings have been found to grow very rapidly but have some challenging characteristics which are being addressed through research.
- Environmental conditions at the hatchery, nursery and market supply stages, all on land, are highly controlled, whereas the ongrowing of juvenile SBT in offshore sea-cages is subject to the local environmental conditions, which are essentially uncontrollable.
- Very little information is available on the optima and ranges of environmental parameters for the different developmental stages of SBT.

26.4. Likely current impacts of climate change

No impacts of climate change are known at this time (Hobday et al. 2008); although interannual variations in production have been related to slight changes in water temperature and the mass mortality event experienced in 1996 was stated to be the consequence of an extremely unusual tropical north-western Australian cyclonic event that also affected the southern coast of Australia, including the Port Lincoln tuna farming region (Clarke 1996).

Key points:

- One-off events and interannual production variability have been said to be related to climate; but not climate change per se.
- The limited timeline of marine environmental and farm production data for the tuna farming region adjacent Port Lincoln means that it is almost impossible at this time to designate climate change as a causative factor in any variability detected.
- Regardless of the above, it seems unlikely that climate change has so far been a dominant factor responsible for any changes in ranching operations, or newly initiated hatchery production.

26.5. Potential impacts of climate change (direct and indirect)

Climate change can affect the southern bluefin tuna ranching and aquaculture business by directly affecting capture of wild fish used to stock the ranching operations, acting on the farm stock, farm infrastructure, and marketing (direct impacts), or on other factors such as baitfish feed availability, fouling organisms (e.g. macroalgae and invertebrates) and parasites, as well as the regional communities that provide and sustain the SBT industry and employees (indirect impacts).

Changes to water temperature are likely to have the greatest impact on the natural distribution of SBT, with a likely southward movement of suitable habitat as temperatures warm on the east and west coasts. SBT are restricted to the cooler waters south of the East Australian Current and range further north when the current contracts up the New South Wales coast (Hobday et al. 2009).

Variation in the availability of prey (sardines and anchovies) may affect the natural distribution and abundance of SBT. Increased strength of south-easterly winds during summer and autumn is likely to increase seasonal upwelling along southern coast between the head of the Great Australia Bight (GAB) and western Victoria. Upwelling regions in southern Australia are important foraging grounds for SBT. If upwelling becomes more intense, this could lead to an increase in the production of small pelagic fishes. Increased pelagic productivity and sardine abundance off southern Australia could be beneficial for the southern bluefin tuna that aggregate each year in feeding grounds of the central GAB.

Key points:

- SBT are highly migratory and pelagic, potentially increasing the species' resilience to changing environmental conditions.
- Increased upwelling could result in greater local baitfish feed (e.g. sardines) availability between the head of the Great Australia Bight and western Victoria.

26.5.1. Potential direct impacts

Southern bluefin tuna performance

Southern bluefin tuna have been commercially ranched in sea cages offshore of Port Lincoln, South Australia since the mid 1990s. Inshore, where farms were in early years, water temperatures typically fluctuate between 11 and 25°C, whereas offshore, where the farms are now, the water temperature range is more restricted, typically 13–23°C (David Ellis, R&D Manager, Australian Southern Bluefin Tuna Industry Association, pers. comm.). Food consumption, food conversion ratio and growth in SBT length is highest in summer, with food consumption and growth declining substantially when water temperature in winter drops below about 15°C, although the condition index of SBT is highest at this time (Glencross et al. 2002b). As the 2070 median estimate (50th percentile) of an increase in surface seawater temperature is 2°C (CBA 2009) for the lower Spencer Gulf region of South Australia and both the minimal surface seawater temperature and the average annual period of seawater temperature higher than 15°C will increase, this may benefit the SBT aquaculture industry in SA. In this region of Spencer Gulf this positive projection is unlikely to be offset by the potential negative effects of salinity increases expected further north. However, higher water temperatures may have a significant effect on the physiology and metabolism of SBT.

Farm infrastructure

In more wave exposed areas, sea-cage infrastructure and moorings will need to be improved so as to better handle the predicted increase in storm frequency. The number of days that such infrastructure can be accessed for key operational tasks may also be reduced (e.g. cleaning infrastructure, removing mortalities, feeding and harvesting).

Marketing

Research has demonstrated that a higher fish-keeping temperature prior to slaughter is one of the factors that negatively affects SBT product quality (Goodrick et al. 2002; Thomas 2007), largely because of the combined effect of rapid ATP depletion, an increase in lactic acid content and a fast drop in pH. While these factors are already managed so as to maximise the quality of SBT for the premium sashimi market, climate change causing warmer temperatures may well require harvesting and transport strategies to be reassessed and improved to continue to ensure that a premium product is produced. This will likely impact on SBT companies that harvest SBT for the chilled market from February to April. However, as most SA ranched SBT is presently marketed other than in summer, this is less likely to be critical until all year round hatchery produced stock are marketed.

26.5.2. Potential indirect impacts

Southern bluefin tuna performance

Health management is not considered by some to be a major factor in tuna ranching because it occurs in relatively oceanic waters, fish are stocked at relatively low densities and the fish held are advanced juveniles that have already faced a number of years of natural selection pressures and have a well developed immune system (Mylonas et al. 2010). The partial endothermy of tuna has also been proposed to convey some enhanced immuno-competency in the fish (Mladineo et al. 2008). However, others have identified that a wide range of diseases and parasites have been found in wild and ranched SBT (e.g. Aiken et al. 2006, 2009; Deveney et al. 2005, 2007; Hayward et al. 2007, 2008, 2009, 2010; Johnston et al. 2008; Munday et al. 1997, 2003; Novak 2004; Nowak et al. 2006). Also, a number of catastrophic losses of tuna have occurred due to environmental factors, such as water turbidity due to run-off and storms (e.g. Clarke 1996), a feed related mortality due to the lipid component of the baitfish fed (Roberts and Agius 2008) and bacterial infection (Mladineo et al. 2006). However, despite this knowledge, the likely consequences of climate change on the immunology of SBT, and parasite loads and infection rates is difficult to predict. Run-off induced turbidity and seafloor sediment suspension might increase with increasing storm activity due to climate change. It is identified that both *Uronema nigricans* (Deveny et al. 2007) and the blood fluke, *Cardicola forsteri* (Aiken et al. 2006) tend to be greatest in winter and as such might be expected to become less of an issue if water temperatures rise as predicted from climate change. On the other hand, Hayward et al. (2009) highlight that peaks of infection of the sea lice, *Caligus* spp. correspond to summer months and as such these taxa might be predicted to become more problematic. Hayward et al. (2007) indicate that epizootics of metazoan gill parasites are independent of season and thus one might hypothesise that they may be unaffected by climate change, although this would be a simplistic interpretation given the many variables that need to be understood.

To minimise the already assessed low risk of feeding imported frozen Californian sardines (*Sardinops sagax*) and mackerel (*Scomber japonicus*), which might be affected by viral hemorrhagic septicemia virus (VHSV), to SBT a protocol exists between the Australian Quarantine Inspection Service and Australian Southern Bluefin Tuna Industry Association to defrost onshore when water temperatures are measured to be below 15°C. With winter minimum water temperatures presently at about 13°C, this 4.0 – 4.5 months period is expected to contract as a result of elevated water temperatures due to climate change.

Moore et al. (2008) believe that if the timing and strength of coastal upwelling winds are affected by climate change, then the occurrence of these events may play an increasingly important role in the development of some microalgal blooms. Microagal blooms can attain high biomass, reducing the amount of light available to the underlying species and decomposition of senescent blooms can deplete the surrounding environment of oxygen (Moore et al. 2008), thus impacting the performance of cultured finfish species. Blooms of this nature can also reduce the appetite of finfish and irritate their gills, inducing mucous production that can consequently lead to death through asphyxiation (Tanner and Ellyard 2003; Oulton 2009). As well as algae, other species can form blooms under favourable conditions. It is thought that jellyfish blooms in southern Australian waters occur when there are elevated nutrients in the water and that an increase in the duration of upwellings may cause this.

Higher summer temperatures will reduce the amount of oxygen gas that sea water can dissolve as well as potentially increase the metabolism of SBT. It is well documented that SBT nets can become heavily fouled (Cronin et al. 1999; Svane et al. 2006) and that this can influence dissolved oxygen levels, which in turn can influence the behaviour and physiology of the SBT (Cheshire and Loo 2008), particularly during South Australian periods of low monthly tidal movement due to dodge tides. The geo-biochemical hydrodynamic models developed for the tuna farming zones highlight the complexity of the mixing between oceanic and gulf water (Tanner and Volkman 2009) and as such climate change induced variations to water flow patterns may affect water exchange rates around SBT farms. Sediment waste assimilation and leaching rates may also be effected, with these having the potential to influence phytoplankton and thus zooplankton abundance (Ellis et al. 2009; Tanner and Volkman 2009).

Higher temperatures in summer also increase the likelihood of the deterioration of baitfish and manufactured SBT feeds if they are not properly stored.

Farming infrastructure

Settlement and growth of barnacles and some seaweeds on farming infrastructure may be enhanced due to increased water temperature and pCO_2 based on some research of the effects of climate change on representative taxa of these types (Oceanus 2010). If this occurs, farm infrastructure, such as nets and pontoons, will need to be cleaned more frequently.

Increases in the biomass of fouling organisms on sea cages could also potentially elevate the infection of SBT by parasites. Investigations have suggested an association between the net fouling and the detection of the intermediate host of the SBT blood fluke, *Cardicola forsteri* (Bott et al. 2008).

Marketing

The increased pathogen loads at elevated temperatures may require more stringent procedures for handling, transport, packaging and storage to maintain existing food safety standards when product is not rapidly frozen after harvest.

Social

SBT farms are located in regional Australia and require full- and part-time staff. Competition for skilled staff can be intense and it is often challenging to attract staff to remote areas, particularly if a high level of services and facilities are not available. The impacts of climate change on other industry sectors, can cause businesses to close and/or people to relocate to more climatically favourable locations resulting in shortages in local casual staff or those that provide the services to the aquaculture employees.

Key points:

- Climate change can affect SBT performance, farming infrastructure, animal husbandry practices and marketing, directly and indirectly.
- In response to climate change, parasites may become a greater issue and if so, improved control measures will need to be developed.
- With increasing water temperatures due to climate change, fouling organisms might increase on sea cages leading to a need to more frequently clean farm infrastructure.
- Climate change, in particular higher temperatures, might increase the potential for the deterioration of baitfish and farmed fish flesh during transport and processing. It might also increase costs of transport.
- There may be possible staff shortages in regional areas due to amenities declining because of the effects of climate change on other industries and communities.
- Increased water temperatures, nutrients, wave induced disturbance of seafloor sediments and land-based run-off may lead to harmful algal blooms and increased issues with pathogens
- Climate change induced variations in water flow patterns in the tuna farming zones may result in decreased water flushing rates under certain conditions.

26.6. Critical data gaps and level of uncertainty

Southern bluefin tuna are ranched in moored offshore sea cages, and as such the performances of ranched SBT and thus SBT aquaculture businesses, are influenced by local (fine scale) environmental conditions. Despite the existence of geo-biochemical hydrodynamic models for the tuna farming zones (Tanner and Volkman 2009), at this time such modelling provides very limited information on climate change impacts. More detailed modelling, environmental monitoring and model validation are required to enable the ranching and hatchery produced SBT industry sectors, resource managers and policy makers to accurately assess and then establish effective methods to address the potential negative impacts of climate change.

Metabolic/physiological and immunological processes are critical biological factors that determine the performance and health status of SBT. Knowledge of the effects of climate change on these processes and information on the optimal and tolerance ranges of SBT to major environmental parameters are limited. This challenges the capability of climate change modellers to predict the impacts of climate change on SBT farming and thus the ability of this industry sector and its managers to develop suitable adaptation strategies.

SBT ranching mortalities, while a low percentage overall, have a substantial financial impact because of the size and value of the fish. Capture and transport stress and the occurrence of the blood fluke are likely to be the key factors responsible, but despite nearly a decade of research of SBT health, there is still much uncertainty. Much more needs to be known about the biology, and ecology of SBT and the pathogens that affect them, as well as treatment methods, not to mention the many other parasites and viruses that could become problematic with or without climate change.

Very limited information is available on the effects of increased seawater pCO_2 on the critical development stages of SBT such as fertilisation, development/growth at different ages, gonad development etc. These stages are all critical to a successful SBT hatchery produced SBT aquaculture business and the recruitment of wild population on which the SBT ranching aquaculture relies.

Very little is known about the interactive responses to climate change of the many other organisms that can affect SBT performance and survival, such as fouling organisms, microalge, and the processing of organically enriched sediments.

There remains uncertainty regarding the level of SBT genetic variation and the ability for selective breeding (once the SBT life cycle has been closed) to cope with the speed and magnitude of the climate changes predicted.

Key points:

- Despite geo-biochemical hydrodynamic modelling of the tuna farming zones, more refinement and validation is required to predict fine-scale climate change impacts on the environmental conditions of offshore leases.
- There is limited information on impacts of climate change on critical SBT developmental stages and their physiology and immunology.
- There is limited knowledge on the responses to climate change of organisms that affect SBT performance, such as parasites, fouling organisms, microalgae, etc.
- Even when the life cycle of SBT has been closed, it is unknown whether selective breeding will prove an effective adaptation strategy to climate change.

Table 26.1. Summary of southern bluefin tuna species profile, which also indicates level of certainty of the associated information. Level of certainty is divided into high (H) = strong clear evidence, backed by several studies with solid datasets with little confounding interactions; medium (M) = evidence supported by one or more studies, conclusions may be partially ambiguous or confounded; low (L) = anecdotal evidence, limited data and/or predicted conclusions based on theoretical knowledge.

Life history stage	Business stage	Farm activity	Current impacts	Predicted impacts	Data gaps
Broodstock	In sea-cages then in specialised environmentally controlled onshore broodstock facilities	Broodstock holding and conditioning		Warmer temperatures likely to accelerate growth rate and therefore reduce the time held in sea-cages to reach reproductive age (M) Little to no other changes as can be managed through settings used in existing environmentally controlled broodstock conditioning system (M)	Reproductive physiology and spawning cues only recently been studied and possible need for further research; information at present commercial in confidence to Cleans Seas Tuna Ltd
Spawning and fertilisation		Spawning induction and fertilisation		Little to none onshore as can be managed through changes in existing environmentally controlled hatchery settings (M) Higher water temperatures likely to enhance the success of transfer to sea cages and early performance of fish (L)	
Larval development	Hatchery	Larval rearing			1. Climate change on larval physiology and developmental biology 2. Causes of larval deformities and mortalities 3. Optimal feeds and feeding practices

Juvenile/fingerling	Nursery	Juvenile/fingerling rearing, onshore in tanks and then offshore in sea-cages			1. Environmental optima and tolerances for optimal fingerling performance 2. Local environmental conditions offshore and their potential impact on fingerling/juvenile performance 3. Implications of climate change on feeds and feeding performance
Adults	Growout	Adult rearing	Presently various causes of fish mortality, possibly associated with stress of capture, tow and transfer, and some parasites (M) Presently the industry's annual environmental monitoring program highlights farming is sustainable (H)	1. Some parasite infections may increase in severity and require development of control methods (M), others may decline (M) 2. Improved annual SBT production due to slightly increased temperature (M) 3. Improved food conversion ratio (M) 4. Reduced growth and survival due to increased stress (L) 5. Increased frequency of net cleaning due to increased fouling (M) 6. Reduced working times on offshore cages (M) 7. Reduced fallowing periods due	1. More detailed and accurate climate change modelling at relevant spatial and temporal scales and of all factors of interest to farmers 2. Species physiology and response to key climate change environmental variables 3. Genetic capability to cope with the magnitude and speed of the predicted climate change when life cycle has been closed 4. Effects of climate change on food conversion ratio 5. Biology and ecology of diseases and parasites as well as the immunology of SBT, and how these will be influenced by climate change 6. Effect of climate change on the

				to enhanced biochemical processes in the sediments at increased temperatures (M); however increased feeding rates may result in additional organic enrichment of sediments (L) 8. Increased potential for occurance of harmful microalgal and jellyfish blooms (M) 9. Requirement to better manage baitfish feed storage to reduce potential rancidity at higher temperatures (M) 10. Increased seafloor sediment suspension from increased storm activity (M) 11. Changed water flow patterns in tuna farming zones may result in decreased water flushing rates under certain conditions (M)	environmental impact of fish farming and its minimisation and amelioration
Postharvest	Market supply and marketing	Harvesting		1. Development of harvest strategies to avoid occurrence of burnt muscle during summer (M) 2. More restricted standards for harvesting and transport to the processor (M)	1. Climate change and physiological modelling at relevant spatial and temporal scales 2. Effect of climate change on the parameters affecting flesh quality and human food safety

		Processing		More restricted standards for processing (M)	Optimal conditions to control the proliferation of marine microorganisms
		Packaging		More restricted standards (M) Reduced shelf-live of raw SBT product due to higher bacteria load (M)	

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27. Sydney rock oyster *Saccostrea glomerata*

Author: Philip Gibbs

27.1. The industry

The 120-year-old, Sydney rock oyster industry in New South Wales (NSW) and southern Queensland is one of the oldest aquaculture industries in Australia. Sydney rock oysters, *Saccostrea glomerata* (formerly known as *S. commercialis*) are farmed in estuarine areas and rivers from Hervey Bay Queensland (latitude 24°S) to the Victoria/NSW border (latitude 37°S) and are farmed at Albany in Western Australia (latitude 35°S). However, the natural distribution of Sydney rock oysters continues on further north from Hervey Bay Queensland, through subtropical Queensland, across the tropical north and down the west coast as far south as Shark Bay (latitude 25°S) in Western Australia (Nell, 2005).

While NSW can trace oyster aquaculture to the 19th century, use of natural stocks of oysters in the state has a much longer history. The Aborigines on the coastal regions harvested oysters and shell beds can be found in the many kitchen middens along the coast. Some of these middens have been carbon-dated to 10,000 years.

With European settlement of NSW and a rapidly increasing population, the demand for oysters grew quickly. The use of oyster shell as a source of lime in cement production resulted in natural oyster stocks being near depletion by the 1860s. Government controls were introduced and this precipitated the introduction of early cultivation practices, the first of which was the establishment of Claires (ponds) based on French cultivation techniques, by Thomas Holt in Gwawley Bay in 1872. Although this technique did not lend itself to local conditions, it demonstrated the potential of the Sydney rock oyster as a commercial species (I&I NSW 2010).

Oyster farming now employs many different techniques, all of which take place on selected sites held under about 3200 aquaculture leases, with a total current area of about 4300 hectares, which are administered by Industry and Investment NSW (I&I NSW). Commercial production in the state occurs in 41 estuaries between Eden in the south to the Tweed River in the north (Figure 27.1). Wallis Lake and the Clyde River are the main producing areas. Pacific oysters (*Crassostrea gigas*) have been commercially cultivated in Port Stephens since 1991, but are declared a noxious fish in all other NSW waters (I&I NSW 2010). Triploid Pacific oyster cultivation is now permitted (at least experimentally) in four other NSW estuaries.

In NSW the current annual production of Sydney rock oyster is approximately 80 million oysters worth in excess of $37 million, with oyster farming the most valuable aquaculture industry in NSW for over 100 years.

Oysters, which are bivalve molluscs, obtain food by filtering and extracting minute marine plants (algae), bacteria and nutrients from the surrounding water. Mandatory depuration of all oysters before sale was been introduced to all NSW estuaries in 1978. This process makes use of the fact that food taken in by the oyster, including bacteria, will be excreted within a short period of time. A depuration plant provides a controlled environment in which oysters spend the final 36 hours before sale in high quality water, allowing any possible contaminants to be removed by purging. The most common method of obtaining water of appropriate quality is by exposing the water to high intensity, germicidal ultra-violet light twice every hour. In a well designed depuration plant, salinity, temperature and dissolved oxygen levels of this water are controlled for maximum efficiency. Progressively, estuaries in NSW are now subject to risk assessments and on the basis of the available microbiological data some areas have been opened to direct harvest.

Key points:

- Sydney rock oyster culture is one of the oldest aquaculture industries in Australia.
- It is the most valuable NSW aquaculture industry.

Figure 27.1: Location of aquaculture leases in NSW.

27.2. Production

The first 75 years of the NSW oyster industry saw production grow to approximately 60 million oysters per year (Figure 27.2). It laid the foundation for unprecedented growth to approximately 175 million oysters per year during the latter 25 years of its history. Production peaked in 1977 and has declined since 1980.

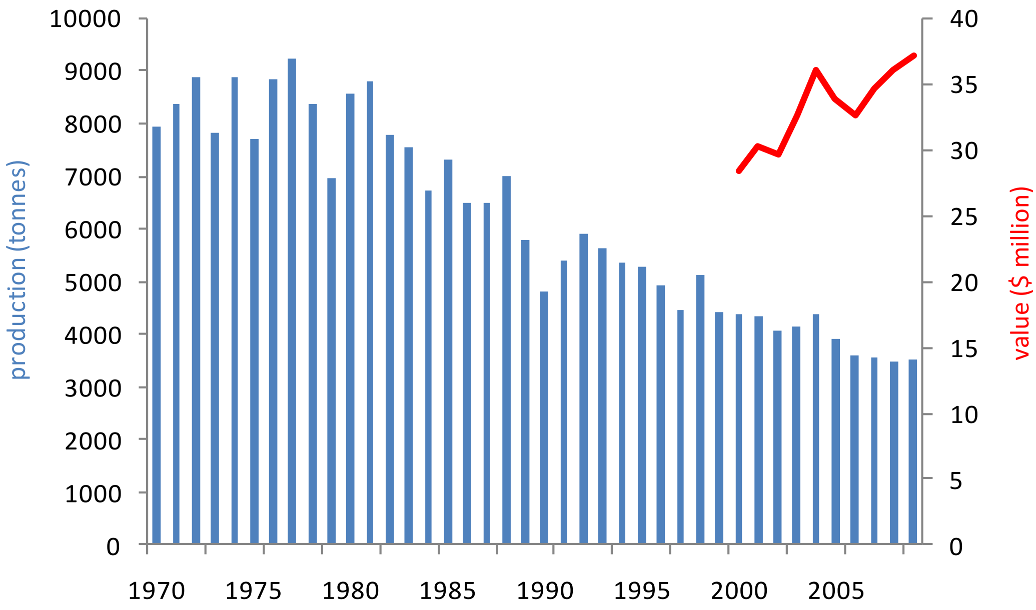

Figure 27.2: Production (tonnes) and value ($, million) of Sydney rock oysters in NSW.

To enhance oyster production I&I NSW ran an oyster breeding program using mass selection techniques which showed a maximum 11 months' reduction in time to grow oysters to a market size of 50 g whole weight whole weight initially. Following five generations of selection, average time to market has been reduced by 12 months. A second research program investigating the faster growth achieved with hatchery produced triploid oysters shows triploidy growth is fully additive to that obtained with selective breeding. These faster growth rates obtained without any change in meat yield or percentage shell cavity and the survival of the selection lines has been higher than the controls at all locations.

Key point:

- Enhancement of oyster production has been achieved by using mass selection breeding techniques.

27.3. Life history stages and stages in farming process

27.3.1. Life history

The Sydney rock oyster industry in NSW and Queensland is largely dependent on natural spatfall, which has in the past been abundant and reliable (Figure 27.3). There are now some constraints to spat movements based on the occurrence of introduced species and the presence of disease in some estuaries and so supply is not as assured as it has been in the past. Increasingly industry is turning to hatcheries, which now supply approximately 20 million seed annually. It takes the Sydney rock oyster on average 3.5 years to reach plate size (50 g whole weight), the most desirable size grade.

Most oyster species, including Sydney rock oyster, change sex during their life. The first spawning is usually as a male and subsequent spawnings as a female. During spawning, adult females disperse up to 20 million eggs and males hundreds of millions of sperms into the water when the tide and current are optimal for the widest distribution. Spawning is so intense during this period that the surrounding water can take on a milky appearance. Fertilisation takes place in the water column and development continues for up to 3–4 weeks as the larval stages of the oyster swim and grow, ultimately settling on a suitable hard clean surface. Survival rates during this phase are less than 0.1%. The surviving oysters are then called ‘spat’ and will grow to maturity in about 3–4 years, never again leaving their chosen position (Nell 1993, 2001, 2002).

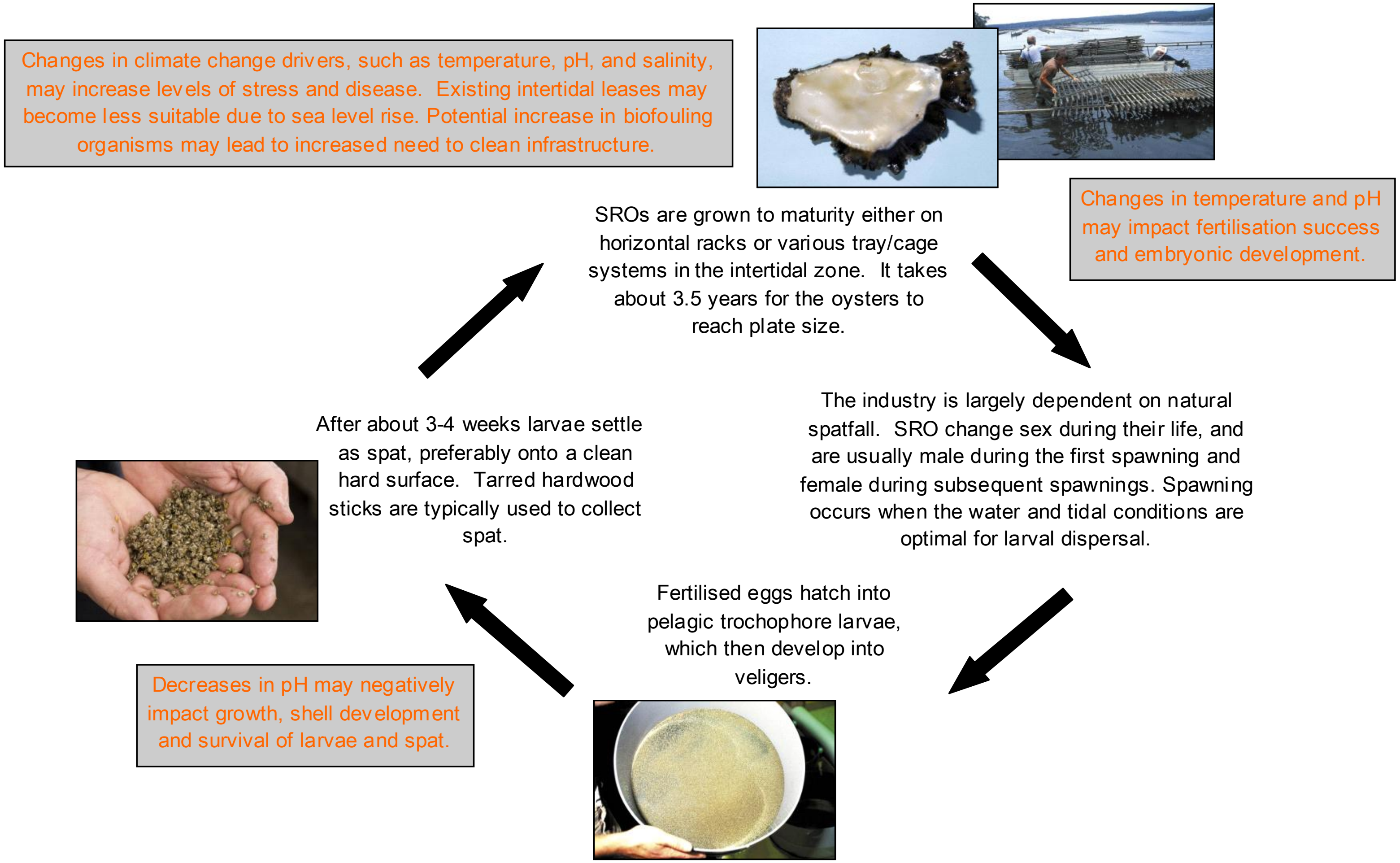

Figure 27.3: Key Sydney rock oyster life cycle and farming stages (this section) and responses to or impacts from relevant climate change drivers (subsequent sections).

27.3.2. Sydney rock oyster cultivation techniques

Three distinct cultivation methods have evolved in NSW over the years: rock culture (now seldom practised), stick culture, and various tray and cage type cultures. This summary below was taken from Nell (1993, 2001, 2002 and 2005) and Dove and Ogburn (2003).

Stick culture has been the mainstay of the industry since the 1930s and commences with oyster larvae settling on tarred (and sometimes additionally cemented) hardwood sticks 1.8 m long and 25 mm square, which are placed in areas of estuaries where spatfall (settling of spat) is most reliable, typically near river mouths. The sticks are then moved to low spatfall areas to reduce 'overcatch' (further spatfall on growing oysters) and are grown to maturity on horizontal racks in the inter-tidal zone. The process takes 3–4 years, with great care required in the first two years to protect the oysters from excessive heat and predators (bream, octopus and stingray). At maturity, the oysters are removed from the sticks and graded into various sizes prior to marketing. The largest (15–25 oysters per kg) are sold as first grade oysters and the next grades (25–35 per kg) are sold as 'bistro' or 'bottle' grade. Oysters too small to meet either of these criteria are usually placed onto trays and returned to the same or other estuaries to develop to a marketable size. While this method has proven to be the most efficient for the industry relying on natural catch, it may be less significant should commercial oyster hatcheries establish and produce single seed oysters.

Oyster trays are usually one metre wide and from 1.8 – 2.7 m in length, of timber and wire or more recently, plastic construction. They have many advantages as a cultivation method over earlier methods and in some cases even stick culture. Trays are more portable, easier to manage and allow precise stocking densities to encourage oysters to grow in a more uniform and marketable shape. Oysters are knocked off the traditional catching sticks at 0.5 – 3.0 years of age for growing intertidally on timber frame trays (1.8 m x 0.9 m) with plastic mesh bottoms, which are placed on timber racks. Oyster farmers have devised techniques to further exploit these advantages, culminating in the 'single seed technology'.

Increasingly, oyster farmers are removing oyster spat from the catching surface (usually sticks or PVC slats) very soon after settlement when the oysters are still only 3–8 mm in diameter. Spat are then either placed on specially constructed trays or in recently developed plastic mesh cylinders or baskets. These systems provide excellent protection from predators and the early removal of the stick prevents oysters becoming misshapen or clumped together. Faster growth rates have also been reported. Whilst single seed techniques require substantial capital investment, faster growing, better shaped oysters generally allow more precise grading and the oysters generally receive a higher market price. Research into the commercial production of 'triploid' oysters, which grow fast and hold market condition longer, is aimed at further enhancing the viability of single seed culture.

Triploid oysters are sterile and grow faster than diploids. Although the commercial benefits of triploidy have been evaluated in the Pacific oyster, eastern oyster, Sydney rock oyster and European flat oyster, so far this technique has only been commercialised for Pacific oysters.

Research with triploid Sydney rock oysters shows they reach market size (40– 60 g) six months earlier than the usual 3.5 years for diploids, hold their meat condition longer in autumn and winter, and death from winter mortality is reduced by more than half. The faster growth rate of triploids becomes most apparent over the second spring–summer growing season. The increased weight gains achieved with triploidy are fully additive to those obtained with selective breeding; triploids produced from oysters selected for fast growth for three generations reach market size nine months earlier than wild-caught oysters. A slight brown discolouration of the gonad has been noted in some triploid Sydney rock oysters. Fortunately this is less noticeable during the cooler months of winter and spring when the superior condition of triploids over diploids makes them most useful to oyster farmers.

Key points:

- The industry relies primarily on natural spatfall.
- Oyster seed production in hatcheries is moving to production of triploid oysters, which have a faster growth rate than diploid oysters.

27.4. Likely current impacts of climate change

While winter mortality (*Bonamia roughleyi*) and QX disease (*Marteilia sydneyi*) are not documented as direct impacts of climate change, under increased stress from temperature, salinity and ocean acidification, disease manifestation may increase in Sydney rock oysters.

Selective breeding of Sydney rock oysters for fast growth in Port Stephens and Georges River began in 1990 (Nell 2001b; I&I NSW 2010). In 1997 the Georges River section of the project was modified to include breeding for winter mortality and QX disease resistance. The successful breeding of a disease resistant oyster has led to the partial recovery of the industry in QX infested estuaries such as the Georges River, and is acting as insurance should yet another estuary fall to this disease. Selection for disease resistance to a winter mortality like disease, in eastern oysters in the US and *Bonamia* in flat oysters in France, has been very successful.

In NSW, QX disease may kill over 80% of all oysters in the upper reaches of seriously affected estuaries annually. Mortality of oysters bred for resistance to QX disease for two generations was reduced from 86% for the controls to 64% for the QX-resistant breeding line, at the worst affected site (Lime Kiln Bar, Georges River). On the basis of these and other results from overseas, it is expected that it would take another four generations or eight years to reduce mortality from 62% to the background level of 10% and produce a fully QX disease resistant oyster (Nell 2001b).

In addition a report (Leith and Haward 2010) reviewing and synthesising knowledge about climate impacts, the potential to build adaptive capacity and resilience, and to define adaption options within the Australian edible oyster industry is to be released soon. This report includes the Sydney rock oyster in NSW.

Key point:

- Selective breeding aims to increase disease resistance and reduce the possible impact of climate induced changes.

27.5. Potential climate change impacts (direct and indirect)

27.5.1. Direct

Performance

Three recent studies (Watson et al. 2009; Parker et al. 2009; Parker et al. 2010 pers. comm.) have looked at the effect of predicted climate-induced temperature increase and acidification of estuarine water on Sydney rock oyster embryonic and larval development.

Larval life-history stages are considered particularly susceptible to climate change, and Watson et al. (2009) showed that *S. glomerata* larvae are sensitive to a high CO_2 world and are, specifically, negatively affected by exposure to pH conditions predicted for the world's oceans for the year 2100. With decreasing pH, survival of *S. glomerata* larvae decreased and growth and development were retarded. Larval survival decreased by 43% at pH 7.8 and by 72% at pH 7.6. Scanning electron microscope images of 8-day-old larvae show abnormalities on the shell surface at low pH suggesting (1) problems with shell deposition, (2) retarded periostracum formation, and/or (3) increased shell dissolution (Watson et al. 2009).

Parker et al. (2009) investigated the synergistic effects of ocean acidification (caused by elevations in the partial pressure of carbon dioxide pCO_2) and temperature on the fertilisation and embryonic development of the economically and ecologically important Sydney rock oyster *S. glomerata* (Gould 1850). As pCO_2 increased, fertilisation significantly decreased. The temperature of 26°C was the optimum temperature for fertilisation, as temperature increased and decreased from this optimum, fertilisation decreased. There was also an effect of pCO_2 and temperature on embryonic development. Generally as pCO_2 increased, the percentage and size of D-veligers decreased and the percentage of D-veligers that were abnormal increased. The optimum temperature was also 26°C and embryonic development decreased at temperatures that were above and below this temperature. The results of this study suggest that predicted changes in ocean acidification and temperature over the next century may have severe implications for the distribution and abundance of *S. glomerata* as well as possible implications for the reproduction and development of other marine invertebrates (Parker et al. 2009).

Ongoing research by Parker et al. (2010) aims to identify the chronic multigenerational response of Sydney rock oysters to ocean acidification and temperature. Studies by Parker et al. (2009, 2010) have already found effects of ocean acidification and temperature on the reproduction and development of oysters with selectively bred oyster populations showing some resilience. The current research is using chronic multigenerational experiments to determine whether populations of the Sydney rock oyster *S. glomerata* have the potential to adapt to future ocean acidification and temperature.

Farming infrastructure

Just as with aquaculture of Pacific oysters a predicted rise in sea level due to climate change with increasing water depth at existing intertidal oyster farm sites, which may lead to a need to modify the infrastructure in place (to cope with deeper water or in some cases a commensurate increase in wave action), and as such result in additional infrastructure costs. Existing husbandry practices may also need to be varied or new practices developed. If sea level changes increase significantly, some existing intertidal sites may become unsuitable for farming, and alternative intertidal sites may not be available.

Social

Restructuring of the industry husbandry practices and shifts in location of infrastructure are likely to result in relocation of labour in small coastal communities.

27.5.2. Indirect

Performance

Often the response of bivalves to temperature, salinity and water acidification stress is an increase in disease. Section 27.4 above outlines the current disease issues for the Sydney rock oyster. Unfortunately, the QX disease resistant oysters identified in the mass selection trials are carriers or hosts for other parasites and, while large batches of several million Sydney rock oyster spat have been produced in hatcheries in NSW, the techniques have not been sufficiently reliable for commercial adoption. This has prevented industry from having reliable access to improved oysters (Nell 2002, 2003; I&I 2010).

Farming infrastructure

Biofouling of oysters and overcatch (young oysters settling on older oysters) is still a problem for the industry. Currently, this problem is dealt with by a mix of methods, such as leaving oysters out of water for up to 7–10 days to kill overcatch, dipping oysters in around

85°C hot water for 2–3 seconds, immediately followed by cooling in cold water, or culling oysters by hand. All these methods are costly and time consuming (Nell 2002). Settlement and growth of fouling on farming infrastructure may increase due to higher water temperature and acidification; this will require farmers to more frequently clean the infrastructure and increased costs.

Marketing and social

Climate-induced changes in the life history of the oysters and subsequent modification of husbandry and production methods may increase the cost of the NSW Shellfish Program which regulates the harvesting of all oysters in the state. The program aims to provide high quality product to consumers. This can be best achieved by rectifying potential pollution point sources in shellfish-producing areas, assessing and controlling production methods at all levels of industry and educating shellfish producers in their responsibilities. This is a mandatory industry-funded program designed to ensure that oysters are only harvested under strict water quality and product guidelines including depuration of all oysters before sale. The program seeks to ensure that public health and high industry standards are observed and promoted.

Key points:

- Recent studies have shown changing ocean acidification in synergy with temperature causes significant reduction in oyster fertilisation success and survival of larval stages.
- Selective breeding offers a possible way to increase oyster resilience to climate-induced changes.

27.6. Critical data gaps and level of uncertainty

Like Pacific oysters, Sydney rock oysters are filter feeders and are farmed on 'fixed' infrastructure and leases, and as such the performance of farmed oysters and thus oyster aquaculture businesses are determined by local environmental conditions. However, very limited or no information on fine scale climate change impacts is available, which is a challenge to oyster growers, resource managers and policy makers to establish effective methods to mitigate the potential negative impacts of climate change.

Further research on the ability of the mass selected Sydney rock oyster breeding lines to cope with the predicted changes in temperature and ocean acidification is needed. A consequence of this is the need to improve and fully commercialize the hatchery production of oyster spat.

Table 27.1: Summary of Sydney rock oyster species profile, which also indicates level of certainty of the associated information.

Life history stage	Business stage	Farm activity	Current impacts	Predicted impacts	Information/data gaps
Spawning and fertilisation (wild)	N/A	N/A	-	Decrease in success (H)	-
Spawning and fertilisation (hatchery)	Hatchery	Conditioning of brood stock and fertilisation	-	N/A	Full commercialisation of hatchery
Larvae and spat (wild)	Spat collection	Spat collection	-	Increased larval mortality and abnormal shell development due to lower pH and/or increased pCO_2	-
Larvae and spat (hatchery)	Hatchery	Larval rearing and artificial settlement induction	-	N/A	Full commercialisation f hatchery
Juveniles / Adults	Growout	Tray or raft culture	Possible disease issues with winter mortality and QX (M)	Increased mortalities due to lower pH and/or increased pCO_2 resulting in decreased calcification rates and elevated temperatures	Mechanisms for evaluating and selecting more suitable farm sites Research on selective breeding and other genetic techniques to improve oyster resilience to climate changes
Postharvest	Market and marketing	Harvesting	Disease issues (M)	Increased cost of quality assurance program	-
		Processing	Disease issues (M)	More restricted standards for transportation and processing	Optimal conditions to control the proliferation of marine bacteria

		Packaging	-	-	-

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27.7. References

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28. Yellowtail kingfish *Seriola lalandi*

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28.1. The industry

Yellowtail kingfish (YTK), also known as gold-striped amberjack or yellowtail amberjack, are a very swift swimming pelagic finfish with a torpedo shaped body, very small smooth scales and bright yellow tail. They prefer clean open coastal water and are distributed circum-globally in temperate regions of the Pacific and Indian Oceans (Poortenaar et al. 2001; Carton 2005). The fish cultured in Australia and New Zealand are identified as *Seriola lalandi lalandi* due to their geographical separation from *S. lalandi dorsalis* and *S. lalandi aureovittata* (Poortenaar et al. 2003; Chai et al. 2009). However, this geographically based classification is disputed. YTK (*Seriola lalandi*) is one of the most valuable kingfish species farmed in the world due to its excellent flesh quality (Poortenaar et al. 2003; O'Sullivan 2005a) and good shelf life (colour, firmness and flavour) of >3 days under refrigeration. In Australia, this species is commercially farmed in Spencer Gulf, eastern Eyre Peninsula, South Australia (SA), although small-scale commercial farming has also been attempted in Western Australia (WA) and New South Wales (NSW) in the past. Hatcheries, from which all farm stock are produced, presently exist in SA (Arno Bay and Port Augusta), NSW (Port Stephens) and WA (Fremantle), with only those in SA privately owned.

In Australia the aquaculture of YTK began in 1999 at Fitzgerald Bay, SA, with the initial emphasis on conditioning broodstock, improving larval rearing, developing growout techniques including managing parasites, and marketing. The growout infrastructure used in Australia is similar to that used elsewhere for sea cage culture of other offshore finfish species, although some modifications have been made to suit the local environmental and management conditions (O'Sullivan 2005b; Chen et al. 2007; Moran 2007; Moran et al. 2007b; Hilton et al. 2008).

The time period required for YTK to grow from fertilised eggs to marketable size varies according to the size targeted and market demand. In SA it normally takes 18–24 months to grow to the initial market size of 3.5 kg (Tanner and Bryars 2007). During this period the fish are generally graded twice to achieve size uniformity and optimal stocking density in individual cages.

Farmed YTK are sold domestically and exported to the USA, European and Asian markets. Two main aquaculture products are produced: gutted whole fish and fillets. Both are prepared at the local seafood processing plants and then chilled or frozen before being transported to retailers or wholesalers; some is smoked, used in sushi and eaten as sashimi

Key points:

- YTK, *Seriola lalandi lalandi*, is endemic to Australia and New Zealand. Its aquaculture was first established in 1999 in SA.
- All YTK stocks farmed in Australia are hatchery produced.
- Offshore sea cages are currently the only system used for YTK growout in Australia.
- Australian farmed YTK are sold domestically and exported to USA, European and Asian countries; popular products include fresh whole gilled and gutted, smoked, sashimi and sushi.

28.2. Production

YTK aquaculture contributes significantly to the economy in SA. In the 2007–08 financial year the combined production volume and farm-gate value of YTK and mulloway was about 2000 tonnes worth $17.7 million (ABARE 2009; EconSearch 2009), with the majority comprising YTK (Chambers and Ernst 2005). In SA, the industry employs about 84 full-time equivalent staff directly (EconSearch 2009). In SA the projected increases of YTK aquaculture production and employment over the period from 2008–09 to 2010–11, relative to 2007–08, were 23% and 12%, respectively (EconSearch 2009). The major producer of YTK in SA, Clean Seas Tuna Ltd is targeting production levels of 5000 tonnes per year by 2011.

In SA there are 31 YTK farming licences issued (ABARE 2009). The three bays with offshore kingfish farming are south to north in Spencer Gulf: Boston Bay, Arno Bay and Fitzgerald Bay (Figure 28.1).

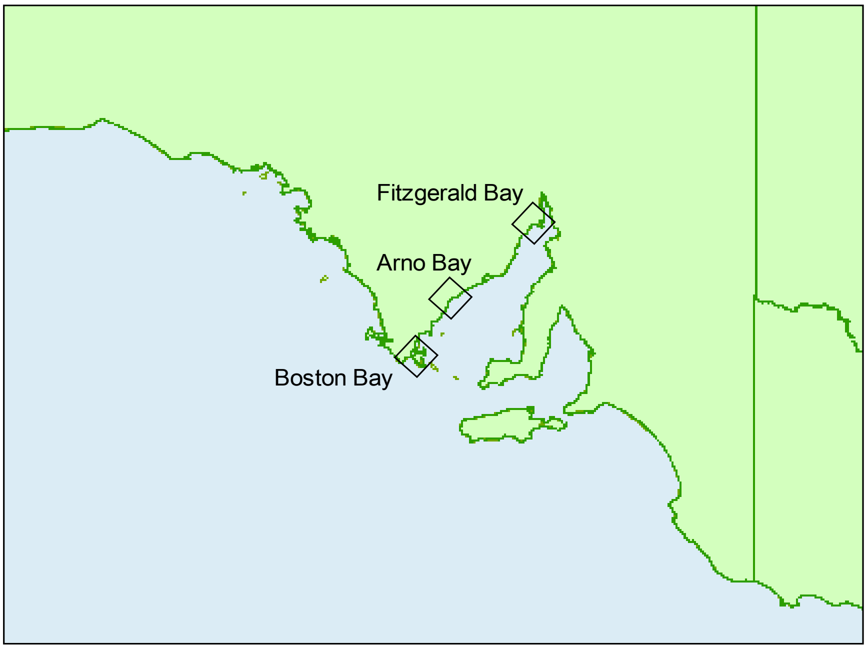

Figure 28.1: YTK farming locations in South Australia.

Key points:

- YTK aquaculture contributes significantly to the economy in SA.
- In 2008–09, about 2000 tonnes of YTK valued at $17.7 million was produced in SA.

28.3. Life history stages, stages in farming process and physiology

28.3.1. *YTK life history*

YTK mature as separate males and females, and cannot be recognised apart morphologically. The wild YTK can produce gametes at fork length (FL) 75 cm (5 kg) and FL 78 cm (6 kg) for males and females, respectively in New Zealand (Stewart et al. 2002; Poortenaar et al. 2003) and slightly smaller in NSW waters (Gillander et al. 1999a, b). However, the F1 farmed YTK reach sexual maturity earlier; in SA most of them are mature when harvested at a weight of 3.5 kg (FL 65 cm). YTK release their gametes into the water column at multiple spawnings during the period from late spring to late summer (Poortenaar et al. 2001). The fertilised eggs are 1.4 mm in diameter and positively buoyant (Moran et al. 2007b). At 17°C they develop into the 20 myomere stage 42 hours post fertilisation and hatch at 103 to 108 hours post fertilisation (Moran et al. 2007b). The newly hatched larvae are positively buoyant and are held inverted at the water surface by the large yolk sac which is absorbed over the proceeding 20 hours. When larval eyes and digestive system fully develop at four days post-hatch at 17°C, first feeding commences (Moran et al. 2007b) (Figure 28.2). The rate of each larval developmental stage is temperature dependent (Moran et al. 2007b).

In the wild, YTK larvae feed exclusively on planktonic crustaceans (Anraku and Azeta 1965; Sakakura and Tsukamoto 1996). The adult kingfish primarily feed on schooling fish, squid and crustaceans (Poortenaar et al. 2003).

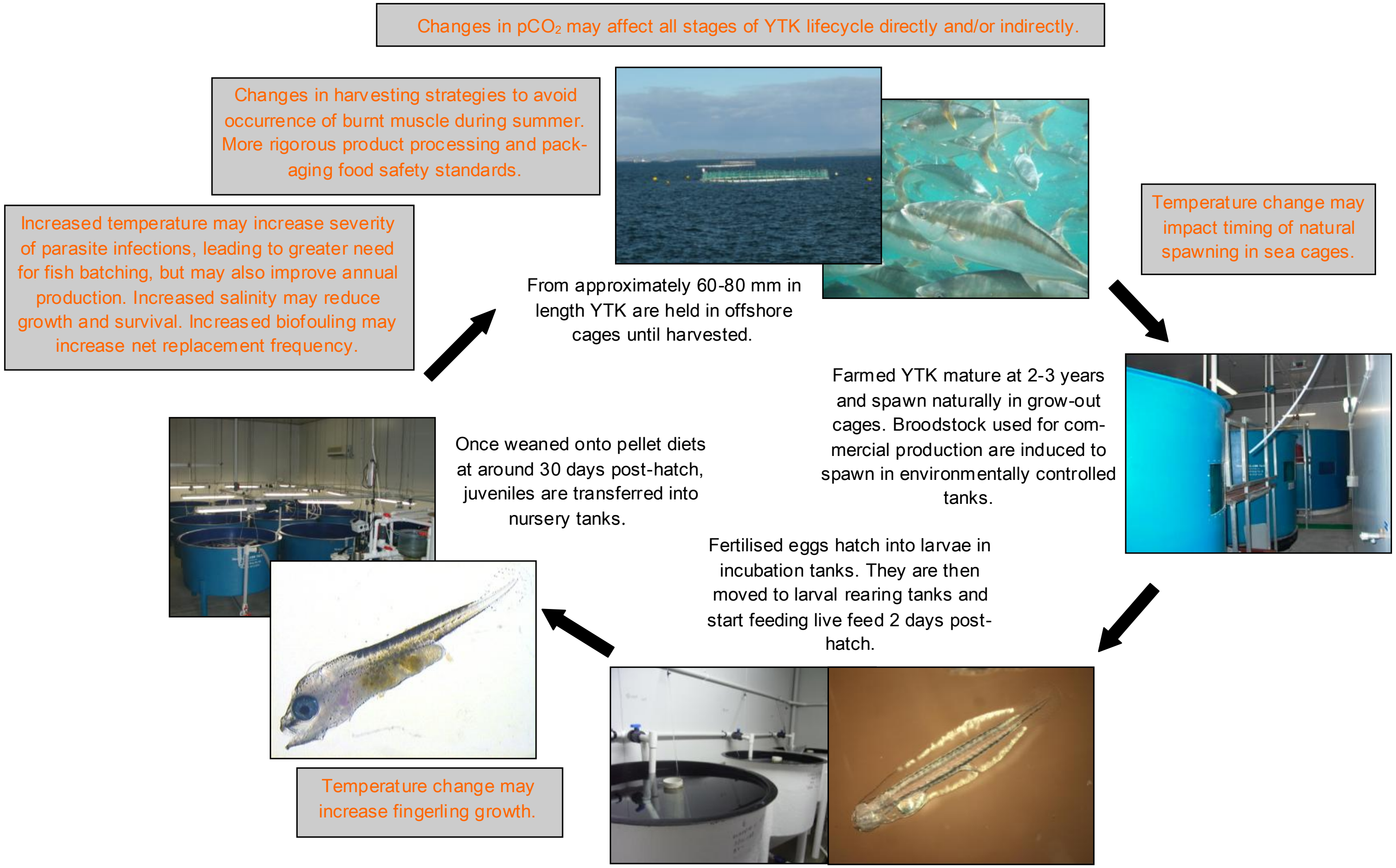

Figure 28.2. Key YTK life cycle stages (this section) and responses to or impacts from relevant climate change drivers (sections 28.4 and 28.5). Image source: B Chen, D Stone and W Hutchinson (SARDI).

28.3.2. YTK aquaculture

The YTK aquaculture business consists of four main stages: 1. Hatchery; 2. Nursery; 3. Growout and 4. Market Supply. Currently there are two types of YTK farms: hatchery and growout based, and growout only. The former is vertically integrated and comprises all four stages, while the later involves only the later two stages.

The hatchery activities include broodstock management, egg collecting and hatching, intensive larval rearing and weaning, nursery and live food production. At spawning time, fertilised eggs, which float, are collected daily from broodstock tanks holding both male and female fish. The fertilised eggs are then transferred to incubation tanks with very gentle aeration and low water flow where after two days at 22°C the larvae hatch. When hatched, larvae are usually moved to larval rearing tanks where gentle aeration is provided to the culture unit to maintain dissolved oxygen at saturation levels. The gentle aeration also promotes a homogeneous distribution of live foods and larvae throughout the tank. For feeding, enriched rotifers are supplied two days post-hatch (just before the onset of first feeding) and enriched *Artemia* are added 10 days post-hatch (Benetti 1997; PIRSA 2002; Chen et al. 2006a, b 2007). The larvae are weaned onto manufactured pellet diets approximately 18 days post-hatch (Chen et al. 2006a, b 2007). Once the juveniles are weaned onto pellet diets, at around 30 days post-hatch, they are transferred into larger nursery tanks where they are continuously monitored and graded by hand sorting to remove deformed fish. YTK show aggressive behaviour at very early developmental stages (10–12 mm total length), with the main aggressors being the larger individuals in the cohort (Sakakura and Tsukamoto 1997; 1998; Moran 2007). When reaching a weight of 5–10 g and about 60–80 mm in length after about two months, they are then carefully transferred to offshore sea cages (O'Sullivan 2005). During the hatchery and nursery period, the tank systems need to be cleaned regularly and grading is best done at night when fish are less active to improve fish survival (Sakakura and Tsukamoto 1997; Yamazaki et al. 2002; Shiozawa et al. 2003; Chen et al. 2006a, b 2007). Larval mortalities are high; 86% or higher are experienced in the commercial-scale larval production of *S. lalandi aureovittata* (Tachihara et al. 1997) with up to 50% during the weaning period of *S. lalandi landi* only (PIRSA 2002).

Typically, growout seeks to get YTK to market size over about an 18-month period by stocking about 8000 fingerlings into each sea cage (25 m in diameter and 6 m deep) in October each year (Tanner and Bryars 2007). During this time they undergo two gradings in an attempt to maintain uniformity in size as well as an optimal stocking density, at which time they are transferred between cages. Standard husbandry procedures include regular feeding of formulated diets via purpose-built boats fitted with bulk hoppers and engine-driven air blowers, changing of nets on the sea cages and bathing fish in freshwater or hydrogen peroxide to remove ectoparasites (Chambers and Ernst 2005; Hutson et al. 2007). The nets on the sea cages are changed every 10 to 20 days (O'Sullian 2005a) in summer, partly as a parasite management procedure (Ernst et al. 2002; Tan et al. 2002), but also because fouling organisms become abundant and reduce the amount of water flow and thus potentially dissolved oxygen levels, particularly at times of low flow – dodge tides (Tanner and Bryars 2007). The fouled nets are taken to shore to be cleaned. The sea cages in the growout area undergo a 2-year fallowing period to allow the seafloor at the site time to recover (PIRSA 2002).

At harvest, the fish are brought close to the suction intake of the fish pump using a crowd net (O'Sullivan 2005a). The harvested fish are stunned by a pneumatic 'stunner' and gill plate bled for premium flesh quality (O'Sullivan 2005a). After being transported to the processing facilities, they are gilled and gutted. If YTK are sold whole (which is most common) they are chilled. The fish are also sliced into cutlets or fillets, vacuum packed and frozen.

The key environmental parameters in YTK hatchery and nursery are highly controlled to provide the optimal conditions to promote or maintain gonad condition in broodstock, and optimise growth and survival in larvae. These include water temperature, light intensity and photoperiod, feed quantity and quality, water quality (dissolved oxygen and ammonia) and water flow/exchange rate. When YTK are transferred into sea cages, they are subjected to local environmental conditions. The methods used by farmers to improve production include maintaining appropriate stocking densities; optimising feeds and feeding; managing ectoparasites, fouling and net integrity; and changing the netting mesh size as the fish grows. Most farms harvest year-round to meet market requirements, but their largest orders are generally in the period just prior to Christmas and New Year.

In the wild, YTK are typically found in temperatures of 15–24°C (Penney 2000), but prefer water temperatures of 18–24°C (PIRSA 2002). They have been successfully cultured in temperatures between 12 and 22°C in New Zealand, although their appetite and growth reduced below 14°C (Poortenaar et al. 2003) and beyond the range of 11–26°C at Fitzgerald Bay, SA. Temperature tolerances may, however, vary at different developmental stages. A study by Moran et al. (2007a) demonstrated that eggs incubated at 17, 19 and 21°C have similar profiles of metabolite concentration during embryogenesis; however, eggs incubated at 23°C are found to have a considerably different pattern of substrate utilisation, possibly indicative of abnormal physiological development at a temperature above that which is routinely encountered in the wild.

During YTK growout operations, the optimal salinity range is said to be from 29.8 – 36.3‰ (Nakada 2002); commercial growout in SA occurs between 36 and 48‰. Dissolved oxygen levels should be greater than 5.7 mg/L (Nakada 2000). The other key environmental parameters for YTK growout should be pH 6–9, unionised ammonia <0.01 mg/L, carbon dioxide <10 mg/L, chlorine <0.04 mg/L, hydrogen sulphide <0.002 mg/L, nitrate <100 mg/L, nitrite <0.2 mg/L and toxins undetectable (PIRSA 2002).

Key points:

- YTK have a simple life cycle.
- YTK show aggressive behaviour at very early developmental stages (10–12 mm total length).
- Environmental conditions at the hatchery, nursery and market supply stages are highly controlled.
- When grown in offshore cages, YTK are subjected to the local environmental conditions, which are essentially uncontrollable.
- The growth performance of YTK reduces substantially when water temperature drops below 14°C.
- Limited information is available on the ranges of environmental parameters that YTK can tolerate at different developmental stages.

28.4. Likely current impacts of climate change

Control of gill (*Zeuxapta seriola*) and skin (*Benedenia seriola*) flukes (also known as mongenean or flatworm parasite) has presented a significant challenge to the YTK aquaculture industry since soon after its inception (O'Sullivan 2005a). The gill flukes feed on blood and the skin flukes on mucus and epithelia cells (Ernst et al 2002). Skin feeding flukes can cause significant wounds that are open to secondary infections by viruses, bacteria and fungi. They also cause irritation to the host and infected fish rub their bodies against sea cage nets, which may worsen lesions (Ernst et al. 2002). Gill (blood-feeding) flukes cause emaciation, lethargy and lethal anaemia (Ernst et al. 2002; Mooney et al. 2006).

Fluke infestations present greater problems for YTK at higher water temperatures. This is due to the temperature dependent nature of the egg laying rhythm, hatch rate and maturation cycle of the flukes (Mooney et al. 2006). For example, for *Z. serioli*, when water temperature is 14°C the first eggs hatch at day 12, the last eggs hatch at day 16, and fluke maturation occurs at 40 days post-spawning. At water temperatures of 18 and 22°C, the cycle accelerates with first eggs hatching at day 6 and day 4, and last eggs at day 9 and day 7, while maturity is reached after 21 and 15 days post-spawning, respectively. As the water temperature rises to 26°C, a scenario that is likely to occur more often with global warming, the parasite life cycle is shortened even further with first eggs hatching on day 4, last eggs on day 6, and maturity occurring at day 10 (Mooney et al. 2006; personal communication Mr Joe Ciura).

Without regular intervention, fluke populations can impact negatively through loss of fish growth, decreased market value due to parasite-induced damage on fish and fish mortality (Ernst et al. 2002; Sharp et al. 2003, Mooney et al. 2006). In 2000, between October and December, about 13,800 fish died as a result of gill parasite infestation, representing a significant loss to the industry at that early stage of its development (O'Sullivan 2005a). In Australia, these flukes are currently managed by bathing fish in freshwater or hydrogen peroxide (Chambers and Ernst 2005; Tanner and Bryars 2007). Bathing fish is expensive because extra personnel and infrastructure are required, feeding days are lost, fish stress is increased affecting productivity, and the size and design of sea cages may be limited (Ernst et al. 2002; Chamber and Ernst 2005).

Key points:

- Gill and skin flukes present greater problems at increased water temperatures.
- Control of gill (*Zeuxapta seriola*) and skin (*Benedenia seriola*) flukes (mongeneans or flatworms) has presented a major challenge to the YTK aquaculture industry since soon after its inception.
- Fluke infestations have resulted in substantial loss of production of farmed YTK.
- These two parasites can be controlled by bathing fish in freshwater or hydrogen peroxide. However, bathing is a time consuming and costly practice.

28.5. Potential impacts of climate change (direct and indirect)

Climate changes can affect the YTK aquaculture business by directly acting on the farm stock, farming infrastructure, and marketing (direct impacts), or on other factors such as fouling organisms (e.g. macroalgae and invertebrates) and parasites, as well as the regional communities that provide and sustain YTK aquaculture employees (indirect impacts).

28.5.1. Potential direct impacts

YTK performance

YTK have been successfully cultured in water temperatures between 12 and 22°C in New Zealand (Poortenaar et al. 2003). However, their appetite and growth rate reduce substantially when water temperature drops below 14°C (Poortenaar et al. 2003). It is anticipated that the result of climate change, both the minimal surface seawater temperature (currently about 12°C in Spencer Gulf, SA, Jones et al. 1995; O'Sullivan 2005) and the average annual period of seawater temperature higher than 14°C will be increased. The general circulation models based on the high emission scenario for SA predict that for 2070 the median estimate (50^{th} percentile) of an increase in surface seawater temperature is 2°C (Climate Change in Australia 2009). This may be beneficial to the YTK aquaculture industry in SA due to increased growth rate given the predicated water temperature increase in summer would have limited, if any, negative effects. However, this positive projection may be offset to a degree by the potential negative effects of salinity increases on YTK growth and survival (Oulton 2009), with high evaporation rates particularly in upper Spencer Gulf leading to higher salinity and density gradients (Oulton 2009). Fish grading, with its associated operational cost, might also have to occur more frequently to balance increased growth rates.

As servicing of offshore YTK sea cages, such as feeding and removal of mortalities, is weather-dependent, it may be negatively impacted by a predicted increase in storm frequency due to climate change.

Farm infrastructure

In more wave-exposed areas there will need to be improvements made to better anchor and strengthen offshore farm infrastructure if storm frequency increases. The number of days that such infrastructure can be accessed for key operational tasks may also be reduced (e.g. cleaning infrastructure, replacing net).

Marketing

The research by Arroyo Mora et al. (2007) has confirmed that a higher fish-keeping temperature prior to slaughter is one of the determinative factors that induces the occurrence of burnt muscle in cultured *Seriola quinqueradiata*. In comparison with those kept at 13°C, the fish kept at 30°C quickly become whiter, softer and more watery after slaughter as a result of the combination effect of rapid ATP depletion, increase in lactic acid content and fast drop in pH; the main causes of deterioration of raw meats in summer. Fish so affected are not suitable for sashimi consumption. If this occurs to YTK during summer as a result of climate change, new harvesting strategies are likely to need to be developed to ensure premium product quality. This might be critical because the largest seafood orders are normally in the period prior to Christmas and New Year; the summer season in Australia.

28.5.2. *Potential indirect impacts*

YTK performance

Fifty seven metazoan parasite species have been found to infect wild YTK in southern Australia (Hutson et al. 2007). Although *B. seriolae* and *Z. seriolae* are currently considered to cause the most significant negative impact on cost-effective sea-cage farming of *S. lalandi* in Australia, their infections can be managed by bathing fish in either hydrogen peroxide or fresh water. The absence of potential treatment methods for *Paradeontacylix* spp., *Kudoa* sp. and *Unicapsula seriolae* suggests that these species may have similar or greater negative consequences for *S. lalandi* aquaculture in Australia in the future (Hutson et al. 2007). *Paradeontacylix* species have been associated with mass mortalities of farmed amberjacks in the Mediterranean (Crespo et al. 1990) and Japan (Ogawa and Fukudome 1994). YTK infections from the last two taxa are not associated with mortality, but can have detrimental effect on product quality and consumer acceptance (Lester 1982; Moran et al. 1999; Hutson et al. 2007). Currently the net effect of climate change on parasite loads and infection rate are unknown because their responses are likely to be species and site specific.

Based on the observations of monogenean species, it is anticipated that the egg production rates, embryonation period, larval longevity and infection dynamics of *B. seriolae* and *Z.*

seriolae will be strongly influenced by temperature increases (Chamber and Ernst 2005; Ernst et al. 2005; Mooney et al. 2006). At higher temperatures, the populations of these monogeneans are likely to develop more rapidly.

Moore et al. (2008) believe that if the timing and strength of coastal upwelling winds are affected by climate change, then the occurrence of these events may play an increasingly important role in the development of some microalgal blooms. Microagal blooms can attain high biomass reducing the amount of light available to the underlying species and decomposition of senescent blooms can deplete the surrounding environment of oxygen (Moore et al. 2008), impacting the performance of cultured finfish species. Blooms of this nature can also reduce the appetite of finfish and irritate their gills, inducing mucous production that can consequently lead to death through asphyxiation (Tanner and Ellyard 2003; Oulton 2009). As well as algae, other species can form blooms under favourable conditions. It is thought that jellyfish blooms in southern Australian waters occur when there are elevated nutrients in the water and that an increase in the duration of upwellings may cause this.

Mortalities and economic losses caused by bacteria in cultured *Seriola* spp. are also reported from Japan (Alcaide et al. 2000). Elevated temperature, increased salinity, turbidity and chlorophyll, all possible due to climate change, have been shown to increase bacterial numbers in some conditions (Zimmerman et al. 2007). However, the development of vaccines could increase fish's resistance to these diseases (Sano 1998) but will take time to develop and will increase farming cost.

Higher temperatures in summer also increase the likelihood of the deterioration of manufactured YTK feed if it is not properly stored on-farm.

Farming infrastructure

Settlement and growth of barnacles and some seaweeds on farming infrastructure may be enhanced due to increased water temperature and pCO_2 based on some research of the effects of climate change on representative taxa of these types (Oceanus 2010). If this occurs, farm infrastructure, such as nets and pontoons, will need to be cleaned more frequently.

Increases in the biomass of fouling organisms on cages could also further elevate the infection of YTK by flukes. Investigations by Ernst et al. (2002) show an association between the number of eggs caught on sea cage nets and the weight of fouling organisms present. They estimate that as many as 165 millions eggs could be caught on a single 30 m diameter sea cage, although the re-infection rate of YTK is not known.

At increased water temperatures, the periods required to fallow the farming sites are reduced due to enhanced biochemical processes in the sediments. However, the increased feeding rates at higher temperature could also result in additional organic enrichment of sediments.

Marketing

Due to increased pathogen loads at elevated temperatures, the susceptibility in-situ may increase, and procedures for handling, transport, packaging and storage may all have to be more stringent.

Social

YTK farms are normally located in regional Australia and frequently require part-time staff for labour intensive activities such as grading, harvesting, etc at peak work periods. However, due to the impacts of climate change on other industry sectors, people might relocate to more climatically favourable locations resulting in shortages in local casual staff or those that provide the services to the aquaculture employees.

Key points:

- Climate change can affect YTK growth performance, farming infrastructure, animal husbandry practices and marketing, directly and indirectly.
- In response to climate change, parasites may become a greater issue and improved control measures may need to be developed.
- With increasing water temperatures due to climate change, fouling organisms might increase on sea cages leading to a need to more frequently clean farm infrastructure.
- Climate change, in particular higher temperatures, might increase the potential for the deteriorated of farmed fish flesh.
- Possible casual staff shortages in regional areas.

28.6. Critical data gaps and level of uncertainty

YTK are farmed in 'fixed' offshore sea cages, and as such the performances of farmed YTK and thus YTK aquaculture businesses, are influenced by local (fine scale) environmental conditions. At this time climate change modelling provides very limited or no information on climate change impacts at this scale. This increases the challenge for the YTK aquaculture industry, resource managers and policy makers to accurately assess and then establish effective methods to address the potential negative impacts of climate change.

Metabolic/physiological and immunological processes are critical biological factors that determine the growth performance and health status of YTK. Knowledge of the effects of climate change on these processes and information on the optimal and tolerance ranges of YTK to major environmental parameters are inadequate. These limit the capability of climate change modellers to predict the impacts of climate change on YTK farming and thus the ability of this industry sector and its managers to develop suitable adaptation strategies.

Fluke infections could be responsible for a substantial 22% proportion of the total *Seriola* spp. production costs (Ernst et al. 2002). More needs to be known about the biology, and ecology of these parasites, as well as treatment methods, not to mention the many other parasites and viruses that could become problematic with or without climate change.

Very limited information is available on the effects of increased seawater pCO_2 on the critical development stages of YTK such as fertilisation, development/growth at different ages, gonad development etc. These stages are all critical to a successful YTK aquaculture business.

Very little is known about the interactive responses to climate change of the many other organisms that can affect YTK performance and survival, such as fouling organisms, microalgae, and the processing of organically enriched sediments.

There remains uncertainty regarding the level of YTK genetic variation and the ability for selective breeding to cope with the speed and magnitude of the climate changes predicted.

Key points:

- Limited information on fine scale climate change impacts on the environmental conditions of offshore leases.
- Limited information on impacts of climate change on critical YTK developmental stages and their physiology and immunology.
- Limited knowledge on the interaction responses to climate change among organisms that affect YTK performances such as fluke, fouling organisms etc.
- Genetic variations associated with environmental parameters driven by climate change are unknown and will determine the effectiveness of selective breeding as an adaptation strategy to climate change.

Table 28.1: Summary of yellowtail kingfish species profile, which also indicates level of certainty of the associated information. Level of certainty is divided into high (H) = strong clear evidence, backed by several studies with solid datasets with little confounding interactions; medium (M) = evidence supported by one or more studies, conclusions may be partially ambiguous or confounded; low (L) = anecdotal evidence, limited data and/or predicted conclusions based on theoretical knowledge.

Life history stage	Business stage	Farm activity	Current impacts	Predicted impacts	Data gaps
Broodstock	Hatchery	Broodstock conditioning and/or holding		Little to none as can be managed through changes in settings used in existing broodstock conditioning systems (H)	Reproduction physiology and spawning cues
Spawning and fertilisation		Spawning induction and fertilisation		Little to none as can be managed through changes in existing settings (H)	
Larval development		Larval rearing			1. Climate change on larval physiology and developmental biology 2. Causes of larval deformities
Juvenile/fingerling	Nursery	Juvenile/fingerling rearing			1. Environmental optima and tolerances for optimal fingerling performance.
Adults	Growout	Adult rearing	Gill and skin fluke infections. Bathing fish to manage fluke infection is expensive (H)	1. Parasites infections - increased severity (M) 2. Improved annual YTK production due to increased temperature (H)	1. Climate change modelling at relevant spatial and temporal scales and of all factors of interest to farmers 2. Reproduction biology and physiology

				3. Improved food conversion ratio (H) 3. Reduced growth and survival due to increased salinity (M) 4. Increased frequency of net replacements due to increased biofouling (M) 5. Reduced working times on offshore cages (M) 6. Increased fish bathing to treat parasite infections (H) 7. New control methods for parasites (M) 8. Increased pathogen load (L) 9. Reduced fallowing periods due to enhanced biochemical processes in the sediments at increased temperatures (M); however increased feeding rates resulting in additional organic enrichment of sediments (M) 10. Increased potential occurrence of microalgal blooms and jellyfish (H)	3. Genetic capability to cope with the magnitude and speed of the predicted climate change 4. Effects of climate change on food conversion ratio 5. Biology and ecology of parasites 6. Effect of climate change on the environmental impact of fish farming and its minimisation and amelioration
Postharvest	Market	Harvesting		1. Development of harvest	1. Climate change and physiological

	supply and marketing			strategies to avoid occurrence of burnt muscle during summer (M) 2. More restricted standards for harvesting, killing and transport to the processor (M)	modelling at relevant spatial and temporal scales 2. Effect of climate change on the parameters affecting flesh quality and human food safety
		Processing		More restricted standards for during processing (M)	Optimal conditions to control the proliferation of marine bacteria and viruses
		Packaging		More restricted standards for during processing (M) Reduced shelf-live of raw YTK product due to high bacteria load (H)	

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