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Management implications of climate change effect on fisheries in Western Australia Part 2: Case studies

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1.0 Western Rock Lobster (*Panulirus cygnus*)

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1.1 The fishery

The Western Rock Lobster *Panulirus cygnus* (George) is taken by commercial and recreational fishers throughout its geographic range along the lower west coast of Western Australia. It is fished by three managed fisheries; West Coast Rock Lobster Managed Fishery (WCRLMF), Augusta–Windy Harbour Managed Fishery and the South Coast Crustacean Fisheries. The WCRLMF is the largest fishery encompassing most of the Western Rock Lobster's (WRL) geographic range (Figure 1.1.1), including the most productive regions and is Australia's largest single-species fishery worth $200–400 million annually.

The WCRLMF operates from inshore regions in shallow waters out to the edge of the continental shelf. The fishery is managed in three zones: south of latitude 30°S (Zone C), north of latitude 30°S (Zone B) and a third offshore zone (Zone A) around the Abrolhos Islands (Figure 1.1.1). Effort is evenly split between the Southern and Northern zones through the implementation of management controls aimed at addressing zone-specific issues, including different maximum size restrictions and seasonal opening and closing dates. The only method of capture is the use of baited pots made of wood slats or from cane material fitted with escape gaps (for undersized lobsters and bycatch). After an overnight soak period, the pots are retrieved the following morning with the captured lobsters of legal size and of appropriate reproductive status (e.g. not berried etc.) placed into holding tanks and returned to on-shore processing plants where the majority are prepared for live shipments.

The fishery has been managed by a total allowable effort (TAE) system and associated input controls until 2009/10. The main control mechanism was the number of units (pots) for the fishery, together with a proportional usage rate, which creates the TAE in pot lifts (i.e. number of pots in the fishery multiplied by the usage rate and the number of days in the season). The TAE system was managed via a limit on the number of licensees and the total number of pots that can operate in the fishery. Each license had a number of pots associated with it and this limited the amount of gear that they could use at any given time within the fishing season. Both the managed fishery licenses and the individual pot entitlements were transferable (within limits). This style of management for this fishery is often described as being an Individual Transferable Effort (ITE) fishery. The fishery also operates with a minimum legal size, maximum size for females and protection for all female lobsters of breeding condition (setose) and a closed season (July to 14 November).

The fishery has had a long-term average catch of about 11,000 t (Figure 1.1.2). However a downturn in puerulus settlement (post larval stage) over the seven years, 2006/07 to 2012/13, resulted in a pro-active management response before these year-classes reached the fishery with a significant reduction in fishing effort (ca. 40-70%) in 2008/09 resulting in a decline in catch to 5,900 t in 2009/10 (de Lestang *et al.* 2012). The fishery has also undergone a major change in management approach moving from an effort-controlled fishery towards an individual transferable quota (ITQ) fishery in 2010/11 with a quota of 5500 t. These reductions in catch and effort were introduced to protect the spawning stock and ensure some carryover of legal lobsters into the periods of poor recruitment.

The Western Rock Lobster is also a popular recreational species with around 45,000 recreational rock lobster licenses issued annually, of which around 80% are utilised. Most of the recreational lobster activity is around the main population centres of Perth and Geraldton. Several restrictions apply to the recreational capture of lobsters including the number of pots per licence, pot design, bag limits, and allowable fishing areas and periods. A catch share arrangement was put in place in 2009/10 between the commercial and recreational fisheries with the shares set at 95% and 5% respectively (IFAAC 2007).

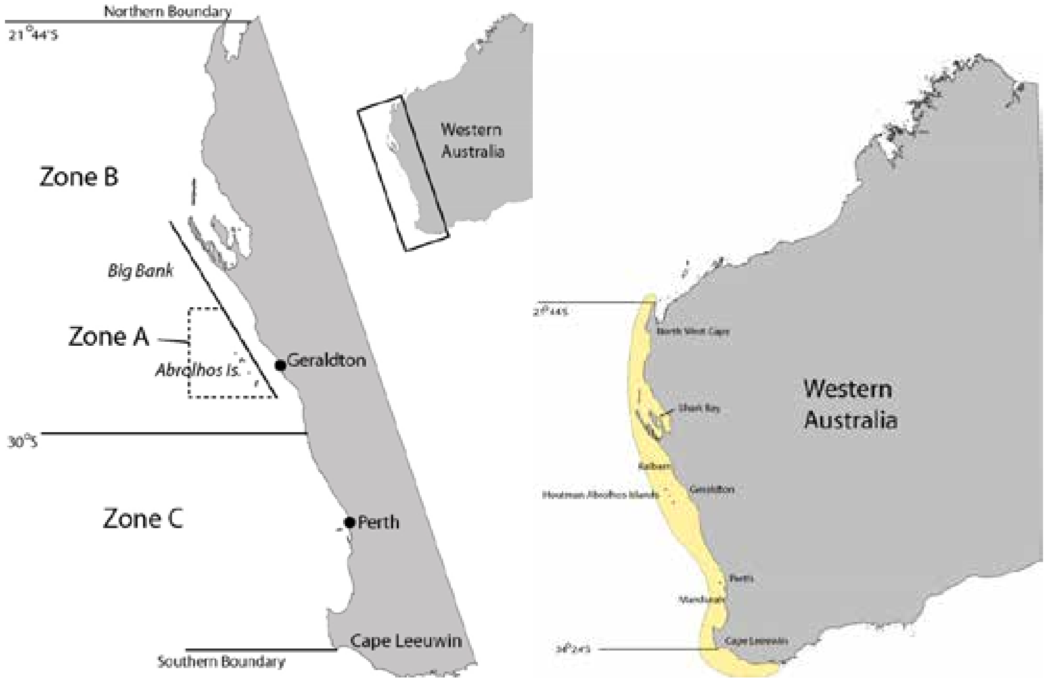

Figure 1.1.1. Distribution of the Western Rock Lobster (*Panulirus cygnus*) along Western Australian coastline.

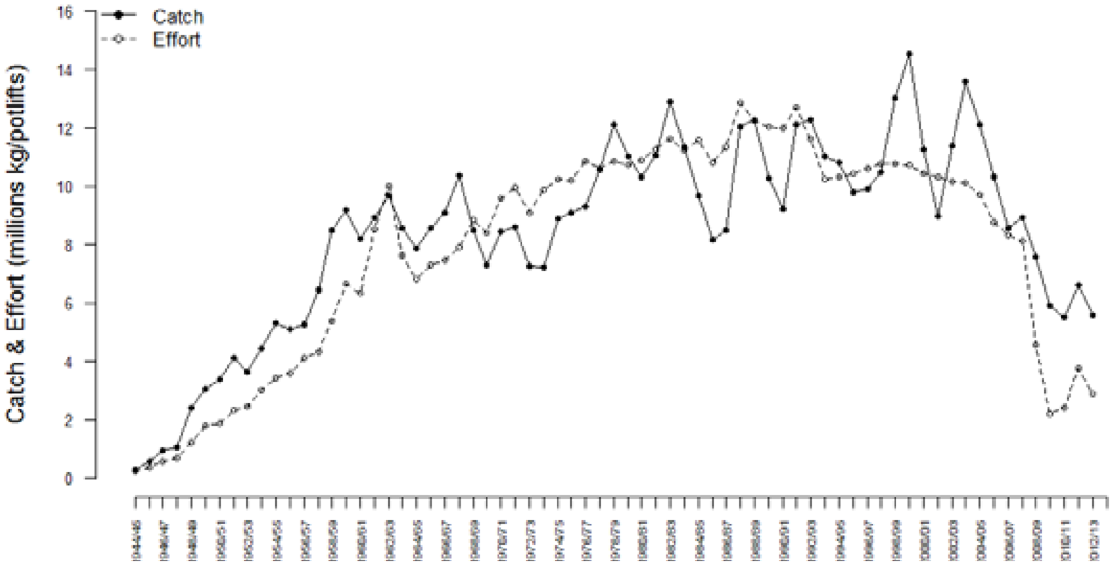

Figure 1.1.2. Annual catch and effort for *Panulirus cygnus* in the WCRLMF.

Key points:

- Western Rock Lobster fishery is Australia's largest single-species fishery currently worth about $200 million
- The fishery moved from an effort-controlled fishery to a catch quota fishery in 2010/11
- There has been a significant downturn in the recruitment to the fishery as measured by the low puerulus settlement since 2006/07.
- Pro-active management measures were taken to protect the spawning stock and ensure carryover of legal lobsters into periods of poor recruitment.

1.2 Life history

1.2.1 Life cycle, age and growth

The mating system of Western Rock Lobsters involves the male attaching a package of sperm generally called a "tarspot" to the female's sternum. At spawning, the female releases eggs from small pores at the base of the third pair of walking legs, sperm is released at the same time by the female scratching the tarspot and the eggs are fertilised as they are swept backwards and become attached to the sticky setae on the pleopods. After successful external fertilisation, the female lobster would carry and care for the egg brood attached to her abdomen for a period of 5 to 8 weeks. The number of eggs produced by a particular female during a spawning period depends on the size of the individual (Chubb 1991). Hence larger females produce more eggs per unit of size than smaller females, with large females capable of producing a million eggs (Morgan 1972) and also have a greater likelihood of spawning twice in a season (Melville-Smith and de Lestang 2006).

Upon hatching, the tiny larvae called phyllosoma spend 9-11 months as plankton in the water column driven by ocean currents. After several moults, the phyllosoma larvae moult into the puerulus stage and swim towards the coast to settle among seagrass beds and algal meadows (Figure 1.2.1). The settlement of pueruli occurs throughout the year, with peaks from late winter to mid-summer, while the rate of settlement of pueruli can vary greatly from year to year and is largely driven by environmental factors (Caputi *et al.* 2000). For example, when the Leeuwin Current is flowing strongly, the settlement of puerulus has historically been high, although this has changed during the recent years of low settlement.

After they moult into the juvenile stage, *P. cygnus* are more prevalent on inshore reefs where they would spend the next 3 to 4 years feeding and growing. When they reach a size of 70-80 mm CL (carapace length), many lobsters undergo a synchronised moult where their new shell would be paler in colouration to their normal bright red colouration (Figure 1.2.1). Lobsters that moult into a paler colour are known as "whites" until they return to their normal red colouration a few months later. The "white' phase of a rock lobster's life coincides with their migratory phase where lobsters leave the coastal reefs and make a mass migration across sandy habitats to their deep-water, offshore breeding grounds. When the "whites' reach the offshore breeding grounds, their shells progressively darken back to a red shell colour and remain in the deep-water habitats. In the following whites period some lobsters undergo a second, more northerly migration, in 100-200 m depth towards the "Big Bank" area, an offshore area from Kalbarri, north of the Abrolhos Is. (de Lestang 2014). The northward extent of this migration each year appears to be associated with at least two main factors, the number of migrating lobsters (i.e. based on the puerulus settlement four years previously and the level of capture before they reach the 100 m depth) and the strength of the southward flowing Leeuwin Current in the northern Abrolhos Big Bank region during the time of the migration. Weaker south-flowing currents and a large number of migrating lobsters will result in this migration extending further north (de Lestang *et al.* 2012). The Western Rock Lobster typically lives for 10 to 15 years and weighs less than 3 kg.

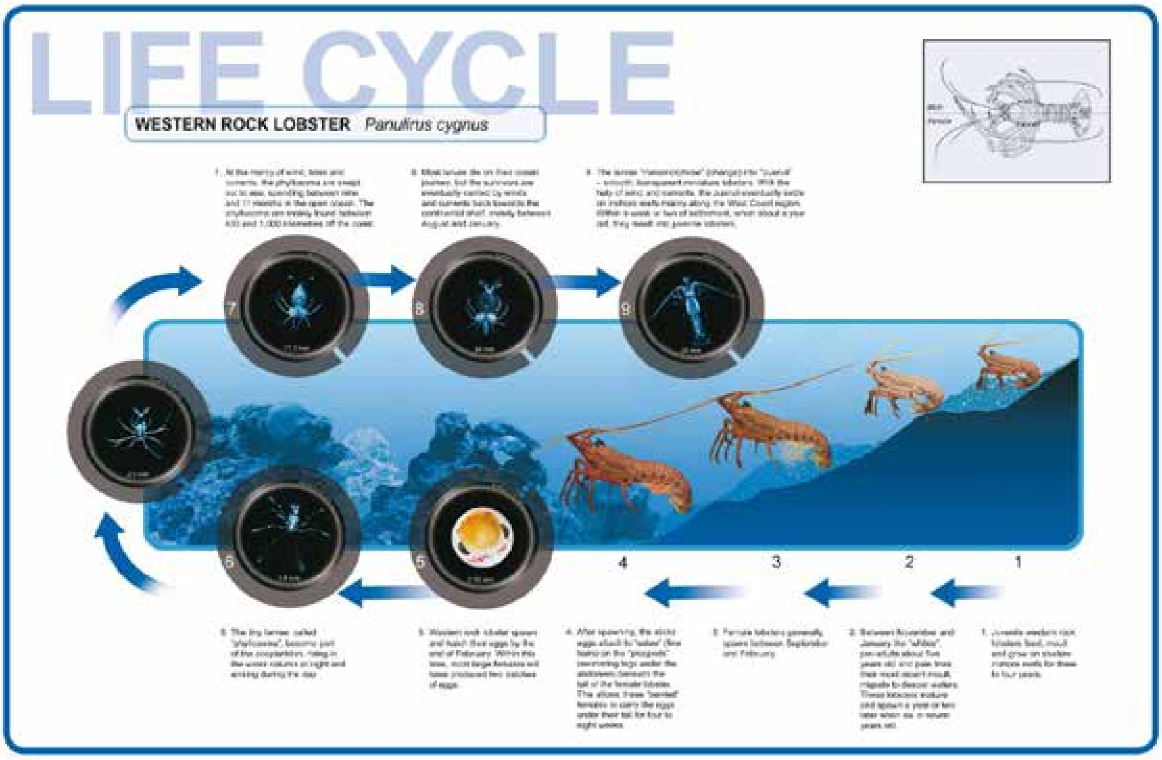

Figure 1.2.1. The life cycle of the Western Rock Lobster

Factors such as temperature, photoperiod, oxygen availability, diet, density, limb damage and size at sexual maturity can all influence the growth rate of *P. cygnus* (Chittleborough 1975). Thus there is considerable spatial variation in the reproductive biology and growth of both male and female Western Rock Lobsters throughout the fishery. In the cold-water southern areas of its distribution, lobsters become mature at about 6-7 years or around 90 mm CL. In the warmer northern waters near Kalbarri and the Abrolhos Islands, they mature at smaller sizes, usually at about 70 mm CL (Melville-Smith and de Lestang 2006). The growth rate of Western Rock Lobsters is faster in warmer waters towards the northern end of the fishery than in the south (de Lestang *et al.* 2009), this has been attributed to increased moult frequency rather than larger moult increments (Chittleborough 1975).

1.2.2 Distribution, habitat and environmental preferences

The Western Rock Lobster is found in temperate waters off the west coast of Western Australia where juveniles populate shallow inshore reefs (<40 m) and adults (>80 mm CL) populate deep-water offshore habitats (40-90 m) including coral reefs at the Abrolhos Islands. Its area of distribution is the continental shelf on the west coast of Western Australia, with greater abundances off the mid-west coast (Geraldton – Perth) than the northern and southern parts of the west coast (Figure 1.1.1).

The waters around the Western Australian coast are dominated by the warm southward-flowing, tropical water of the Leeuwin Current. In contrast, the Capes Current runs inshore of the Leeuwin Current and when pushed by strong south-westerly winds during the summer months, it causes cool, high-salinity water to flow northwards along the coast.

The Western Rock Lobster has a large geographic range covering 22-34ºS with a considerable variation in average sea surface temperatures, 17-23ºC (August) and 20-27ºC (February) (Pearce 1991) which is also an advantage in studying climate change effects. The geographical range in water temperatures affects the biological parameters (e.g. size at maturity and migration) of lobsters in the different areas (Melville-Smith and de Lestang 2006; Caputi *et al.* 2010). This provides some insights into how long-term changes in water temperature due to climate change may affect the fishery overall.

The habitat of *P. cygnus* is largely confined to the limestone reef systems fringing the central coast of Western Australia, coral reef systems surrounding offshore islands (e.g. Abrolhos Islands) and offshore reef systems in deeper waters (e.g. Big Bank). However rock lobsters can be found across the continental shelf where they use a range of habitats at different stages of their life cycle. During its larval phase, a phyllosoma spends up to 12 months in the water column before settling as puerulus onto seagrass and algal meadows found within nearshore habitats. Post-puerulus western rock lobsters (<25 mm CL at first year after settlement) usually inhabit small holes in the reef as well as on the reef face among algal or seagrass communities both as a shelter and a food resource. As lobsters grow they move into larger spaces where they begin to share the den habitat of juvenile lobsters in caves and ledges (Fitzpatrick *et al.* 1990). Sub-adults of 4-5 years of age migrate across the deep-water regions of sand and reefs to settle among offshore, deep-water habitats as mature breeding lobsters. The migratory path of "whites" lobsters is generally from the coast to the edge of the continental shelf, but their movements over or around different habitats is not known. Migratory immature "white" rock lobsters are regularly caught on sandy or silty bottoms in deeper waters and it's unlikely they seek refuge on these habitats due of the lack of shelter and paucity of food resource.

1.2.3 Predators and prey

The Western Rock Lobster is an opportunistic omnivore, feeding on a wide range of food items from coralline algae to molluscan and crustacean fauna (Joll and Phillips 1984; Edgar 1990). The diet and feeding strategies of juvenile rock lobsters vary greatly between seasons and between habitats and is reflective of the abundance and size distribution of the available benthic macrofauna (Edgar 1990). For adult lobsters in the deepwater habitats the diet is primarily carnivorous and consists of crabs, amphipods and isopods, and supplemented by bait items (pilchards) from lobster pots and discards from fishing boats (Waddington *et al.* 2008; Waddington and Meeuwig 2009). There is no evidence that lobster size (65-120mm CL) or sex affects the lobster's diet or trophic position in deep-water ecosystems (Waddington *et al.* 2008). As juveniles, *P. cygnus* are eaten by a number of fish species whilst at large sizes they are one of a number of prey items for octopus and a variety of larger finfish. There are no predators that rely on Western Rock Lobsters as their only prey item (Waddington *et al.* 2008).

1.2.4 Recruitment

Most lobster larvae do not survive their long oceanic journey. Many are eaten by predators or are not returned close enough to the shallow reefs by the ocean currents to enable them to settle. Therefore, the number settling can vary greatly from year to year, largely as a result of changes in environmental factors (Caputi *et al.* 2000). When the Leeuwin Current is flowing strongly, the settlement of puerulus is generally high (Caputi *et al.* 1995) and a higher proportion of the larval lobsters return to the coast. Possibly the warmer oceanic waters may increase the development rate and survival of phyllosoma larvae. Westerly winds at the time of year when the puerulus are ready to settle may also help more of them to reach the shallow reefs along the coast. The strength of the Leeuwin Current is generally weaker during El Niño events and stronger during La Niña events. The settlement of pueruli occurs throughout the year, with peaks from late winter to mid-summer, and generally occurs at night, around each new moon.

The abundance of puerulus settlement stage has been monitored for over 40 years and provides a reliable indicator of recruitment to the fishery 3-4 years later. Since 2006/07 the puerulus settlement has remained below average with 2008/09 being the lowest in over 40 years. This has occurred despite a strong Leeuwin Current in 2008 and 2011 and a generally very high breeding stock in most areas of the fishery since the 2010/11 breeding season. The cause of the low settlement has been under investigation in a number of studies and indications are that it may be related to earlier spawning time as a result of warmer waters and reduction in the winter storms (Caputi *et al.* 2014).

Key points:

- Larvae called phyllosoma spend 9-11 months as plankton in the water column driven by ocean currents
- Larvae moult into the puerulus stage and settle in the inshore coastal areas with peak settlement occurring from late winter to mid-summer.
- Juveniles migrate at 4-5 years from inshore to deeper waters with some undergoing a more extensive northerly migration in 100-200 m.
- Distributed in temperate waters off WA where juveniles populate inshore reefs (<40 m) and adults deep-water habitats including coral reefs at Abrolhos Is. with greater abundances off mid-west coast.
- Lobsters are opportunistic omnivores, feeding on a wide range of food items from coralline algae to molluscan and crustacean fauna.
- Puerulus settlement has been monitored for over 40 years and provides a reliable indicator of recruitment to the fishery 3-4 years later. Since 2006/07 the puerulus settlement has been below average with 2008/09 the lowest recorded.
- Current research indicates that the cause of the low settlement may be related to earlier spawning time as a result of warmer waters and reduction in the winter storms.

1.3 Current impacts from climate change

Climate change is causing an increase in water temperature (Pearce and Feng 2007), particularly in the autumn-winter (Caputi *et al.* 2009), a weakening of storms (westerly winds) in winter (IOCI 2012), and a changing frequency of El Niño and La Niña events that affect the Leeuwin Current.

Rising water temperatures over 35 years may have resulted in a decrease in size at maturity and the size of migrating lobsters from shallow to deep water; an increase in abundance of undersize and legal-size lobsters in deep water relative to shallow water; and a shift in catch to deep water (Caputi *et al.* 2010). The size of the migrating lobsters is related to the water temperature about the time of puerulus settlement (about 4 years previously). The water temperature increases affect puerulus settlement, catchability, females moulting from setose to non-setose, timing of moults and timing of peak catch rates.

Pearce and Phillips (1988) showed that puerulus settlement is much higher in La Niña years when the Leeuwin Current is flowing strongly and water temperatures are warmer than during ENSO events. Therefore changes in water temperature during February have historically been associated with significant effects on early puerulus settlement (Caputi *et al.* 2001). However the settlements between 2007/08 and 2009/10 were abnormally low suggesting that other factors dominated in these years. Hence this relationship has, however, broken down in recent years as the February water temperature variation is no longer consistent with the recent pattern of low settlement. An oceanographic larval model identified the timing of spawning as an important factor explaining some of the variation in puerulus settlement (Caputi *et al.* 2014). An examination of the timing for the start of the spawning period based on data from the fishery-independent breeding stock survey has indicated that in recent years there has been an earlier start to the spawning season compared to previous years. This earlier start appears to be due to higher water temperatures near the onset of spawning (October) which have been estimated since the mid-2000s. This may be a key factor why recent years have had consistently below-average settlement. It is possible that the earlier spawning causes a mismatch with other environmental factors such as peaks in ocean productivity and/or storms (westerly winds) that assist the larvae return to the coast.

Rainfall during July to November was identified in the early 1990s as being a significant factor related to puerulus settlement (Caputi *et al.* 1995). In an update to this assessment rainfall during May-October when combined with the breeding time index provided a good fit (R^2=0.72) to the variation in puerulus settlement since the early 1990s (Caputi *et al.* 2014). The rainfall represents an index of storm activity affecting the lower west coast of WA. It influences water conditions and is generally associated with westerly winds that may help bring larvae back to the coast. These two variables (breeding time and storms) provide a plausible hypothesis to explain the decline in puerulus settlement in recent years. There may be climate change implications associated with the environmental factors (water temperature and storm activity) affecting the spawning and larval period as both these variables are showing long-term trends.

Key points:

- There has been an increase in water temperature, particularly in autumn-winter, a weakening of storms (westerly winds) in winter, and a changing frequency of El Niño and La Niña events that affect the Leeuwin Current.
- Rising water temperatures may have resulted in a decrease in size at maturity and size of migrating lobsters.
- Puerulus settlements since 2006/07 have been below average for seven years and a long-term environmental change may be the cause. Current research indicates that earlier spawning time as a result of warmer waters and reduction in the winter storms may be implicated.

1.4 *Sensitivity to change*

The fishery is influenced by a number of environmental factors such as water temperatures, the strength of the Leeuwin Current, and the winter storms which affect the strength of the westerly winds (Caputi *et al.* 2001). These key environmental factors can affect the Western Rock Lobster throughout its complex life cycle from spawning; the larval stages over the 9–11 months they spend offshore of the continental shelf (Figure 1.2.1, Pearce and Phillips 1988; Caputi and Brown 1993; Caputi *et al.* 2001); the level and spatial distribution of the puerulus settlement along the coast; the growth rates of the juveniles (Johnston *et al.* 2008); the size of the juveniles migrating from shallow (<40 m) to deeper water (40–100 m) and the subsequent catch distribution; the strength of their pre-adult northerly migration (de Lestang *et al.* 2012); their size at maturity (Melville-Smith and de Lestang 2006); the moulting of mature females from setose to non-setose condition (de Lestang and Melville-Smith 2006); and the catchability of lobsters in the pots (Morgan 1974).

The southerly winds in summer, at the time when the early stage larvae of the rock lobster rise to the water surface, cause an offshore movement in the near-surface waters (the so-called Ekman transport) which carries the larvae out into the open ocean at the start of their 9-11-month migration (Phillips 1981). In late winter the late-stage phyllosoma are returning towards the shelf and transforming into puerulus before settling on the coastal reefs. Caputi *et al.* (2001) showed that puerulus settlement is enhanced when there have been strong storm-generated westerlies between July and November to assist the migration of puerulus to the coast. The Leeuwin Current strength during the period of settlement has also been shown to affect the spatial distribution of the settlement along the coast (Caputi 2008), with increased settlement southwards when the southward-flowing Leeuwin Current is stronger.

As there are many aspects of the life history of the Western Rock Lobster that are influenced by environmental effects, the stock must be regarded as being sensitive to climate change effects. This is confirmed by the sensitivity assessment (Appendix 4). Climate change models project that the warming trend and reduction in winter storms will continue, therefore change in the biological trends may continue. The changes may have some significant implications for the fishery and it is important they be taken into account in stock assessments and management of the fishery.

Key points:

- Many aspects of the life history of the Western Rock Lobster (spawning, larvae, puerulus, growth, migration and catchability) are influenced by environmental effects such as water temperature and winter storms. Hence the stock must be regarded as sensitive to climate change effects as long-term trends are apparent in these variables.
- Climate change models project that the warming trend will continue, therefore change in the biological trends are likely to continue. The changes may have some negative or positive implications for the fishery.

1.5 *Resilience to change*

The Western Rock Lobster occurs over a large geographic range covering 22–34ºS with a considerable variation in average sea surface temperatures, 17–23ºC (August) and 20–27ºC (February) (Pearce 1991) which would make the overall fishery resilient to changes in water temperature.

The pro-active management arrangements as a result of the recent low puerulus settlement have resulted in egg production being at record levels throughout the fishery as measured by the fishery-independent breeding stock surveys in 2011 and 2012. This will increase the resilience of the fishery.

Key points:

- The Western Rock Lobster occurs over a large latitudinal range 22–34ºS with a considerable variation in SST, 17–27ºC which would make the overall fishery resilient to changes in water temperature.
- Egg production was at record levels throughout the fishery in 2011 and 2012.

1.6 Ecosystem level interactions

Lozano-Montes *et al.* (2013) used a regional, ecosystem mass-balance model (Ecopath with Ecosim) to evaluate the possible changes in flows of mass and energy between the benthic and pelagic components of the Jurien Bay Marine Park in temperate Western Australia (latitude ~30ºS; area = 823 km^2). It evaluated the effects of reducing the biomass of Western Rock Lobster by changes in the abundance of the puerulus stage of lobster to simulate the reduced puerulus settlement since 2006/07. The model comprised 80 functional groups (more than 250 species) including 31 fish groups, 26 invertebrates, 11 primary producers, two marine mammals, two seabirds and eight non-living groups, and included 8 commercial fisheries. Some of the overall ecosystem metrics from the model were used to evaluate the role of the rock lobster in the ecosystem. For example, the energy pathways and trophic links were used to estimate the main sources of mortality for lobster. Commercial lobster fishing was the most important source of mortality of adult lobster, removing about 380 $kg \cdot lobster \cdot km^{-2}$ and causing around 28% of the total lobster mortality. There is also an important pre-adult spawning migration to deep water that results in a significant reduction in lobster biomass in shallow water. A simulated 50% increase in fishing effort was predicted to lead to a 35% reduction in lobster biomass. The biomass of the main lobster predators, such as octopus and some fish associated with reefs e.g. serranids (i.e. *Epinephelus homosinensis*), wrasses (i.e. *Pseudolabrus parilus*) and basses (i.e. *Psammaperca waigiensis*) were also predicted to decline by up to 15%, while the biomasses of some lobster prey (e.g. urchins, crabs and epifauna) were predicted to increase by between 10% and 20%. We investigated the consequences of fishing lobster under different levels of abundance of puerulus (average, 50% lower and 90% lower than 2005 levels) from 2005 to 2025. The model predicted that under the levels of fishing effort in 2005, a simulated reduction of 90% of puerulus biomass resulted in a ~25% reduction in biomass of adult lobster after 20 years. When fishing pressure was reduced by 50% from the 2005 level, at the same low level of puerulus settlement, the biomass of adult lobsters was predicted to increase slowly and steadily to 10% heavier in 2025 than in 2005. In general, the model predicts that the variations in lobster biomass, whether induced from the fishing or declining puerulus settlement simulated here, had relatively small effects on the biomass of the main predators and prey of lobster.

1.7 Additional (multiple) stressors

The fishery is regarded as fully exploited. The management decision rules are currently focused on maintaining the egg production above a threshold level. However there have been concerns about the status of the egg production in the northern part of the fishery near Big Bank and this area has been closed to fishing since 2009 and the stock has improved considerably. There has been a proposed change to the decision rule to establish a target harvest range at maximum economic yield that will result in reduced fishing effort and improved catch rates and egg production. This should result in a reduced stress on the stock.

The marine heatwave effects in the summer of 2010/11 resulted in water temperatures reaching 3–5ºC above average in the mid-west region of WA (Pearce *et al.* 2011). When these temperatures were combined with calm conditions in late February and early March, some localized mortality of rock lobsters was reported. However there did not appear to be a significant effect on the overall stock.

Key points:

- Fishery is regarded as fully exploited.
- Egg production in the northern part of the fishery near Big Bank has been low and this area was closed to fishing in 2009 and stock has improved.
- A target harvest range has been proposed that will result in reduced fishing effort and higher egg production and hence reduced stress on the stock.

1.8 Critical data gaps and level of uncertainty

A possible explanation about the cause of the low puerulus settlement since 2006/07 has been identified (Caputi *et al.* 2014) however this requires further years of assessment to verify. If the long-term increase in water temperature (which affects the time of breeding) and the decrease in winter storms continue then the negative effect on the puerulus settlement may continue. The potential factors that can affect the settlement may occur from before the spawning period, during the long larval period of 9-11 months that mainly occurs 100s km off the continental shelf, or during the puerulus settlement period and therefore can cover over 18 months over a large geographic area. There is also uncertainty about the long-term trend of the strength of the Leeuwin Current (Feng *et al.* 2012) and therefore its effect on the rock lobster fishery is uncertain.

1.9 Future climate scenarios (2030/2060)

There are climate change implications associated with the environmental factors (water temperature and storm activity) affecting the spawning and larval period, respectively, and hence the puerulus settlement, as both these environmental variables are showing historic long-term trends. Water temperature increases have also affected other aspects of the life history such as a decrease in size at maturity and the size of migrating lobsters; an increase in abundance of undersize and legal-size lobsters in deep water relative to shallow water; catchability, females moulting from setose to non-setose, timing of moults (Caputi *et al.* 2010). The size of the migrating lobsters is related to the water temperature about the time of puerulus settlement (about 4 years previously). These trends in water temperature and storm activity are projected to continue (Feng *et al.* 2012; Indian Ocean Climate Initiative 2012).

1.10 Management Implications

The low puerulus settlement in recent years, which included the record-low settlement in 2008/09, presented an important challenge to the management of the fishery. Settlement stayed below average in 2011/12 and 2012/13 despite egg production being very high, suggesting that some long-term environmental factor(s) was the major cause affecting the downturn in settlement. The current assessment indicates that an earlier time of breeding (due to warmer water temperatures) and decline in winter storms are the major contributing factors (Caputi *et al.* 2014).

The initial focus of management was to adjust management settings to ensure that the downturn in puerulus settlement in combination with heavy fishing pressure did not result in the egg production being driven to unsustainable levels. The early warning of the downturn in recruitment to the fishery provided the opportunity for a pro-active management response before these year-classes entered the fishery (there is 3-4 year lag between settlement and recruitment to the fishery). The management changes resulted in a significant reduction in fishing effort (ca. 40-70%) since 2008/09. These effort reductions were introduced in years when recruitment to the fishery was still good. They resulted in a significant increase in fishable biomass and very high catch rates during these two years as well as supporting the fishery during the following years with predicted low recruitment (to the fishery), which commenced in 2010/11 (Reid *et al.* 2013). The fishery management was also changed from an input control to an output-control fishery using individual transferable quotas (ITQs) in 2010/11.

While a change in the recruitment abundance is the key factor in the stock assessment, changes in other biological parameters can also affect the assessment of fisheries. Increasing water temperatures have resulted in a decrease in size at maturity and the size of migrating lobsters from shallow to deep water (Caputi *et al.* 2010). These climate change effects have been taken into account in the stock assessment model. Most fishery models generally assume that biological parameters do not change over the years (stationarity assumption) and they generally assume an average level of recruitment when making projections. These stationarity assumptions may become less robust under climate change scenarios. Long-term changes in the abundance of fish stocks, particularly declines, require an appropriate adjustment of fishing effort or catch quota, for the stocks to be managed sustainably.

The change in the size of migration due to environmental factors (Caputi *et al.* 2010) and reduced level of fishing in recent years may have altered the distribution of lobsters between management zones, Abrolhos (Zone A) and North Coastal Zone (B). The approach applied in recent years to deal with this issue has been to fix the share of the quota between the two zones based on their historic share. The formalization of this approach is currently part of the harvest strategy proposal for discussion with industry (Department of Fisheries 2013).

The Western Rock Lobster fishery provides an example of a management adaptation response to the long-term decline in puerulus settlement. Catch and fishing effort were reduced to ensure that there was a carryover of stock into the years when the poor year-classes entered the fishery and that the spawning stock remained at sustainable levels.

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2.0 Western King Prawn (*Penaeus latisulcatus*)

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2.1 The fishery

2.1.1 Commercial fishery

There are a number of multi-species prawn fisheries that target Western King Prawn in Western Australia, with the largest commercial stocks being fished in Shark Bay and Exmouth Gulf (Figure 2.1.1.1). Management of these major fisheries is based on input controls, including limited entry, seasonal and area openings and closures, moon closures and gear controls. Management arrangements are designed to keep fishing effort at levels that will maintain a sufficient spawning biomass of prawns and minimise environmental impacts on the fishery while incorporating a flexible fishing regime to optimise size and value of prawns. Stringent measures are in place to ensure that the prospects of both recruitment and growth over-fishing are avoided. The annual cycle of operation for the prawn fishery depends on the strength and timing of recruitment: The process for in-season fishing area opening/closing is dynamic and involves real-time management. Opening and closing dates vary each year, depending on environmental conditions, moon phases and the results of fishery-independent pre-season surveys that provide a catch prediction.

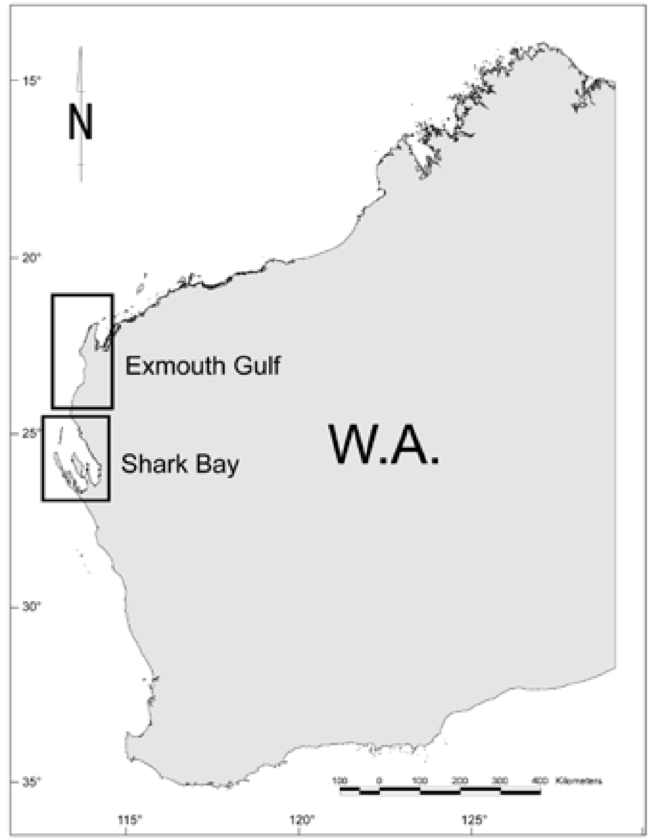

Fig. 2.1.1.1. Major Western King Prawn fisheries in Western Australia

Catch rates have been used to provide an annual index of abundance to assess individual fishery performance. Commercial monitoring and fishery-independent trawl surveys have been conducted in these fisheries to assess the status of the spawning stock and subsequent strength of recruitment along with data on the general prawn population.

The total commercial catch of Western King Prawns for WA during 2012 was 1245 t; of which 1075 t was taken in Shark Bay (18 boats), 157 t in Exmouth Gulf (6 boats) and 12 t in Broome. Boats operating in smaller fisheries around the state took negligible quantities of Western King Prawns in 2012.

2.1.2 Recreational fishery

Recreational prawn fishing mainly occurs in rivers and estuaries in the State's south-west. The most popular areas include the Swan and Canning Rivers near Perth and the Peel Inlet. The Western King Prawn and Western School Prawn are the main species taken. Controls include restrictions on type of gear, a daily bag limit and seasonal closures. There is no estimate of the take by the recreational sector but it is considered to be minor.

2.1.3 Individual fisheries

Shark Bay: Commercial landings of Western King Prawns have remained between 800 and 1300 t over the last 10 years. This is generally within the 'interim target range' of 950 to 1450 t and the species is considered to be quite resilient to exploitation. Throughout the history of this fishery, Brown Tiger Prawns have been the primary focus of management in the major fisheries with respect to sustainability, because they have been found to be the most vulnerable species to overfishing retained by this fishery (Penn and Caputi 1986; Penn *et al.* 1995). The suite of management strategies implemented to maintain the Brown Tiger Prawn stocks provide appropriate protection to the breeding stocks of Western King Prawns which because of their behavioural and reproductive characteristics are known to have a much lower vulnerability to the fishery than Brown Tiger Prawns. In addition, spatial and seasonal closures that take into account pre-season survey results, are also implemented specifically for the Western King Prawn to reduce growth and recruitment overfishing.

Exmouth Gulf: As Western King Prawns have a longer breeding period than Tiger Prawn and lower catchability (Penn 1984; Penn and Caputi 1986), they have long been considered to be less vulnerable to overfishing than Brown Tiger Prawns. However, since 2000, total landings of King Prawns only remained within the target range of 350-500 t in 2004 to 2006, whereas in all other years, they were below the target range, generally between 250 and 350 t except in 2011 and 2012 when they were 97 t and approximately 160 t respectively.

Moreover, during the last two years, total landings and recruitment levels (measured in pre-season surveys) were the lowest seen since surveys have been undertaken. Standardised catch rates (from daily logbook data), as an indicator of abundance to monitor changes in stock levels from year to year, also indicate a decline in mean catch rate since 2008. There is a need for a better understanding of the reasons behind these declines. Firstly, the lower annual landings since 2000 may, in part, reflect declining effort in the fishery as a result of changing markets trends and targeting. However, environmental factors may also be affecting King Prawn recruitment. For example, in very recent years the effect of the record high water temperatures in the Gascoyne region in early 2011 and their possible effect on the record low abundance of Western King Prawns is being examined. This, however, may not fully explain the decline in annual landings since 2000, and the combined effect of post cyclone Vance (likely change in habitat structure) and water warming may have had a detrimental impact on King Prawns.

After Cyclone Vance, the annual landings returned to normal levels for three years but have declined since 2007 and reached a very low level in 2011. A slight recovery was observed in 2012 but landings still remain very low. The King Prawn stocks will be closely monitored and if the King Prawn catches remain at the 2011 and 2012 levels then management will be reviewed with regard to potential rebuilding of stocks.

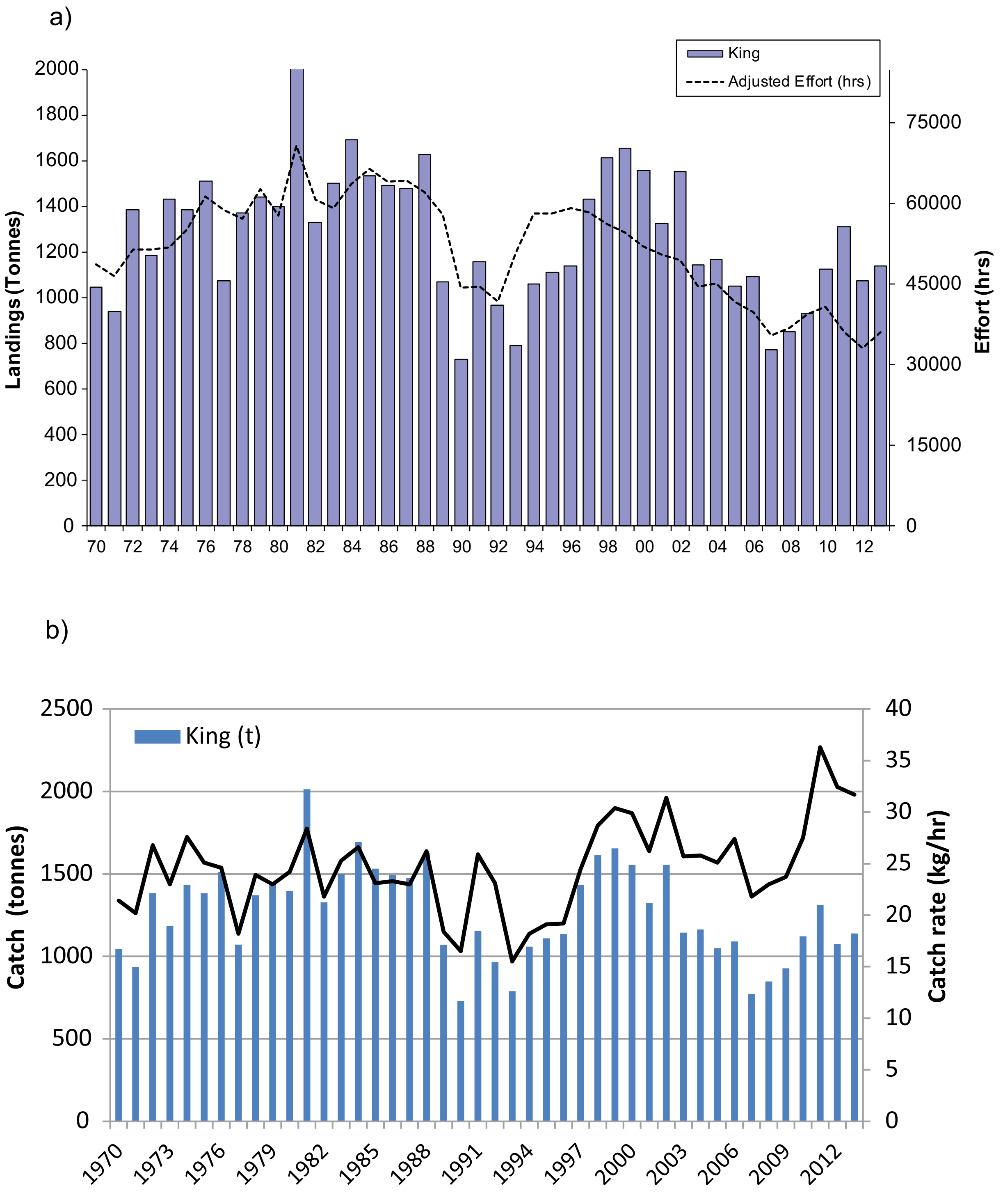

Figure 2.1.3.1. a) Effort and b) catch and catch rate of Western King Prawns for Shark Bay

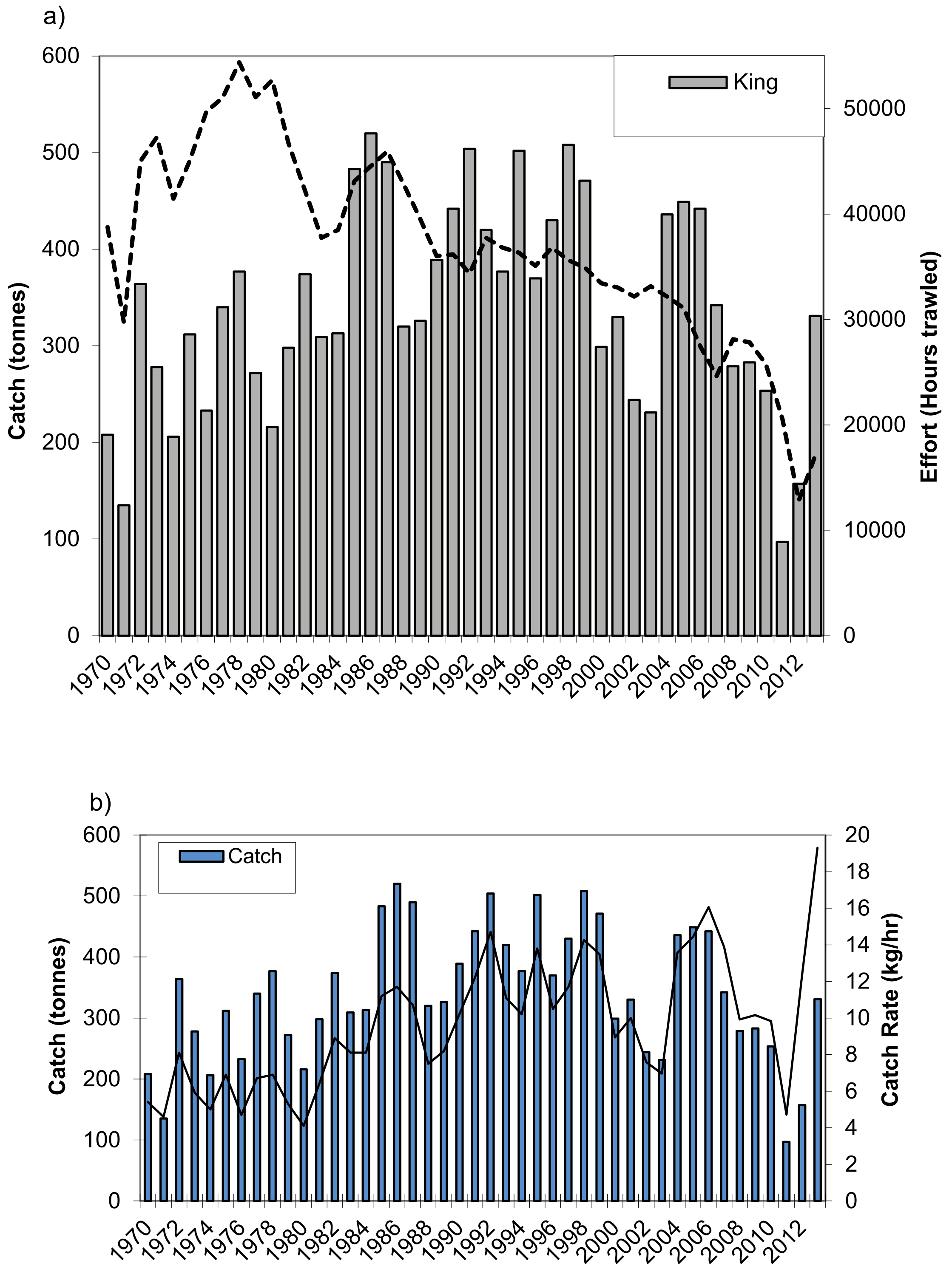

Fig. 2.1.3.2. a) Effort and b) catch and catch rate of Western King Prawns for Exmouth Gulf

Other fisheries: The Broome prawn fishery is the only other fishery in WA that targets the Western King Prawns, however, very little fishing effort (and landings) has been recorded for this fishery in the last five years. This is related to low stock abundance and subsequently low effort.

Key points:

- The harvest strategy for the Shark Bay and Exmouth Gulf prawn fisheries is based on a constant escapement policy which includes robust performance measures (i.e. catch rate based reference points) that are explicitly designed to achieve the management objectives (e.g. to avoid recruitment overfishing) via the use of control rules.
- Management controls are input controls that began as limited entry, with controls on maximum boat and trawl net sizes with maximum headrope length and the maximum fishing days (season duration). Gear controls include restrictions on the number of nets and the size of the trawl otter boards and ground chains.
- This basic management framework has been supported by a system of seasonal, spatial and temporal closures (nursery and spawning area).
- The total commercial catch of Western King Prawns for WA during 2012 was 1245 t; of which 1075 t was taken in Shark Bay (18 boats), 157 t in Exmouth Gulf (6 boats) and 12 t in Broome.

2.2 Life history

2.2.1 Life cycle, age and growth

This species can live for up to four years, although animals greater than two years are rarely caught under current harvesting practices. The larval development of *P. latisulcatus* has been described by Shokita (1984) and Dixon *et al.* (2010). During spawning the females swim near the bottom releasing the eggs, which float and usually hatch within 24 hours (Dall *et al.* 1990). After hatching from the egg the larvae called nauplii swim freely in the water column but do not feed. During the nauplii stages the larvae utilise stored food from the egg, completing a series of six moults before developing to the next larval stage (Penn and Stalker 1975). The larval development continues through several stages: protozoea, mysis and postlarvae (Figure 2.2.1.1). This process generally takes from one to three weeks before the larvae are at the stage where they can settle onto the sea floor as postlarvae.

Key parameters that affect larval development and survival are generally considered to be: temperature, salinity and food availability (Preston 1985; Jackson and Burford 2003; Bryars and Havenhand 2006; Lober and Zeng 2009). The effect of water temperature is an important factor, with faster development and higher survival in warmer water (Hudinaga 1942; Roberts *et al.* 2012). Roberts *et al.* (2012) found that the total larval period varies from 12.7 days (at 24.4°C) to 31.3 days (at 17.1°C) under constant laboratory conditions, while larval survival was greatest at 25°C (74%) and lowest at 17°C (36%), demonstrating the strong tropical affinity of this species. During this period, predators are responsible for high mortality rates of the larvae. If by this time the larvae have drifted to a suitable nursery area (i.e. shallow sand/mud flats) they will settle (at around 10 mm total length) and continue to grow into juveniles. If settlement occurs into unsuitable habitats they are likely to perish (Penn and Stalker 1979).

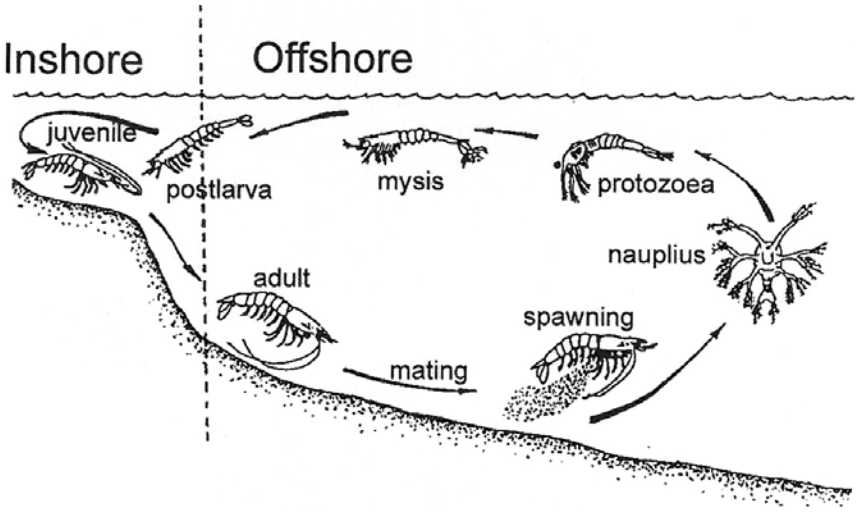

Figure 2.2.1.1. Life cycle of the Western King Prawn

In order to grow, prawns have to moult (shed their external shell). Crustacean growth is a stepwise process and moult frequency depends on the sex and size of the individual as well as the environmental factors such as food quality and quantity, population density, light, temperature and salinity (Dall *et al.* 1990). The size attained by crustaceans at any age is determined by the number of moults and the increase in size at each moult (Dall *et al.* 1990). When prawns are small they moult frequently, daily to weekly (Kangas 1999). Adults moult around every month to two months. This often coincides with the lunar cycle and a higher proportion of 'soft' or recently moulted prawns are found during the full moon period. These recently moulted individuals often remain buried in the sediment because they are much more vulnerable to predation. The exoskeleton hardens within a few days and they re-emerge at night to feed.

Due to the lack of hard parts, ageing of crustaceans by traditional age determination methods cannot be applied (Garcia and Le Reste 1981) and is generally done using modal analysis of size frequencies or tagging studies. The von Bertalanffy growth model has been used to describe crustacean growth (Garcia and Le Reste 1981; Rothlisberg 1998)

2.2.2 Distribution, habitat and environmental preferences

Penaeus latisulcatus has been reported from the Indo-West Pacific region, the Red Sea, and Arabian Gulf in the west, through Malaysia, Korea and Japan to the north and through Indonesia to New Guinea and Australia to the south (Grey *et al.* 1983). Within Australian waters *P. latisulcatus* has been reported from South Australia (SA), Western Australia (WA), Northern Territory, Queensland, and down the east coast to northern New South Wales (Grey *et al.* 1983).

Juveniles and adults exist in separate geographic areas and distinct habitats. The adults prefer mainly marine environments with bare sand or with silt and shell grit, sponges and bryozoans (King 1977; Penn 1980). Postlarval and juvenile prawns can be found on shallow tidal flats with sand or mud sediments, which are often backed by mangroves (Kangas and Jackson 1998). Because there is very little freshwater input the inshore areas have salinities higher than seawater (hypersaline waters). The juveniles of Western King Prawns prefer this habitat unlike most species of prawns, which prefer estuarine conditions where seawater is diluted by freshwater. The juveniles are found inshore, but can be found around shallow waters in the northern part of the fishery where they remain in shallow water nursery grounds for three to six months with the adults moving offshore to spawn. This species is generally found in coastal waters down to a maximum depth of about 80 m. Juveniles bury during the day into the substrate, which is generally shallow sandy banks (Penn and Stalker 1979; Kangas 1999; Kangas and Dixon 2008). *Penaeus latisulcatus* uses the sand as a defensive mechanism by burying itself to avoid predators (Tanner and Deakin 2001). *Penaeus latisulcatus* is highly sensitive to light and is nocturnal and their activity is influenced by lunar cycles as well as temperature (Penn 1980). This nocturnal behaviour makes them less vulnerable to natural predators.

2.2.3 Predators and prey

Known predators of penaeids include squid, cuttlefish, mantis shrimp, crabs, rays, birds, reptiles, dolphins, and fish (Dall *et al.* 1990).

Penaeus latisulcatus are mainly detritus feeders, consuming benthic fauna and organic debris (Wassenberg and Hill 1987). They are nocturnal, burying themselves during the day and emerging at night to feed. Juvenile penaeid prawns feed on copepods, decapods ostracods, gastropods, diatoms, filamentous algae and small protozoa diatoms, algae, and seagrass (O'Brien 1994). The plant requirements of juveniles changes as they grow, from diatoms to filamentous algae to seagrass (O'Brien 1994). Smaller juveniles consume more copepods than larger juveniles (O'Brien 1994).

2.2.4 Recruitment

Size is the major factor triggering movement of juvenile penaeid prawns onto the fishing grounds (Penn 1980; Courtney *et al.* 1995). Temperature and salinity can affect recruitment with catch rates of penaeid prawns being negatively correlated with salinity and positively correlated with temperature (Courtney *et al.* 1995).

2.3 Effects of climate change

The production of Western King Prawns in the minor trawl fisheries (Onslow, Nickol Bay, Broome and Kimberley) along the north-west coast has seen a decline over the last five years and whilst much of the decline is likely to be attributed to lower effort in most of these fisheries, changes in the environmental conditions may also be contributing but these factors are not well understood. Similarly landings of Western King Prawns in Exmouth have seen a declining trend over the last few years, below the long term averages. Only in Shark Bay have the landings been within target ranges in general.

By 2030 waters around Australia are likely to warm by 1-2ºC and 2-3ºC by 2070, and there is likely to be a weakening of the Leeuwin Current (Hobday *et al.* 2008). In the Northern Fisheries Hobday *et al.* (2008) has suggested that extended periods of elevated temperatures in shallow estuarine waters might affect the distribution of prawn nursery habitats, such as seagrasses.

Growth, survival and abundance of various life stages of penaeid species are sensitive to extreme temperatures and shift in temperature regimes (Hobday *et al.* 2008). Hobday *et al.* (2008) has suggested that several studies have shown that high water temperatures can cause decreased growth and survival of penaeid species. Increased cyclones are also likely to affect prawns stocks (Hobday *et al.* 2008). The effects on seagrass and mangrove communities can be significant (Hobday *et al.* 2008).

2.3.1 Leeuwin Current and water temperature

Changes to the Leeuwin Current are likely to have an important impact on fisheries in Western Australia. The Leeuwin Current may weaken slightly which would result in cooler temperature along the southern coast: however warming of the surface waters may result so the overall outcome in relation to subsurface temperature is uncertain (Hobday *et al.* 2008).

Earlier work during the 1980s and 1990s relating Western King Prawn (*Penaeus latisulcatus*) catches and Leeuwin Current (LC) strength showed a very good correlation (Lenanton *et al.* 1991; Caputi *et al.* 1996) with higher catches related to stronger LC flows during the March to June period. This was considered to be due to strong LC causing an extension of the peak in the annual temperature cycle to match the main March to June fishing season at a time when King Prawns are recruiting onto fishing trawl grounds from the nursery and/or shallow inshore areas. Higher catches were thought to be related to improved catchability, growth and survival (Caputi *et al.* 1996).

Although Western King Prawns are distributed widely within both temperate and tropical regions it is found in higher abundance in semi-tropical and temperate regions and it may be that warmer temperatures may not be optimal for the species. The juveniles have a fairly high temperature tolerance range and are considered fairly resilient.

2.3.2 Rainfall

Juvenile prawns are good osmoregulators (Dall 1981). However, juvenile Western King Prawns prefer hypersaline (higher salinities than seawater) conditions and therefore higher rainfall and outflows onto the shallow nursery areas could affect juvenile survival and movement away for lowered salinity areas.

2.3.3 Cyclone activity

Although Western King Prawn juveniles prefer sandy/muddy substrates, these could be disturbed and re-distributed during cyclone events which could affect prawn populations.

2.4 Sensitivity to change

Western King Prawns are considered to be reasonably robust to change with fairly broad tolerance levels for most environmental changes. However their sensitivity assessment indicated high sensitivity level based on the 12 sensitivity attributes which was mainly due to the phenology attributes (Part 1, Appendix 4).

2.5 Resilience to change

Western King Prawns are considered to be fairly resilient to change but the current observed lower abundance in some northern areas may continue in the longer term.

2.6 Ecosystem level effects

Fishing for Western King Prawns is considered low risk to the trophic structures of these regions. Although harvest rates are relatively high, such species have very high natural mortality rates and make up only a relatively small proportion of the total biomass on the trawl grounds.

Predators of prawns have to be opportunistic due to the natural variations in prawn populations, consequently, given the small areas and time periods now fished it is considered unlikely that the commercial take of prawns impacts significantly on other trophic levels.

2.7 Additional stressors

The level of fishing effort in WA prawn fisheries is considered to be sustainable under current environmental conditions. If stock abundance is reduced due to climate change then the level of fishing effort would need to be reviewed.

2.8 Critical data gaps and level of uncertainty

Understanding the environmental effects on spawning and recruitment cycle and water circulation patterns if these conditions change is a critical gap. Long-term monitoring of the recruits and spawning stock occurs in the Shark Bay and Exmouth Gulf prawn fisheries but does not occur for the more northern minor prawn fisheries. Understanding the environmental effects on King Prawns in Exmouth and the northern stocks represents a key gap.

2.9 Future climate scenarios (2030/2060)

The strength of the Leeuwin Current and/or water temperature has been shown to influence King Prawn recruitment in Shark Bay. While a reduction of the Leeuwin Current transport (strength) by 15-20% from 1990s to 2060s is projected, the Current has experienced a strengthening trend during the past two decades. This indicates that natural decadal climate variations may influence short-term climate projection, e.g. 2030s. Historic and projected changes in water temperature rise are also likely to affect prawn recruitment. Prawn recruitment in Shark Bay has been shown to be positively related to water temperature and the recent heat wave temperatures also resulted in a good recruitment.

2.10 Management Implications

The effect of Leeuwin Current and water temperature trends on the King Prawn recruitment in Shark Bay and Exmouth needs to be monitored as is currently undertaken using the preseason surveys. This provides the basis for early intervention of management in case there is a downturn in recruitment.

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3.0 Brown Tiger Prawn (*Penaeus esculentus*)

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3.1 The fishery

3.1.1 Commercial fishery

There are a number of multi-species prawn fisheries that target the Brown Tiger Prawn in Western Australia, with the largest commercial stocks being fished in Shark Bay and Exmouth Gulf (Figure 3.1.1.1). Management of these major fisheries is based on input controls, including limited entry, seasonal and area openings and closures, moon closures and gear controls. Management arrangements are designed to keep fishing effort at levels that will maintain a sufficient spawning biomass of prawns and minimise environmental impacts on the fishery while incorporating a flexible fishing regime to optimise size and value of prawns. Stringent measures are in place to ensure that spawning stock levels for Brown Tiger Prawns are maintained at adequate levels and the prospects of both recruitment and growth over-fishing are avoided. The annual cycle of operation for the prawn fishery depends on the strength and timing of recruitment: The process for in-season fishing area opening/closing is dynamic and involves real-time management. Opening and closing dates vary each year, depending on environmental conditions, moon-phases and the results of fishery-independent pre-season surveys that provide a catch prediction.

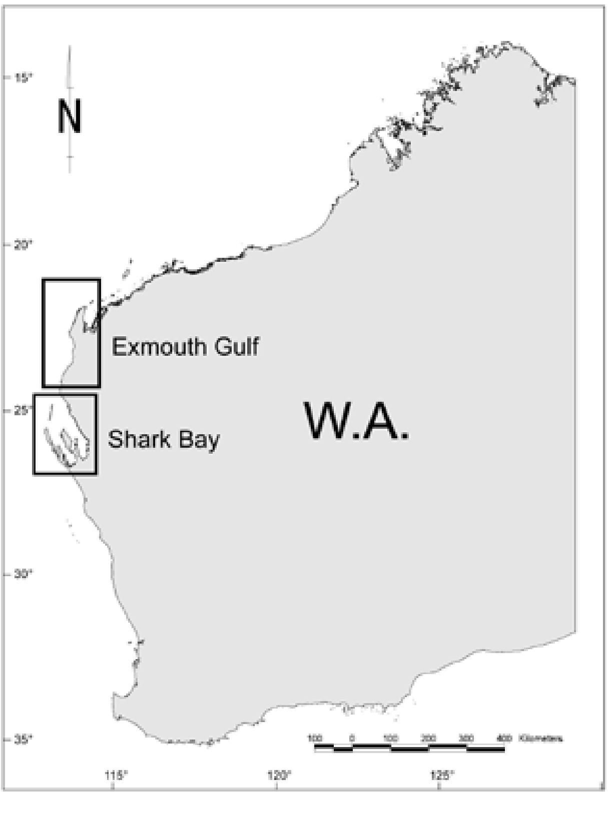


Figure 3.1.1.1. Major Brown Tiger Prawn fisheries in Western Australia

Catch rates have been used to provide an annual index of abundance to assess individual fishery performance. Commercial monitoring and fishery-independent trawl surveys have been conducted in these fisheries to assess the status of the spawning stock and subsequent strength of recruitment along with data on the general prawn population.

The total commercial catch of Brown Tiger Prawns for WA during 2012 was 544 t; of which 494 t was taken in Shark Bay (18 boats), 46 t in Exmouth Gulf (6 boats) and 4 t in the Kimberley prawn fishery. Boats operating in smaller fisheries around the state took negligible quantities in 2012.

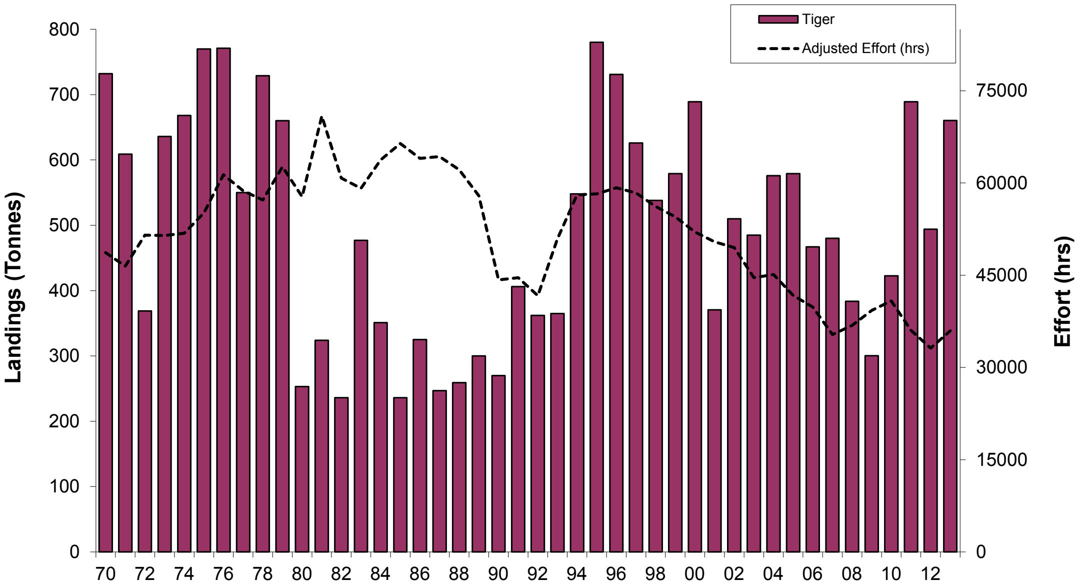
3.1.2 Recreational fishery

There is no recreational fishery for Brown Tiger Prawns.

3.1.3 Individual fisheries

Shark Bay: Commercial landings of Brown Tiger Prawns have been fluctuating within its target catch range (400 to 700 t) in the majority of years over the past couple of decades. Since the 1980s, Brown Tiger Prawns have been the primary focus of management in the major fisheries with respect to sustainability, because they have been found to be the most vulnerable species to overfishing retained by this fishery (Penn and Caputi 1986; Penn *et al.* 1995). A suite of management strategies are implemented to maintain the Brown Tiger Prawn stocks and provide appropriate protection to the breeding stock.

a)



b)

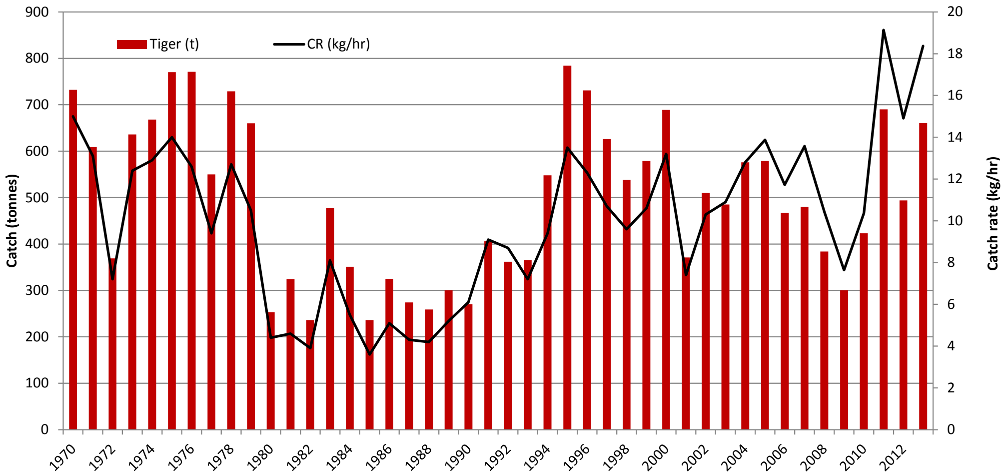


Figure 3.1.3.1. a) Effort and b) catch of Brown Tiger Prawns for Shark Bay

Exmouth Gulf: The Brown Tiger Prawn landings in 2012 were the lowest recorded in this fishery and were as a result of very low recruitment levels in 2012 and highly conservative fishing to ensure adequate breeding stock remained. The reasons for the low levels of recruitment in 2012 are not well understood but it is believed that the environmental conditions were the major cause as the spawning stock in 2011 was very good. The low spawning stock levels observed in 2012 have resulted in moderate recruitment over the history of the fishery and therefore recruitment should not be impaired under normal environmental conditions (i.e. no heat wave, negative cyclone impacts, or habitat damage).

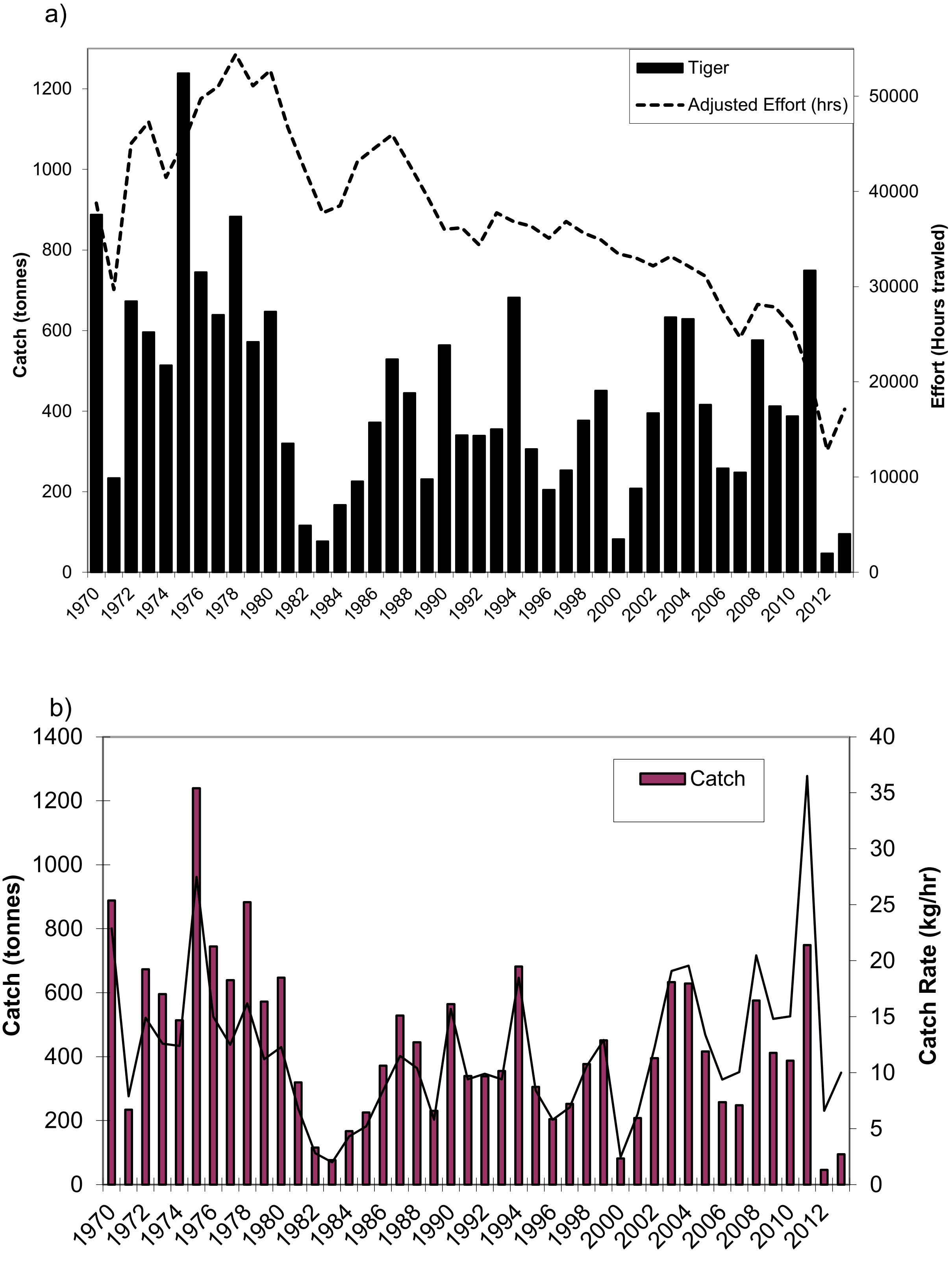


Figure 3.1.3.2. a) Effort and b) catch of Brown Tiger Prawns for Exmouth

Other fisheries: The Kimberley prawn fishery is the only other fishery that retained small quantities of Brown Tiger Prawns but Banana Prawns are the target species in this fishery.

Key points:

- The harvest strategy for the Shark Bay and Exmouth Gulf prawn fisheries is based on a constant escapement policy which includes robust performance measures (i.e. catch rate based reference points) that are explicitly designed to achieve the management objectives (e.g. to avoid recruitment overfishing) via the use of control rules.
- Management controls are input controls that began as limited entry, with controls on maximum boat and trawl net sizes with maximum headrope length and the maximum fishing days (season duration). Gear controls include restrictions on the number of nets and the size of the trawl otter boards and ground chains.
- This basic management framework has been supported by a system of seasonal, spatial and temporal closures (nursery and spawning area).
- The total commercial catch of Brown Tiger Prawns for WA during 2012 was 544 t; of which 494 t was taken in Shark Bay (18 boats), 46 t in Exmouth Gulf (6 boats) and 4 t in the Kimberley prawn fishery.

3.2 Life history

3.2.1 Life cycle, age and growth

The species can live for over two years although animals greater than two years are rarely caught under current harvesting practices. Brown Tiger Prawns become mature at six to seven months of age at a size around 25 – 28 mm carapace length (Penn and Stalker 1979). Brown Tiger Prawns spawn in the deeper waters and more offshore waters of Exmouth Gulf (Penn and Caputi 1986) and Shark Bay. The planktonic larvae move through several naupliar, protozoeal, mysis larval stages at which time if they have been transported into structured habitats in shallow coastal areas, as postlarvae they settle on beds of seagrass and algae two to four weeks after the eggs are released from the females (Dall *et al.* 1990; Haywood *et al.* 1995; Liu and Loneragan 1997).

Although spawning females are found between June to end of summer (Penn and Caputi 1986) the key spawning period in Shark Bay is June/July and in Exmouth Gulf is between August and October (White 1975; Penn 1980; Penn and Caputi 1986). At spawning the females swim near the bottom releasing the eggs, which float and usually hatch within 24 hours. After hatching from the egg the larvae, called nauplii, swim freely in the water column but do not feed. During the nauplii stages the larvae utilise stored food from the egg, completing a series of six moults before developing to the next larval stage (Penn and Stalker 1979). The larval development continues through several stages: protozoea, mysis and postlarvae. During this period, predators are responsible for high mortality rates of the larvae.

Active vertical migration during the pelagic larval stage in combination with transport by water currents is the most probable method bringing post larvae to their nursery areas (Penn 1975; Dall *et al.* 1990). If the larvae have drifted to a suitable nursery area (i.e. inshore structured habitats which fringe sand flats) they will settle (at around 10 mm total length) and continue to grow into juveniles. If settlement occurs in unsuitable habitats they are likely to perish (Penn and Stalker 1979). Juvenile Brown Tiger Prawns take on the colour of the habitat they are living on, and this colouration provides camouflage until the juveniles leave the weed beds (Penn and Stalker 1979).

Growth is a stepwise process and moult frequency depends on the sex and size of the individual as well as the environmental factors such as food quality and quantity, population density, light, temperature and salinity (Dall *et al.* 1990). The size attained by crustaceans at any age is determined by the number of moults and the increase in size at each moult (Dall *et al.* 1990). When prawns are small they moult frequently, daily to weekly (Kangas 1999). Adults moult around every month or two. This often coincides with the lunar cycle and a higher proportion of 'soft' or recently moulted prawns are found during the full moon period. These recently moulted individuals often remain buried in the sediment because they are much more vulnerable to predation. The exoskeleton hardens within a few days and they re-emerge at night to feed.

Due to the lack of hard parts, ageing of crustaceans by traditional age determination methods cannot be applied (Garcia and Le Reste 1981) and is generally done using modal analysis of size frequencies or tagging studies.

3.2.2 Distribution, habitat and environmental preferences

Penaeus esculentus is generally regarded as an endemic Australian species. They have a distribution around the northern coast of Australia and whilst the electrophoretic study on this species (Mulley and Latter 1981) found no genetic differences amongst regions, there are a large number of functionally independent stocks around Australia (Kailola *et al.* 1993)

Adult Brown Tiger Prawns are generally found in marine coastal waters down to approximately 60 m but a few have been recorded to a depth of 200 m (Grey *et al.* 1983). They tend to be found mostly in sediments with high mud content (Gribble *et al.* 2007) and are therefore most commonly captured by trawlers in mud or sandy mud substrates at 10 – 20 m depth (Grey *et al.* 1983). Most spawning females are found in 13-20 m of water (Penn 1988, Penn *et al.* 1995).

Juveniles occupy shallow waters associated with seagrass/algal communities that forms the main juvenile habitat for this species (Kenyon *et al.* 1997) and also explains their distinctive colouration. A strong association with structured habitats has been observed for this species (Haywood *et al.* 1995, Kenyon *et al.* 1995, Loneragan *et al.* 1998, Loneragan *et al.* 2013) although Brown Tiger Prawn larvae do not discriminate between different types of seagrass when they settle (Loneragan *et al.* 1998).

Adult *Penaeus esculentus* show limited regulation below isosmotic point of 30 ppt with a lower lethal limit of 10 ppt in studies completed by Dall (1981). Adaptation above 30 ppt was much better tending to flatten at 50 ppt indicating this species could potentially adapt to higher salinities (Dall 1981).

3.2.3 Predators and prey

Known predators of penaeids include squid, cuttlefish, mantis shrimp, crabs, rays, birds, reptiles, dolphins, and fish (Dall *et al.* 1990). Brown Tiger Prawns feed primarily at night and their diet includes small molluscs, crustaceans and polychaete worms (Wassenburg and Hill 1987; Dall *et al.* 1991). The natural diet of juveniles includes copepods, decapods ostracods, gastropods, diatoms, filamentous algae and small protozoa diatoms, algae, and seagrass (O'Brien 1994a).

3.2.4 Recruitment

Environmental factors have been identified as a major cause of variation in penaeid recruitment (Garcia and Le Reste 1981). Rainfall, temperature and salinity have been shown to affect recruitment of *P. esculentus* – being negatively correlated with salinity and positively correlated with temperature (Penn and Caputi 1986; Penn *et al.* 1995; Courtney *et al.* 1995). Juvenile *P. esculentus* can withstand a range of temperatures and salinities, though when exposed to extreme temperatures (15 and 35 °C) and salinities (5‰ and 55‰) there are high mortality rates (O'Brien 1994b). In Exmouth Gulf, cyclones have been shown to have both a negative and positive effect on recruitment depending on the timing, location and severity of the cyclone (Penn and Caputi 1985). Loneragan *et al.* (2013) describe a strongly negative impact on recruitment of *P. esculentus* in Exmouth Gulf after the destruction of inshore nursery areas by severe tropical Cyclone Vance in 1999.

The migration of prawns from nursery areas onto the fishery grounds is size-dependent and commences when prawns attain 25-27 mm (Penn and Caputi 1986; Penn 1988; Courtney *et al.* 1995). Size recruitment for *P. esculentus* is approximately 25-27 mm CL. Recruitment timing for *P. esculentus* in Shark Bay and Exmouth Gulf can vary between years, but generally takes place over 3 – 4 months between February and May (Penn and Caputi 1986).

3.3 Current impacts of climate change

Cyclonic activity and water temperature have been shown to affect Tiger Prawn recruitment in Exmouth Gulf and Shark Bay.

3.3.1 Temperature

Brown Tiger Prawns occur from Shark Bay north but if climate change results in warmer waters further south there could be some range extension of this species provided there is the appropriate habitat. The juveniles have a fairly high temperature tolerance range and are considered fairly resilient.

The heatwave during summer of 2010/11 may have had a positive effect on the recruitment for 2011 but may have influenced the poor recruitment of 2012. This may have been a direct effect on the spawning of 2011 or an indirect effect via its impact on the seagrass habitat.

3.3.2 Rainfall

Juvenile prawns are good osmoregulators (Dall 1981). However, juvenile Brown Tiger Prawns prefer hypersaline (higher salinities than seawater) conditions and therefore higher rainfall and outflows onto the shallow nursery areas could affect juvenile survival and movement away for lowered salinity areas.

3.3.3 Cyclone activity

In Exmouth Gulf, cyclones have had significant negative and positive effects on recruitment depending on the timing, location and severity (Penn and Caputi 1985). In some cases nursery areas have been adversely affected by severe cyclones (Loneragan *et al.* 2013). Juvenile Brown Tiger Prawns are associated with structured habitats and their survival and recruitment success has been correlated with the amount of structured habitat available in nursery areas.

3.4 Sensitivity to change

Brown Tiger Prawns are considered to be reasonably robust to change with fairly broad tolerance levels for most environmental changes. However because of its sensitivity to environmental effects it has been ranked as having a high sensitivity to climate change (Appendix 4).

3.5 Resilience to change

Brown Tiger Prawns are considered to be fairly resilient to change but the current observed lower abundance in some northern areas that may be associated with the marine heat wave may be an indirect effect on the habitat and may continue in the longer term.

3.6 Ecosystem level effects

Fishing for Brown Tiger Prawns is considered low risk to the trophic structures of these regions. Although harvest rates are relatively high, such species have very high natural mortality rates and make up only a relatively small proportion of the total biomass on the trawl grounds. Predators of prawns have to be opportunistic due to the natural variations in prawn populations, consequently, given the small areas and time periods now fished it is considered unlikely that the commercial take of prawns impacts significantly on other trophic levels.

3.7 Additional stressors

The heatwave during summer of 2010/11 may have influenced the poor recruitment of 2012 as a result of a direct effect on the spawning of 2011 or an indirect effect via its impact on the seagrass habitat.

3.8 Critical data gaps and level of uncertainty

Understanding the environmental effects on spawning and recruitment cycle and water circulation patterns if these conditions change is a critical gap. Long-term monitoring of the recruits and spawning stock occurs in the Shark Bay and Exmouth Gulf prawn fisheries but does not occur for the more northern minor prawn fisheries. The effect of environmental conditions on seagrass habitat could be a critical gap that requires long-term cost-effective monitoring.

3.9 Future climate scenarios (2030/2060)

The most important factors likely to impact Brown Tiger Prawns as a result of climate change include changes in temperature, ocean currents, winds (cyclones), rainfall, sea level, ocean chemistry and extreme weather conditions (Hobday *et al.* 2008).

The number and intensity of cyclones have remained steady historically, however they are projected to decrease in number but increase in intensity with a shift further south that is associated with increasing water temperatures (IOCI 2012). The increase in intensity could negatively affect the seagrass habitat as occurred with Cyclone Vance which affected the recruitment for a couple of years. The shift south in cyclones may result in more cyclones affecting Shark Bay which currently experiences little cyclone activity. This may affect Tiger Prawn recruitment as currently occurs in Exmouth.

Historic and projected increases in water temperature rise are also likely to affect prawn recruitment. Tiger Prawn recruitment in Shark Bay has been shown to be positively related to water temperature and the recent heat wave temperatures also resulted in a good recruitment. Water temperature in Exmouth is about 2ºC warmer than Shark Bay and so positive correlation with recruitment was observed, although there was a good recruitment during the heat wave event of 2010/11. Therefore warmer temperatures in Shark Bay may be beneficial to recruitment.

3.10 Management Implications

The effect of cyclones and water temperature trends on the Tiger Prawn recruitment in Shark Bay and Exmouth needs to be monitored as is currently undertaken using the preseason surveys. This provides the basis for early intervention of management in case there is a downturn in recruitment.

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4.0 Saucer Scallop (*Amusium balloti*)

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4.1 The fishery

4.1.1 Commercial fishery

The largest scallop fishery in WA is in Shark Bay, followed by the Abrolhos Islands and Mid-West trawl fishery. In Shark Bay, scallops are retained by a dedicated scallop fleet as well as prawn trawlers whilst in the Abrolhos, only a dedicated scallop fleet fishes for scallops. The scallop and prawn fleets use low-opening otter trawls.

Lesser quantities are landed in the South West and South Coast trawl fisheries and negligible quantities are landed as byproduct in some other minor prawn trawl fisheries

4.1.2 Recreational fishery

There is no recreational fishery for Saucer Scallops in WA.

4.1.3 Individual fisheries

Shark Bay: The Shark Bay fishery is the most valuable scallop fishery (AUD 10-57 million). This species is short-lived, has fast growth and highly variable recruitment which is primarily environmentally driven. There are 11 A Class licences that target scallops and account for approximately 70% of the catch and 18 B Class boats, which primarily fish for prawns (in the Shark Bay Prawn Managed Fishery) with scallops a secondary target species. A catch share allocation for scallops provides for 70% for A Class boats and 30% for B Class boats.

Annual scallop surveys, conducted between October and December, have been undertaken since 1983, and provide size and abundance information from over 80 trawl sites within the bay. These data are used to determine an index of recruitment strength during that year (individuals derived from the current years spawning). They also provide an index of the size of the residual stock (older scallops remaining from the year before and possibly 2 years before, noting the life span is 2-3 years) and together provide the basis for predicting the catch the following year. The annual survey also provides information on scallop size and abundance and distribution patterns that enable the season fishing arrangements of the fishery to be determined that take into account fishing scallops at an optimum size.

The scallop stock abundance in Shark Bay in 2012 and 2013 is extremely low, mainly attributed to anomalous environmental conditions from late 2010. This has prompted a conservative management approach with a closure of the fishery in 2012 and 2013 (Figure. 4.1.3.1).

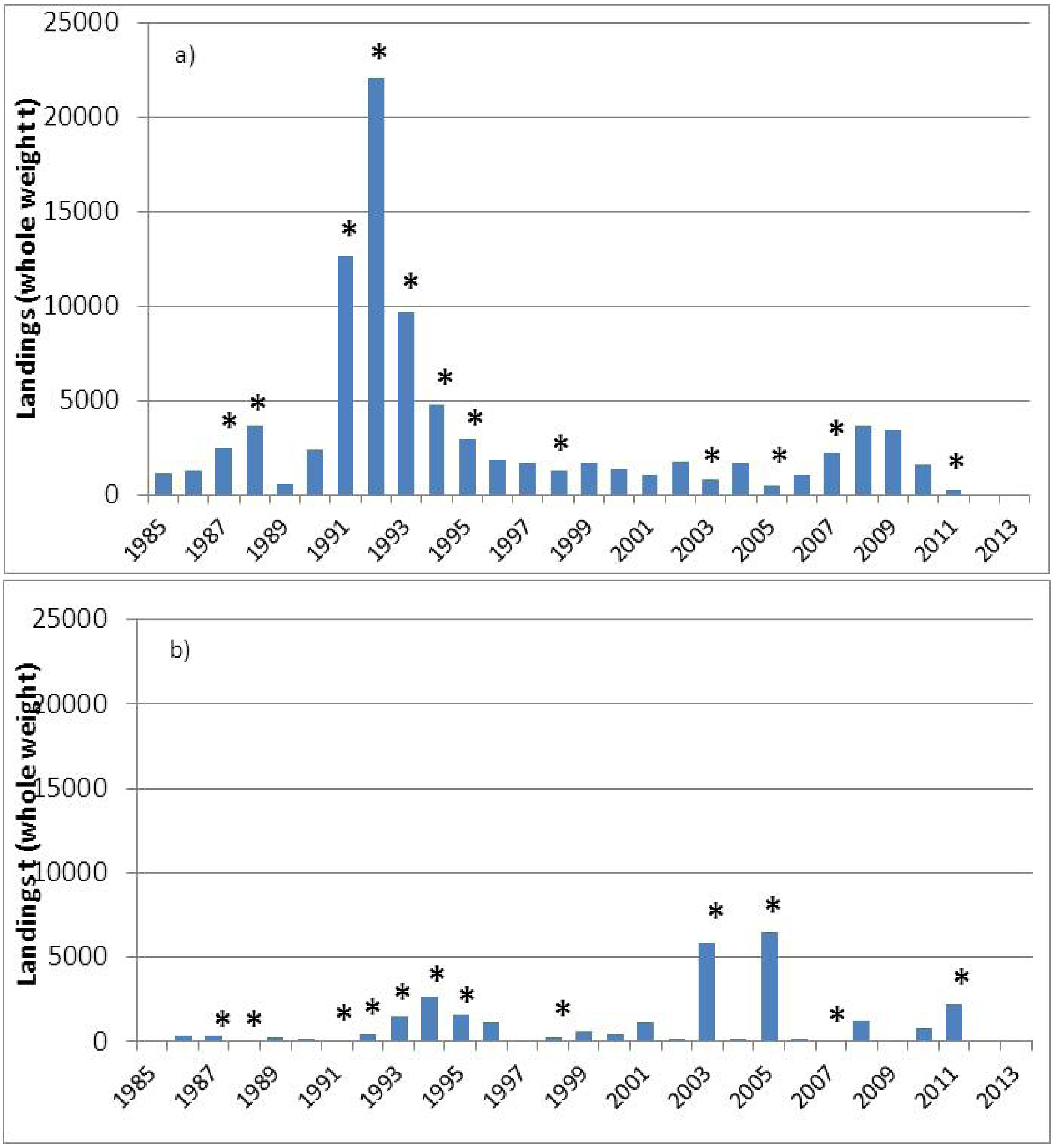

Figure 4.1.3.1. Time series of (a) Shark Bay (including Denham Sound) and (b) Abrolhos scallop catches (with ENSO events in the previous year indicated).

Abrolhos Islands: The Abrolhos Islands and Mid-West Trawl Fishery operates under an input control system, with a maximum total net headrope capacity restriction, specified net mesh size, along with seasonal closures and significant spatial closures protecting all near-shore waters and sensitive reef areas. Currently there are 9 boats licensed to fish for scallops. Bycatch reduction devices (grids) to release large species are fully implemented. The fishery also operates to a catch rate target of 250 kg meat weight per 24 hours trawling to cease fishing.

The Abrolhos Islands and mid-West trawl fishery also has experienced high variability in annual settlement and resultant scallop catches but as with the Shark Bay scallop fishery, the 2011 fishing season produced significantly less scallop meat than had been predicted from the annual pre-season survey. In 2011 and 2012 the pre-season scallop survey indicated low abundances with almost no scallops found in 2012, so that this fishery was closed for 2012 and will not be open for the 2013 season (Figure. 4.1.3.1).

Other fisheries: Scallops are the main target species caught in the South Coast and South West multi-species trawl fisheries but in most years the quantities are low with only a few operators. In 2012 only 32 t meat weight (157 t whole weight) was caught from these fisheries which constituted all the scallops caught in WA in this year.

Key points:

- Principal management tools to protect breeding stock involves controlling fishing effort and ceasing fishing to a target catch rate as well as seasonal and spatial closures.
- The major fisheries of Shark Bay and the Abrolhos Islands remained closed for 2012 and 2013 due to very low scallop abundance. Commercial catch of Saucer Scallops for WA during 2012 was low with 24 t meat weight (118 t whole weight (in the South Coast trawl fishery and 8 t meat weight (40 t whole weight) in the South West Trawl fishery.
- The Shark Bay and Abrolhos Islands scallop fisheries appear to have been significantly impacted by the summer heat waves over 2010/11 to 2012/13.

4.2 Life history

4.2.1 Life cycle, age and growth

Early growth of this species is rapid and although Saucer Scallops have been recorded reaching 140 mm in length and living up to 3-4 years (Heald and Caputi 1981) most appear to live no more than two years and usually attain a maximum size around 115 mm (Heald 1978; Dredge 1988).

The reproductive cycle in Shark Bay scallop stocks is generally between April/May through to December (Joll and Caputi 1995a) whilst in the southern scallop fisheries it is generally between August/September to January. Given the energetic demands of reproduction, food availability for adults as well as larvae may be an important factor in determining the timing of the reproductive cycle (Joll and Caputi 1995a). The timing of spawning is crucial to ensure temperatures and concentrations of phytoplankton are adequate for larval development (Cragg 2006). Changes in environmental patterns may however, lead to different periods of the spawning cycle having a greater importance as contributors to overall recruitment (Joll and Caputi 1995a).

Saucer Scallops are broadcast spawners, releasing their eggs and sperm into the surrounding waters for fertilisation to occur in the water column (Kailola *et al.* 1993). During this period larvae are susceptible to being passively transported by tides and currents whilst in the water column. Larval survival is affected by food availability and predator abundance, and the length of the larval period (assuming survival is enhanced by reducing time in the plankton community) can also be influenced by water temperature. The life cycle for the Saucer Scallop is depicted below.

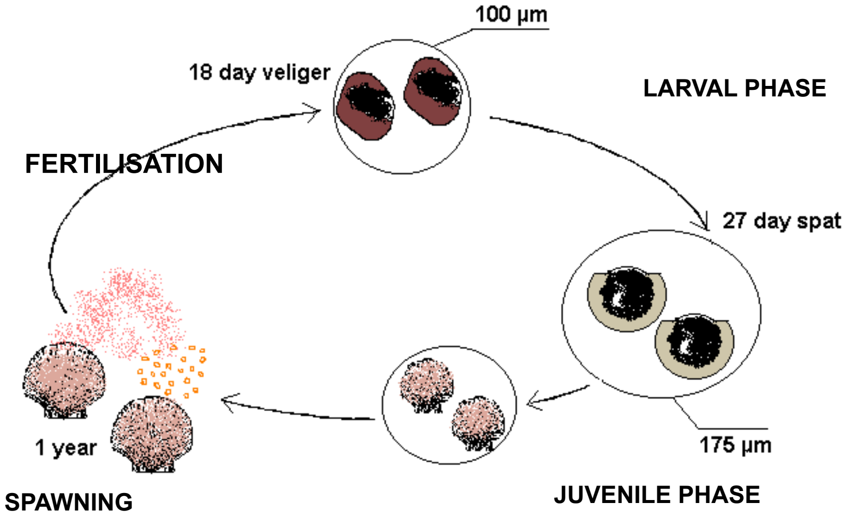

Figure 4.2.1.1. Life cycle of the Saucer Scallop, *Amusium balloti*.

The planktonic, larval phase of the Saucer Scallop lasts between 12 and 24 days (Rose *et al.* 1988). Success of the larval phase appears to be governed by prevailing oceanographic events, which greatly influence settlement locations and subsequent recruitment patterns. The predominant oceanographic influence along the WA coast is the Leeuwin Current (LC), a southward flowing current of relatively warm, tropical water that is low in salinity (Joll and Caputi 1995b). While the environmental mechanisms relating to the recruitment variability of *A. balloti* are not fully understood, it appears that in years of strong LC (that are associated with La Niña events and result in warmer waters) there is an increased likelihood that larvae survival is lower and/or they are flushed away from areas of suitable recruitment habitat.

Growth of the shell is allometric with the height of the shell growing more rapidly than length. Growth of these new recruits is rapid with scallops reaching the size of sexual maturity within one year and at this size (>90 mm shell length) they are suitable for commercial harvest. Daily growth rings are visible in juvenile scallops (Joll 1988) but become difficult to read in mature animals (older than 8-9 months).

Seasonal growth in bivalves, including Pectinidae, is influenced by the interaction of a number of environmental variables particularly water temperature and food supply (Broom and Mason 1978; Bayne and Newell 1983). Food availability has often been found to exert a greater influence on growth rate than temperature in temperate species (Orensanz 1984). In Shark Bay, a slower growth rate is observed during the spawning months (April to July), which is likely due to energy diverted into reproduction (Rogers *et al.* 1983), although lower temperatures may also play a part.

Seasonal variation in the size and condition of the adductor muscle for *A. balloti* has been observed in Shark Bay (Joll and Caputi 1995a) and much of this variation is related to the reproductive cycle. The adductor muscle size also varies according to the shell size of the scallop. Short-term variation in somatic tissue weight or energy content is a more sensitive indicator of growth fluctuations within the individual than a change in shell dimensions, because unlike the soft tissue the shell cannot shrink rapidly under adverse environmental conditions (MacDonald and Thompson 1985).

4.2.2 Distribution, habitat and environmental preferences

Amusium balloti is distributed on the east and west coast of Australia and in New Caledonia (Kailola *et al.* 1993). The western population of *A. balloti* has a distribution spanning most of the WA coast, having been recorded from Broome in the north to Israelite Bay in the south (Figure 4.2.2.1). The greatest numbers are found in Shark Bay and around Abrolhos Islands (Joll 1989). The eastern population of *A. balloti* occurs from Innisfail, Queensland to Jervis Bay, New South Wales (Kailola *et al.* 1993). Therefore, the distribution of the eastern and western populations of Saucer Scallops are separated across the northern Australian waters thus resulting in two separate populations.

Although *A. balloti* has an extensive distribution, it tends to be restricted to areas of bare sand in the more sheltered environments found in the lee of islands and reef systems. The species has been reported occurring in depths from 10–75 m in discrete beds, up to 15 km in length, at densities of up to 1 per m^2 (Dredge 1988; Kailola *et al.* 1993). Joll (1994) recorded average densities in Shark Bay of $2/m^2$ with peak densities of $7/m^2$. Salinity is another ecological factor that clearly limits distribution, but there have been few studies of distribution in relation to salinity or of the salinity tolerance of scallop species (Brand 2006).

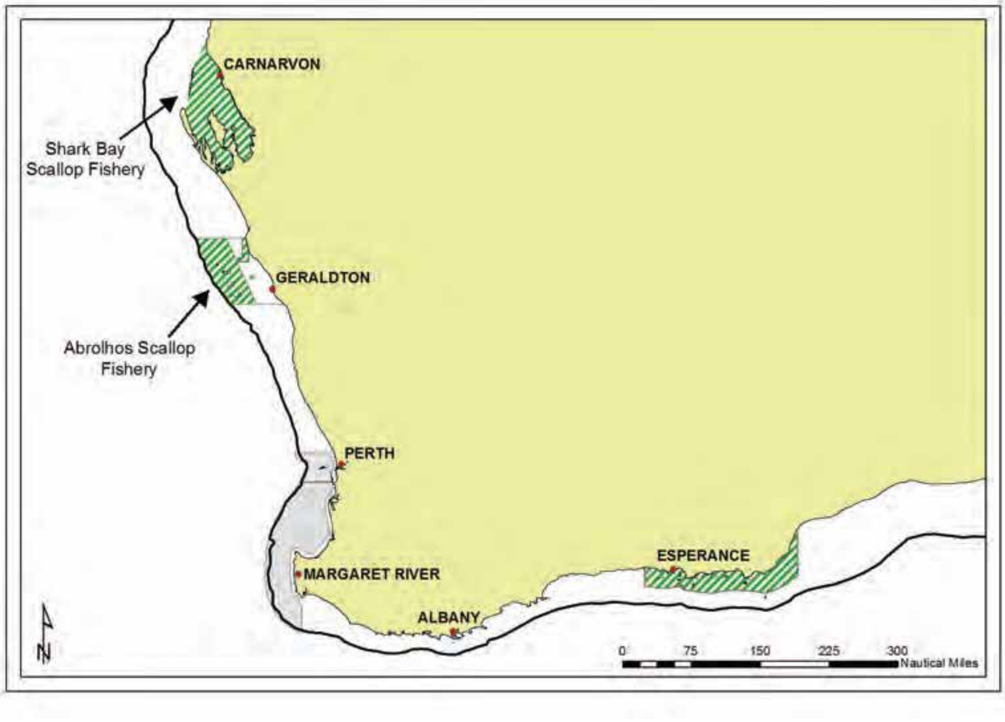

Figure 4.2.2.1. Map showing main areas of distribution of Saucer Scallops in Western Australia

4.2.3 Predators and prey

Saucer Scallops are filter feeders, removing small phytoplankton, organic material and particulates from the surrounding water (Harris *et al.* 1999). Scallops are active suspension-feeding bivalves, which rely on suspended detrital material and phytoplankton as their food source (MacDonald *et al.* 2006).

Known scallop predators within Shark Bay include Pink Snapper (*Pagrus auratus*) and octopus (Harris *et al.* 1999). A potential predator of the Saucer Scallop is the Slipper Lobster (*Thenus* *orientalis*) as it strongly prefers scallops and its foraging behaviour appears to be adapted to hunting and ambushing scallops (Himmelman *et al.* 2009). Escape response studies by Himmelman *et al.* (2009) indicated that *A. balloti* showed a consistent and vigorous swimming response to *Thenus orientalis*, Blue Swimmer Crab (*Portunus armartus*) and Coral Crab (*Charybdis cruciate*). Sea Stars also are generally considered to be key predators of scallops (Thomas and Gruffydd 1971; Wilkens 1981).

4.2.4 Recruitment

Recruitment is highly temporally and spatially variable (Mueller *et al.* 2012). There is a weak correlation between recruitment strength and both water temperature (May to August) and Leeuwin Current strength (May to August). A recent analysis (Lenanton *et al.* 2009) suggested that if both of these environmental indices are low then there is an increased probability of good recruitment. The main factors influencing recruitment success remain largely unknown despite extensive research efforts (Heald and Caputi 1981; Joll 1994; Joll and Caputi 1995a). This project has identified that water temperature, particularly the heat wave of 2010/11, has had a significant effect on recruitment which has resulted in record low levels of spawning stock (Part 1, Section 7.2.4).

4.3 Current impacts of climate change

The major environmental factor influencing these stocks appears to be the flow of the Leeuwin Current along the outside of the embayment in Shark Bay and its influence in the Abrolhos Islands. A relationship exists between sea level (at Fremantle) and the recruitment of scallops in Shark Bay, particularly in the Red Cliff area. Generally, high sea levels corresponding to strong Leeuwin Current correlate with poor recruitment. The strong La Niña conditions have generally resulted in below-average scallop recruitment and in 2011 increased water temperatures and flooding events may have contributed to high mortality of residual scallops in Shark Bay. Continued low recruitment and high mortality of residual scallops in 2012 are likely to be attributed to anomalous environmental conditions (continued above-average water temperatures).

Within the Abrolhos Islands, as far back as 2008 (which was another year of strong Leeuwin Current) there was evidence of poor growth and stunted stocks of scallops in the northern fishing grounds and this persisted for several years. The 2011 fishing season produced significantly less scallop meat than had been predicted from the annual pre-season survey again indicating poor growth and survival of scallops. In 2012 the pre-season scallop survey indicated low abundances with almost no scallops found in 2012 indicating a very high mortality rate of scallops with the most recent decline most likely due to the heat wave events.

Increasing water temperatures may be having a negative impact on scallop stocks within the Gascoyne and Mid-West bioregions. At this stage there is no apparent impact on stocks in the southern parts of WA and it was expected that with increased water temperatures recruitment in the southern waters would be improved. However, this is not apparent in the scallop landings on the south coast in 2013. Scallops also prefer oceanic conditions and therefore increased rainfall and flooding events as also occurred in Shark Bay in 2010/11 may also impact scallop stocks.

4.4 Sensitivity to change

Scallops already exhibit highly variable recruitment associated with environmental conditions and therefore are sensitive to climate change. Their lack of mobility also means that they cannot escape adverse environmental conditions such as the heat wave. They were rated at medium-high sensitivity (Appendix 4).

4.5 Resilience to change

The large latitudinal range of the species between the Gascoyne and southern waters makes the overall stock resilient to change, albeit with significant changes occurring in the individual stocks depending on their location.

4.6 Ecosystem level interactions

As scallops are filter feeders, removing small phytoplankton, organic material and particulates from the surrounding water, they may be vulnerable to changes in productivity.

4.7 Additional stressors

The low recruitment and high mortality of residual scallops since the heat wave events since 2011 have reduced the spawning stock in Shark Bay and Abrolhos Is. to record low levels despite no fishing for scallops since 2012. This means that good environmental conditions are required to improve the spawning stock before a significant recovery to the recruitment is likely to occur.

4.8 Critical data gaps and level of uncertainty

Improved understanding of the tolerance levels of scallops and larval advection and movement pathways within each of the key fisheries. The continued monitoring of the pre-recruit abundance is vital for management and industry to plan for the continued variation in recruitment due to environmental conditions

4.9 Future climate scenarios (2030/2060)

The Leeuwin Current strength is projected to decrease in the long term however there may be decadal variations associated with this as there has been an increase occurring over the last two decades. Water temperature is projected to continue to increase. These two projected changes may have some positive and negative effects on recruitment, respectively, for the Shark Bay and Abrolhos populations so the extent of the effect will be dependent on the nett effect of these changes and when they are likely to occur.

4.10 Management implications

Scallop recruitment is very sensitive to environmental factors so therefore there are likely to be significant implications associated with climate change for these fisheries. They were rated as a high risk to climate change. The extreme heat wave event had a major effect on the recruitment in Shark Bay and Abrolhos resulting in the closure of these fisheries since 2012. The viability of translocation and/or enhancement will be investigated. The project climate change may result in increased abundance in scallop fisheries in the south-west.

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5.0 Blue Swimmer Crab (*Portunus armatus*)

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5.1 The fishery

5.1.1 Commercial fishery

There are a number of Blue Swimmer Crab fisheries in Western Australia, with the largest commercial stocks being fished in Shark Bay, Cockburn Sound and Peel-Harvey Estuary (Fig. 5.1.1.1). Individual commercial fisheries are managed under an input control system, primarily through the regulation of vessel and trap (hourglass) numbers, minimum size limits, gear specifications and seasonal and daily time restrictions. The principal management tools employed to ensure adequate breeding stock in the commercial crab fisheries involves controlling the fishing effort and maintaining minimum size limits well above the size at sexual maturity to allow female crabs to spawn at least once before entering the fishery.

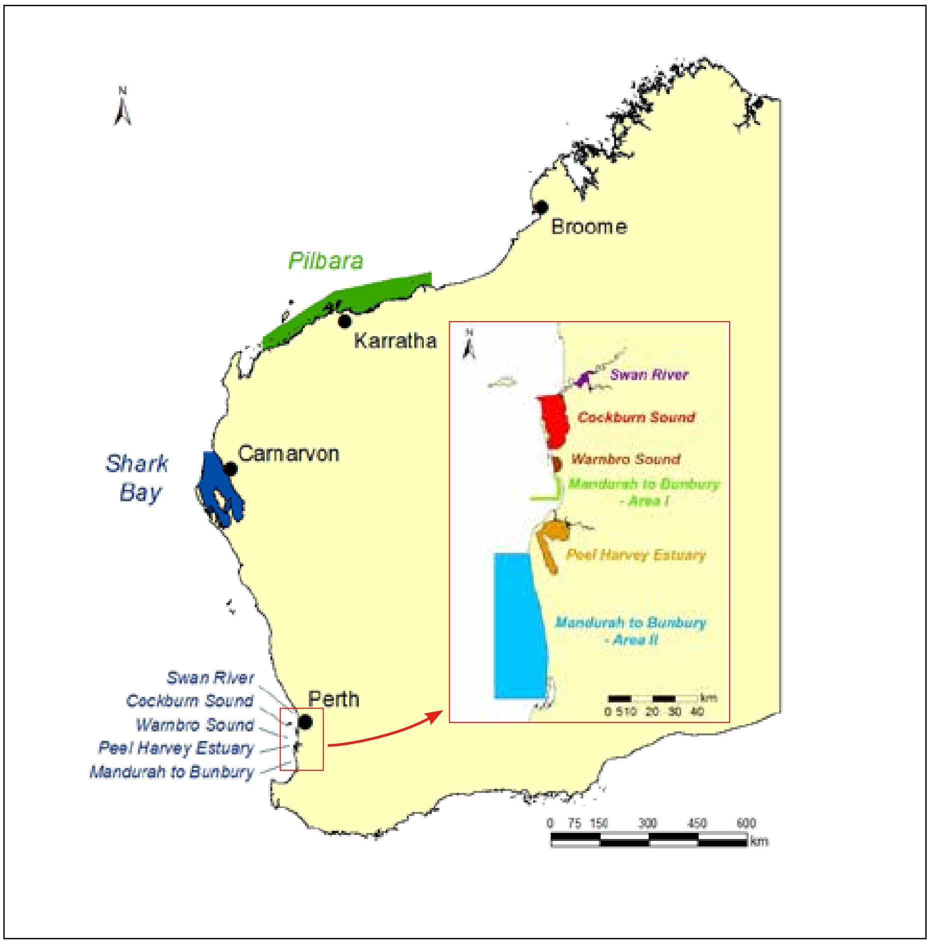

Figure 5.1.1.1. Commercial Blue Swimmer Crab fisheries in Western Australia.

Catch rates have been used to provide an annual index of abundance to assess individual fishery performance. Commercial monitoring and fishery-independent trawl and pot surveys have been conducted in some of these fisheries (Cockburn Sound, Shark Bay and Peel-Harvey Estuary) to assess the status of the spawning stock and recruitment along with data on the general crab population.

The total commercial catch of Blue Swimmer Crabs for WA during 2010/11 was 1047 t; of which 828 t was taken in Shark Bay (from 4 trap vessels and 18 trawl vessels), 68 t in the Peel-Harvey Estuary (from 9 vessels) and 49 t in Cockburn Sound (from 4 vessels in a restricted season). Five vessels operating in smaller fisheries around the state took the remaining 126 t. Total commercial catch in Western Australia declined in 2011/12 to 352 t due to the collapse of the Shark Bay crab fishery, with 46 t taken in Cockburn Sound, 81 t in Peel-Harvey Estuary and 113 t (59 t trap and 54 t trawl) in Shark Bay.

5.1.2 Recreational fishery

A minimum legal size limit of 127 mm carapace width (CW) applies for recreational fishers, of Blue Swimmer Crabs in Western Australia, along with a bag limit of 20 crabs per person or 40 crabs per boat. In October 2007, the recreational bag limits in the West Coast bioregion were halved to 10 crabs per person and 20 crabs per boat. Further controls were introduced in March 2010 when a Recreational Fishing from Boat Licence was introduced that restricts catch to 20 crabs per powered boat when there are two or more people on-board holding Recreational Fishing from Boat Licences and 10 crabs if there is only one person on-board holding a Recreational Fishing from Boat Licence. The majority of recreational fishers use drop nets or scoop nets fished from boats or from shore.

Blue Swimmer Crabs are the most commonly recreationally fished invertebrate species in Western Australia. Most of the recreational Blue Swimmer Crab fishing in Western Australia occurs in the West Coast bioregion, with 92% of the recreational crab catch reported in a state-wide survey of boat-based recreational fishing in 2011/12 coming from this area (Ryan *et al.* 2013). The survey was conducted between 1st March 2011 and 29th February 2012 and utilised the "Recreational Fishing from Boat" licence database in a 12 month phone-diary survey in conjunction with boat ramp surveys of boat-based fishers. Catch data were recorded in numbers of animals, and have been converted to weight for this report using a mean state-wide estimate of 229 g/animal. The survey provided a state-wide boat-based recreational estimate of retained Blue Swimmer Crabs for the 12-month period of 97 t. The boat-based estimate for the West Coast bioregion was 87 t, compared with total landings of 174 t by the commercial sector over the same period.

A 12-month recreational catch and effort survey in the Peel-Harvey Estuary was completed in October 2008. This survey covered fishing from boats, shore, canals, and houseboats. Recreational catch for the Peel-Harvey Estuary from November 2007 to October 2008 was estimated to be between 107-193 t, compared to the recreational catch estimate of 251-377 t from the last survey undertaken in 1998/99. Boating has become the dominant fishing method with a decline in the amount of scoop netting undertaken. The majority of fishers are now locals rather than people from the Perth metropolitan area.

Within Cockburn Sound, recreational crabbing surveys in 1996/97 and 2001/02, and in the 2002, 2003 and 2004 calendar years, produced relatively consistent recreational catch estimates of 24 t, 25 t, 18 t, 23 t and 18 t respectively. However, the recreational catch for the 2005/06 financial year was estimated to be just 4 t. It should be noted that these figures are likely to under-estimate the total recreational Blue Swimmer Crab catch in each of these years, as the surveys commenced at various times between 7 and 9am and finished between 4 and 8pm so missed any crabbing activity that potentially occurred before or after the survey began or finished.

The portion of Cockburn Sound south of a line drawn between Woodman Point and the northern end of Garden Island was closed to recreational crabbing in 2006 to protect crab stocks that were significantly depleted due to fishing pressures and environmental conditions that resulted in poor recruitment. The whole of Cockburn Sound was re-opened to recreational crabbing for the 2009/10 season from December 15th 2009 to March 31st 2010. A survey quantifying recreational catch and effort in the West Coast bioregion was conducted over a two-year period between July 2008 and June 2010. The survey provided a recreational catch estimate for the 3½ months of the 2009/10 season of 15.4 t (S.E.±3.3 t) of Blue Swimmer Crabs, for an area covering Cockburn Sound (south of latitude 32º05'S), Shoalwater Bay and the northern half of Warnbro Sound (north of latitude 32º20'S). However, the survey covered only the period during the day between 9am and 5pm. As there is a significant level of early morning recreational crabbing in Cockburn and Warnbro Sound, an additional survey was conducted between 5.30 am and 9am during the 2009/10 crabbing season. This survey provided an additional recreational catch estimate for this area of 18.8 t (S.E.±5.5 t) of Blue Swimmer Crabs for the 3½ months of the 2009/10 season.

A 12-month survey of recreational fishing in the Swan/Canning Estuary Basin between August 1998 and July 1999 estimated the total recreational Blue Swimmer Crab catch to be 7.3 t. This compares with a commercial catch during the 1998/99 financial year of 24 t. In subsequent years, commercial catches have ranged between 10 t and 20 t, but no further recreational surveys have been undertaken specifically in the Swan-Canning Estuary.

Both the Leschenault Inlet and Geographe Bay are now exclusively for recreational use. Previous surveys have found the annual recreational Blue Swimmer Crab catch from Geographe Bay to be between 7 – 11 t per year.

5.1.3 Individual fisheries

Cockburn Sound: Following the second highest annual catch on record in 2000 (340 t) the catch declined to the point where low stock abundance (depleted due to fishing pressure and environmental conditions that resulted in poor recruitment) required closure of the fishery in December 2006. Recovery of the breeding stock and subsequent recruitment was slow with annual recruit and residual indices and catch estimates well below historic catch ranges for 3 years. Fishery-independent trawl surveys and commercial monitoring surveys indicated that the strength of recruitment and breeding stock had improved sufficiently to re-open the fishery in December 2009, initially for a reduced period of 3.5 months, an increased minimum size of 140 mm CW and 20 % pot reduction. The season length has now extended to 6 months, with a minimum size back to its original 130 mm CW, but retaining the 20% pot reduction. The fishery is predominantly a commercial fishery with a small recreational catch. Commercial monitoring and fishery independent recruitment and breeding stock surveys have been undertaken since 2000 and are ongoing.

Peel-Harvey Estuary: Commercial catches fluctuate generally between 60 and 90 t depending on environmental conditions with a large proportion of the stock taken recreationally. Stocks appear to be sustainably fished as the breeding stock is protected to some extent as spawning occurs outside the estuary following flushing of crabs during winter. Fishery-independent surveys and commercial monitoring of the stock commenced in 2007 and are ongoing.

Shark Bay: The crab trap fishery has expanded rapidly over the past 10 years to become Australia's highest producing Blue Swimmer Crab fishery, with total (trap and trawl) landings of 828 t in 2010. Shark Bay represented approximately 80% of the WA commercial Blue Swimmer Crab catch in 2010. Crabs are taken by dedicated trap fishers and retained by prawn fishers. Trap catch and effort increased during the experimental phase of the fishery and stabilised around 500 t following conversion to interim managed status in 2005. Retained catch of crabs by the Shark Bay trawl fleet has also increased significantly in the past few years. A catch sharing arrangement has been finalised with 66% allocated to the trap sector and 34% allocated to the trawl sector.

A significant stock decline was experienced in 2011/12 which is believed to be due to the combined impact of environmental conditions (marine heat wave and possibly the two flooding events) in the summer of 2010/11. This resulted in a closure to the fishery in April 2012. Some improvements in stocks have been identified and a partial opening of the fishery for 2013/14 with a nominal quota of 400 t.

Warnbro Sound: Annual catches in Warnbro Sound have fluctuated between 1 and 21 t between 1990 and 2010, with recent catches increasing significantly to 31 t in 2011 and 2012. Catch rates in these years also increased significantly from less than 1.0 kg/traplift to 1.2 and 1.3 kg/traplift, reflecting an improved efficiency in fishing by the operator. Males dominate the catch over summer with non-berried females dominating the catch from April to September. Recent large increases in catch will be closely monitored but it appears stocks are being fished sustainably. Commercial monitoring in this fishery commenced in 2007 and is ongoing. The fishery is predominantly a commercial fishery with a small recreational catch.

Swan River: Annual catches in Swan River have ranged between 6 and 21 t (1990-2012) with catches averaging around 8 t between 2010 and 2012. Most crabs are taken over summer with catches between May and November contributing only 10% of the catch. The Swan River fishery is a net fishery with days fished averaging around 180 days per year between 2010 and 2012. Males dominate the catch over summer with non-berried females dominating the catch between May and September. Berried females and juvenile crabs are noticeably absent from catches with crabs characterised by their large size and dark colour and fetch premium prices. Swan River is an important recreational crab fishery. Commercial monitoring in this fishery commenced in 2007.

Mandurah-Bunbury Developing Crab Fishery: This fishery is divided into Area I (Comet Bay) and Area II (Mandurah-Bunbury) with catches in Comet Bay ranging between 2 and 13 t since 2000 (mean 11 t, 2010–2012) and Mandurah-Bunbury between 0 and 10 t (mean 4 t, 2010–2012). Fishing occurs year round in Comet Bay, but has been focused between February and June in Mandurah-Bunbury in recent years. Catch rate fluctuates significantly between 0.5 and 1.8 kg/traplift in Mandurah-Bunbury (2004/05–2011/12) whereas it averages around 0.7–0.8 kg/traplift in Comet Bay. Catches in both areas are dominated by females, except for January and February in Comet Bay only. Commercial monitoring commenced in this fishery in 2007.

Pilbara Developing Crab Fishery: Blue Swimmer Crabs in the Pilbara are targeted by trap fishers operating around Nickol Bay in the Pilbara Developing Crab Fishery and retained by the Onslow and Nickol Bay prawn trawl fishery. Their combined catch during 2011/12 was 12 t. Trap catch rates generally range between 0.7 and 1.0 kg/traplift, but have been up to 1.6–1.8 kg/traplift during favourable environmental conditions.

Key points:

- Principal management tools to protect breeding stock involves controlling fishing effort and a minimum size limit well above the size at sexual maturity to allow female crabs to spawn at least once before entering fishery.
- Commercial catch of Blue Swimmer Crabs for WA during 2010 was 1047 t; with 828 t taken in Shark Bay which was then the largest crab fishery in Australia.
- Blue Swimmer Crabs are the most important recreationally-fished species in terms of community participation rate in WA. The total recreational catch for WA from a phone-diary survey of licensed-boats for 2011/12 was 97 t with 92% coming from the West Coast bioregion.

5.2 Life history

5.2.1 Life cycle, age and growth

Blue Swimmer Crabs begin life as tiny larvae, called ‘zoea’, which grow and change shape over a four-to-six-week period during early summer (Figure 5.2.1.1). They drift in bays or along the coast up to 80 kilometres out to sea. They are prey for fish and the death rate is high. The survivors reach shallow nursery areas by late summer. They settle to the sea or estuary bottom and moult frequently while rapidly growing. They turn into a more crab-like state called ‘megalopae’. By autumn, most are crab-shaped. They continue growing rapidly and by winter, the carapace is about nine centimetres wide. During the final moult to reach maturity, females mate for the first time. Most mating takes place in the autumn. Males moult first, so that their new shells have hardened beforehand. A courting male then catches a female and carries her beneath him for four to 10 days while fending off other males. He helps her to moult then turns her over to mate while she is still soft-shelled. After mating, he continues to carry and protect her for another three-to-four days while her new shell hardens. In southern WA waters, the females retain the males’ sperm over winter until their ovaries develop – helped by rising water temperature in spring.

In the ocean, big females mostly spawn in late spring and early summer. Estuarine crabs tend to spawn later in summer, having moved to the sea or estuary mouth during winter rains. Each female produces between 180,000 and two million eggs in a single spawning – and may spawn more than once in a season. The eggs are fertilised by the stored sperm and, when laid, they attach under the female’s abdomen, forming a spongy mass. The female incubates the eggs for about 18 days. When the embryos inside are mature she shakes the eggs off and they hatch into zoea.

Life cycle

The timing and movements of blue swimmer crabs vary between locations. Estuarine crabs, such as those living in the Leschenault Inlet, Peel-Harvey Estuary and Swan River, tend to move from estuaries into nearby marine waters during winter. Crabs in marine embayments such as Cockburn Sound and Shark Bay spend their entire lives within different parts of the embayment.

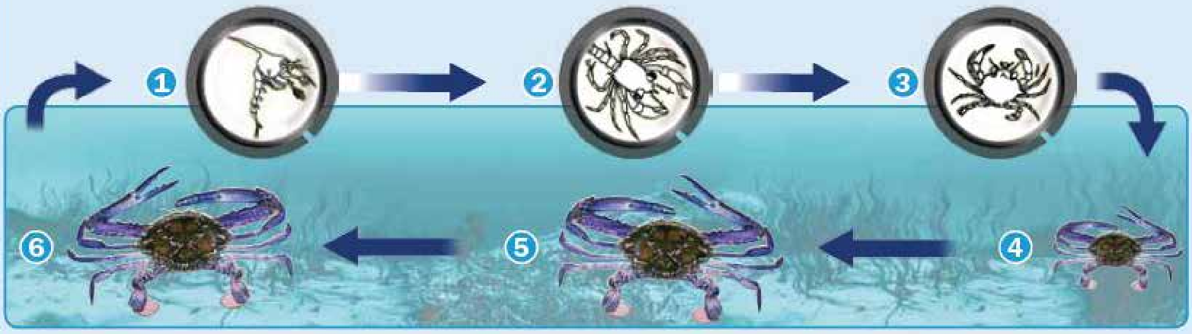

Figure 5.2.1.1. Life cycle of the Blue Swimmer Crab in Western Australia.

5.2.2 Distribution, habitat and environmental preferences

P. armatus is a tropical species that occurs in nearshore, marine embayment and estuarine systems throughout the Indo-West Pacific region (Stephenson 1962). They live in a wide range of inshore and continental shelf habitats, including sandy, muddy or algal and seagrass habitats, from the intertidal zone to at least 50 m depth (Williams 1982; Edgar 1990). In Western Australia their distribution extends along the entire coast with the majority of commercial and recreational fishing concentrated in coastal embayments and estuaries between 34° and 24° S.

5.2.3 Predators and prey

White *et al.* (2004) described predation of *P. armatus* in Shark Bay by four species of elasmobranch. He reported a significant level of predation by the Giant Shovelnose Ray (*Rhinobatus typus*) and adult specimens of the Nervous Shark (*Carcharhinus cautus*), with only moderate predation by the Lemon Shark (*Negaprion acutidens*) and the Milk Shark (*Rhizoprionodon acutus*). Blue Swimmer Crabs are omnivorous scavengers on invertebrates including molluscs and crustaceans. de Lestang *et al.* (2000) reported the diets of *Portunus armatus* in the Peel–Harvey and Leschenault estuaries in south-western Australia but other key fisheries including Shark Bay have not been investigated.

5.2.4 Recruitment

The reproductive cycle of Blue Swimmer Crab populations along the WA coast is strongly influenced by water temperature (de Lestang *et al.* 2010). While the spawning period of Blue Swimmer Crabs in the temperate waters of southwest WA is restricted to spring/summer (de Lestang *et al.* 2010; Johnston *et al.* 2011), the warmer, tropical waters of Shark Bay induce spawning all year round (de Lestang *et al.* 2003; Harris *et al.* 2012) with a peak in spawning between July and September. Incubation of released eggs takes 10 to 18 days, and the larval phase extends for up to six weeks (Kangas 2000). Blue Swimmer Crabs moult frequently during the juvenile phase, and growth is rapid.

Water temperature has been implicated as an important factor in the majority of the recruitment-environment relationships for marine fish and crustacean species and is often robust enough to persist over substantial time frames (Caputi *et al.* 1995; Uphoff 1998). Water temperature may affect recruitment in a variety of ways. For example, elevated water temperatures typically have a positive effect on decapod recruitment by accelerating larval development and reducing the duration of the larval phase and larval mortality (Bryars and Havenhand 2006; Fisher 2007). Elevated water temperatures prior to spawning may also directly affect the timing of larval release by controlling gonad development, mating and the timing of spawning (Rosenkranz *et al.* 2001) as well as the larval habitat through changes to the abundances of larval foods and predators. de Lestang *et al.* (2003) demonstrated that the spawning season of *P. armatus* in Shark Bay, where water temperatures remain above 18º C for a substantial part of the year, is considerably more protracted (spawns year round) than in the temperate waters of Cockburn Sound where the spawning season is restricted to spring and summer.

5.3 Current impacts of climate change

5.3.1 Temperature

The vulnerability of *P. armatus* to environmental fluctuations in Cockburn Sound has been shown by de Lestang *et al.* (2010) and Johnston *et al.* (2011). As a tropical species, the temperate waters of Cockburn Sound and other south-west crab fisheries (~32ºS) are towards the southern extreme of its distribution and the spawning period of Blue Swimmer Crabs in these southern waters is limited (to spring/summer). A strong correlation between water temperature and recruitment success was reported in Cockburn Sound, with poor recruitment resulting from four years of lower than average water temperatures in the months of August and September prior to spawning (de Lestang *et al.* 2010; Johnston *et al.* 2011).

It is possible that elevated water temperatures in sub-tropical locations such as Shark Bay can have a deleterious effect on spawning and recruitment. Since July 2011, the relative abundance of all size classes of crabs in Shark Bay has declined significantly. The reasons for this unexpected and substantial decline are yet to be clearly understood, but it is possibly linked to several adverse extreme environmental events that occurred during the summer of 2010/11 associated with a very strong La Niña event. The possible effect of fishing on the spawning stock will also be examined but preliminary assessment indicates that the spawning stock that led to the low recruitment was within historic ranges. Two major flood events occurred in the Shark Bay region during December 2010 and February 2011, coinciding with a major temperature anomaly that saw sea surface temperatures in Shark Bay at record high levels (3–4.5° C above average) between December 2010 and March 2011. These water temperature increases were part of the record increases that were observed for the entire Gascoyne and mid-west region of WA that has been associated with the mortality of a number of invertebrate and fish species (Pearce *et al.* 2011; Pearce and Feng 2013). An assessment of the effect of water temperature on the Shark Bay crab stocks was undertaken by this project and showed a negative correlation with summer water temperatures during the early juvenile phase and a positive correlation with water temperatures during April-August near the period of peak spawning (Part 1, Section 7.2.4)

Anecdotal evidence suggests growth patterns of crabs in the sub-tropical waters of Shark Bay are notably different to those in the temperate waters of south west WA so future increases in temperature will lead to variations in growth patterns. It is likely elevated temperatures will increase growth and influence size at maturity over future generations.

5.3.2 Rainfall

Historic trends and long-term climate change predictions indicate that rainfall is continuing to decrease over time in the south-west of WA. Lower rainfall will lead to reduced flushing of estuaries. This will result in reduced exchange of crabs between estuaries and oceanic waters potentially leading to higher risk of mated pre-spawn females being caught by fishers in estuaries such as Peel-Harvey as these females are generally flushed out in winter to spawn in oceanic waters adjacent to the estuary. Spawning may also occur within estuaries and river systems such as Swan River where habitat and environmental conditions are likely to be sub-optimal for larval growth and survival. Hypersaline conditions may increase mortality of juveniles and adults resulting in reduced crab abundance in these areas and a general shrinking of suitable waters in Shark Bay and estuaries such as the Peel-Harvey. Changes in rainfall and sea level rises may also negatively impact seagrass habitat leading to a reduction in suitable nursery grounds for juvenile crabs.

5.4 Sensitivity to change

Given the sensitivity of the spawning/larval phase in Cockburn Sound to water temperature, the effect of the marine heatwave in Shark Bay and the effect of rainfall in Peel-Harvey and other estuaries, the Blue Swimmer Crab appears to be sensitive to climate change effects. As water temperatures are expected to increase and rainfall expected to decrease the likelihood of changes to the crab stocks are relatively high. It scored as medium-high sensitive based on the 12 sensitivity attributes and was rated at high risk to climate change (Appendix 4).

The effects of climate change are likely to differ between Blue Swimmer Crab fisheries in Western Australia based on the large latitudinal range between the northern (Gascoyne) and south-western waters. Crab fisheries in the south-west are at the southern extreme of their temperature range whereas those in the Gascoyne are currently in the optimal temperature range. Sensitivities to climate change will differ depending on the particular ecosystem the crabs inhabit.

Depending on the effect of temperature increases on growth and recruitment, it is possible that there may be longer-term flow-on impacts including potential resource limitation and density-dependent growth retardation if growth rates and recruitment increase significantly in some stocks.

5.5 Resilience to change

The large latitudinal range between the northern (Gascoyne) and south-western waters makes the overall stock resilient to change, albeit with significant changes occurring in the individual stocks depending on their location. Warmer sea temperatures may result in range extension of the species into further southern latitudes, which is likely to influence community structure in these areas. The flexible nature of the Blue Swimmer Crab diet suggests that their populations may be unaffected by changes in community structure.

5.6 Ecosystem level effects

The overall impact of climate change on the ecosystems occupied by Blue Swimmer Crabs in Western Australia is difficult to assess. Direct impacts of lower water temperatures during key spawning periods has been demonstrated on crab stocks in Cockburn Sound and conversely of elevated temperatures and flooding events have been demonstrated in Shark Bay. Both scenarios have occurred during sustained periods of high fishing pressure and resulted in closure of the respective fisheries due to significant declines in stock levels. Knock on effects of declines in crab abundance will occur for predator and prey relationships with potential decreases in predator numbers and increases in crab prey abundance. Shifts in species dominance are also likely to occur in the longer term if crab abundance remains low.

Implications of climate change for habitat also need to be considered, in particular the apparent loss of seagrass in Shark Bay in response to the marine heatwave event in 2010/11 (Caputi *et al.* 2014) and the cumulative loss and gains over time in Cockburn Sound. A loss of nursery habitat for juvenile Blue Swimmer Crabs would have a detrimental effect on recruitment and possibly alter juvenile distribution within fisheries. Seagrass is an integral part of the Blue Swimmer Crab lifecycle and absence or loss will inhibit the successful completion of the lifecycle in affected areas. This would directly impact the success of populations and their distributions along the Western Australian coastline.

5.7 Additional stressors

The combination of heavy fishing pressure and a reduction in water temperatures that affected recruitment was responsible for the collapse of the Cockburn Sound crab stocks. It is also possible that heavy fishing pressure played a role in the collapse of crab stocks in Shark Bay following the marine heatwave in 2010/11. Therefore it is important that the level of fishing pressure is managed appropriately if the stocks are deemed vulnerable to climate change.

Coastal developments that affected juvenile seagrass habitat will also be additional stressors to crab stocks.

5.8 Critical data gaps and level of uncertainty

Understanding the spawning and recruitment cycle in Shark Bay and the development of pre-recruit index of abundance to assist in the stock assessment and early management intervention is a critical gap which is being addressed by a current FRDC project.

Similarly long-term monitoring of the pre-recruits and spawning stock in the Peel-Harvey Estuary and the corresponding marine areas to follow up on the life history study in recent years (Johnston *et al.* 2014) will help the stock assessment and management of this important recreational and commercial fishery.

The relationship between environmental parameters, particularly temperature, and stock abundance also needs to be examined closely as long term datasets are developed in fisheries such as the Peel-Harvey Estuary. Temperature has been associated with the collapse of the Cockburn Sound crab fishery (de Lestang *et al.* 2010; Johnston *et al.* 2011) and has also been implicated in the collapse of the Shark Bay crab fishery. These long term datasets in crab abundance and environmental parameters will be developed in the future for all crab fisheries.

5.9 Future climate scenarios (2030/2060)

Projected changes such as a water temperature rise by 1–2ºC over the next 50 years in the south-west of WA could have a beneficial impact on spawning, and subsequent recruitment. The period of spawning may also expand from spring-summer, as the Blue Swimmer Crab stocks in Shark Bay and Exmouth Gulf spawn all year.

Long-term climate change predictions indicate that rainfall will continue to decrease in the south-west of WA (IOCI 2012). Lower rainfall will lead to reduced flushing of estuaries which may result in reduced movement of crabs from the estuaries into oceanic waters potentially leading to higher risk of mated pre-spawn females being caught by fishers in estuaries such as Peel-Harvey. This may affect the spawning success of crabs.

5.10 Management Implications

Changes in recruitment abundance in crab fisheries will need to be addressed by adjusting fishing effort and/or quota. The development of pre-recruit measures that enable the detection of the changes in abundance will allow for early intervention of management.

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6.0 Gloomy Octopus (*Octopus* cf *tetricus*)

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6.1 The fishery

The Gloomy Octopus (*Octopus* cf *tetricus*) is the most commonly caught and encountered octopus species in Western Australia, by commercial and recreational fishers alike. Targeted by the Developmental Octopus Fishery (DOF) and the Cockburn Sound Line and Pot Managed Fishery (CSLPF), *O.* (cf) *tetricus* is also a significant byproduct species of the West Coast Rock Lobster Managed Fishery (WCRLF) and occasionally landed in small quantities by numerous trap and trawl fisheries (Hart *et al.* 2013). Current commercial landings of octopus in Western Australia are approximately 208 t, across all fisheries, with catches typically peaking in late autumn early winter. Recreational catches of *O.* (cf) *tetricus* are generally unknown, however, are believed to be relatively consistent and low in quantity (17 t, 2001 estimate) (Henry and Lyle 2003). Recreational fishers mostly catch octopus using octopus targeted pots or as bycatch in lobster pots. Other species of octopus are occasionally caught by commercial and recreational fishers in Western Australia, including: *Octopus cyanea*, *Macroctopus maorum* and *Octopus ornatus* (Herwig *et al.* 2012).

Prior to 2009 the WCRLF landed the majority of octopus in Western Australia, peaking at 140 t in 2002 (86% of the total catch). However, the introduction of a new gear type, the trigger trap, into the DOF during 2010, led a 400% increase from 33 t in 2009 to 170 t in 2010. This resulted in the DOF surpassing the WCRLF as the primary supplier of octopus in Western Australia. The present catch proportions across the DOF, WCRLF and CSLPF are 65%, 20% and 14.5%, respectively, with the remaining 0.5% as bycatch from a collection of other fisheries (Hart *et al.* 2013) (Fig. 6.1.1 and 6.1.2).

Two types of gear are used in the DOF, trigger traps and shelter pots. The trigger trap was developed by industry during 2007 – 2009. Comprised of three plastic traps set in a cradle, each trap is baited with a plastic crab attached to a trip wire, which when handled by an octopus sets off a trap door. Prior to the introduction of trigger traps, shelter pots were the only gear used in the fishery. Shelter pots are a passive gear type, consisting of an open ended plastic pot generally deployed in waters shallower than 20 m, with approximately 500 pots connected to a demersal longline. Shelter pots rely on an octopus using the pot as a lair in habitat-limited environments, such as seagrass meadows. Trigger traps have largely replaced shelter pots in the DOF contributing to >96% of the catch in 2012. The ascension of the trigger trap as the main gear used in the fishery is due to the fact they catch larger animals, have higher catch rates and shorter soak periods than shelter pots. In addition, the greater weight of a cradle of trigger traps (45 kg) compared to a shelter pot (3.5 kg) enables them to be used in more exposed waters, thus providing an impetus for the fishery to expand along the coast.

The DOF is presently managed through limited entry (currently 5 exemption holders) and gear allocations (shelter pots and trigger traps). There are approximately 17 vessels operating in the fishery from Kalbarri in the north to Esperance in the south east. Historically, catch and effort has focused on the Perth metro region. However, with the introduction of the more versatile trigger trap, fishers are starting to explore the great expanses of the west coast from Kalbarri to

Cape Naturaliste, with the remote southern coast of W.A. mostly yet to be explored by fishers. Research is currently being undertaken to determine potential sustainable harvest rates in the DOF. The outcomes of which will be used to help guide the rapid development of the fishery and move the fishery towards managed fishery status.

Key points:

- Prior to 2009 the WCRLF landed the greatest proportion of octopuses in Western Australia.
- In 2010 the introduction of trigger traps contributed to a 400% increase in catch, making the DOF the largest supplier of octopus in the state.
- The DOF is presently expanding as fishers explore Western Australia’s western and southern coasts.
- The DOF is transitioning to ‘managed fishery’ status.

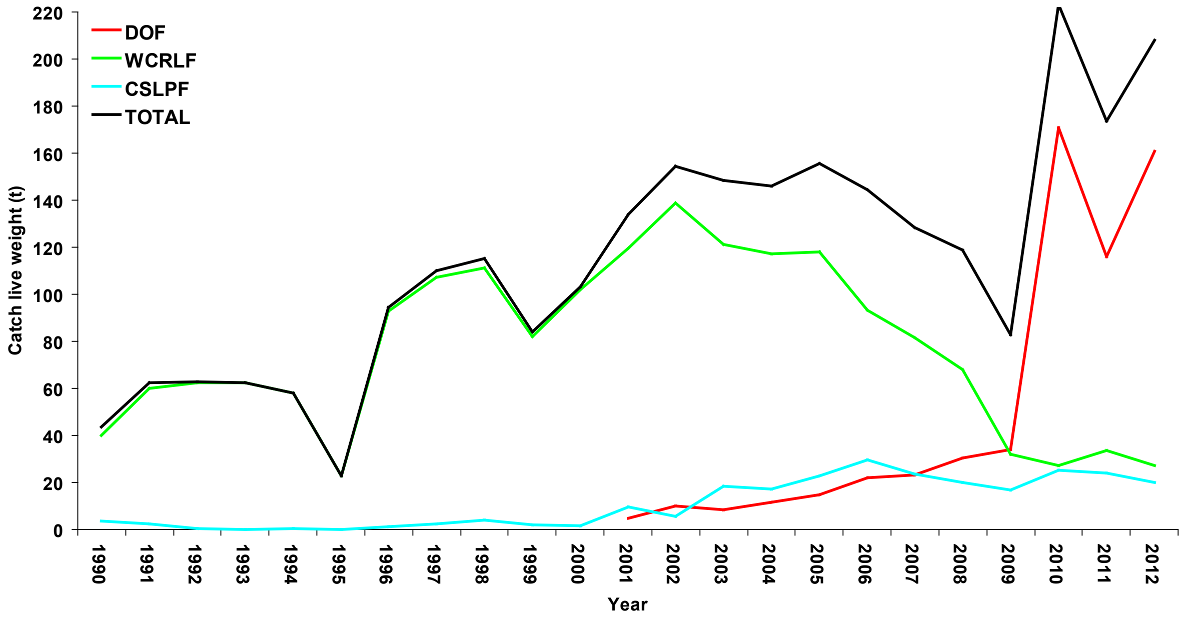

Figure 6.1.1. Historical catches of octopus across different fisheries in Western Australia.

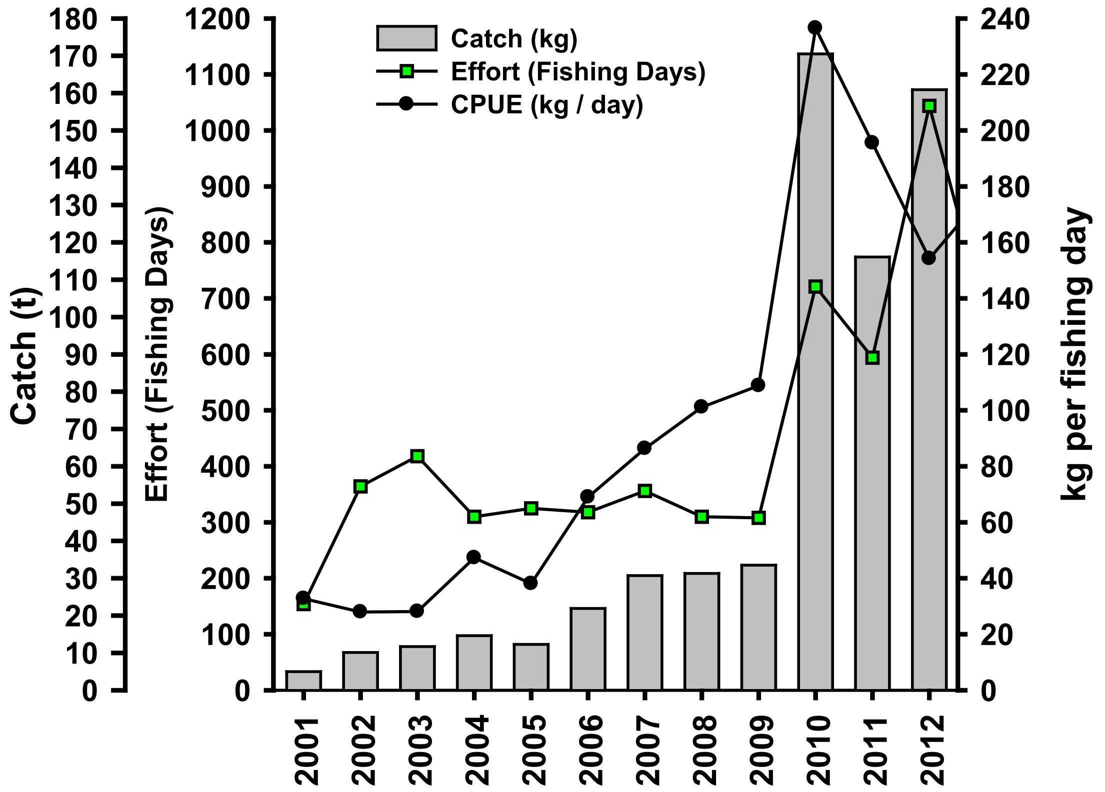

Figure 6.1.2. Catch per unit of effort in the developmental octopus fishery during 2001 – 2012. The new trigger trap was introduced in 2010.

6.2 Life history

6.2.1 Life cycle, age and growth

Octopus (cf) *tetricus* is a medium-sized octopus species, reaching a maximum weight of 4 kg and age of 18 months. Short lived and fast growing, this species becomes mature at approximately 950 g or 270 days for males, and 1800 g or 380 days for females (Leporati *et al.* in prep.). A semelparous species, females lay a single clutch of eggs, tending to them for 1 – 2 months until hatching, perishing not long afterwards (Joll 1976). A typical clutch of eggs may contain >100,000 eggs, generally hatching in large pulses over a period of a few days (Joll 1983). Similar to other octopus species, males continue to mate with available females until they reach senescence, living for a similar length of time as females (Leporati and Hart in prep.).

A merobenthic species, the paralarvae drift in the water column at the mercy of the currents for >50 days, then metamorphose and settle onto the benthos taking up the usual benthic life of an octopus (Villanueva and Norman 2008). This life history strategy is in contrast with 'holobenthic' octopus species (i.e. *Octopus pallidus*, *O. berrima* and *O. australis*), which do not have a paralarval stage. Such species generally have considerably larger eggs in smaller clutches and bigger more developed hatchlings, leading to more localised distribution than merobenthic species. Thus making them more susceptible to small scale environmental fluctuations and continuous fishing pressure (Leporati *et al.* 2009) (Figure 6.2.1.1).

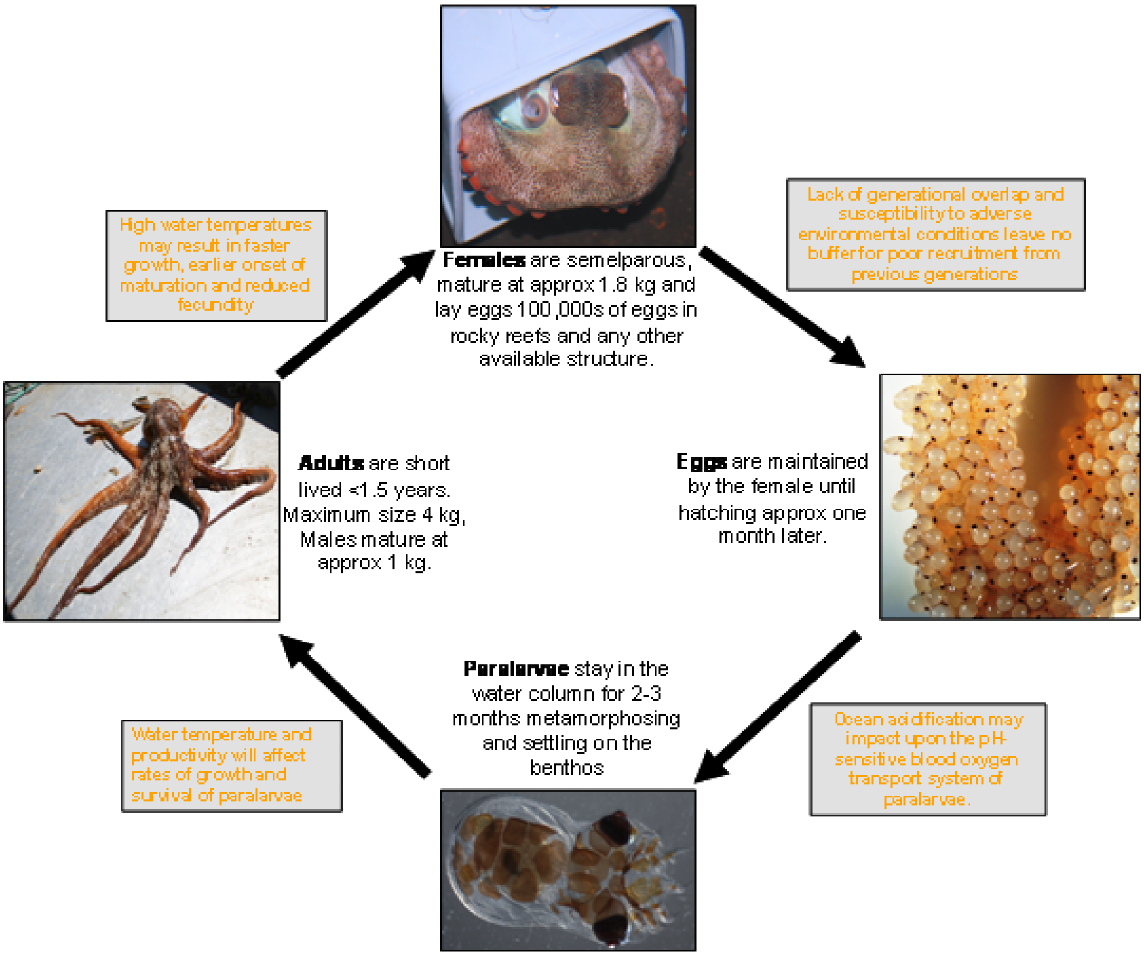

Figure 6.2.1.1. Summary of life cycle, and points of exposure relevant to climate change drivers or known impacts, for *Octopus* (cf) *tetricus*.

Octopus growth is generally considered to follow a two-phased pattern. Comprising of a short exponential stage of high growth, followed by a slower, usually power growth stage, where more energy is invested in reproductive development (Mangold 1983). Temperature has a very strong influence on octopus growth, with the greatest potential influence during the exponential phase (Forsythe and Van Heukelem 1987; Leporati *et al.* 2007). This is exemplified by the Forsythe effect, where "as hatching occurs over a period of increasing water temperatures, each monthly cohort will encounter warmer temperatures and thus grow significantly faster than cohorts that hatched only weeks previously" (Forsythe 1993). Higher temperatures at hatching (up to 22°C) have been shown to increase the growth rate of immature *Octopus* (cf) *tetricus*, in the wild. However, at temperatures beyond 22°C growth rates have been shown to drop (Leporati *et al.* in prep.). Similar results have also been observed in captivity, where growth and mortality rates are negatively affected by temperatures >22°C, during the exponential growth phase (S. Kolkovski *pers. Comm.*). This complies with the sea surface temperature (SST) profile at the northern extremes of *O.* (cf) *tetricus*' distribution, where SST exceed 22°C 77% of the time for a mean of 23.5°C.

6.2.2 Distribution, habitat and environmental preferences

O. (cf) *tetricus* is endemic to Western Australia, inhabiting waters from Shark Bay in the north to the South Australian border in the south-east. Found at depths from 0 to 70 m, *O.* (cf) *tetricus* inhabits rocky reefs, seagrass beds and sandy substrates (Norman 2000). Similar to other octopus species, *O.* (cf) *tetricus* is generally believed to be asocial, with competition for lairs leading to conflict and cannibalism (Hanlon and Messenger 1996). Initial results indicate that females, closely followed by males, may migrate from sandy substrates and seagrass, to reefs to find appropriate brood sites (Leporati *et al.* in prep.).

The west coast of W.A. is currently the focal point for the expansion of the DOF. Stretching across five degrees of latitude from sub-tropical to temperate waters, this body of water is dominated by the southward flowing Leeuwin Current and to a lesser degree the northward inshore Capes Current (Pearce and Feng 2013). The uniformity of this coastline has resulted in a strong correlation between SST and latitude. Commercial catch data and biological sampling from the DOF has revealed that mean octopus weight increases towards southern latitudes, with octopus caught in Busselton (33.5° S) on average 260 g or 18% bigger than those caught in Dongara (29.5° S) (Figures 6.2.2.1 and 6.2.2.2).

Until recently, the *Octopus tetricus* populations on the eastern and western coasts of Australia were considered to be the same species. However, Amor (2011) has identified they are comprised of two very closely related, yet separate species, without overlapping distributions. Hence, the west coast species, *Octopus* (cf) *tetricus*, is denoted with a cf until a new species name is determined.

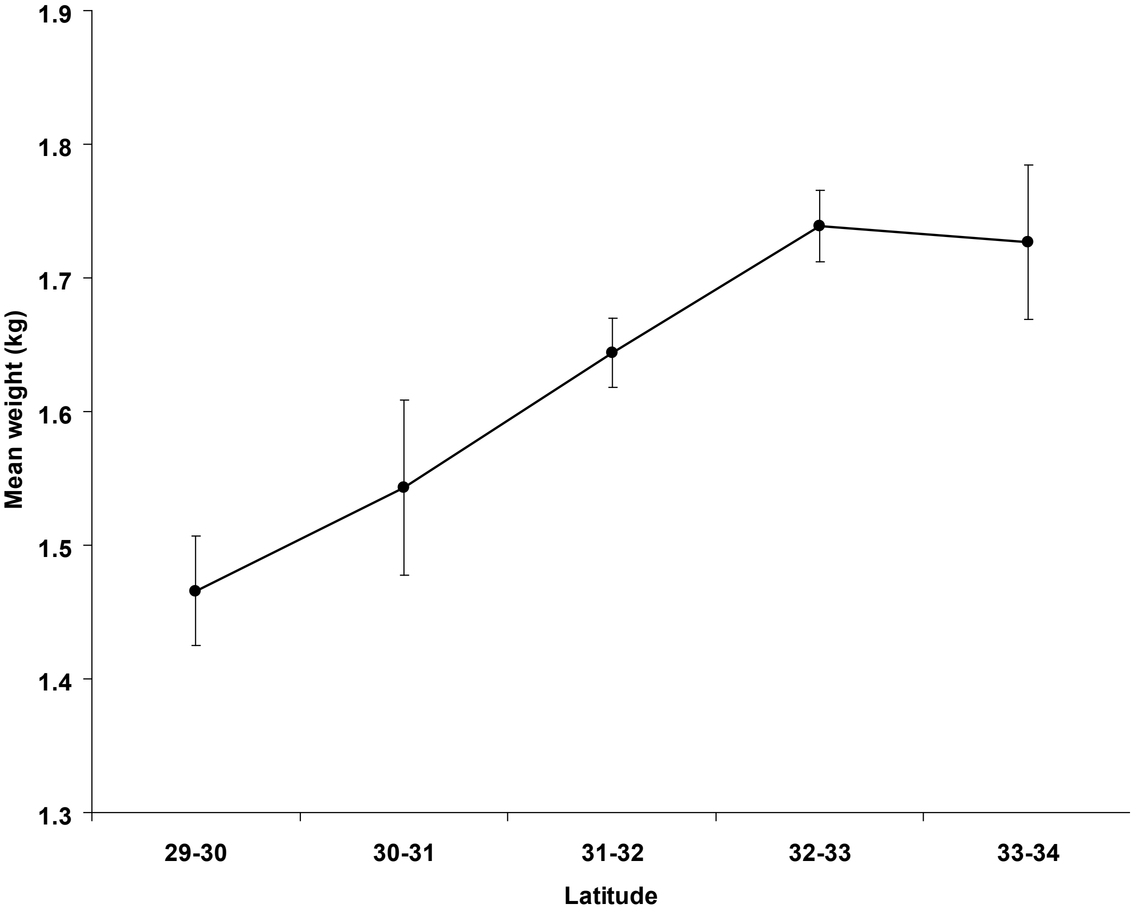

Figure 6.2.2.1. Mean weight of *Octopus* (cf) *tetricus* caught in the developmental octopus fishery by latitude

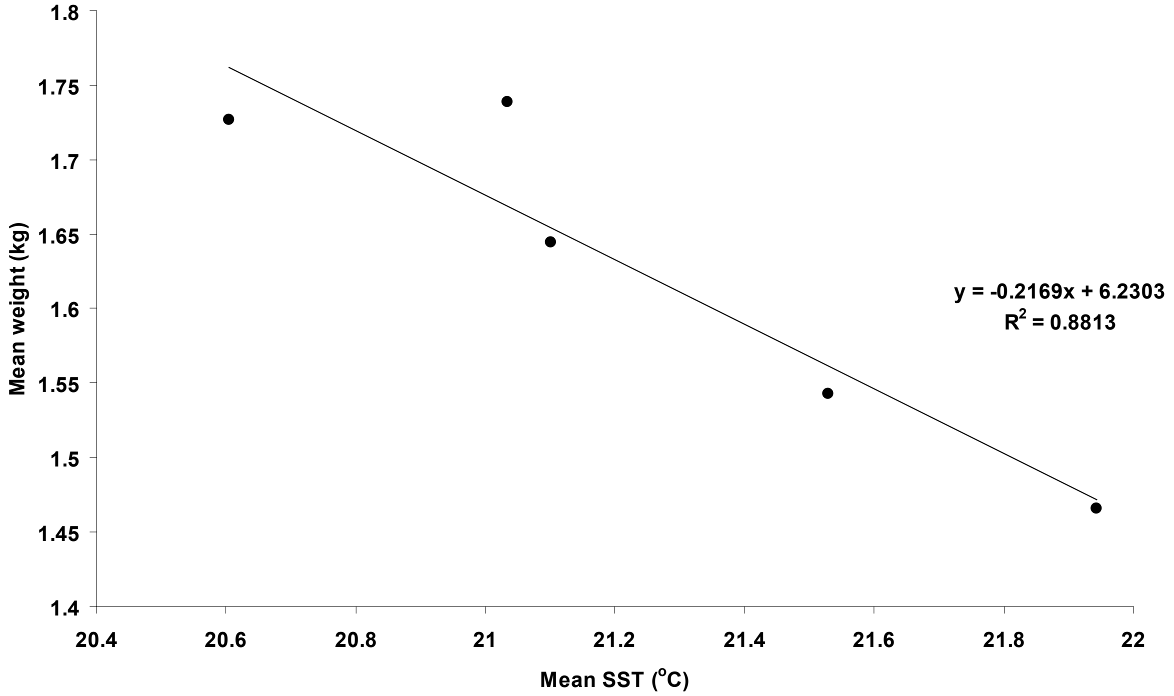

Figure 6.2.2.2. Mean weight of *Octopus* (cf) *tetricus* caught in the developmental octopus fishery by mean sea surface temperature in relation to latitude

6.2.3 Predators and prey

O. (cf) *tetricus* feeds on a variety of prey, including: crustaceans, shelled molluscs, fish and other cephalopods. In addition, it is a major predator of pot-caught Western Rock Lobster (*Panulirus cygnus*) in the WCRLF, with predation of lobsters outside of pots considered to be considerably less, due to the slower swimming speeds of octopuses (Joll 1977). The major predators of *O.* (cf) *tetricus*, are believed to be small benthic shark species, large teleost species such as the iconic West Australian Dhufish (*Glaucosoma hebraicum*), dolphins and seals. To determine the exact trophic role of *O.* (cf) *tetricus*, diet studies need to be conducted.

6.2.4 Recruitment

Octopus (cf) *tetricus* breeds throughout the year, with hatching pulses occurring approximately every six months. With a maximum age of 18 months and maturing at 12 months, females have roughly a six month window of opportunity to spawn (Leporati *et al.* in prep.). However, the ability to mate prior to maturation and store sperm for up to 16 weeks, helps to ensure females lay eggs when necessary, rather than being completely bound by environmental cues (Joll 1976; Rodriguez-Rua *et al.* 2005). Age at recruitment into the fishery for both genders ranges from 100 – 150 days and 250 – 300 days for shelter pot caught and trigger trap caught animals, respectively (Leporati *et al.* in prep.).

The catch composition from the trigger traps is dominated (75%) by mature males weighing >1 kg and >1 year old. Inshore shelter pot fishing primarily catches animals weighing <1 kg, with equal proportions of males and females that are mostly immature. The greater propensity of trigger traps to catch males helps to offset some of the effects larger catch rates from this gear type may have on recruitment.

Key points:

- Short lived, fast growing, highly fecund ecological opportunists;
- Semelparous females lay 100,000s of eggs.
- Larger octopus at the central area of their distribution;
- Growth decreases above 22°C SST;
- Year round spawning with six-monthly pulses.

6.3 Current impacts of climate change

The current impacts of climate change on W.A.'s octopus populations and the potential implications for fishing are presently unknown.

6.4 Sensitivity to change

The biological processes of cephalopods are highly influenced by environmental variables. In particular laboratory studies have demonstrated a strong positive influence of temperature on growth and reproductive development (Caddy and Rodhouse 1998; Leporati *et al.* 2007; Forsythe and Van Heukelem 1987; Forsythe 1993; André *et al.* 2009; Semmens *et al.* 2004). Such attributes have led to cephalopods being regarded as one of the potential taxa to benefit from the predicted rise in oceanic temperatures as a result of climate change (Pecl and Jackson 2008). This assumption, however, is predominantly based on the premise that at higher temperatures, within the natural range of a species, octopus will grow and mature faster, yet does not account for the full complexity of their life histories.

Octopus are generally regarded as ecological opportunists (Hanlon and Messenger 1996) that display life strategies typified by short life spans, fast growth and high metabolic rates (Mangold 1983). However, this fast and dynamic life history is a 'double-edged sword'. Populations can respond exceptionally quickly to favourable conditions, yet consist of a single generation exhibiting large annual fluctuations in stock abundance. Thus making them more susceptible to the influence of dramatic environmental changes than many other taxa with multi-generational populations (Boyle 1990; Rocha *et al.* 2001). Therefore a lack of generational overlap and susceptibility to adverse environmental conditions, leaves octopus populations without a buffer for poor recruitment from the previous generation (Caddy 1983). Without a buffer, there is a high possibility that recruitment will fail in the following year if environmental changes have negative impacts on distribution, abundance and productivity of a population (Moltschaniwskyj and Pecl 2003). In a climate change scenario, where previously extraordinary events become more prevalent, the likelihood of such impacts occurring is greatly increased and the potential to predict such impacts greatly reduced. This is compounded by our minimal understanding of many rudimentary biological and ecological factors for the majority of Australia's octopus species.

The dynamic nature of octopus populations and the ease of which environmental variables can significantly alter stocks is a major consideration for fisheries research and management, particularly under climate change scenarios. Initial studies have demonstrated that although some octopus species may thrive, this will come at a trade off with a potential decrease in generation time, streamlining of the life cycle and possible loss of resilience to catastrophic events (André *et al.* 2010). In effect, the sporadic dynamics of octopus populations will be more enhanced, potentially leading to a greater propensity towards boom and bust cycles in commercial fisheries.

Octopus and other cephalopod species which have a pelagic larval stage (i.e. merobenthic) could be amongst the most sensitive of taxa to be affected by ocean acidification, due to their high metabolic rate and extremely pH-sensitive blood oxygen transport system, (Villanueva and Norman 2008). The biological processes in cephalopods that may be significantly influenced by increased temperatures and ocean acidification include: growth, metabolic rate, reproductive and larval development, mobility and stress levels (Lacoue-Labarthe *et al.* 2009). All of which influence population dynamics, potentially leading to a number of detrimental outcomes such as reduced fecundity, biomass and survivorship, or even recruitment failure.

Key points:

- Increases in growth, earlier maturation, reduced fecundity and survivorship of paralarvae.
- Lack of generational overlap can leave a population more susceptible to the impacts of environmental perturbations resulting in reduced recruitment;
- Diminished resilience to significant environmental perturbations.
- Ocean acidification may impact upon growth and survival of paralarvae.

6.5 Resilience to change

The risk of negative implications from climate change are generally lower for the *O.* (cf) *tetricus* population than many other marine taxa, such as long lived teleost and sessile invertebrates. The key component to this reliance is the octopus' position as an ecological opportunist in a wide array of habitats. With the ability to a) manipulate habitat structures to create protective hides, b) explore their environment without the constraints of a shell or exoskeleton, and c) a formidable ability to tackle any prey up to its own size, *O.* (cf) *tetricus* can survive in a multitude of conditions and environments. Specific biological attributes which also contribute to this resilience include: broad paralarval dispersal, high fecundity, fast growth and maternal nesting, where the care females take to ensure the condition and security of their egg clutches helps to enhance recruitment success.

In context to the DOF, the selectivity of trigger traps towards large, old mature males will help to minimise the combined influence climate change impacts and fishing pressure may have on the population. By inadvertently protecting females and small mature males, the possible impacts on recruitment will be far less than in other octopus fisheries where females dominate catch composition (Leporati *et al.* 2009). To maintain and manage this, appropriate assessment and monitoring practices need to be put in place as the fishery expands into new waters and habitat types. This is particularly relevant for waters in the northern extent of *O.* (cf) *tetricus*' distribution, where the bathymetry, location of reefs and temperature regimes differ considerably to the current focal area of fishing effort in the Perth Metropolitan region.

Key points:

- Octopuses are ecological opportunists and play key roles in a large variety of habitats.
- Larval dispersal, high fecundity, fast growth and maternal nesting aid resilience.
- Selectivity of trigger traps will aid in abating the combined impacts of fishing climate change effects may have on recruitment.

6.6 Ecosystem level interactions

Information on the diet and trophic profile of *O.* (cf) *tetricus* is presently unknown. However, octopuses have a ubiquitous distribution throughout the world's marine habitats, playing a central ecological role as predators of molluscs, crustaceans and fish, and as prey for large fish, sharks and marine mammals (Boyle and Rodhouse 2005). These attributes in conjunction with their plastic life history strategies and the clear responses they display to major ecological perturbations, make octopuses a keystone group for drivers in ecosystem change and potential climate change indicators (André *et al.* 2010).

In a fishery context, the high level of interconnectedness between the DOF and the WCRLF indicates that any significant fluctuations in the octopus population will have a direct influence on octopus predation of pot caught lobsters.

Key points:

- Octopus play central ecological roles in a large variety of marine habitats
- Strong responders to environmental change may make octopuses potential climate change indicators

6.7 Additional (multiple) stressors

Additional stressors have not been identified for *O.* (cf) *tetricus* or the developmental octopus fishery, in the context of climate change.

6.8 Critical data gaps and level of uncertainty

Habitat requirements for spawning females are currently unknown. At present rocky reefs are assumed to be the most likely habitat for females to brood their eggs. However, until this has been proven, it is not possible to identify the range and extent of suitable habitat. This has potential implications on the possible impact of climate change on recruitment. For brooding females are effectively sessile, where once a female has laid her eggs she will stay with her clutch of eggs, protecting, cleaning and aerating them. If a female is removed from her eggs, the eggs will generally not survive due to suffocation in silt or predation (Batham 1956). Therefore if the water temperature becomes unsuitable, due to an extreme event such as a marine heat wave or gradually due to climate change, the available habitat for spawning may be greatly diminished.

Information on the distribution and abundance of *O.* (cf) *tetricus* stocks outside of the Perth metropolitan waters is very limited, due to fishers only accessing these waters with trigger traps since 2011. Further research is required on the distribution and abundance of *O.* (cf) *tetricus* in northern waters from 27° to 30° latitude, including the Abrolhos Islands. These areas have been identified as large potential fishing grounds for the DOF, but will also be the first to witness the brunt of climate change impacts. At the other end of the species distribution, on the south coast, even less is known including whether or not it is part of the same population as the west coast. As the southern extreme this region may see increases in the *O.* (cf) *tetricus* population under certain climate change scenarios. This has been witnessed on the east coast of Australia, where *Octopus tetricus* has increased its southerly distribution through the strengthening and increased penetration of the East Australia Current (Leporati pers. obs.).

Key points:

- Uncertainty on habitat requirement of spawning females.
- Lack of knowledge about the distribution and abundance of the species beyond present fishing grounds, for this expanding fishery.

6.9 Future climate scenarios (2030/2060)

Research has not been conducted or is currently planned, to address the impacts of future climate scenarios on the *O.* (cf) *tetricus* population or the developmental octopus fishery.

6.10 Management implications

Without information available on the current or potential implications of climate change on stocks in the DOF, it is difficult to identify management strategies that will negate any negative impacts. Regardless, the key to managing this uncertainty is the construction of flexible and adaptive management arrangements. As an extremely dynamic population that is driven and highly responsive to environmental change, particularly temperature, it will be a matter of course that the *O.* (cf) *tetricus* population will fluctuate with climate change. These factors, plus lack of generational overlap and possible shortening of generation times, places great emphasis on the need to assess stocks annually. Hence, respect to latitudinal difference in the population may also need to be considered, as more is learnt from the expansion of the fishery into new grounds. To address this, spatial considerations and zoning of catch and effort controls, may be beneficial.

Key points:

- Need for flexible management arrangements that integrate spatial and temporal considerations in regard to latitudinal difference in the octopus population (s).

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7.0 Greenlip and Brownlip Abalone (*Haliotis laevigata*; *H. conicopora*)

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7.1 The fishery

The Greenlip/Brownlip Abalone Managed Fishery (AMF) is a dive fishery, operating in shallow coastal waters off the south-west and south coasts of Western Australia (WA) (Figure 7.1.1). The fishery targets two abalone species: Greenlip Abalone (*Haliotis laevigata*) and Brownlip Abalone (*H. conicopora*). Both are relatively large, deeper water *Haliotis* species, growing to around 200 mm shell length, and are primarily restricted in distribution to the south coast of Australia. In WA, abalone are fished mainly by commercial fishers, however a small recreational fishery amounting to approximately 3-4% of the total catch also exists (Hart *et al.* 2010).

The Greenlip/Brownlip AMF is managed primarily through output controls in the form of Total Allowable Commercial Catches (TACCs), set annually for each species in each area and allocated to licence holders as Individual Transferable Quotas (ITQs). ITQs are specific to management areas (Table 7.1.1). The TACC for the AMF is administered through 16,100 ITQ units, with a minimum unit holding of 450 units required before a Managed Fishery License (MFL) can be granted (Table 7.1.1). The licensing period runs from 1 April to 31 March of the following year for all species and fishing grounds. The catch of Greenlip and Brownlip has been relatively steady over the last 20 years with about 180 and 30 t, respectively (Figure 7.1.2).

A Legal Minimum Length (LML) exists for both abalone species. The LML for Greenlip and Brownlip Abalone is 140 mm shell length, although the commercial industry fishes to self-imposed size limits of 153 mm, 147 mm and 145 mm in various parts of the main stocks (Table 7.1.1). Size-at-maturity is (75–90 mm) which is well below LML. Slow growing or 'stunted stocks' are also fished. These stocks have been shown to not grow to the current LML, and are fished at 120 mm under special fisheries exemption permits. Stunted stock fishing is strictly controlled to pre-arranged levels of catch and effort.

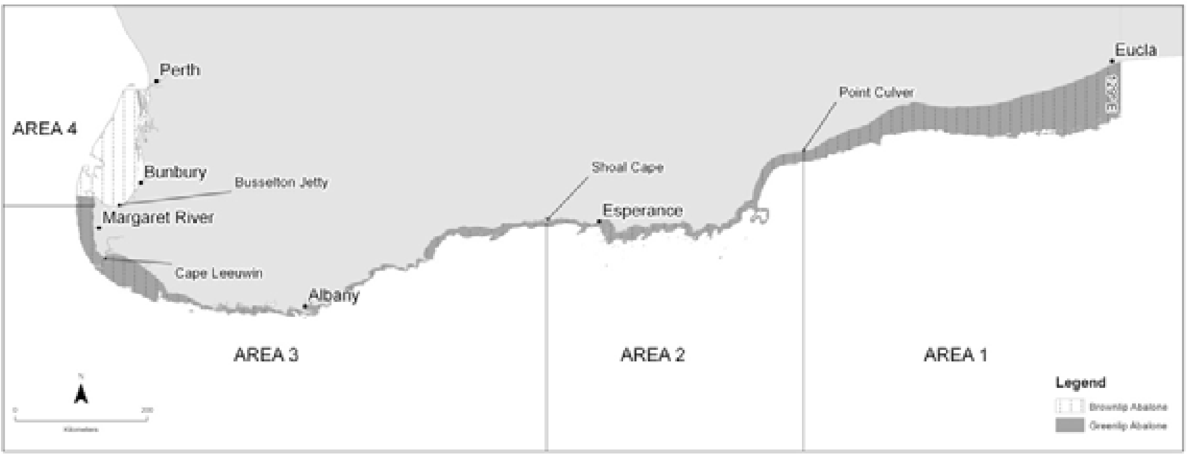

Figure 7.1.1. Distribution of Greenlip and Brownlip Abalone in Western Australia, and the management areas used to set quotas for the commercial fishery. Area 4 currently has no quota allocated.

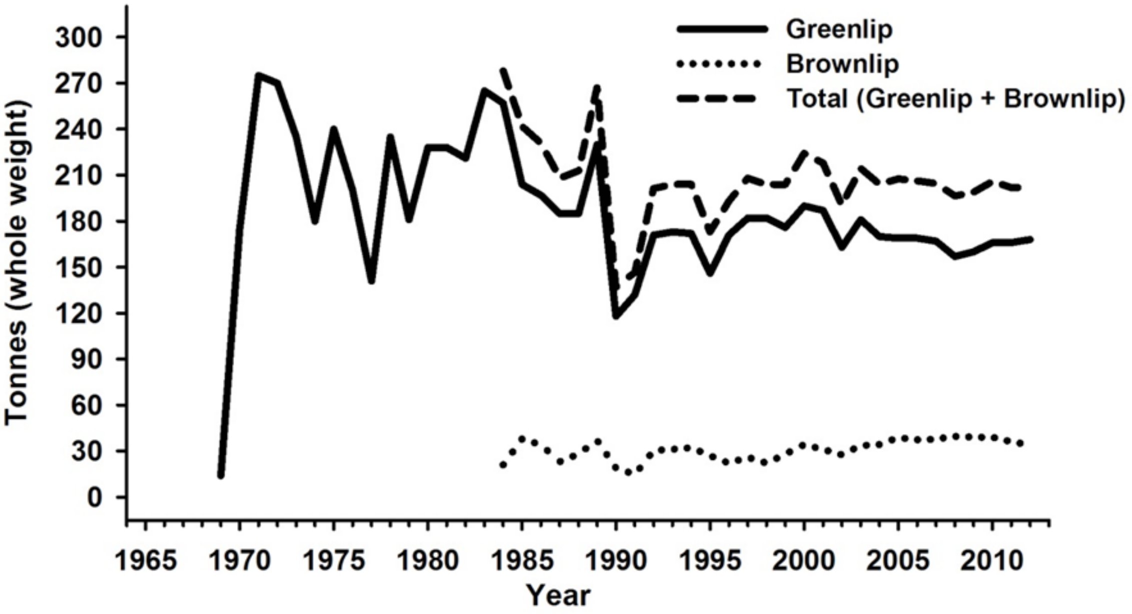

Figure 7.1.2. Historical commercial catch estimates (tonnes whole weight) from Greenlip and Brownlip Abalone fisheries in Western Australia.

Table 7.1.1. Management details relevant to commercial Greenlip and Brownlip Abalone fisheries in Western Australia. Commercial minimum lengths refer to self-imposed voluntary minimum lengths imposed by the commercial fishers.

Species	Area	No. of Fishery Licenses (MFLs)	ITQs	Current TACC (t) (2013)	Current value of ITQs (kg)	Legal Minimum Lengths (mm)	Commercial Minimum Lengths (mm)
Greenlip	1	6	600	3.2	5.33	120	120
	2	6	6000	76.8	12.8	140	145
	3	8	7200	93.3	12.96	140	147 & 155
Brownlip	1	6	60	0.06	1.0	140	150
	2	6	1440	18.0	12.5	140	150
	3	8	800	18.0	22.5	140	150
TOTAL				209			

Key points:

- The Greenlip and Brownlip dive fishery is Western Australia’s most valuable abalone fishery with the catch over the last 20 years being about 180 and 30 t respectively and is currently worth about $8 million.
- The fishery has been a catch quota control fishery since 1988.

7.2 Life history

7.2.1 Life cycle, age and growth

Greenlip Abalone (*H. laevigata*; Figure 7.2.1.1) and Brownlip Abalone (*H. conicopora*; Figure 7.2.1.2) belong to the Family Haliotide, which comprises around 75 species of shelled marine gastropods (Geiger and Owen 2012). Haliotidae are distributed worldwide and all species of abalone are described within this family. Abalone are found along rocky shores in temperate and tropical waters, and are generally found in shallow subtidal waters from 0 to 30 m depth. There are no abalone species of global distribution and most species have restricted ranges. Greenlip and Brownlip Abalone are co-occurring temperate endemic Australian species whose distribution extends from the south-west of Western Australia to Tasmania. Brownlip Abalone is considered a sub-species of *H. rubra*, which is the primary commercial abalone species in eastern Australia (Geiger and Owen 2012).

Greenlip and Brownlip Abalone are broadcast spawners; they release gametes (both sperm and eggs) into the water column where fertilisation occurs. The ova develop into a veliger stage and settlement usually occurs around 8 to 10 days post-hatching. When they are ready to metamorphose they settle onto suitable habitat. Evidence has been found for the preferential selection onto certain habitat based on chemical cues emanating from coralline algae and biofilms that have been grazed by conspecifics (Roberts 2001).

The breeding season of Greenlip Abalone varies between locations but is generally confined to the spring/summer months. Shepherd *et al.* (1992) found an extended season from September to March at one location, and a restricted season (December) at another location in South Australia. In Western Australia the spawning months were also confirmed as between October and December, with a peak in December (Wells and Mulvay 1992). Some sites showed evidence for partial spawning during the late summer months and it is likely that the exact timing within a season varies from year to year and location to location depending on the food availability (primarily dictated by swell) and temperature regime.

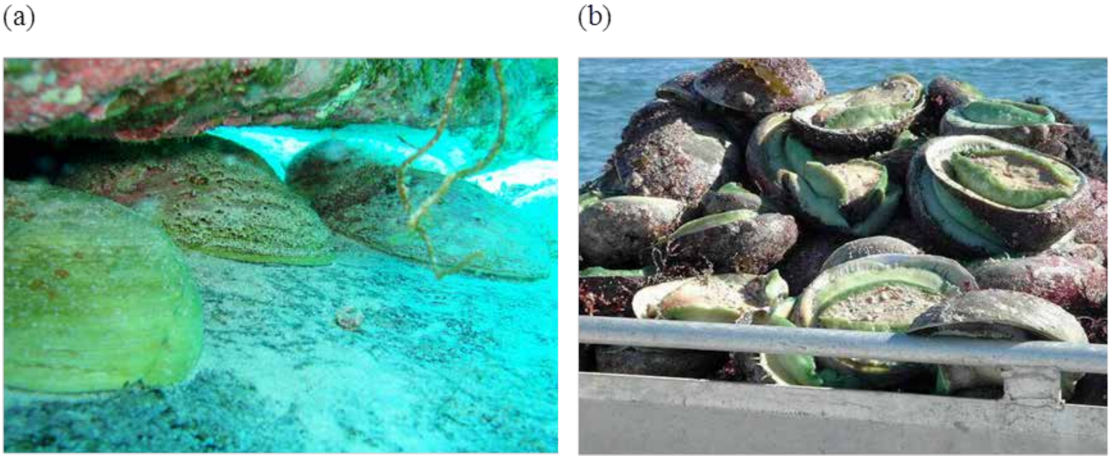

Figure 7.2.1.1. Greenlip Abalone in its (a) natural habitat, and (b) harvested for sale.

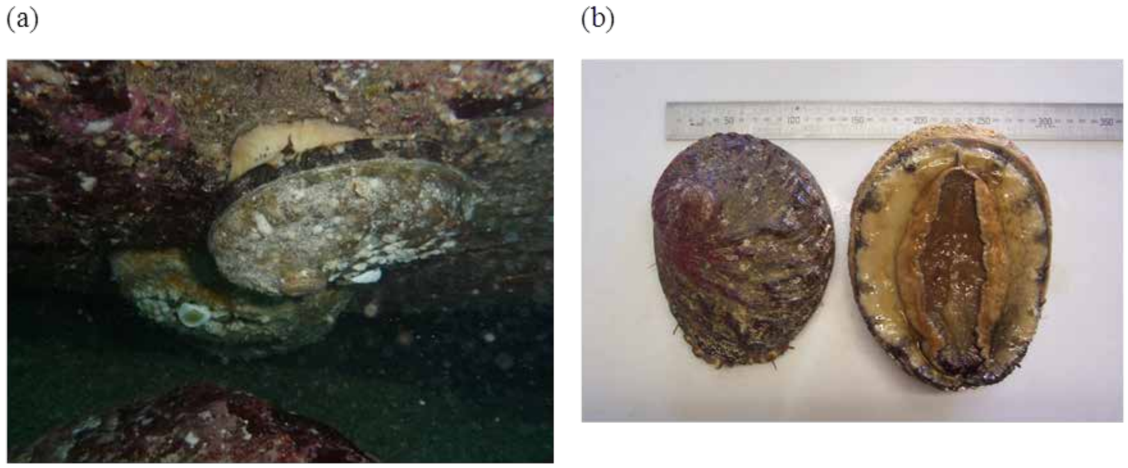

Figure 7.2.1.2. Brownlip Abalone in its (a) natural habitat and (b) harvested for sale.

All abalone exhibit large spatial heterogeneity in growth, with "stunted" populations occurring in all abalone fisheries (Figure 7.2.1.3). At the larger/faster end, Greenlip Abalone populations reach an average maximum size of about >180 mm. At the lower end of the growth spectrum, stunted stocks grow to about 125–133 mm shell length, which is below the legal minimum length. This is a difference in growth of between 12 and 38 mm yr-1 for an 80 mm animal in different areas.

To ensure optimal and sustainable exploitation, populations with different growth characteristics require harvest strategies that account for this variability. Typically, this is achieved via the use of spatially varying size-limits and TACCs matched to the productivity of the population (Mayfield and Saunders 2008; Tarbath and Officer 2003). In the case of Greenlip Abalone, comparisons of growth parameters from tag-recapture studies across Australia reveal wide variability within and between fisheries (Figure 7.2.1.3).

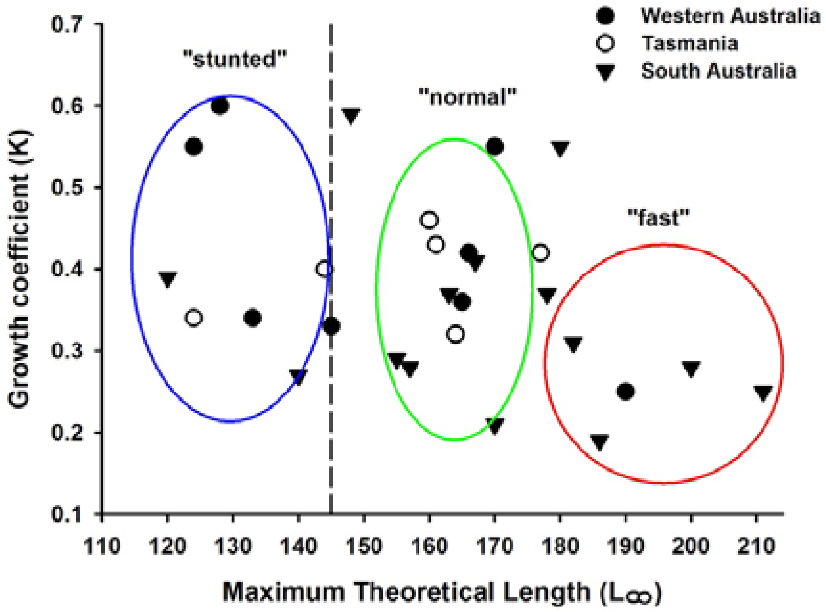

Figure 7.2.1.3. von Bertalanffy growth parameters (K, L∞) from Greenlip Abalone populations within and between state fisheries in Australia. Data have been grouped into "stunted", "normal" and "fast" growth stocks in relation to the LML of 140 mm (dashed line) for the WA fishery. Growth parameters sourced from: Hart *et al.* (2013a), Mayfield *et al.* (2003), Officer (1999), Shepherd and Hearn (1983), Shepherd *et al.* (1992), Wells and Mulvay (1995).

7.2.2 Distribution, habitat and environmental preferences

Greenlip and Brownlip Abalone comprise small spatially disaggregated populations within a broader overall metapopulation structure (Shepherd and Brown 1993). Genetic studies show significant differences in allele structure between populations at relatively fine scale of tens of km, such that stocks are composed of local populations linked by occasional larval dispersal into metapopoulations. Genetic subdivision across SE Australia indicated that Greenlip do not comprise a single, large, panmictic population (Mayfield *et al.* 2014). Differentiation was most evident at the two largest scales: among biogeographic regions (i.e. hundreds of kilometres) and among locations within regions (i.e. tens of kilometres). These yielded a strong pattern of isolation by distance. Overall, Mayfield *et al.* (2014) estimated that populations generally encompass reef areas of around 30 km^2, which are largely maintained through self-recruitment, and that distances of up to 130 km are effective barriers to larval dispersal.

Greenlip and Brownlip Abalone inhabit suitably exposed hard surfaces (usually granite or limestone) on subtidal rocky reefs between 1 and 40 m depth, however the commercial fishery primarily targets the 5 to 25 m depth range. The habitats need to be firm enough to provide a suitable substrate for attachment, be capable of trapping floating seaweed which the abalone feed on, and be sufficiently endowed with a supply of certain types of red algae (Rhodophyta) which are the preferred food source for this species (Shepherd and Steinberg 1992). The delicate structure and susceptibility of red algae to wave exposure ensures that the highest swell-exposed areas are usually sub-optimal habitat, not capable of supporting larger populations of Greenlip Abalone. In the case of Greenlip, the largest populations are found in the Augusta and Cape Arid regions of Western Australia, which are characterised by small island complexes and headlands that buffer the southerly swells, create localised hydrodynamics that promote recruitment, and allow sufficient seagrass meadows and Rhodophyte communities to develop. Seagrass meadows are particularly important due to the prevalence of epiphytic red algae that are the sought-after food species; the typical feeding pattern arises after sustained oceanic swells dislodge the algae and render them available to be trapped within the reef complexes and consumed by the resident abalone populations. Although inhabiting the same general reef areas, Brownlip Abalone have more specialised habitat requirements. They are a far more cryptic species, generally requiring a complex boulder structure that they shelter underneath, typically known as “caves”.

Habitats in general are very restricted and there is a large patchiness to the extent of commercially fished stocks.

7.2.3 Predators and prey

Greenlip and Brownlip Abalone are preyed upon by a number of roving predators. In the small juvenile stage (<4 cm length), wrasses (Family Labridae), crabs, and octopus are significant predators, as the animals obtain adult size they are less vulnerable and the main predator is the Eagle Ray. Greenlip Abalone have a stronger, heavier shell and prefer more exposed areas, whereas Brownlip Abalone, although larger, possess a weaker, lighter shell and remain cryptic as adults to ensure protection. They are opportunistic feeders on drift algae and have no prey as such.

7.2.4 Recruitment

Recruitment of two-year old juveniles in Greenlip has been shown to be density dependent, with the likely mechanism hypothesised to be limitation in appropriate crevice habitat for sheltering juveniles (Dowling *et al.* 2004). However the degree to which this occurs is location-specific, with areas carrying a higher proportion of suitable juvenile habitat exhibiting less density dependence. For example, Hart *et al.* (2013b) experimentally increased recruitment of Greenlip Abalone through a series of stock enhancement experiments, which resulted in significantly increased adult densities in the short-term, indicating that density dependence had not limited survival of recruits at those sites. Dixon (2011) experimentally examined density dependence in juvenile Greenlip Abalone by constructing and modifying experimental boulder habitats and found a strong density-dependence effect on growth and a significant, but weaker, density-dependent effect on survival. An environmental signal affecting recruitment of both Greenlip Abalone and invertebrates in general on the west coast of South Australia was also postulated by Dowling *et al.* (2004) but the mechanism remains unconfirmed. Allee effects (or depensation) have also been implicated in the collapse of recruitment due to the importance of aggregation for fertilisation success and Dowling *et al.* (2004) constructed a stock-recruitment curve that incorporated a parameter (the x-intercept) for depensation in greenlip abalone in South Australia.

Key points:

- Greenlip and Brownlip Abalone are broadcast spawners; they release gametes (both sperm and eggs) into the water column where fertilisation occurs.
- The ova develop into a veliger stage and settlement usually occurs around 8 to 10 days post-hatching.
- As a result of the restricted larval duration, Greenlip and Brownlip Abalone comprise small spatially disaggregated populations within a broader overall metapopulation structure. They are restricted to the south-west and south coasts of Western Australia.
- Abalone are opportunistic feeders on drift algae and are preyed upon by a number of roving predators including wrasses, crabs, octopus, and eagle rays.
- Recruitment is positively related with spawning biomass, but has also been shown to be density dependent, with the likely mechanism hypothesised to be limitation in appropriate crevice habitat for sheltering juveniles.

7.3 Current impacts from climate change

Climate change is causing an increase in water temperature (Pearce and Feng 2007), particularly in the autumn-winter (Caputi *et al.* 2009), a weakening of storms (westerly winds) in winter (IOCI 2012), and a changing frequency of El Niño and La Niña events that affects the Leeuwin Current. The increase in water temperature is higher on the lower west coast and less on the south coast. The marine heat wave in the summer of 2010/11 was strongest on the mid-west but also influenced the lower west coast with a lesser effect on the south coast. However the water temperatures during the summer of 2012/13 were at record-high levels on the south coast.

Rising water temperatures over 35 years may result in a decrease in size at maturity, and maximum size, and a decline in growth rate and general productivity. Optimal temperatures for Greenlip Abalone are around 18°C, whereas Brownlip can tolerate lower temperatures and a larger range in temperatures (Freeman 2001).

Key points:

- There has been an increase in water temperature, particularly in autumn-winter, a weakening of storms (westerly winds) in winter, and a changing frequency of El Niño and La Niña events that affects the Leeuwin Current.
- Rising water temperatures may result in a decrease in size at maturity and maximum size of Greenlip and Brownlip Abalone.
- Greenlip and Brownlip Abalone species in general are considered to be at medium-high risk to climate change.

7.4 Sensitivity to change

The restricted larval distribution of Greenlip and Brownlip abalone, the patchiness of suitable habitat, and relatively sensitive tolerance to temperature renders these species susceptible to climate change. Greenlip in particular are considered the most vulnerable as their range is more restricted than Brownlip. For example, the most productive population of Greenlip Abalone is currently at the western extreme of the range distribution. It is therefore the most vulnerable.

The risk assessment of Greenlip and Brownlip Abalone rated them as a medium-high risk with a sensitivity assessment of high (see Table 7.2.2.3 in Part 1 of report).

7.5 Resilience to change

Both Greenlip and Brownlip Abalone occur over a large geographic range (Greenlip: 34–41ºS; Brownlip: 31–43ºS) with a considerable variation in average sea surface temperatures, which would make the overall fishery resilient to changes in water temperature. Furthermore, the large plasticity in growth rates and maximum size indicate an ability to adapt to changing environments.

The pro-active management arrangements, including recent TAC drops in parts of the fishery, in response to declining productivity, will increase the resilience of the fishery.

Key points:

- Both Greenlip and Brownlip Abalone occur over a large geographic range with a considerable variation in average sea surface temperatures, which would make the overall fishery resilient to changes in water temperature.
- The pro-active management arrangements, including recent TAC drops in parts of the fishery, will increase the resilience of the fishery.

7.6 Ecosystem level interactions

A comprehensive analysis of the ecological role of *Haliotis rubra* on reef ecosystems in Victoria found limited evidence of any impact of fishing, indicating that ecological effects of abundance changes are likely to be highly localised and undetectable at a population scale (Hamer *et al.* 2010). Being opportunistic feeders that rely on drift algae as a primary food source, abalone are not generally considered to play a major role in the structuring or performance of their ecological community.

7.7 Additional (multiple) stressors

The fishery is regarded as fully exploited. The harvest control rules are currently focused on maintaining the egg production above a threshold level.

The marine heatwave effects in the summer of 2010/11 resulted in water temperatures reaching 3–5ºC above average in the mid-west region of WA (Pearce *et al.* 2011). When these temperatures were combined with calm conditions in late February and early March, a catastrophic mortality of a closely related commercial species (*Haliotis roei*) occurred at the northernmost extent of its distribution. No mortalities were observed in Greenlip and Brownlip, however declines in density of the very largest size animals at the westernmost stocks (Cape Leeuwin) may be partly caused by temperature related declines in growth.

Key points:

- Fishery is regarded as fully exploited with harvest control rules to adjust the quota according to any changes in abundance observed.
- Marine heat wave effects may have been felt in the most western part of its distribution.

7.8 Critical data gaps and level of uncertainty

The large spatial variation in growth and maximum size indicates that abalone have a capacity to accommodate significant changes in their localised environment, particularly in relation to food supply. Therefore despite their inherent susceptibility, they may also possess a strong capacity to adapt to a changing environment. The main knowledge gap is information on long-term recruitment patterns and how this is correlated with climate factors. The establishment of a long-term recruitment monitoring program will address this knowledge gap.

7.9 Future climate scenarios (2030/2060)

Climate change implications associated with the environmental factors (water temperature and storm activity) have been shown to affect the spawning and larval period of other marine invertebrates, crab and lobster, for example. These trends in water temperature and storm activity are projected to continue (Feng *et al.* 2012, Indian Ocean Climate Initiative 2012, Part 1 of this report). Significant effects of climate factors on growth and mortality have already been demonstrated for *Haliotis roei*. The most likely change is a shifting of the main areas of production eastward.

7.10 Management Implications

Currently management is retrospective in the Greenlip and Brownlip Abalone fisheries, and relies on trends in abundance of commercial fishery catch rates. For management to be more responsive to climate change effects, predictive measures of upcoming year classes based on pre-recruit abundance are required. This is a current area of investigation.

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8.0 Roe's Abalone (*Haliotis roei*)

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8.1 The fishery

The Western Australian fishery for Roe's Abalone is a dive and wade fishery, operating in shallow coastal waters along WA's western and southern coasts (Figure 8.1.1). Roe's Abalone are found in commercial quantities from the South Australian border to Shark Bay, although they are not uniformly distributed throughout this range.

The commercial fishery harvest method is a single diver working off a 'hookah' (surface supplied breathing apparatus) using an abalone 'iron' to prise the shellfish off rocks. Abalone divers operate from small fishery vessels (generally less than 9 metres in length). The recreational fishery harvest method is primarily wading and snorkelling, with the main area of focus for the fishery being the Perth metropolitan stocks in the WCB.

Commercial catches began in this fishery in 1964 on the Perth metropolitan stocks, and peaked at 170 t in 1971, before declining to a relatively constant level of around 100 t between 1980 and 2010. Recreational catch is significant in this fishery, currently comprising around 40% of the total catch (Hart and Brown 2010). Recreational catch estimates are available since 1992, however considerable recreational catch also occurred in the 1980s. From 2005 to 2010 the recreational increased, then decreased along with total catch (Figure 8.1.2).

Figure 8.1.1. Roe's abalone distribution in Western Australia.

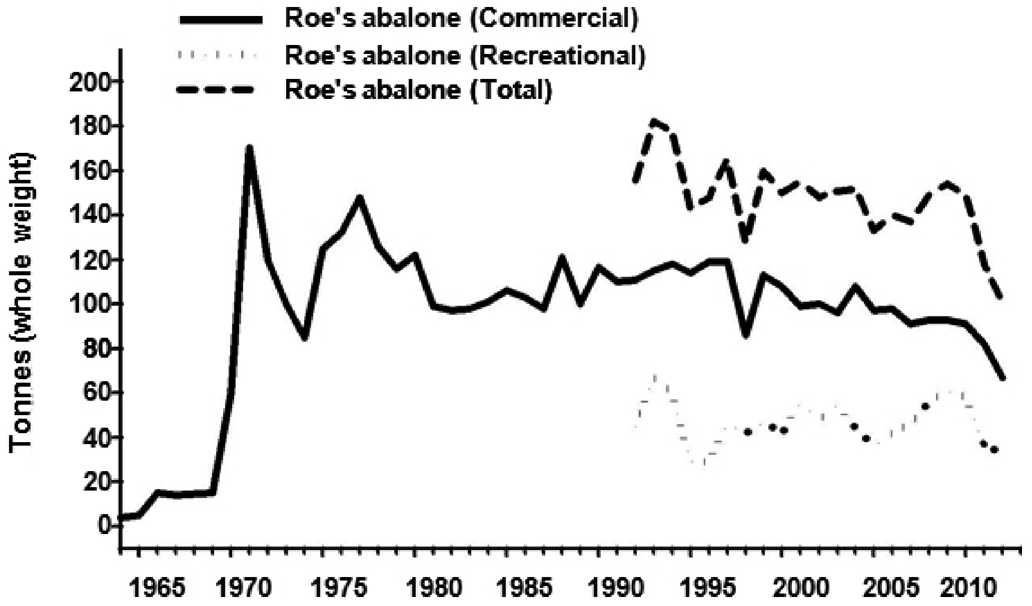

Figure 8.1.2. Historical commercial and recreational catch estimates (tonnes whole weight) from Roe's abalone fisheries in Western Australia.

8.2 Life history

8.2.1 Life cycle, age and growth

All commercially targeted Western Australian species of abalone live on exposed, high-energy coasts and have evolved life-history characteristics to enable survival in this environment. General traits include: a muscular foot capable of providing solid attachment during periods of prolonged exposure; a feeding behaviour primarily focused on drifting algae dislodged by wave action, rather than actively grazing as do many other gastropods herbivores (Shepherd and Steinberg 1992); broadcast spawning by separate sexes, synchronised by seasonal cues such as change in water temperature and lunar periods, a relatively short larval life-span of between 5 and 10 days to allow for quick settlement back into localised populations (McShane 1992), use of specialised larval settlement substrate such as crustose coralline algae, and a relatively slow and long-lived life duration (McShane 1992).

Figure 8.2.1. *Haliotis roei* in its (a) natural habitat, and (b) harvested for sale.

8.2.2 Distribution, habitat and environmental preferences

Roe's Abalone (*Haliotis roei*; Figure 8.2.1) belong to the Family Haliotide, which comprises around 75 species of shelled marine gastropods (Geiger and Owen 2012). Haliotidae are distributed worldwide and all species of abalone are described within this family. Abalone are found along rocky shores in temperate and tropical waters, and are generally found in shallow sub-tidal waters from 0 to 30 m depth. There are no abalone species of global distribution and most species have restricted ranges. Roe's Abalone are found in commercial quantities from the South Australian border to Shark Bay (Figure 8.1.1), although they are not uniformly distributed throughout this range.

Roe's Abalone populations occur on semi-continuous reef complexes, each of which is generally less than 10 km of length. The habitat occupied by this species is the intertidal reef platforms and shallow adjoining sub-tidal reef for up to 30 to 40 m beyond the reef platforms. The settlement zone for new recruits is primarily the "outer habitat" zone on the reef platforms. They inhabit areas of high wave action and are most abundant on inter-tidal and shallow sub-tidal limestone platforms on the west coast. This species is mainly found in depths of 0 to 3 metres and prefers water temperatures of 14 - 26°C (Yearsley *et al.* 1999).

Roe's Abalone are sedentary animals and generally only make small–scale movements within their local habitats, primarily to feed. Long-term survey data suggests a small scale movement from the area of settlement (outer habitat on platform reefs) to other intertidal and subtidal areas of the reef. In particular, sub-tidal areas have a significantly larger mean size of abalone. Aggregative behaviour has been noted in relation to spawning (Shepherd 1986), but the primary source of movement is in the larval stage, mediated by ocean currents.

Roe's Abalone are broadcast spawners; they release gametes (both sperm and eggs) into the water column where fertilisation occurs. The ova develop into a veliger stage and settlement usually occurs around 8 to 10 days post-hatching. When they are ready to metamorphose they settle onto suitable habitat. Evidence has been found for the preferential selection onto certain habitat based on chemical cues emanating from coralline algae and biofilms that have been grazed by conspecifics (Roberts 2001).

Roe's Abalone had major spawnings in winter in Perth metropolitan stocks (Wells and Keesing 1989), whereas in South Australia the species appears capable of spawning all year round (Shepherd and Laws 1974).

Egg production by an individual female can be very high. Individual fecundity of large females has been measured at up to 8.6 million eggs in a large (122 mm) Roe's Abalone (Wells and Keesing 1989). Size-at-maturity and length-fecundity relationships for this species at two sites in WA are shown in Table 8.2.1.

Table 8.2.1. Size-at-maturity and length-fecundity relationships for Roe's Abalone in WA. Length-fecundity equations are of the form $F =aLb$, where F is fecundity (millions of eggs), and L is length (mm).

Location	Size at 50% maturity (mm)	Length-Fecundity parameters		Source
		a	b	
Perth (Waterman)	40	1.98×10^{-2}	4.52	Keesing (1984)
Perth (Marmion)*		9.00×10^{-8}	4.28	Unpublished data

* the fecundity parameters (a,b) for Marmion are for length-gonad weight equations of the form $GW = aL^{b}$, where GW is gonad weight (g).

8.2.3 Predators and prey

Post settlement abalone feed on diatoms and at approximately 5 mm long, commence feeding on a macro-algal diet. Between 5–10 mm this is largely comprised of crustose coralline algae.

Roe's Abalone are macroalgal herbivores and feed on the most prevalent type of algae found in their particular area. All Australian abalone species feed primarily on red algae (70–80%) with small amounts of the more palatable brown algae such as *Lobospira* sp. also consumed (Shepherd and Steinberg 1992) when red algae is not as abundant. Roe's Abalone primarily feed on drift algae; the typical feeding pattern arises after sustained oceanic swells dislodge the algae and render them available to be trapped within the subtidal reef complexes and subsequently consumed by the resident abalone populations. Volumes of algae in gut contents were found to be greatest in winter, which coincides with the period of sustained oceanic swells and therefore highest food availability.

Predators of the large-sized individuals include stingrays, fish, octopus, rock lobsters, starfish and predatory whelks.

An Australia-wide survey of diseases and parasites in abalone found a number of organisms with disease potential, including *Perkinsus* and *Vibrio* species (Handlinger *et al.* 2006). The principal parasite affecting several abalone species (which may infect Roe's abalone) is a protozoan parasite known as *Perkinsus* (Goggin and Lester 1995). This causes flesh deformities which greatly reduces market value, and is pathogenic in naive populations such as in areas of the NSW Blacklip Abalone fishery (Handlinger *et al.* 2006). *Perkinsus* parasites have been found in over 30 species of molluscs and are naturally occurring in Greenlip Abalone from South Australia (Goggin and Lester 1995) and New South Wales (Liggins and Upston 2010). It was found to be seasonally variable, being more abundant in late summer and autumn than in late winter, and abalone are more susceptible to infection at high temperatures. *Perkinsus* was heavily implicated in the demise of the New South Wales Blacklip Abalone fishery and evidence of substantial tissue necrosis, organ damage and haemocyte activity associated with *Perkinsus* sp. cells in surveys between 2002 and 2005 showed that this parasite is pathogenic to abalone in that state (Liggins and Upston 2010). With respect to Roe's Abalone, limited evidence has been found of parasites, however this species naturally hybridises with Greenlip Abalone in the wild so may be similarly susceptible.

8.2.4 Recruitment

Factors affecting recruitment in juvenile Roe's Abalone are not well understood. The animal lives in a highly exposed environment with a spatially-limited recruitment. In the largest fishery which encompasses the Perth metropolitan area and provides a significant recreational and commercial catch, recruitment surveys have been undertaken since 1997. Recruitment in Roe's Abalone in this area is measured by the density of Age 1 animals derived from fishery-independent monitoring surveys. Overall, density of Age 1 animals is significant positively correlated with spawning biomass (2 years previously), however there are substantial differences between sites (Figure 8.2.2). Recruitment over time at most sites has been stable, with the exception of Mettams, where it has declined (Figure 8.2.2).

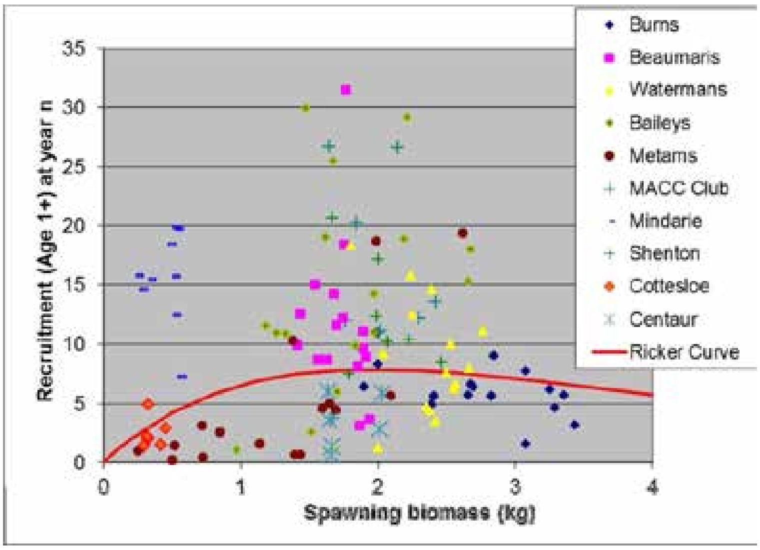

Figure 8.2.2. Ricker stock-recruitment equation (curved line) fitted to data for Roe's Abalone in WA. Equation fitted to spawning biomass (Year *n-2*) paired with future recruitment density of Age 1+ animals (Year *n*). Equation is fitted to data obtained from fishery-independent surveys and density and biomass units are per m^2.

8.3 Current impacts from climate change

Roe's Abalone are at high-risk in terms of their susceptibility to climate change. Evidence of their susceptibility has already been confirmed, with Roe's Abalone in the most northern fishery (near Kalbarri) experiencing catastrophic mortality due to the marine heat wave during the summer of 2010/11 in WA and the fishery has been closed indefinitely (Hart *et al.* 2013). In addition, this assessment has identified potential negative effects on growth and mortality from this heat wave within the Perth metropolitan area (see Part 1, Section 7.1.2; Figure 8.3.1).

8.4 Sensitivity to change

The hypothesis that Roe's Abalone in the Perth metropolitan fishery were heavily impacted by the marine heat wave in 2011 has been explored by comparing relative abundances and size structures in fished and non-fished areas. The data provide strong evidence that the recent downturn in recruitment was not caused by excessive fishing on the overall stock, i.e. as recruitment trends in fished areas are essentially mirrored by those in unfished areas.

The Waterman's Reserve is a marine protected area within the Perth Roe's Abalone fishery which has been protected for over 40 years. Annual monitoring of densities in this area is carried out to provide information on environmental effects on recruitment that can be measured independent of any effects of fishing.

Between 1997 and 2012, the total density of Roe's Abalone in fished areas was, on average, about 60% of unfished densities (Figure 8.3.2a). In comparison, there was no difference in mean density of Age 1+ animals between fished and unfished areas (Figure 8.3.2b), however trends in recruitment were highly correlated ($r = 0.85$), confirming that environment is the main driver of recruitment levels in this fishery. The three worst years of recruitment (2012–2014) were the same for both fished and unfished stocks. The environmental effect is hypothesized to be the marine heat wave of 2010/11, which completely decimated the Roe's Abalone stock several hundred kilometres to the north of Perth, in Kalbarri. The fishery was at the northernmost limit of the distribution of this species in WA.

A clear pattern emerges when examining the percentage of the population that is comprised of ≥75 mm abalone (Figure 8.3.2c). There is a declining trend between 2003 and 2010 in both fished and unfished stocks; however the rate of decline increases sharply between 2010 and 2012. Large animals in the marine reserve declined from a high of 20% in 2003 to 5% in 2012/13 (Figure 8.3.2c). A similar decline occurred in fished stocks, however not as severe.

This decline in both recruitment and large animals was associated with a period of elevated sea surface temperatures during summer (January to April) in the Perth region from 2011 to 2013 (Figure 8.3.2d). It is hypothesised that the large declines in density of large Roe's Abalone, particularly in platform habitats (recreationally fished stocks) resulted from a combination of heavy recreational pressure during the 3 years preceding the heatwave (2008–2010) followed by mortality and/or stunting in growth during the high SST years of 2011–2013.

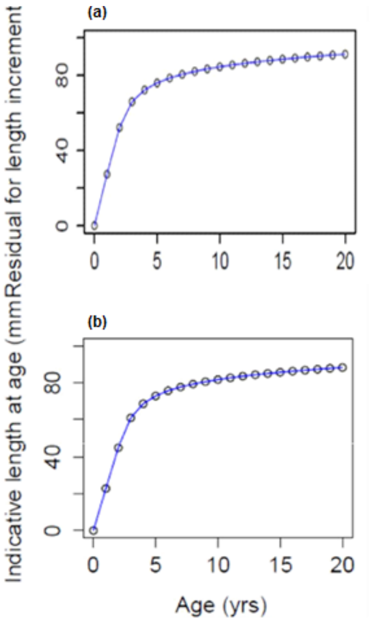

Figure 8.3.1. Expected lengths at each integer age. Plots associated with the fitting of an inverse logistic model to tag increment data for Roe's abalone from (a) commercial fishery (subtidal habitat) and (b) recreational fishery (platform habitat).

It is also worth noting that a large recruitment in 1999 (Age 1+ density of 15 m^{-2}) in the Watermans Reserve (Figure 8.3.2b) was followed by a peak in percentage of abalone ≥75 mm in 2003 (Figure 8.3.2c). This four year lag has been confirmed previously for fished stocks. It is also corroborated by growth analyses, which suggest there is an average of 4 years growth period between individuals of ~25 mm length compared with ~76 mm (i.e. from age 1 to 5 years) (Figure 8.3.1). However, the peak in large animals only lasted 2–3 years. This is likely related to the fact that the previous and subsequent year's recruitment (Age 1+ density in 1998 and 2000) in the Marine reserve were only 13% and 35% respectively, of the 1999 recruitment.

Based on a 4-year lag, the higher recruitment years in 2008 to 2010 in the Watermans Reserve should have resulted in increases in percentage of large animals over the 2012 to 2014 period. However, this has not occurred to date (Figure 8.3.2c). In fact the opposite is true; the percentage of large animals is at its lowest level ever. This is further evidence of a major environmental effect on mortality and/or growth.

The risk assessment of effects of climate change on species in WA has ranked Roe's Abalone as having high sensitivity and high exposure and hence a high risk ranking. The effect of the marine heat wave on stock in recent years has provided some support of that risk ranking.

Cheung *et al.* (2012) used a dynamic bioclimate envelope mode to predict that the major impact of climate change on 30 marine species in WA. They projected that centroid of Roe's Abalone population could shift 151 km along the coast.

a) b)

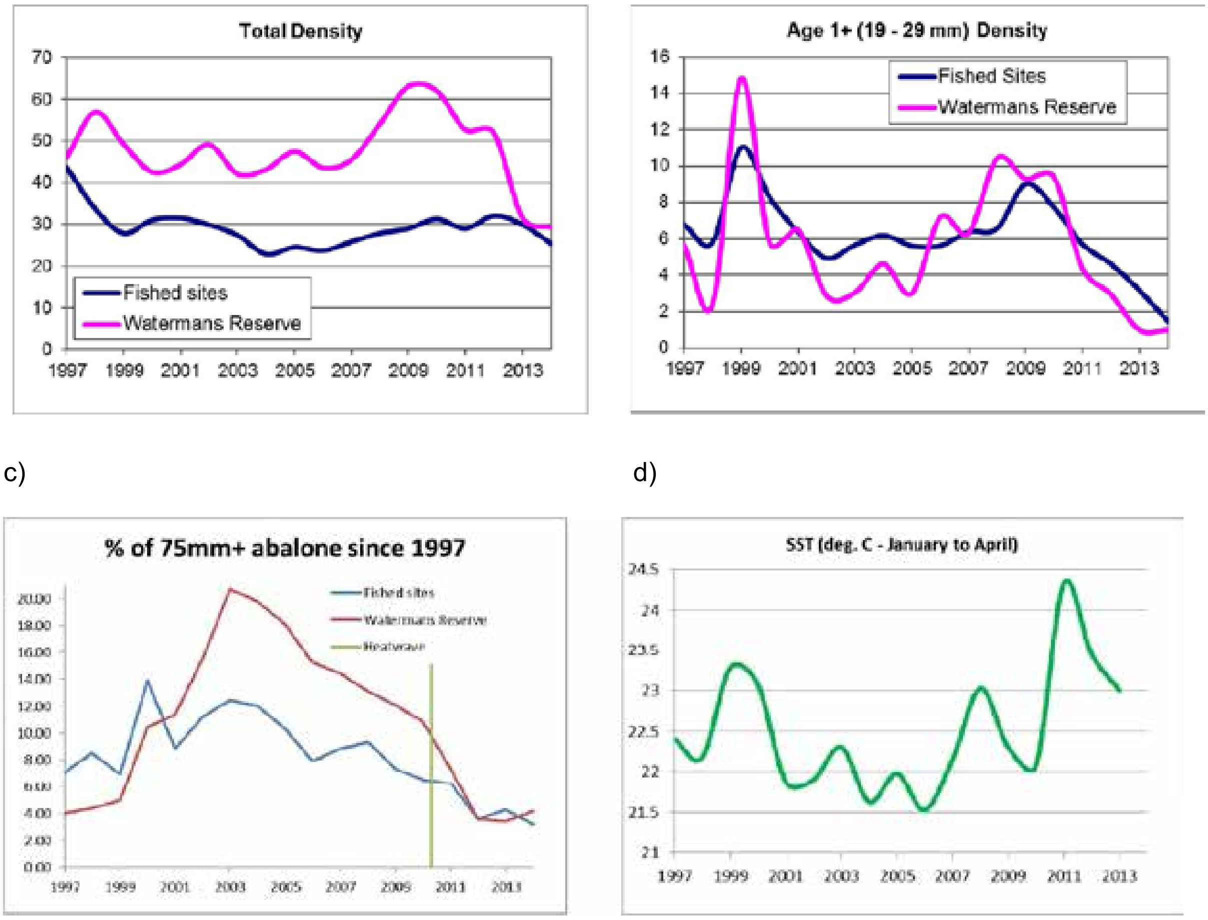

Figure 8.3.2. A comparison of (a) total density, (b) recruitment density, and (c) % of large animals (≥75 mm) of Roe's Abalone between fished sites and the Watermans Reserve. Trends in Sea Surface Temperature (SST; d) also provided. Density units are # per m^2

8.5 Resilience to change

Roe’s Abalone occurs over a large geographic area covering 27–35ºS (Figure 8.2.2) with a considerable variation in SST which would make the parts of the overall stock resilient to changes in water temperature.

8.6 Ecosystem level interactions

As herbivores, whose food is drift algae dislodged by wave action, Roe’s Abalone are not considered to be a major prey source upon which the overall food chain is highly dependent. Therefore there are no reference points specifically relevant to this as a lower trophic level species.

8.7 Additional (multiple) stressors

The marine heat wave effects in the summer of 2010/11 resulted in water temperatures reaching 3–5ºC above average in the mid-west region of WA (Pearce *et al.* 2011). When these temperatures were combined with calm conditions in late February and early March, a catastrophic mortality of *Haliotis roei* occurred at the northernmost extent of its distribution.

8.8 Critical data gaps and level of uncertainty

The large spatial variation in growth and maximum size indicates that abalone have a capacity to accommodate significant changes in their localised environment, particularly in relation to food supply. Therefore despite their inherent susceptibility, they may also possess a strong capacity to adapt to a changing environment. The main knowledge gap is information on how climatic factors affect the long-term recruitment patterns. The continuation of the long-term recruitment monitoring program such as occurs in the Perth metropolitan area and the assessment of the key environmental factors will address this knowledge gap.

8.9 Future climate scenarios (2030/2060)

Climate change implications associated with the environmental factors (water temperature and storm activity) have been shown to affect the spawning and larval period of other marine invertebrates, lobster, for example. These trends in water temperature and storm activity are projected to continue (Feng *et al.* 2012; Indian Ocean Climate Initiative 2012). Significant effects of climate factors on growth and mortality has already been demonstrated for *Haliotis roei*. The most likely change is a shifting of the main areas of production eastward.

8.10 Management Implications

The heat wave effect on the Roe’s Abalone stock in Kalbarri has resulted in the closure of the fishery in this area. The very low numbers of abalone remaining has made the natural recovery of this stock uncertain. Therefore different approaches to help rebuild the stocks such as translocation from surviving populations in the region and the release of hatchery-grown populations are being evaluated. The likelihood of the reoccurrence of the marine heat wave and the long-term viability of the stock in this region under climate change needs to be evaluated.

The heat wave may have also affected the abalone stocks in the Perth metropolitan area (Figure 8.3.1) which has affected the catch in this area, particularly that of the recreational fishery that is focused on the reef platform. The management implications of this for the 2014/15 season are being examined. The availability of the fishery-independent measures of pre-recruits and legal-size abundance enables management to take into account the projected trends in legal-size abundance in their decision making.

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9.0 Pearl Oyster (*Pinctada maxima*)

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The Silver Lipped Pearl Oyster (*Pinctada maxima*) belong to the Family Pteriidae, which is a small family of bivalve molluscs. Four species of the genus *Pinctada* occur in Western Australia (WA): *P. maxima*, *P. albina*, *P. fucata*, and *P. margaritifera* (Hynd 1955). Of these only *P. maxima*, *P. margaritifera* and *P. fucata* are currently being used for pearl production in WA. *P. maxima* is the only species subject to a commercial fishery and is the world's largest species of pearl oyster.

9.1 The fishery

The WA Pearl Oyster Fishery began in 1867, initially as a wading fishery utilizing mainly Australian Aboriginals, and later South-Sea Islanders and Malays (Bach 1955). By the early 1890s, surface-assisted or "hard-hat" diving had been implemented across all fisheries, and eventually became the iconic image of the early *P. maxima* industry. By the 1880s the large mother of pearl (MOP) shells became the focus of the fishery due to their use as material for buttons in the clothing industry. By 1910 there were nearly 400 luggers and 3 500 people in the industry which supplied up to 75% of the world output of MOP shell with up to 2000 tonnes (approx. two million individuals) of shell collected per year (Malone *et al.* 1988; Southgate *et al.* 2008).

The 1920s and 1930s were low points for the industry, first with the introduction of plastic buttons, which was then followed by the Great Depression. Similarly, during World War II pearling operations in WA almost entirely disappeared. Pearling activity recommenced after the war finished, with up to 1700 tons of MOP caught in 1957, declining to about 200 tons per annum (approx. 450 000 individuals) up to 1966 (Figure 9.1.1).

By the end of the 1970s most of the industry had started to move into cultured pearl production and the catch of MOP-sized shell had declined to less than 300 tonnes with around 400,000 culture sized shells captured (Malone *et al.* 1988). This shift saw a change in the types of shell targeted and the location of fishing. Thus, the smaller 'culture-sized' shell (< 175 mm shell length) were being targeted not the larger MOP shells (175+ mm). Consequently, there was a reduction in effort on deeper beds into more shallow regions where the proportion of the culture-sized shells was higher.

Prior to 1984, there was scope for companies to take in excess of the quota by making a request to the Department of Fisheries. However, by 1985 individual companies were strictly adhering to the total allowable catch (TAC). By 1987 all allowances for the collection of MOP-sized oyster were eliminated, as licence owners believed that stocks of breeding sized pearl oysters should be strengthened. Consequently, there are a large number of historic fishing grounds where pearl shells are no longer harvested.

The fishery was reviewed in the late 1980s by Malone *et al.* (1988), from which a series of recommendations about the management of the resource were developed. This included recommendations for the quotas to be set by annual stock assessments using the catches and catch rates, the complete phasing out of MOP-sized collection and the zoning of the fishery to provide more precise management. These recommendations provided the basis of management from 1988 till the present day.

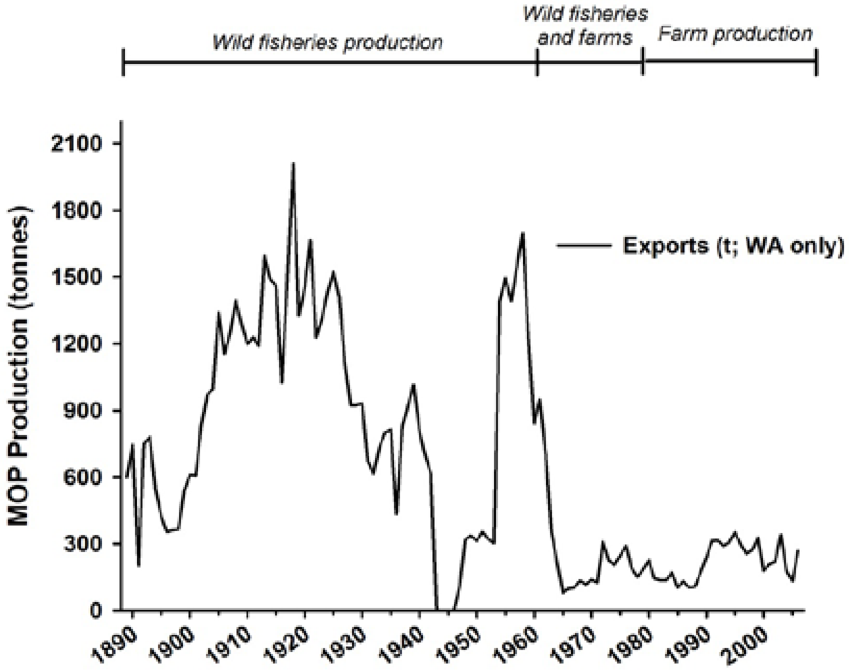

Figure 9.1.1. Historical export (t) of Mother-of-Pearl (MOP; *P. maxima*) from Western Australia. Three phases of production are historically observed. Currently all exports of MOP are from pearl farms (animals either bred on-farms, or caught from the wild, and utilised to grow pearls prior to being sold for their nacre).

The Western Australian Pearl Oyster Fishery is the only remaining significant wild-stock fishery for pearl oysters in the world. It is a quota-based dive fishery, operating in shallow coastal waters along the North West Shelf.

The harvest method is drift diving, in which six to eight divers are attached to large outrigger booms on a vessel and towed slowly over the pearl oyster beds, harvesting legal-sized oysters by hand as they are seen (Figure 9.1.2). The fishery is a "gauntlet" fishery which primarily targets the smaller, faster growing 'culture' shells (100–175 mm shell length) as these are the best size-group for pearl production.

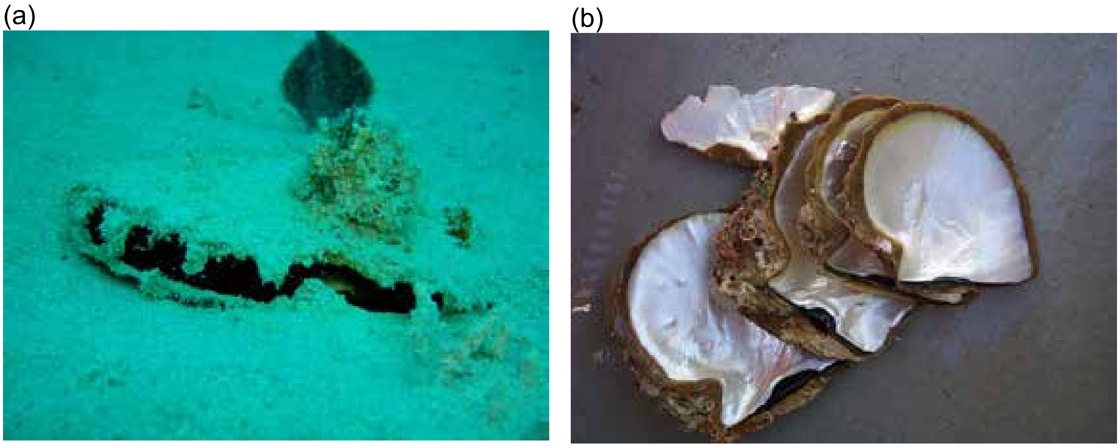

Figure 9.1.2. *Pinctada maxima* in its (a) natural habitat, and (b) processed for sale.

9.2 Life history

9.2.1 Life cycle, age and growth

Pinctada maxima is a protandrous hermaphrodite. The animals mature first as males, at approximately three to four years of age and at a size of 110 to 120 mm, beyond this the animals begin to undergo a sex change and become female (Figure 9.2.1). By 170 mm in length, half of the animals are males and half are females. By 190 mm the majority of the population is female. Since the animals can spawn every year, each individual can function as both a male and then a female for several spawning seasons. Very few animals are both male and female simultaneously (Rose *et al.* 1990; Rose and Baker 1994), however pearl oysters are rhythmical hermaphrodites, and can have more than one sex reversal during their lifetime (Saucedo and Southgate 2008). This is thought to be related to a complex interaction of endogenous factors and varying environmental conditions. The principal hypothesis is that "maleness" is favoured when energy reserves are low, while "femaleness" is favoured when energy reserves are high.

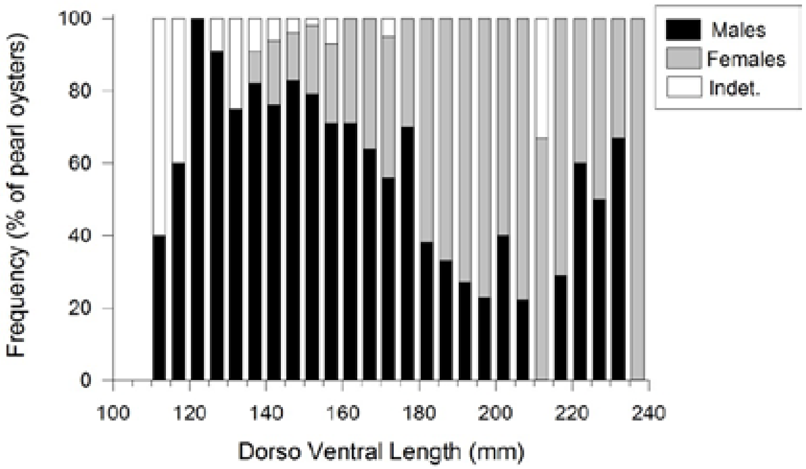

Figure 9.2.1. Per cent frequency distribution of sex by size for *Pinctada maxima*. Data sourced from Hart and Joll (2006).

The breeding season of *P. maxima* starts in the spring months of September and October extending to the autumn months of April and May. Although there is variability from month to month, the primary spawning occurs from the middle of October to December. A smaller secondary spawning occurs in February and March (Rose *et al.* 1990; Rose and Baker 1994). Collection of settling spat in the field has confirmed the spawning periodicity (Knuckey 1995).

P. maxima are broadcast spawners; they release gametes (both sperm and eggs) into the water column during the spawning season, where fertilisation occurs. The ova develop into a tiny veliger stage and settlement usually occurs around 28 to 35 days post-hatching. When they are ready to metamorphose they settle to the bottom and test for a suitable habitat. If an appropriate area is found, they settle on it and metamorphose into the juvenile stage. If no suitable settlement site is located within a short period the animals will metamorphose and die.

Egg production by an individual female is extremely high. Laboratory studies have shown that females can release from two to 12 million ova in a single spawning event (Rose and Baker 1994), however the estimated number of eggs found in mature female gonads (> 170 mm shell length) varies between 20 and 50 million (Figure 9.2.2). No significant correlation was found between fecundity (no of eggs) and shell length of *P. maxima* for either fixed or dried gonad samples (Figure 9.2.2).

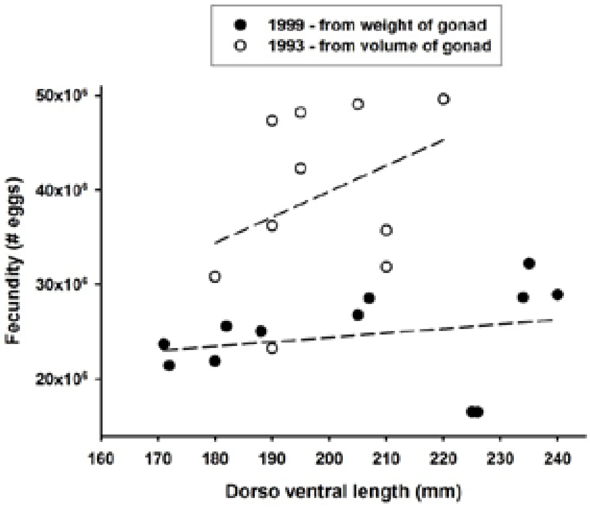

Figure 9.2.2. Fecundity estimates as a function of shell length in mm for two different methods. Figure modified from Hart and Friedman (2004).

Pinctada maxima growth is typically described by a von-Bertalanffy growth curve. Growth parameters (L_∞, K) were estimated at 210 mm length (± 16 mm SD) and 0.74 at the Lacepede Islands, L_∞ of 199 mm length (± 6 mm SD) and K of 0.79 on 80 Mile Beach, and L_∞ of 194 mm (± 6 mm SD), and K of 0.72 at Exmouth Gulf respectively. In the main section of the fishery animals generally spend about three years in the exploited phase of the life cycle until they reach the area specific maximum legal size. Once the maximum legal size is reached the pearl oysters are considered no longer suitable for round pearl culture. Large oysters of > 200 mm have been estimated to be 15 to 20 years old and the maximum length recorded for an individual for *P. maxima* is 270 mm (Rose and Baker 1994).

9.2.2 Distribution, habitat and environmental preferences

Pinctada maxima is distributed within the central Indo-Pacific region, bounded by the Bay of Bengal to the West, Solomon Islands to the east, the Philippines to the North, and Northern Australia to the south (Figure 9.1). Originally distributed from the shallow sub-tidal, it occurs in depths in excess of 50 m. Some early reports from the Sulu Islands in the Philippines suggested that *P. maxima* live as deep as 120 m (Talavera 1930). Strong tidal currents appear to be the common habitat / environmental feature of both historical and presently important areas of wild stocks.

Pinctada maxima is a broadcast spawner that can each produce greater than 30 million viable eggs under hatchery spawning conditions, and whose egg and larval stages spend up to 3 weeks in the plankton. It is widely dispersed within tropical Western Australia and the Indo-Pacific; however, the boundaries of commercially fished populations are Exmouth Gulf in the south-west of its range, and Lacepede Channel in the north-east, a distance of about 1200 km. Within these populations, areas fished are discrete and separated by large distances. The first studies of allozyme variation found little variation between Exmouth Gulf and Cape Bossut (80 Mile Beach, shallow), indicating high connectivity over 800 km (Johnson and Joll 1993). The pattern was consistent with other species along this coastline with planktotrophic larvae (Johnson and Joll 1993), and is likely to be correlated with the extensive water currents arising from six to twelve metre tidal ranges.

Figure 9.1.3. Distribution of *Pinctada maxima* and areas of historical and current wild fisheries and pearl farms.

The movements of pearl oyster larvae prior to settlement on the benthos are dictated by physical oceanographic processes such as wave action, prevailing winds and currents. Condie *et al.* (2006) determined that *P. maxima* larvae on WA's north-west shelf are predominantly transported < 30 km, however some as far as 60 km. During the juvenile and adult phases of the life cycle of *P. maxima*, it attaches to the sea bottom by tiny threads. *P. maxima* require a hard surface for attachment, once attached the connection is permanent.

With regard to the north coast pearl oyster fishery, the oysters are commonly found in areas where the seabed has crevices that allow spat to settle and attach onto a protected and hard substratum. The seabed is typically a flat basement rock with very little relief. Fine sediment accumulates on the basement rock to a depth of a few millimetres, obscuring the underlying rock surface. A variety of organisms attach to the rock. These organisms provide a vertical relief of up to 1 m off the bottom (Figure 9.2.4). There can be a substantial overlap in the fauna on the various bottom types, the types are determined by the dominant species present. The industry has recognised the variety of bottom types within the fishing grounds and developed names for them over the years, such as potato bottom and garden bottom (Figure 9.2.4).

The dominant species on the potato bottom is a low, round densely packed ascidian species, which lives attached on the benthos. The sea floor in this bottom type has a flat plate of underlying rock overlain with a few millimetres of sand. In areas of heavy potato bottom the ascidians are almost completely dominant. Sponges are the next dominant group, with a large variety of vase shaped, basket sponges and massive sponges up to 0.5 m high interspersed with smaller sponges of only a few centimetres. A large variety of other diverse taxa are commonly present, however, total densities are low. Very few corals (Turbinaria) are typically present in pearl oyster areas. Faunal density rapidly decreases in areas where the sediment is 2-3 cm deep. Bare sand patches can be interspersed between areas of potato bottom.

The garden bottom is a very diverse assemblage dominated by hydroids. Distance between hydroids is variable, but on average they grow about one metre apart. The hydroids grow rapidly to up to one metre in height and quickly become encrusted with a variety of organisms, some very colourful, so the bottom does in fact resemble a garden. Other than hydroids, a variety of sponges are present on the bottom. Ascidians are present, but are a larger species than that found on potato bottom. Other fauna present include soft corals, sea pens and crinoids. No hard corals are generally present.

While potato and garden bottom dominate in the fishing area, several other bottom types are recognised by the industry including collar, asparagus etc. All share the common feature of being located on a bottom with underlying rock and are composed of a wide variety of invertebrates. Only potato and garden bottom have commercial quantities of pearl oysters and are away from more ecologically sensitive areas such as seagrasses, coral reefs or mangroves. The relative frequencies of fishing effort on the different habitat types are monitored annually.

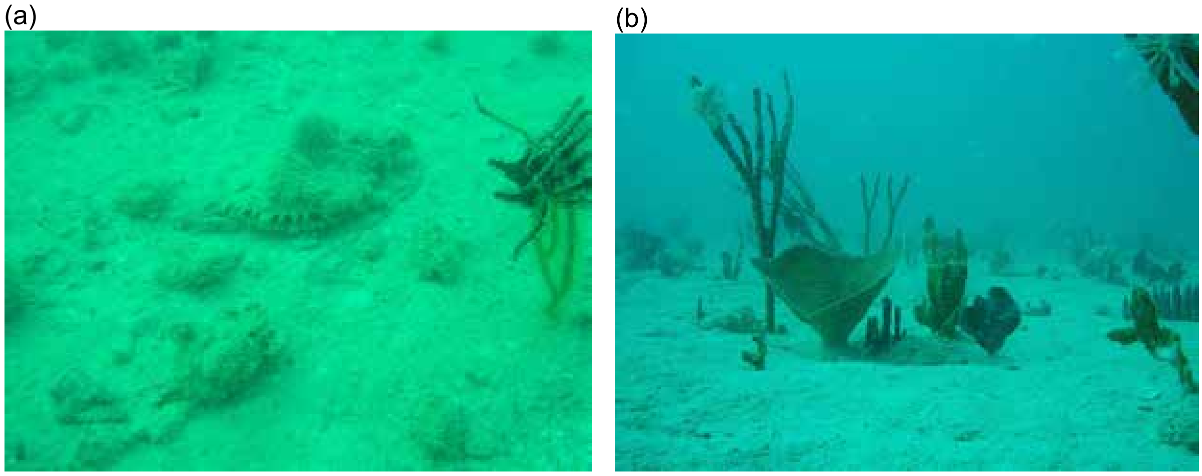

Figure 9.2.4. Examples of the two main habitat types found in the Pearl Oyster Fishery (a) "potato" (ascidian) habitat with pearl oyster, and (b) "garden" habitat.

9.2.3 Predators and prey

In the planktonic stage, predators of *Pinctada maxima* include pelagic fish such as mackerel and tuna. In the spat stage, when the shell is soft, predators include demersal fish such as snapper. By the adult stage the shell is harder and there are low natural mortalities in this stage, although predators such as turtles and boring worms can prey on adults.

Pearl oysters, like other bivalves, are suspension feeders. They collect nutrients from the water by trapping suspended particulate organic matter in mucus that coats the gills; these particles are then conveyed by cilia to the mouth (Campbell 1996). Clearance rates, respiration and excretion have been shown to increase exponentially with body size for *P. maxima* (Yukihira *et al.* 1998). The variety of substrates *P. maxima* inhabits, such as mud, sand, gravel, seagrass beds and deepwater reefs, can influence the composition and quantity of nutrients available, hence influencing growth and maturation.

9.2.4 Recruitment

Recruitment of juveniles in the *P. maxima* fishery is measured by annual surveys of the Age 0+ and 1+ year classes (Hart and Joll 2006). Sea surface temperature (SST), rainfall, and wind conditions were all found to influence settlement, with SST being the most important factor (Hart *et al.* 2011). Annual variation in settlement can result in major changes in abundance and this variation appears primarily driven by environmental conditions (Hart *et al.* 2011).

9.3 Current impacts from climate change

There are no documented effects of climate change on *P. maxima*. SST increases off the west coast of WA have been primarily occurring on the lower west coast with smaller increases occurring on the north-west coast of WA (Caputi *et al.* 2009) where the Pearl Oyster fishery occurs.

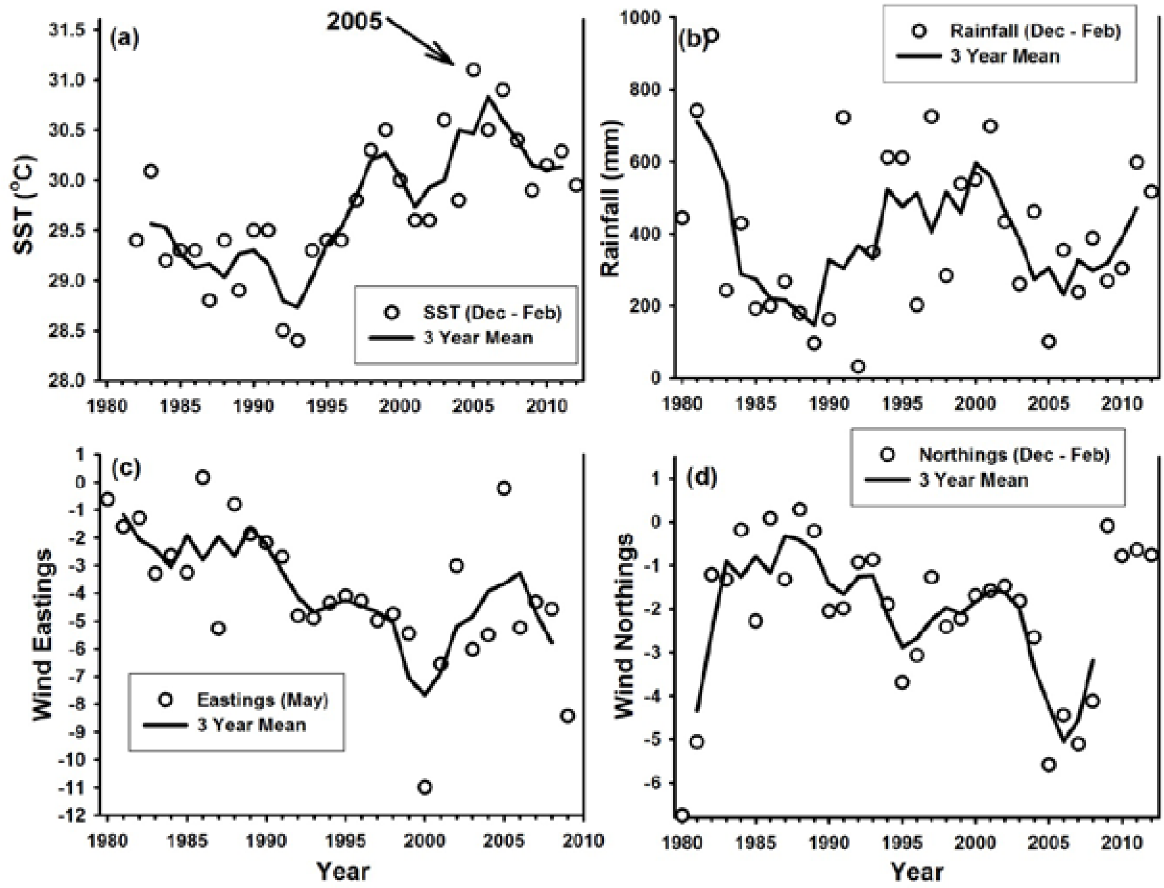

Figure 9.4.1. Environmental variables during December to February in the Pearl Oyster Fishery from 1980 to 2010.

9.4 Sensitivity to change

Environmental factors have a relatively large influence on both pearl oyster abundance and fishing efficiency. For example, Hart *et al.* (2011) detected a significant negative relationship between abundance and rainfall, and a positive relationship between abundance and temperature for both spat settlement and fishery CPUE at appropriate lags. Also, northerly winds (negative northings) during December to February significantly enhanced settlement. However easterly winds (negative eastings) in the main fishing month of May positively influenced fishing power (Hart *et al.* 2011). Consequently, analysis of environmental effects is routinely carried out during stock assessments. Long-term trends in the relevant environmental indices are shown in Figure 9.4.1. Given that recruitment is variable and influenced by a range of environmental factors including SST, predicted increases in the global temperature might plausibly affect this species (Hart *et al.* 2011). Therefore the species ranked high for sensitivity to climate change but medium for exposure, resulting in an overall risk ranking of medium-high.

9.5 Resilience to change

Given the wide distribution of the species (Figure 9.2.3) and the projected warming of SST off the west coast of WA, should result in the species being reasonably resilient under climate change scenarios.

The fishery is generally fished conservatively as a gauntlet fishery with the larger MOP only being fished at very low levels in recent years. The management approach results in the fishery having a well-protected spawning stock which should increase the resilience of the stock.

9.6 Ecosystem level interactions

As filter feeders with robust shell, *P. maxima* is not considered to be a major prey source upon which the overall food chain is highly dependent. Therefore there are no reference points specifically relevant to this as a lower trophic level species.

9.7 Additional (multiple) stressors

The fishery is generally fished conservatively so no major additional stressors have been identified.

9.8 Critical data gaps and level of uncertainty

The monitoring of the 0+ and 1+ spat which are a reliable predictor of the commercial catch rates about 4-5 years later enable the pro-active management by setting the catch quota on expected abundance of legal-size pearl oysters. This enables the fishery to react quickly to any change in recruitment due to climate change. Therefore continued monitoring of the pre-recruit year classes and the environmental variables trends that influence their abundance are critical to the proper management of this fishery.

9.9 Future climate scenarios (2030/2060)

Increases in SST and possible decreases in rainfall projected for the north-west of WA are likely to influence the recruitment in the pearl oyster fishery. The current environmental relationships indicate that these trends may have a positive effect on recruitment. However projections of recruitment based on changes in environmental conditions outside the historic range need to be treated cautiously. The nature of the environment-recruit relationship may change and other biological parameters may be affected if there are changes in environmental conditions outside the historic range.

9.10 Management Implications

The key management implication is to be aware of the recruitment variability due to changing environmental conditions and to ensure that the catch quota continues to be set based on the abundance of pre-recruit so that the spawning stock continues to be well protected.

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10.0 Australian Herring (*Arripis georgianus*)

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Australian Herring, *Arripis georgianus* (Valenciennes, 1831), is a member of the Family Arripidae. The species is endemic to southern Australia, occurring from Shark Bay (Western Australia (WA)) southward along the coast to Port Phillip Bay (Victoria) (Hutchins and Swainston 1986). Australian Herring is essentially an inshore marine species, forming pelagic schools over a range of habitats. Australian Herring is targeted commercially and recreationally in WA and South Australia (SA). Minor quantities are taken in Victoria.

10.1 The fisheries

- Commercial catches are taken in Western Australia and South Australia.
- Western Australia generates around 70% of the Australian commercial catch.
- In Western Australia, Australian Herring is the most common finfish species retained by recreational fishers. It is also commonly caught by recreational fishers in South Australia.

Western Australia

Australian Herring is an important commercial and recreational species in WA. In WA, the majority (~75%) of the commercial catch is taken by the South Coast herring trap net fishery (Smith *et al.* 2013a). The trap net fishery targets Australian Herring during the annual autumn spawning migration as fish move from nursery areas on the south coast of Australia around to the lower west coast to spawn. The fishery season typically only lasts around one to two months. Smaller quantities of Australian Herring are also landed by the South Coast Estuarine Fishery, South-west Beach Seine Fishery, Cockburn Sound (Fish net) Fishery and the West Coast Estuarine Fishery.

In the 1950s and 1960s, the total WA annual commercial catch of Australian Herring ranged between approximately 200 and 600 tonnes (t). After the late 1960s, WA annual landings increased rapidly to peak at 1,185 t in 1973. Landings declined to 509 t in 1977 and then steadily increased to reach an historical peak of 1,537 t in 1991. Since 2000, the total WA state annual commercial catch of Australian Herring has steadily declined from 818 t in 2000 to an historical low of 147 t in 2011. In 2012, total WA landings were 163 t (Smith *et al.* 2013b).

To date, the 2000/01 National Recreational and Indigenous Fishing Survey has been the only state-wide survey of shore- and boat-based fishing conducted in WA (Henry and Lyle 2003). The results from this survey revealed that Australian Herring was the most landed finfish species by recreational fishers in WA, with an estimated catch of 3,873,411 fish (= 484 t, assuming 125 g per fish). In WA, the West Coast Bioregion (WCB) is the main recreational fishery area for Australian Herring, where approximately 85% of the total State recreational catch is taken. The remaining recreational catch is taken in the South Coast Bioregion (SCB). The majority (~ 65%) of the WCB recreational catch is taken by shore- and estuary-based fishing (Henry and Lyle 2003; Smith *et al.* 2013a).

South Australia

Commercial landings of Australian Herring in SA increased from 100-200 t per year in the 1950s to 300-400 t in the 1990s. Landings have been 100-200 t since 2001. The proportion of national annual commercial landings taken in SA each year has been relatively constant from the early 1970s until 2008, typically ranging between 20-30% each year. Since 2008, SA annual landings have comprised about 42% of the national catch (Smith *et al.* 2013b)

Australian Herring was the most commonly retained finfish species in the SA recreational catch in 2000/01 and the 3rd most commonly retained finfish species in the SA recreational catch in 2007/08. In 2000/01, an estimated 2,535,404 (=254 t, assuming 100 g per fish) were retained by recreational fishers in SA (Henry and Lyle 2003). In 2007/08, an estimated 598,774 herring (= 93 t, assuming 155 g per fish) were retained by recreational fishers in SA (Jones 2009).

Victoria

Historically, commercial landings of Australian Herring in Victoria have been consistently low (<60 t per year). In recent years, only 1-5 t per year was harvested commercially in Victoria, with the exception of 2009/10 when 11 t was landed.

In Victoria, an estimated 11,354 herring (~ 1 t) were retained by recreational fishers in 2000/01 (Henry and Lyle 2003).

10.2 Life history

10.2.2 Life cycle, age and growth

Australian Herring spawn annually on the lower west coast of WA, potentially between the Abrolhos Islands and Bremer Bay (Fairclough *et al.* 2000a), but mainly north of Cape Leeuwin (WFRC 1973, Smith *et al.* 2013a). Spawning occurs between April and late June, with a pronounced peak in activity during late May/early June (Fairclough *et al.* 2000a; Smith *et al.* 2013a). Spawning appears to be synchronised with the onset of the annual peak in flow by the Leeuwin Current. The pelagic eggs and larvae are transported southward and then eastward along the southern coast by the Leeuwin Current before settling into nursery habitats in sheltered nearshore waters in WA, SA and Victoria. Higher levels of recruitment to the eastern section of the WA south coast and in SA tend to occur during years of strong Leeuwin Current flow due to the increased advection of larvae. At maturity, fish undertake a pre-spawning migration to the spawning area in south-western WA during February to April (Ayvazian *et al.* 2000). There is no return (post-spawning) migration, and thus the spawning stock occurs only in WA (Ayvazian *et al.* 2004).

Australian Herring are capable of reaching sizes of approximately 41 cm (Hutchins and Swainston 1986), but are rarely caught over 30 cm (Smith *et al.* 2013a). Australian Herring is relatively short lived with the oldest reported specimen from WA being 12 years from a south coast estuary and 10 years from the ocean (Smith *et al.* 2013a). In SA, the oldest age reported was 8 years (Fairclough *et al.* 2000b).

Over 50% of males are mature at the end of their 2nd year and over 50% of females are mature at the end of their 3rd year (Smith *et al.* 2013a). Australian Herring are multiple spawners with females estimated to release between ~32,000 and 207,000 eggs per year (Fairclough *et al.* 2000a). Australian Herring are gonochoristic. Females generally attain a larger size than males

(Fairclough *et al.* 2000a; Smith *et al.* 2013a). Growth parameters in WA are shown below (Table 10.2.2.1). Growth rate is slightly slower in the SCB than in the WCB, presumably due to temperature differences.

Using the maximum age method of Hoenig (1983) and the maximum age observed for the WCB population where the breeding stock occurs (10.5 years), the estimate of natural mortality for Australian Herring is 0.42 year^{-1} (Smith *et al.* 2013a). Being short-lived, relatively fast growing, with a high rate of natural mortality, and low size and age at maturity, Australian Herring are considered to have a high production potential and to be fairly resilient to over-exploitation.

Table 10.2.2.1. Von Bertalanffy growth parameters for WA Australian Herring.

Location	Sex	L_∞	K	t_o	Reference
WA	♀	272.8	0.57	-0.26	Smith *et al.* 2013a
	♂	237.3	0.87	-0.06	
WA WCB	♀	271.5	0.57	-0.30	Smith *et al.* 2013a
	♂	236.7	0.86	-0.08	
WA SCB	♀	295.8	0.48	-0.20	Smith *et al.* 2013a
	♂	246.0	0.79	0.02	

10.2.3 Distribution, habitat and environmental preferences

Australian Herring is endemic to southern Australia, occurring from Shark Bay (WA) southward along the coast to Port Phillip Bay (Victoria) (Hutchins and Swainston 1986). Australian Herring constitutes a single stock across its range (Ayvazian *et al.* 2004; Moore and Chaplin 2013). Most of the adult stock resides in WA. Australian Herring is essentially an inshore marine species and mainly occurs in nearshore coastal waters, around offshore islands (including Rottnest Island) and in the lower reaches of estuaries. Juveniles grow to maturity in nursery areas, which are mainly associated with seagrass beds, in protected marine embayments along the southern Australian coast of WA, SA and Victoria (Malcolm 1973). Juvenile fish (0+ year class) are often associated with detached macrophytes in shallow waters of the surf-zone. The accumulations of plant material provide food and also protection from larger predatory fish and diving birds (Lenanton *et al.* 1982). Adults and juveniles form pelagic schools over a range of habitats (reef/sand/weed).

Figure 10.2.3.1. Distribution of Australian Herring.

10.2.4 Predators and prey

Juveniles and adults of Australian Herring are opportunistic carnivores, feeding on a wide range of organisms at all levels of the water column (surface, mid-water and bottom). Juvenile Australian Herring feed mainly on small marine invertebrates, especially crustaceans, but also consume fish and insects (Lenanton *et al.* 1982; Greenwell 2001). Adult Australian Herring consume small fish (e.g. Whitebait, Anchovies, Garfish, Pilchards) and invertebrates (Lenanton *et al.* 1982; Greenwell 2001). Highly opportunistic feeding behaviour leads to regional differences in diet (Greenwell 2001).

Juvenile and adult Australian Herring are consumed by various large predators such as dolphins, seabirds, sharks, Fur Seals, Western Australian Salmon, Tailor, Yellowtail Kingfish and Mulloway (Kailola *et al.* 1993).

10.2.5 Recruitment

Spawning by Australian Herring mainly occurs along the lower west coast of WA during May/ early June. This timing coincides with the peak flow of the Leeuwin Current, which flows southward and then eastward along the southern Australian coast. Modelling of larval dispersal suggests that larvae spawned on the west coast are transported to nurseries along the south coast (including WA and SA) by a combination of the Leeuwin Current, wind-driven surface currents and swimming behaviour.

Higher levels of recruitment to nursery sites in the eastern region of the WA south coast and in SA and Victoria tend to occur during years of strong Leeuwin Current flow.

10.3 Current impacts of climate change

There are no known current impacts of climate change on Australian Herring. Annual variations in the strength of the Leeuwin Current are believed to influence the distribution of juvenile Australian Herring and the distribution of the adult spawning stock (Smith and Brown 2014).

During the summer of 2010/11, a record strength Leeuwin Current resulted in abnormally high ocean temperatures in coastal waters off the west and south-west coasts of WA (Pearce *et al.* 2011). This marine 'heatwave' event impacted the distribution of Australian Herring, with many adult fish remaining on the south coast rather than migrating to traditional spawning grounds on the lower west coast (Smith and Brown 2014). In addition, these conditions were believed to be unfavourable for spawning by Australian Herring, with relatively low recruitment levels observed during this year (Smith *et al.* 2013b).

10.4 Sensitivity to change

Very little is known of the sensitivities of Australian Herring to environmental factors although Fairclough *et al.* (2000a) observed that sexual maturation and spawning are tightly regulated by environmental cue(s). Variations in recruitment numbers are largely due to annual variations in coastal currents (particularly Leeuwin and Capes Current), and therefore, changes to current patterns will impact on stock levels.

In addition, limited evidence suggests a maximum temperature threshold for Australian Herring. Juveniles in the mid-west zone of the WCB (i.e. north of Perth) display slower growth than in the southern WCB or in the SCB (Smith and Brown 2014). This suggests sub-optimal conditions for growth in the northern part of the species range, perhaps due to higher temperatures. During the heatwave event in 2011, the pre-spawning migratory behaviour (and hence the distribution of the spawning stock) of Australian Herring was substantially disrupted by atypically high temperatures. Spawning success was apparently affected by these conditions with poor (well below average) recruitment by the 2011-year class. Thus, warmer coastal sea temperatures in future years are predicted to negatively impact on recruitment success.

Australian Herring predominantly exist in nearshore environments and may therefore be influenced by anthropogenic activities.

10.5 Resilience to change

Australian Herring are found over a wide latitudinal and temperature range. Within this extensive area they exist over a variety of habitats, including estuaries, inshore waters and offshore islands. They are a highly migratory species, consisting of a single genetic stock across their range. Australian Herring are opportunistic feeders with a highly variable diet. All of these attributes suggest that Australian Herring are a resilient species to varied environmental conditions.

10.6 Ecosystem level interactions

Juvenile Australian Herring are dependent upon detached macrophytes in shallow waters of the surf-zone for food and protection from predators (Lenanton *et al.* 1982).

10.7 Additional (multiple) stressors

Current stock assessment in WA identified a severe risk to the sustainability of the Australian Herring stock (Smith *et al.* 2013a). Evidence suggests age truncation (i.e. reduced proportion of older fish in the stock) has occurred over time, possibly as a result of fishing pressure. Currently, the majority of the population is comprised of young fish (2 and 3 years of age). Commercial and recreational catch levels have declined in WA and SA suggesting lower stock abundance (Smith *et al.* 2013a). The ability of the Australian Herring stock to respond to changes in environmental conditions is placed under further stress due to low spawning stock levels.

10.8 Critical data gaps and level of uncertainty

Better estimates of recreational harvest of Australian Herring, particularly shore-based anglers, are required to better assess the stock status in WA. Critical gaps that need to be investigated are the sensitivity of Australian Herring to environmental variation including temperature, salinity and pH, particularly for early life history stages.

10.9 Future climate scenarios (2030/2060)

Australian Herring are a temperate species and are likely to be negatively impacted by the predicted future climate scenarios. A continuation of the warming trend in coastal waters of south-western Australia, which has been observed over the past decade, may result in the northern limit of the species range in WA contracting southwards. Similarly, the traditional spawning grounds off the lower west coast of WA may move further south. These shifts would likely result in spatial changes in recruitment patterns, particularly reduced recruitment to nurseries within the WCB. Reduced adult stock abundance (leading to lower fishery catches) in the northern half of the WCB, including the Perth area, is also likely.

Leeuwin Current strength is predicted to weaken as a result of climate change (Hobday and Lough 2011), which would result in lower recruitment to SA and Victoria. The combined effect of these predicted impacts i.e. WCB warming and reduced Leeuwin Current flow, would likely result in a contraction of the species range.

10.10 Management implication

Australian Herring are at a high risk of undesirable impacts due to climate change (Table 7.2.2.3). To manage this high risk, continued monitoring of the commercial and recreational catches, particularly shore-based catches is required. With a possible reduced adult stock abundance predicted for the northern half of the WCB, including the highly populated Perth metropolitan area, an expansion of fishing effort in this region associated with a growing human population, is likely to place further stress on the Australian Herring stock. The continued monitoring of recruitment levels is therefore important as a forecasting tool of relative stock abundance. The development of biomass estimates, as well as the continued monitoring of the age structure to determine estimates of the instantaneous rate of fishing mortality, will provide support to management decisions regarding stock status.

10.11 References

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11.0 Baldchin Groper (*Choerodon rubescens*)

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Baldchin Groper, *Choerodon rubescens* (Günther, 1862), belongs to the Labridae (wrasses) and is endemic to the west coast of Australia from about Coral Bay (23°S) to Cape Naturaliste (33.5°S) (Hutchins and Swainston 1986). It is iconic among both recreational and commercial line fishers.

11.1 The fisheries

- Baldchin Groper is caught by commercial, recreational and charter fishers.
- Most of the catch is taken in the West Coast Bioregion (27°S to 115°30E).
- Annual estimates of commercial catch are obtained from statutory logbooks.
- Periodic estimates of recreational catch are available.
- Charter sector catches are estimated annually (since 2002/03).

Choerodon rubescens is a sought after commercial and recreational species in Western Australia (Fairclough *et al.* 2013). It is caught as part of the West Coast Demersal Scalefish Fishery (WCDSF), which includes a managed commercial line fishery (the West Coast Demersal Scalefish Interim Managed Fishery, WCDSIMF) and a recreational fishery (comprising boat-based recreational fishers and charter fishers). Small catches are also taken in the West Coast Bioregion (WCB) by the temperate demersal gillnet and demersal longline fishery and the Western Rock lobster fishery and in the Gascoyne Coast Bioregion by the commercial Gascoyne Demersal Scalefish Managed Fishery and recreational and charter fishers.

Due to sustainability issues, significant changes were introduced in the late 2000s to the management of commercial and recreational fisheries that catch demersal species in the WCB. These changes were aimed at reducing effort and thus catch by at least 50 % of those in 2005/06 in the WCB. Since their introduction, catches of *C. rubescens* by the WCDSIMF have remained below 50 % of those in 2005/06 (i.e. ≤ 17 t). For example, in 2012 ca 16 t of *C. rubescens* were caught by the WCDSIMF. A phone-diary survey of boat-based recreational fishing in 2011/12 estimated that 29 t of *C. rubescens* were caught in the WCB and charter fishers reported catching 9 t in that year (Fairclough *et al.* 2014; Ryan *et al.* 2013). The total recreational fishery catch (recreational plus charter fishers) in that year was close to 50% of the total for the recreational fishery in 2005/06 of 33 t.

A large part of the catch of this species is taken at the Houtman Abrolhos Islands. A survey in 2006 of the different sectors that fish in that location indicated that a relatively significant catch (26 t) was taken by recreational fishing by Western Rock Lobster fishers living at the islands during the fishing season (Sumner 2008). This is consumed mostly at the islands and thus not well accounted for in recreational fishing surveys.

While management is in place to recover stocks of demersal species, the stock status of *C. rubescens*, based on fishing mortality rates, has not changed between 1993/94-1994/95 and 2008/09-2010/11 (Fairclough *et al.* 2014).

11.2 Life history

11.2.1 Distribution, habitat and environmental preferences

Choerodon rubescens is endemic to ca 1300 km of the west coast of Australia, from about Coral Bay (23°S) to Cape Naturaliste (33.5°S; Figure 11.2.1). It is believed to be most abundant at the Houtman Abrolhos Islands, which is at about the centre of that range. Its adults occur mostly over both limestone and coral reefs to approximately 100 m (Hutchins and Swainston 1986; Nardi *et al.* 2004; Allen 1999). Small juveniles are usually found in habitats adjacent to those reefs, including rubble, sponge and algal habitats (Hutchins and Swainston 1986; Fairclough 2005).

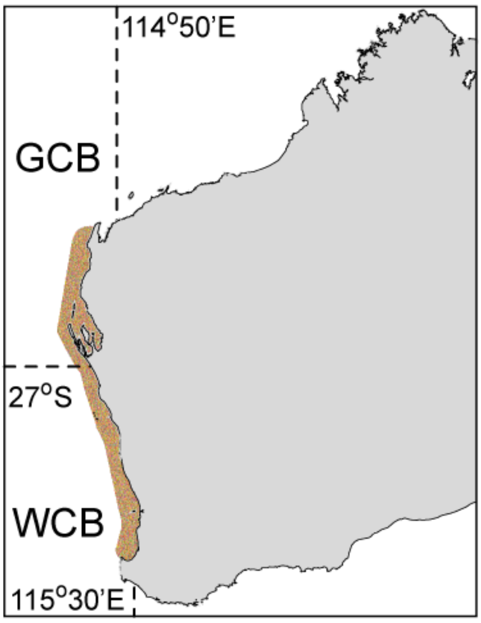

Figure 11.2.1.1. The distribution of *Choerodon rubescens* (stippled), showing the boundaries of the Gascoyne Coast (GCB) and West Coast Bioregions (WCB).

11.2.2 Life cycle, age, growth and reproduction

Like many labrids, *C. rubescens* is protogynous, i.e. individuals commence life as females, mature as females and later change sex to males (Fairclough 2005; Nardi *et al.* 2004). This species can reach approximately 70 cm and 7 kg (Hutchins and Swainston 1986). It is also moderately long-lived, but maximum recorded age ranges from 16 y in the north (Shark Bay) to 28 years in the south-west (Fairclough 2005; Fairclough *et al.* 2014; DoFWA unpublished data). Comparative studies of its biology demonstrate that *C. rubescens* grows more slowly at the Abrolhos Islands (28°30S) than at Shark Bay (26°S) and has a smaller estimated asymptotic length (Table 11.2.2.1). While females mature at the same length at both latitudes (ca 280 mm), sexual maturity occurs one year later at the Abrolhos Islands (4 years). Females change to male at ca 471 mm and 12 years at the Abrolhos Islands and 545 mm and 10.5 years at Shark Bay (Fairclough 2005; Nardi *et al.* 2006). The sex ratio of adults at each location is biased towards females (14:1), while that in commercial catches (i.e. fish ≥ 400 mm) is 1:1.

Wise *et al.* (2007) estimated natural mortality for *C. rubescens* at 0.21 year^{-1} from a maximum age of 22 years. Using a regression method, a similar estimate was obtained (0.22 year^{-1}), however, confidence limits were wide (0.07 – 0.55 year^{-1}) (Hoenig 1983; Hewitt and Hoenig

2005). Nardi *et al.* (2004) also estimated *M* using a range of methods and produced highly variable results ($M = 0.05$-0.58). Given *C. rubescens* has a limited distribution, is protogynous, relatively long-lived and slow growing and has moderately high natural mortality, this species is considered vulnerable to over-exploitation (Department of Fisheries 2011).

Choerodon rubescens spawns predominantly between early-spring and mid-summer, i.e. October to January (Fairclough 2005; Nardi *et al.* 2004; DoFWA unpublished data). Females produce multiple batches of eggs during the spawning season (Table 11.2.2.2). Males have relatively very small testes, indicating that they are likely to spawn with an individual female at any one time (Fairclough 2005). Nothing is currently known of larval biology, but pelagic larval duration is being estimated as part of a PhD project (K. Cure, UWA PhD candidate).

Table 11.2.2.1. von Bertalanffy growth parameters for *Choerodon rubescens*. Note a single growth curve has been fitted to lengths at age of both sexes in each study. 95 % confidence intervals in parentheses where available.

Location	L_∞	k	t_o	r^2	Reference
Shark Bay	639.7 (613.6, 665.7)	0.16 (0.14, 0.17)	-0.82 (-1.00, -0.62)	0.92	Fairclough 2005
Abrolhos Islands	534.7 (521.1, 548.3)	0.19 (0.17, 0.21)	-0.16 (-0.48, 0.16)	0.79	Fairclough 2005
Abrolhos Islands	498.4	0.26	-0.46	0.59	Nardi *et al.* 2004

Table 11.2.2.2. Parameters (± 95% confidence intervals in parentheses) for the linear regressions fitted to data for ln batch fecundity (BF) vs ln total length (TL, mm), according to the equation $\ln BF = a \ln TL + b$, and for batch fecundity vs total weight (W), according to the equation $BF = aW + b$, for *Choerodon rubescens* in Shark Bay and the Abrolhos Islands. (Fairclough 2005).

Independent variable	Location	Parameters		R^2
		a	b	
ln Total length	Shark Bay	3.237 (2.176, 4.298)	-8.486 (-14.799, -2.173)	0.738
	Abrolhos Islands	5.050 (4.037, 6.063)	-19.614 (-25.633, -13.595)	0.808
Total weight	Shark Bay	37.02 (20.78, 53.25)	3276.49 (-19649, 26202)	0.61
	Abrolhos Islands	48.11 (38.92, 57.30)	-21599 (-34660, -8537)	0.823

Choerodon rubescens consists of a single genetic stock across its range (Gardner and Chaplin 2011). Otolith microchemistry indicates stock separation of adults at the management area scale in the WCB and possibly among locations within management areas (Fairclough *et al.* 2011). Those data also indicated that by the early juvenile phase, individuals will have settled in locations adjacent to their adult habitats where they will remain. These studies demonstrate that dispersal in this species will occur predominantly at the egg/larval stage.

11.2.3 Predators and prey

Choerodon rubescens consumes predominantly invertebrates, particularly bivalves, echinoderms and gastropods (Lek 2004). This species exhibits size-related dietary changes, switching from crustaceans, bivalves and gastropods in small individuals to echinoderms, particularly sea urchins, in larger individuals (Lek 2004). Predators of *C. rubescens* are likely to be elasmobranchs and/or large piscivorous teleosts (e.g. Epinephelids).

11.2.4 Recruitment

There is no available information on the recruitment dynamics of *C. rubescens*. Age structure data does not indicate substantial interannual recruitment variability (Wise *et al.* 2007; Fairclough *et al.* 2014).

11.5 Current impacts of climate change

Existing impacts of climate change recorded for *C. rubescens* include mortalities at the Houtman-Abrolhos Islands during the 2011 marine heatwave along the west coast of Australia (Pearce *et al.* 2011).

11.6 Sensitivity to change

Little is known if this subtropical species is sensitive to change in environmental factors. However, it does occur across a substantial latitudinal range (23-33.5°S) indicating tolerance to a wide range of water temperatures. Juveniles have been recorded in shallow environments, but it is not known if there is exclusive use of such habitat during that stage and thus risk to that life cycle stage from changes in environmental conditions (Fairclough *et al.* 2008). Spawning in *C. rubescens* occurs at the same time of year across its range, suggesting temperature is not the only factor involved in gonadal recrudescence (Fairclough 2005), which may reduce sensitivity. However, studies have not been conducted to examine whether (1) a specific water temperature range is required for successful spawning, or (2) it is the change in water temperature from decreasing to increasing that occurs at approximately the beginning of spring, that triggers recrudescence.

11.7 Resilience to change

Choerodon rubescens occurs across a substantial latitudinal range (23-33.5°S) and in waters of 1 to 100 m across the continental shelf indicating robustness to a wide range of water temperatures. They are almost exclusively associated with reef and their diet is diverse. Stock delineation of adults and results of previous assessments indicate vulnerability to localised depletion. The extent of dispersal of eggs/larvae would be influenced by changes in strength of prevailing currents and location of egg/larval production along the coast (Feng *et al.* 2010). While this species is likely to be resilient to a certain extent to changing environmental conditions, e.g. increasing water temperature, the extent of such effects on its invertebrate food sources are unknown. Declines in growth of scallops in Shark Bay may have been related to a period of unusually high water temperatures along the West Australian coast (Pearce *et al.* 2011).

11.8 Ecosystem level interactions

Choerodon rubescens are reliant on invertebrates as a food source.

11.9 Additional (multiple) stressors

Management changes have reduced commercial catches of *C. rubescens* to levels that would allow stock recovery, after overfishing was detected in stock assessments of this species at the Abrolhos Islands. However, the 50% reduction in recreational/charter catch was not achieved for this species in 2011/12 (Fairclough *et al.* 2014). In addition, recreational catch by Western Rock lobster fishers while staying at the Abrolhos Islands has, in the past, been substantial. However, this is not likely to be well-accounted for in recreational surveys and may be having continued impact on stocks in this region, in addition to other large recreational vessels that visit the islands, but consume fish while there. Any changes to water current patterns associated with climate change may influence dispersal and exacerbate effects of fishing.

11.10 Critical data gaps and level of uncertainty

Monitoring of recreational catch by Western Rock Lobster fishers of *C. rubescens* at the Abrolhos Islands is required to better assess exploitation levels in this area. This is particularly important given the fishery season at the islands now encompasses the whole year (de Lestang *et al.* 2013). The sensitivity of *C. rubescens* to environmental variation, including pH, temperature and extreme events are not known, particularly for early life history stages. However, extreme water temperatures have been found to cause mortalities in shallow water. Increased pH levels, reflecting ocean acidification, have been shown to affect otolith morphology, which influences fish hearing (Bignami *et al.* 2013). This may impact on the ability of larvae to settle in suitable habitats, when reliant on specific cues, e.g. reef noise. Sensitivity of the prey of this species to such variations is also not known. Widespread mortality of prey could severely impact on food availability. The importance of types of reef habitat, e.g. coral vs limestone is not well known, in addition to home range. Also, as labrids rest at night, they require refuges, which may be impacted by climate change effects, e.g. coral collapse after bleaching related depths.

11.11 Acknowledgements

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12.0 Bight Redfish (*Centroberyx gerrardi*)

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Bight Redfish, *Centroberyx gerrardi* (Günther 1887), belongs to the Berycidae (the Alfonsinos). This species occurs across southern Australia from approximately Lancelin on the west coast to the southern coast of New South Wales. It is an important species in Commonwealth trawl fisheries in the Great Australian Bight and state commercial line fisheries of Western Australia.

- Commercial catches are taken primarily in the Great Australian Bight (GAB) and continental shelf waters of Western Australia
- Annual Commonwealth trawl fishery catches are in the order of 100s of tonnes compared with 10s of tonnes by state commercial and recreational fisheries

12.1 The fisheries

State Fisheries

Centroberyx gerrardi is important in state-managed commercial line fisheries in the West (WCB) and South Coast Bioregions (SCB) of WA. *Centroberyx* spp. (predominantly Bight Redfish) contributed ca 25 to 43 t per year to total annual catches of the West Coast Demersal Scalefish Interim Managed Fishery (WCDSIMF) between 2008 and 2011 (Fairclough *et al.* 2013). Most of those catches are taken in the South-west Area of the WCDSIMF. In the South Coast Bioregion (SCB), open access commercial line fishing landed between 31 and 47 t per year between 2008 and 2012 (Norriss *et al.* 2013). Smaller annual catches (≤ ~ 10 t) are also landed by temperate demersal gillnet and longline fisheries in southern Western Australia (Braccini *et al.* 2013).

In 2011/12 less than 2 t of *Centroberyx* spp. was caught by recreational fishers in the West Coast Bioregion (WCB) and ca 12 t was landed in the SCB (Ryan *et al.* 2013). Less than 2.5 t per year has been landed by charter fishers in the WCB between 2008 and 2012 (DoFWA unpublished data). Between 2002/03 and 2007/08, *C. gerrardi* ranked highest in charter catches in the SCB, with about 4,500-6,000 fish caught per year (Telfer 2010). Weight was not estimated for those catches.

In South Australia, estimated recreational and commercial catches were ca 15 t and 3 t, respectively in 2007/08 (Jones 2009). Knight and Vainickis (2011) reported that the South Australian charter sector landed between 14,000 and almost 18,000 *C. gerrardi* per year between 2008/09 and 2010/11. Based on the average weight per fish of 0.61 kg of Jones (2009), this would equate to ca 8.5 t to 11 t.

Centroberyx gerrardi has not been specifically reported in commercial catch data from Victoria. However, landings of fish, other than those listed, were less than 1 t per year between 2007/08 and 2010/11 (see http://www.dpi.vic.gov.au/fisheries/commercial-fishing/commercial-fish-production-2011).

Commonwealth trawl fishery

Substantial catches of *C. gerrardi* are taken annually by the Great Australian Bight Trawl Sector (GABTS) of the Southern and Eastern Scalefish and Shark Fishery. This species is targeted mainly in shelf waters of ca 120–160 m (Wilson *et al.* 2009). Very small catches have been taken historically by the Western Deepwater trawl fishery, which operates off the west coast of Australia. Catches of the GABTS increased from approximately 86 t in 1988/89 to 1000 t in 2006/07 before declining to ca 300 t in 2010/11 along with a reduction in effort (Klaer 2012).

Stock assessments

The stock status of *C. gerrardi* in south-western Australian waters is unknown. At the beginning of 2012/13, the spawning stock biomass for the Great Australian Bight stock, extending from eastern waters of the south coast of Western Australia to central South Australia, was estimated to be 90 % of unexploited stock biomass (Klaer 2012). A WANRM funded project is currently underway to assess the status of stocks of Bight Redfish in the SCB and South-west Area of the WCB and is due for completion in 2015.

12.2 Life history

12.2.1 Distribution, habitat and environmental preferences

Centroberyx gerrardi is endemic to waters of southern Australia, from approximately Lancelin on the west coast to southern New South Wales (Figure 12.2.1.1). It occurs singly or in pairs, using ledges and caves in rocky reef habitats between about 11 and 260 m (Gomon *et al.* 2008). There is no information on nursery habitats. However, Brown and Sivakumaran (2007) indicated that small, immature fish may be found inshore (< 100 m).

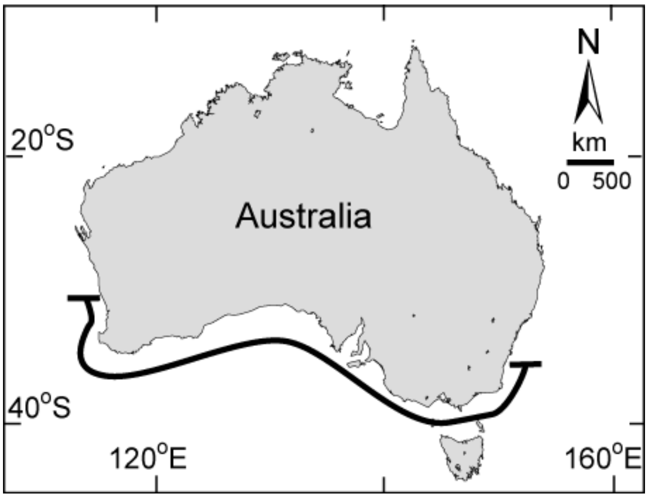

Figure 12.2.1.1. The distribution of *Centroberyx gerrardi*.

12.2.2 Life cycle, age, growth and reproduction

Centroberyx gerrardi reaches approximately 66 cm and 4.6 kg (Hutchins and Swainston 1986). Longevity has been reported as 71 years from fish collected in the GABTS and 75 in WA stocks (Stokie and Krusic-Golub 2005; P. Coulson, Murdoch University, unpublished data). *Centroberyx gerrardi* is a gonochorist, i.e. has separate sexes.

von Bertalanffy growth curves derived from length at age data from *C. gerrardi* collected from the GABTS demonstrated an asymptotic growth pattern (Stokie 2004; Stokie and Krusic-Golub 2005). However, those data did not contain small, young fish, which would have influenced the estimates of k and t_0. While inter and intra-reader growth zone counts have been validated in each study, validation of annual formation of growth zones was not conclusive. However, validation of annual growth zone formation is underway as part of a WANRM funded project to assess the status of this species' stocks. The rate of natural mortality was reported by Klaer (2012) as approximately 0.1.

Table 12.2.2.1. von Bertalanffy growth parameters for *Centroberyx gerrardi*.

Sex	FL_∞	k	t_o	Reference
Great Australian Bight stock				
Female	481	0.023	-30.9	Stokie 2004
Male	420	0.034	-27.6	
Combined sexes	430	0.031	-24.8	
Female	430	0.066	-5.9	Stokie and Krusic-Golub 2005
Male	401	0.081	-4.2	
Combined sexes	413	0.075	-4.6	
Western South Coast Bioregion stock				
Female	512	0.083	-1.097	Coulson, P. Murdoch University, unpublished data
Male	478	0.103	-0.629	
Combined sexes	496	0.091	-1.022	

Female *C. gerrardi* are indicated to reach sexual maturity at 250 mm FL and nine years of age on average (Brown and Sivakumaran 2007). However, those authors recognised that their sampling did not include fish < 250 mm and all fish ≥ 250 mm were mature. In the Great Australian Bight, *C. gerrardi* spawns between late January and early May, peaking in March and April (Brown and Sivakumaran 2007). This appears also to be the case in south-western Australia (Mackie *et al.* 2009; DoFWA, unpublished data). Females have indeterminate fecundity and are multiple spawners and the presence of large testes in mature males indicates that fish spawn in groups. There is significant evidence that this species aggregates to spawn (Mackie *et al.* 2009). Batch fecundity and total annual fecundity have not been estimated for *C. gerrardi*. However, Brown and Sivakumaran (2007) estimated "total fecundity", i.e. the number of yolk granule, migratory nucleus and hydrated oocytes prior to spawning, in a sample of six females. Total fecundity estimates ranged from 0.55–0.84 million oocytes kg^{-1} of fish. The stock structure of this species between the south-west of Western Australia, the SCB and the Bight is currently being investigated. This study is using molecular and otolith microchemistry techniques, as part of the WANRM project, to test the hypothesis that the species forms a single stock across its range.

Based on its biological characteristics, including its aggregating behaviour, longevity and low natural mortality, *C. gerrardi* is vulnerable to over-exploitation.

12.2.3 Predators and prey

Centroberyx gerrardi is carnivorous, potentially targeting teleosts, cephalopods and other invertebrates (see Mackie *et al.* 2009). It is likely to be predated upon by elasmobranchs and/or large piscivorous teleosts, e.g. *Seriola hippos*.

12.2.4 Recruitment

There is no published information on recruitment of Bight Redfish. However, larval survival is likely to exhibit interannual variability due to variation in environmental and biological conditions, e.g. the strength of the Leeuwin Current that flows along the shelf edge on the lower west and south coasts.

12.3 Current impacts of climate change

There are no known current impacts of climate change on *C. gerrardi*.

12.4 Sensitivity to change

Juveniles may occupy shallower nearshore and inshore environments than adults and be influenced by changing environmental factors, e.g. water temperature. Spawning occurs at the time of year when the prevailing Leeuwin Current is stronger. Thus, predicted reductions in current strength may reduce dispersal of eggs and larvae from western spawning locations. This may influence stock size in the eastern part of the species range.

12.5 Resilience to change

Centroberyx gerrardi are found across the continental shelf in waters of southern Australia and thus experience a wide temperature range. Their habitat preferences at different stages of life are not well-known, however, adults are commonly found associated with hard structure, which obviously also support their preferred food types. As the species aggregates during spawning, specific habitat needs may be required at that time. The composition of these habitats, e.g. benthos, algae and food sources, may or may not be resilient to change and could influence spawning behaviour/success.

12.6 Ecosystem level interactions

Unknown.

12.7 Additional (multiple) stressors

Based on recent assessments of indicator species for the demersal suite of species in south-western WA (Wise *et al.* 2007; Fairclough *et al.* 2014), *C. gerrardi* can be considered to be recovering. This is after significant management changes were made to address overfishing of demersal species on the west coast of Australia between late 2007 and early 2010 (McAuley and Sarginson, 2011). In 2012, *C. gerrardi* was adopted as an indicator species for the South-west area of the WCB and for the SCB and will form part of an assessment to be completed in 2015. The biological characteristics of this species, particularly its longevity and thus low natural mortality rate, make it vulnerable to the effects of fishing.

The predicted spawning stock biomass in the GABTS for 2012/13 was 90 % of unexploited stock biomass (Klaer 2012). Although catches in the fishery in recent years have declined with a concomitant decrease in effort, catches are very large relative to WA. Thus, ongoing monitoring needs to occur and to consider the decrease in modal length observed in catches between 2005 and 2009, which may be an effect of fishing (Knuckey *et al.* 2009).

12.8 Critical data gaps and level of uncertainty

Specific knowledge gaps in relation to stock status, catch of each sector and stock structure are being addressed as part of a WANRM project to be completed in 2015. However, larval duration and impacts of changes in prevailing dispersal mechanisms, e.g. the Leeuwin Current, are unknown. The sensitivity of *C. gerrardi* to environmental variation, including pH, temperature and extreme events are not known, particularly for early life history stages. Increased pH levels, reflecting ocean acidification, have been shown to affect otolith morphology of fish species, which is likely to influence hearing (Bignami *et al.* 2013). This may impact on the ability of larvae to settle in suitable habitats, if reliant on specific cues, e.g. reef noise. Sensitivity of the prey of this species to such substantial environmental variations is also not known.

12.9 Acknowledgements

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13.0 Narrow-Barred Spanish Mackerel (*Scomberomorus commerson*)

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The Narrow-Barred Spanish Mackerel, *Scomberomorus commerson* (Lacepède, 1800), is a member of the Family Scombridae (mackerels, tunas and bonitos). The species is widely distributed throughout tropical and subtropical waters of the Indo-West Pacific (Collette and Nauen 1983). Its Australian distribution includes northern Australia to as far south as Geographe Bay in south-western Australia (Allen and Swainston 1995) and Sydney on the east coast. Narrow-Barred Spanish Mackerel are often found over reefs, in the lee of islands and associated with bathymetric features. Spanish Mackerel is a significant species for both commercial and recreational fishers throughout its distribution.

13.1 The fisheries

- Commercial catches in Australia are taken in Western Australia (WA), Northern Territory (NT) and Queensland
- An estimated 1,140 t of Spanish Mackerel were landed by Australian commercial fisheries in 2010/11 (Skirtun *et al.* 2012)
- Western Australian commercial catches of 284 t represented approximately 25% of total Australia commercial catches in 2011.
- Recreational catches of Spanish Mackerel from Western Australia from the Statewide boat survey of 2011 were 68 t.

In Western Australia, Spanish Mackerel are commercially captured in the Mackerel Managed Fishery, which operates between the NT/WA border and Augusta (34°22.51’S) in south-western Australia (Molony *et al.* 2012). Small amounts (14 t in 2011) of other pelagic fishes are also captured, dominated by Grey Mackerel (*Scomberomorus semifasciatus*, 13 t). Throughout their range, Spanish Mackerel are also targeted by recreational fishers.

A majority of the commercial catches are landed from the northern Kimberley Area (Area 1) of the Mackerel Managed Fishery (Molony *et al.* 2012), with relatively low catches from the Gascoyne/West Coast Area, reflecting the more tropical distribution of the species (Table 13.1.1). A record catch of approximately 500 t was reported from the fishery in the early 2000s. However, a TACC of 410 t for all zones (acceptable catch range of 246–410 t) was set in 2003 as the fishery moved to an interim managed fishery, and finally a fully managed fishery (2011).

Table 13.1.1. Commercial catches of Narrow-Barred Spanish Mackerel in Western Australia for the 2011 season and acceptable catch ranges.

Area	2011 catch (t)	Acceptable catch range (t)
Kimberley	183	110 - 205
Pilbara	55	80 - 126
Gascoyne/West Coast	47	56 - 79
Total	284	246 - 410

Estimates of recreational catches of Spanish Mackerel in Western Australia have been undertaken intermittently. Most recreational catches of Spanish Mackerel have been reported in the Gascoyne Bioregion, where recreational catches were of a similar magnitude to the commercial catch (Table 13.1.1). However, these surveys are not directly comparable with commercial catches, especially for the Kimberley region where the recreational survey was limited to around the Broome area only. The most recent recreational estimates were generated from the 2011/12 Statewide fishing from boat survey (iSurvey, Ryan *et al.* 2013) which indicated a total catch of 68 t and a similar magnitude of catch and release (Table 13.1.2).

Table 13.1.2. Estimates of recreational catches of Narrow-Barred Spanish Mackerel in Western Australia.

a) Historical estimates

Survey	Survey date	Recreational Spanish Mackerel catch (t)	Source
Pilbara, plus Broome	1999/2000	28	Williamson *et al.* 2006
Gascoyne Bioregion	1998/1999	48	Sumner *et al.* 2002
West Coast Bioregion	2005/2006	7	Sumner *et al.* 2008

b) Most recent iSurvey estimate, 2011/12 (Ryan *et al.* 2013).

Bioregion	Retained catch (std. error)	Released catch (std. error)	Total catch (std. error)
North Coast	26.2 t (3.66 t)	30.8 t (6.58 t)	57.0 t (8.59 t)
Gascoyne Coast	21.3 t (2.80 t)	24.0 t (4.81 t)	45.2 t (6.61 t)
West Coast	20.7 t (3.02 t)	6.3 t (1.46 t)	27.0 t (3.81 t)
Statewide (total)	68.1 t (9.47 t)	61.2 t (12.84 t)	129.3 t (19.01 t)

The Spanish Mackerel stock in Western Australia is considered sustainable and approaching full exploitation (Molony *et al.* 2012).

13.2 Life history

13.2.1 Distribution, habitat and environmental preferences

There are three main stocks of Narrow-Barred Spanish Mackerel in Australia. However, five stocks are considered for management purposes; East Coast (Queensland), Gulf of Carpentaria, Torres Strait, Northern Territory and Western Australia. There are likely to be many smaller biological stocks within these broad units (Holmes *et al.* 2012). All Narrow-Barred Spanish Mackerel in Western Australia are considered to be a single stock.

The Australian distribution of Narrow-Barred Spanish Mackerel includes northern Australia to as far south as Geographe Bay in south-western Australia (Allen and Swainston 1995) (Figure 13.2.1.1) and Queensland on the east coast. However, it is more abundant in the tropical (northern) part of its distribution.

Narrow-Barred Spanish Mackerel (*S. commerson*) is a pelagic fish and found over most northern shelf waters. They tend to aggregate in more inshore locations during the summer spawning periods, typically near reefs and in the lee of islands. They are suspected to move out over deeper waters during other times of the year (Mackie *et al.* 2003).

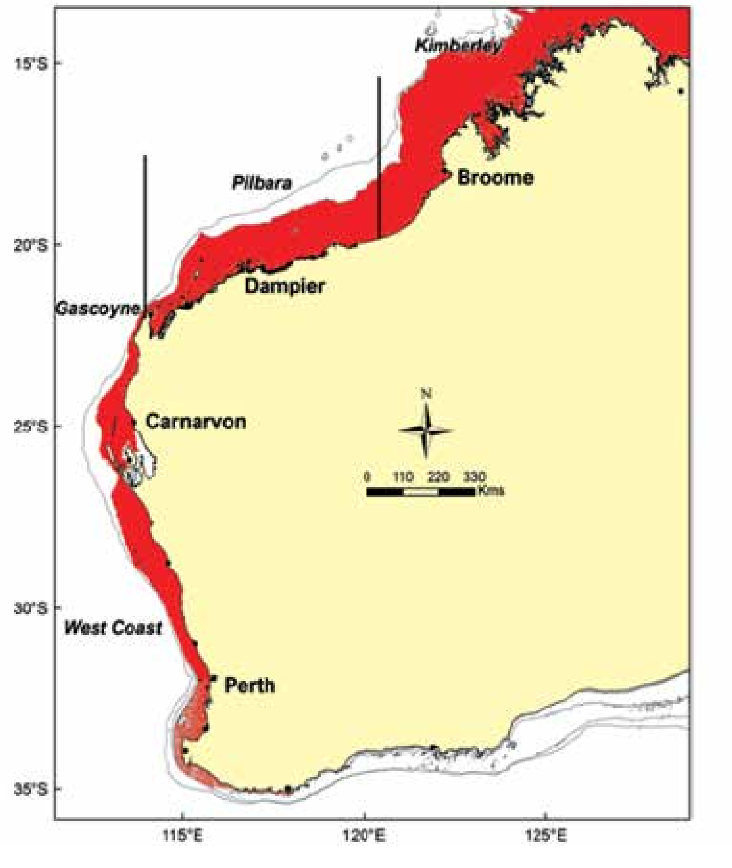

Figure 13.2.1.1. The Western Australian distribution of Narrow-Barred Spanish Mackerel (*Scomberomorus commerson*).

13.2.2 Life cycle, age and growth

Narrow-Barred Spanish Mackerel (*S. commerson*) have been reported to exceed 22 years (Mackie *et al.* 2003), reaching 235 cm and nearly 45 kg (Allen and Swainston 1995). *S. commerson* is a gonochorist (i.e. has separate sexes).

Narrow-Barred Spanish Mackerel (*S. commerson*) are fast growing, reaching 500-600 mm by the end of their first year and approaching their asymptotic size within four years (Mackie *et al.* 2003). Females grow faster than males although males tend to dominate older age classes. West Australian commercial catches are dominated by fish between one and four years of age. Mackie *et al.* (2003) reported that Pilbara *S. commerson* (both sexes) reach slightly larger sizes than Kimberley or West Coast fish. However, Pilbara *S. commerson* in Western Australia do not reach the large sizes of fish from Queensland (McPherson 1992) and are generally smaller than Northern Territory fish (Buckworth 1998) (Table 13.2.2.1).

Narrow-Barred Spanish Mackerel (*S. commerson*) reach sexual maturity at a young age (<1.5 years) in Western Australia (Mackie *et al.* 2003). Spawning occurs at specific shelf locations, often associated with bathymetric features such as reefs. Most spawning occurs between October and January, with an extended season in the Kimberley Area. There is no evidence of spawning south of approximately Exmouth (Mackie *et al.* 2003). In Western Australia, the current minimum legal length of 900 mm ensures that 50% of females are mature and more than 90% of males are mature.

Mortality estimates are relatively high but vary among studies and locations. Mackie *et al.* (2003) applied a range of methods to estimate natural mortality for Australian stocks of *S. commerson* and generated estimates of natural mortality (M) between 0.19 year^{-1} and 1.19 year^{-1}, with most estimates in other studies within the range of 0.4 – 0.6 year^{-1} (Mackie *et al.* 2003). Natural mortality estimates tended to be higher at lower latitudes (closer to the equator).

Narrow-Barred Spanish Mackerel are therefore considered to have a high production potential, being fast growing, having a high natural mortality, a large size and low age at 50% maturity. This makes Narrow-Barred Spanish Mackerel relatively robust to exploitation.

Table 13.2.2.1. von Bertalanffy growth parameters for Western Australian, Queensland and Northern Territory Narrow-Barred Spanish Mackerel (From Mackie *et al.* 2003).

State	Area	Sex	L_∞ (mm)	K	t_o	Source
WA	Kimberley	♂	1067	0.85	-0.21	Mackie *et al.* 2003
	Kimberley	♀	1219	0.65	-0.26	Mackie *et al.* 2003
	Pilbara	♂	1155	0.69	-0.29	Mackie *et al.* 2003
	Pilbara	♀	1259	0.63	-0.29	Mackie *et al.* 2003
	West Coast	♂	1140	0.76	-0.21	Mackie *et al.* 2003
	West Coast	♀	1205	0.66	-0.26	Mackie *et al.* 2003
QLD		♂	1275	0.25	-1.72	McPherson 1992
		♀	1550	0.17	-2.22	McPherson 1992
NT		♂	1286	0.10	-9.80	Buckworth 1998
		♀	1218	0.12	-6.31	Buckworth 1998
WA	Kimberley	Combined	1151	0.71	-0.25	Mackie *et al.* 2003
	Pilbara	Combined	1209	0.67	-0.28	Mackie *et al.* 2003
	West Coast	Combined	1167	0.72	-0.23	Mackie *et al.* 2003
NT		Combined	1218	0.24	-3.25	Buckworth 1998

13.2.3 Predators and prey

Narrow-Barred Spanish Mackerel are a pelagic predatory fish. The guts of most (86%) Narrow-Barred Spanish Mackerel examined by Mackie *et al.* (2003) contained fish, a majority of which were pelagic. In addition, cephalopods were reported in approximately 12% of guts of Narrow-Barred Spanish Mackerel. Crustaceans were reported in less than 1% of guts (Mackie *et al.* 2003).

Predators of Narrow-Barred Spanish Mackerel are likely to include other pelagic predators including a range of sharks, billfishes and tunas.

13.2.4 Recruitment

Little is known of the recruitment and recruitment dynamics of Narrow-Barred Spanish Mackerel. Anecdotal observations from commercial fishers suggest that there is variable inter-annual recruitment in Western Australia (Mackie *et al.* 2003), likely driven by variability in environmental conditions. Strong cohorts can be traced throughout the fishery in subsequent years (Mackie *et al.* 2003).

13.3 Current impacts of climate change

There is little direct data on the impacts of climate change. However anecdotal information suggests that Narrow-Barred Spanish Mackerel are distributed further south during periods of above average water temperature. It is likely, therefore, that the range of Narrow-Barred Spanish Mackerel will extend southwards and that the centre of the biomass of stock may also move more southerly. It is also possible that the total biomass of Narrow-Barred Spanish Mackerel in Western Australia will increase due to the relatively high productivity the stock, the likely extension of the breeding season with higher water temperatures extending further southwards and the availability of additional suitable habitats further south.

13.4 Sensitivity to change

Little is known of the sensitivities of Narrow-Barred Spanish Mackerel to environmental factors. However, given its extensive latitudinal range, Narrow-Barred Spanish Mackerel is likely to tolerate a wide range of water temperatures and other environmental variables. Their sensitivity to change may be reflected in closer examination of catches and catch rates in relation to environmental conditions, particularly sea surface temperatures. Anecdotally, this is observed in the southwards extension of their range during periods of above average water temperatures (i.e. during strong Leeuwin currents and during the austral summer).

13.5 Resilience to change

Narrow-Barred Spanish Mackerel have an extensive distribution and are not strongly habitat associated. Additionally, being a pelagic fish, they are able to respond to changes in habitat suitability (e.g. temperature) by moving rapidly to remain within favourable conditions. Narrow-Barred Spanish Mackerel consume a range of pelagic and reef associated species and will accept a wide range of baits; thus they are likely to be a generalist carnivore. Overall, Narrow-Barred Spanish Mackerel appear to be a very resilient species to environmental changes and may be one of the ‘winners’ under a scenario of increasing water temperatures.

13.6 Ecosystem level interactions

Narrow-Barred Spanish Mackerel are a pelagic piscivore, but also consume reef associated species of fish. They are highly mobile and are likely to have a significant role in linking different habitats and ecosystems.

13.7 Additional (multiple) stressors

Current levels of fishing for Narrow-Barred Spanish Mackerel in Australia are considered sustainable (Holmes *et al.* 2012), including in Western Australia (Molony *et al.* 2012). There is an unquantified risk due to the marine operations associated with oil and gas development (e.g. seismic surveys, marine drilling, etc.) and port construction.

13.8 Critical data gaps and level of uncertainty

Little is known of the environmental tolerances of Narrow-Barred Spanish Mackerel. While they are likely to tolerate a wide range of temperatures as adults, environmental requirements for successful fertilisation and larval and juvenile success are unknown.

Examination of reproduction at fine spatial scales (kilometres) is required to confirm the spawning frequency of sub-populations and confirm anecdotal reports of commercial fishers that suggest that ‘groups’ of Narrow-Barred Spanish Mackerel are at different reproductive stages within kilometres of each other. Further survey work is required to confirm the lack of spawning south of Exmouth, which would include biological sampling from Exmouth to Geographe Bay. This work may be useful in determining range extension of Narrow-Barred Spanish Mackerel.

13.9 Future climate scenarios (2030/2060)

Spanish Mackerel are likely to benefit from the projected climate change scenarios. Their relatively low age to maturity, fecundity and ability to rapidly move is likely to result in this species being able to capitalise on opportunities of expanding suitable habitats (waters above 20°C). It is likely Spanish Mackerel will be reported more often in the West Coast Bioregion and in greater numbers, as sea surface temperatures increase the range of suitable habitats. It is also likely that this species will be reported from the South Coast Bioregion in the future.

It is likely that biomass will increase across all management areas. This is due to the reproductive strategy of Spanish Mackerel, the generalist nature of its diet and the current management strategies that protect most fish until at least 50% have reached sexual maturity (Mackie *et al.* 2003). Spanish Mackerel have a protracted spawning period in warmer waters and thus it is likely that the spawning period will extend as water temperatures increase and food available continues. Therefore, spawning biomass will likely increase in the Kimberley and Pilbara areas and it is likely that spawning may commence in the Gascoyne Bioregions; mature fish have not been previously recorded from this Bioregion (Mackie *et al.* 2003).

Increasing biomass and increasing occurrence and abundance of Spanish Mackerel in the temperate Bioregions will increase the catches in all Bioregions. For the commercial catches, this is likely to result in zonal TACCs (total allowable commercial catches) being reviewed and potentially increased in the future. For the recreational fishery, it is likely that increasing catches will be reported by the boat based sector in all Bioregions (including the South Coast Bioregion) via iSurvey in the future.

13.10 Management implications

Management will require continued close monitoring of catches by both sectors in all zones and Bioregions. In addition, a mechanism (e.g. control rules) around reviewing and potentially increasing zonal TACCs (and therefore total TACC) for the commercial fishery are required. Defining recreational TARC (total allowable recreational catches) is also likely to be required, especially for the temperate Bioregions. This is not only to manage and limit the expansion of the recreational fishery, but to respond to the likely human population growth, and therefore growth in recreational fishers projected for this area (e.g. 3 million people in Perth by 2050).

Along with continued and potentially increased monitoring of catches of Spanish Mackerel by both sectors, other monitoring should also be considered. Additional monitoring and research could include;

- Development of biomass estimates across the fishery and within each Bioregion.
- Monitoring of age structure across the fishery and within each Bioregion.
- Confirmation of the increased spatial extent of spawning, commencing in the Northern Gascoyne Bioregion.
- Potential for recruitment monitoring either directly or via age structure monitoring, to confirm increases in spawning biomass.
- Monitoring of the spatial distribution of catches (CPUEs) within each management zone in order to determine changes in extent of areas of relatively higher local abundance.
- Assessment of the impact and risks of post-release mortality by the growing recreational sector, especially in Bioregions where Spanish Mackerel are currently rare.
- Spatial patterns in size and age of recreational catches.

13.11 Acknowledgements

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14.0 Snapper (*Chrysophrys auratus*)

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Snapper, *Chrysophrys auratus*, a member of the family Sparidae (Seabreams and Porgies), is widely distributed throughout the warm temperate and subtropical waters of the eastern Indian Ocean and western Pacific, primarily in southern Australia and northern New Zealand (Paulin 1990; Gomon *et al.* 2008; Parsons *et al.* 2014). In Australia, the species is found in coastal waters around the southern half of the continent from north-east Queensland to north-western Australia (Kailola *et al.* 1993). Snapper are an important component of commercial and recreational fisheries throughout their Australian distribution (Jackson *et al.* 2012).

14.1 The fisheries

- Significant commercial and recreational catches are taken in Queensland, New South Wales, Victoria, South Australia and Western Australia
- The total WA catch (all sectors) represents around 20-25% of the total Australian catch
- Important recreational fisheries in the Gascoyne Coast and West Coast bioregions of WA are reasonably well understood

Western Australia

Snapper is one of the most important commercial and recreational finfish species in Western Australia particularly in the Gascoyne and West Coast bioregions (Fairclough *et al.* 2013a; Jackson *et al.* 2013). Snapper are commercially caught mostly by line-fishing and as byproduct in temperate demersal gillnet and longline fisheries (Braccini *et al.* 2013). Commercial Snapper fishing in waters of the Gascoyne off Shark Bay dates back to the early 1900s with the modern-day Snapper fishery well established by the early 1950s. Catches increased from around 200 t in 1952 to a peak around 1300 t in 1985 (Marriott *et al.* 2012). Following the creation of the Shark Bay Snapper Managed Fishery in 1987, catches remained relatively stable at around 450-550 t between the late 1980s and early 2000s. The fishery, now part of the Gascoyne Demersal Scalefish Fishery, has been managed by quota since 2001 with a TACC currently set at 277 t (Jackson *et al.* 2013). In the West Coast Bioregion, commercial Snapper catches ranged between ca 170 and 340 t from 1989/90-2006/07, but have been maintained below ca 180 t since the commencement of the West Coast Demersal Scalefish Interim Managed Fishery in 2008 (Fairclough *et al.* 2013a). In the South Coast Bioregion, commercial catches ranged between ca 10 and 60 from 1990 to the present. Snapper are a much sought after recreational species, particularly at locations such as the inner gulfs of Shark Bay and in Cockburn Sound near Perth.

Other states

Commercial and recreational Snapper fisheries in Queensland (~700 t), New South Wales (~500 t), Victoria (~500 t) and South Australia (~900 t) contribute to a national catch of approximately 3,500 t per year (Jackson *et al.* 2012)

14.2 Life history

The biology of Snapper, a warm-temperate species, is reasonably well understood based on the numerous studies undertaken in Australia and New Zealand since the 1960s.

14.2.1 Distribution, habitat and environmental preferences

The biological stock structure of Snapper within its Australian distribution is complex (Jackson *et al.* 2012). In Western Australia, Snapper are currently divided into six management units, some of which represent separate biological stocks. In the inner gulfs of Shark Bay, separate biological stocks in the Eastern Gulf, Denham Sound and Freycinet Estuary have been identified based on genetics, otolith chemistry and tagging (Johnson *et al.* 1986; Edmonds *et al.* 1999; Moran *et al.* 2003; Bastow *et al.* 2002; Norriss *et al.* 2012). Snapper found in the open oceanic waters off the WA coast that comprise the remaining three management units, i.e. Shark Bay oceanic, west coast and south coast, show low levels of genetic differentiation over hundreds of kilometres consistent with a semi-continuous genetic stock where gene flow is primarily limited by geographic distance (Gardner and Chaplin 2011). Otolith chemistry analyses have indicated high levels of residency of adult snapper in the Gascoyne, West and South Coast bioregions with adult recruitment coming from several key nursery areas (Fairclough *et al.* 2013b). Tagging studies support these findings with the majority of adults tagged at the key spawning locations in the Gascoyne and West Coast bioregions recaptured within 100 km (Moran *et al.* 2003; Wakefield *et al.* 2011).

Adult Snapper may be associated with reefs but are also found over mud and sand out to depths of more than 300 m. Juveniles typically inhabit sheltered marine waters such as bays and inlets, often over mud and seagrass (Wakefield *et al.* 2013). On the lower west coast the earliest year classes (0+ and 1+) are found in Jurien Bay, the lower Swan River and in high abundance in Cockburn and Warnbro Sounds (Wakefield *et al.* 2011). The occurrence of 0+ and 1+ fish in open marine waters off the WA coast is poorly known.

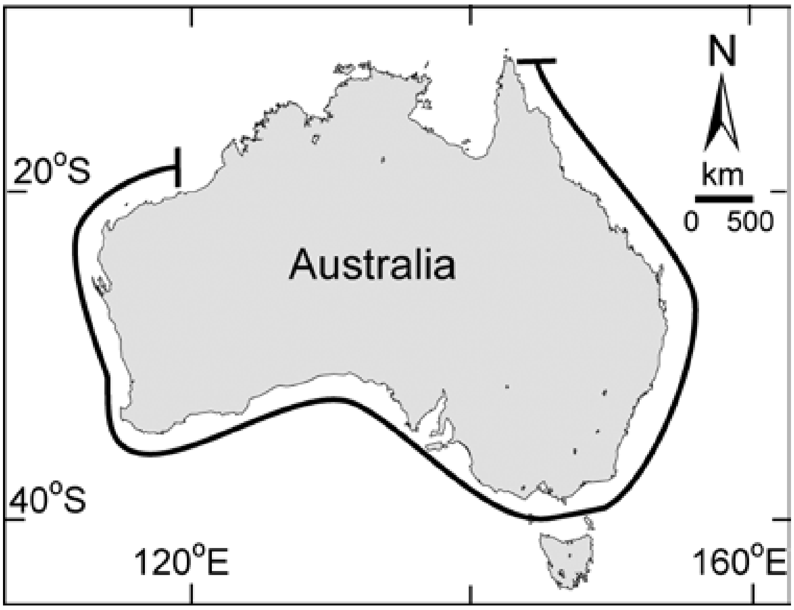

Figure 14.2.1. The Australian distribution of Snapper, *Chrysophrys auratus*

14.2.2 Life cycle, age and growth, reproduction

The species is long-lived in the warmer waters of Australia, where the reported maximum age is 41 years (Norriss and Crisafulli 2010), compared with 55–60 years in the cooler waters of New Zealand (Francis *et al.* 1992). While growth is moderately fast over the first 4 or 5 years, Snapper are considered relatively slow growing overall. Studies in WA have found no biologically significant differences in growth between the sexes but have shown considerable variation among locations across the species distribution (Table 14.2.2.1).

Table 14.2.2.1. von Bertalanffy growth parameters for *Chrysophrys auratus*

Location	Sex	L_∞ (mm, FL)	k (yr^{-1})	t_0 (yr)	Reference
Gascoyne:					
Oceanic	Female	599	0.214	-0.144	Marriott *et al.*
	Male	561	0.244	-0.79	2012
Inner Shark Bay	Female	755-773	0.142-0.178	-0.32-0.125	Jackson *et al.*
	Male	660-766	0.173-0.181	-0.071-0.075	2010
Perth Metro	Female	973	0.12	-0.41	Wakefield
	Male	954	0.12	-0.46	2006
South Coast	Female	777	0.14	-0.84	Wakefield
	Male	763	0.14	-0.98	2006

Snapper are functionally gonochoristic (Francis and Pankhurst 1988). In Western Australia, as with growth, size and age at maturity have been shown to vary significantly among locations (Table 14.2.2.2).

Spawning season also varies with location in WA occurring in late-autumn through to early spring in the Shark Bay region (Wakefield 2006; Jackson *et al.* 2010), spring to summer on west coast and summer on south coast (Wakefield 2006). Spawning is typically highly localized and occurs mostly in similar locations each year (e.g. Cockburn Sound, inner Shark Bay, Koks Island) however no single common feature (e.g. depth, substrate type) is apparent other than oceanographic gyre-type features (Nahas *et al.* 2003; Wakefield 2010). Spawning activity is strongly associated with water temperature, mostly occurring between 19-21ºC (Wakefield *et al.* in prep). There is evidence of localised spawning omission due to low water temperatures on the south coast of WA (Wakefield *et al.* in prep) and for indeterminate reasons in New Zealand (Sim-Smith *et al.* 2011).

Snapper are batch spawners with indeterminate fecundity. Females spawn multiple batches of eggs over the spawning season that can be 4-5 months duration in Shark Bay to 2-3 months on south coast (Wakefield 2006; Jackson 2007). Batch fecundity increases with increasing female size (Jackson 2007). Broadcast spawning is highly synchronised with pelagic eggs (ca. 850-950 µm diameter) released and fertilized within the upper layers of the water column (Jackson 2007).

Table 14.2.2.2. Maturity parameters for *Chrysophrys auratus*

Location	Sex	*Lmin*	*L50*	*Amin*	*A50*	Reference
Upper west (i.e. Gascoyne)	Female	*229*	*320*	*3.2*	*4.0*	Wakefield 2006
	Male	*218*	*299*	*3.1*	*3.9*	
Inner Shark Bay	Female	*193*	*348-420*	*1.9*	*3.2-5.5*	Jackson *et al.* 2010
	Male	*202*	*243-330*	*1.9*	*1.6-2.7*	
Mid west	Female	*405*	*487*	*3.7*	*5.5*	Wakefield *et al.* 2009
	Male	*319*	*426*	*2.2*	*3.8*	
Perth Metro.	Female	*320*	*505*	*2.8*	*5.7*	Wakefield 2006
	Male	*348*	*488*	*2.9*	*5.6*	
South Coast	Female	*400*	*518*	*3.8*	*7.0*	Wakefield 2006
	Male	*314*	*506*	*3.1*	*6.5*	

Egg development is influenced by environmental conditions, particularly water temperature, with hatching taking place after ca. 20-30 hours (Norriss and Jackson 2002; Wakefield 2010). A pelagic larval phase of ca. 20-25 days (Tapp 2003; Fowler and Jennings 2003) occurs prior to metamorphosis and settlement occurs when the juveniles are ca. 8-12 mm in length (TL) (Battaglene and Talbot 1992; Fowler and Jennings 2003; Breheny *et al.* 2012). Length of larval duration has been shown to influence growth and survival: fish with a short larval duration (<20 days) grew significantly faster during the larval period and resulted in larger size-at-age juveniles (Sim-Smith *et al.* 2012). In Shark Bay, juveniles grow to ca. 100-120 mm FL by end of first year and ca. 200 mm FL by end of second (Tapp 2003; Moran and Kangas 2003; Wakefield *et al.* 2007).

14.2.3 Predators and prey

The species is a highly opportunistic carnivore with a broad diet that can include a wide variety of mainly benthic organisms such as crustaceans, molluscs, echinoderms, marine worms and teleosts depending on availability (Colman 1972; Ang 2003; Coutin *et al.* 2003). Ontogenetic differences in diet related to body size and season have been shown on the WA west coast (French *et al.* 2012). The species is known to be cannibalistic. Snapper larvae have a broad diet, which includes copepod nauplii, calanoid copepodites, cladocerans, invertebrate eggs and bivalve veligers (Murphy *et al.* 2011; 2012). Finding wild food at first feeding (3-4 days post-hatch, Pankhurst *et al.* 1991) is particularly important for larval snapper because they are at the small end of the spectrum of size-at-hatch in teleosts (Miller *et al.* 1988).

Predators of Snapper eggs and larvae include Chaetognaths (Arrow Worms), Hydromedusae (Jellyfish), crustaceans (e.g. copepod and decapod larvae) and other small fish (Zeldis *et al.* 2005). Predators of juvenile Snapper include seabirds (e.g. Cormorants), piscivorous fish including larger Snapper and other larger teleosts such as Cod spp. (Epinephelidae/Serranidae), sharks and dolphins. Competitors in oceanic waters off the west coast of WA include members of the Lethrinidae, Epinephelidae/Serranidae, Labridae and Lutjanidae.

14.2.4 Recruitment

Studies in Australia (Fowler and Jennings 2003; Hamer and Jenkins 2004; Saunders 2009) and New Zealand (Francis 1993) have shown high levels of inter-annual variability in 0+ recruitment. While the driving mechanism(s) are not fully understood, environmental factors, in particular, water temperature, have been linked with recruitment variation. Warmer years either during the spawning season or shortly thereafter, have been linked with stronger recruitment, and conversely, cooler years with weaker recruitment in New Zealand (Francis 1993) and southern Australia (Fowler and Jennings 2003; Hamer and Jenkins 2004; Saunders 2009).

Recruitment variation in snapper is linked with larval survival that in turn is linked to plankton production (Zeldis *et al.* 2005; Murphy *et al.* 2011, 2012). Characteristics of larval diet have been shown to affect recruitment variability in Port Philip Bay, Victoria with extensive prey switching to larger prey, high foraging success and increased diet carbon content found in medium to high recruitment years (Murphy *et al.* 2012). The effect of larval duration on early growth, survival and recruitment variation has been shown in New Zealand with fish with short (<20 days) larval duration growing faster and reaching larger size at age than fish with longer (>24 days) larval duration (Sim-Smith *et al.* 2012)

In Shark Bay, spatial differences in habitat usage by 0+ and 1+ Snapper have been found. Moran and Kangas (2003) concluded that in the Freycinet Estuary, 0+ fish reside in the deeper basins (depth 10-12 m) over sandy/muddy bottoms from the time of settlement (ca. 20 days) until well after their first birthday. In contrast, and possibly due to the greater range of suitable habitat types that are available, in Denham Sound and the Eastern Gulf, 0+ fish delay their movement into the deeper waters until their first summer (ca. 6 months of age) and remain there until their second summer (ca. 18 months of age). In Cockburn and Warnbro Sounds on the lower west coast, the prevailing south-westerly winds that coincide with spawning through late spring-summer result in the retention of eggs and larvae in this embayment (Wakefield 2010; Breheny *et al.* 2012). Juveniles are known to remain within this embayment until about 2-3 years and 250-300 mm FL (Wakefield *et al.* 2011), and predominantly inhabit the silt substrate of the deeper (ca 20 m) central basin area, dredged channels, limestone outcrops and rockwalls (Wakefield *et al.* 2013).

14.3 Current impacts of climate change

The current impacts of climate change on *C. auratus* in WA are not well understood. However, as climate change is known to be causing an increase in water temperature, particularly in autumn and winter (i.e. the spawning season for Snapper in the Shark Bay region) and affecting the Leeuwin Current, it can be reasonably assumed that these changes are already impacting Snapper populations off the WA coast, and have been doing so for some considerable time. Given the spatial variation in life history characteristics in Snapper in WA, these impacts would be expected to vary according to the magnitude of the change and location. As Snapper is a warm-temperate species, populations at the northern (Shark Bay) and southern margins (south coast) would be most likely to be impacted by any temperature-related effects of climate change. Because most spawning appears to occur within a relatively small temperature range (i.e. 19-21ºC, Wakefield 2006; Wakefield 2010; Wakefield *et al.* in prep), there is potential, with increasing temperatures, for a latitudinal shift from the historical spawning grounds off Gascoyne Coast to locations further south. Such a shift would see reduced stock abundances in northern areas with potential corresponding increases in areas to the south, subject to other requirements being met (e.g. prey and habitat availability). Any shift in spawning locations will likely result in corresponding changes in recruitment patterns. The effect of the Leeuwin Current on Snapper spawning at offshore/oceanic locations off Shark Bay during the winter months is not well understood nor is the extent to which dispersal of eggs and larvae may contribute to recruitment to Snapper populations further to the south (e.g. off Kalbarri). More broadly, the factors affecting juvenile recruitment and the linkages between larval survivorship and plankton production are poorly understood.

14.4 Sensitivity to change

Chrysophrys auratus and the closely related *Pagrus major* are important aquaculture species and considerable research has been undertaken on their temperature and salinity tolerances. Studies in Japan with *P. major* (Woo and Fung 1981) showed individual growth was significantly reduced in summer when water temperatures increased to 28-29ºC with 32ºC the lethal limit. Water temperatures around 30-32ºC were recorded inside Shark Bay during the 2010-11 marine heatwave event with significant Snapper mortalities observed to south of Monkey Mia (Pearce *et al.* 2011). There is potential for growth effects due to increasing temperatures, initially with increased individual growth followed by decreased growth as temperatures reach the upper tolerance limits. Spawning in Snapper is well known to be temperature related, mostly occurring around 19-21ºC (Wakefield 2006; Wakefield 2010; Wakefield *et al.* in prep.). The spawning season varies with location with winter spawning occurring in the Shark Bay region and spring/summer spawning occurring on the lower west and south coast. While there is no evidence of spawning omission due to elevated water temperatures in the Gascoyne, the upper threshold is likely to be around 24°C (Okuzawa and Koichiro 2013). There is however evidence of spawning omission on the south coast in 2005, due to record low temperatures (Wakefield 2006). Warming on the south coast may result in more regular and extended spawning activity in this region of the species range in WA. Snapper are able to tolerate an extremely wide range of salinities, up to 50+ in inner Shark Bay, so increasing salinity is unlikely to be a significant influence.

14.5 Resilience to change

Snapper is a highly successful species with a very large geographic range indicative of its ability to adapt to a broad range of conditions (‘environmentally plastic’). Snapper are highly mobile and therefore able to move in response to ocean warming. There is some anecdotal evidence of a shift in the centre of the spawning population in oceanic waters off Shark Bay to locations further to the south, possibly driven by reducing winter water temperature minima (spatial analysis of historical catch and effort data is currently being undertaken). There are still major questions in relation to the role of the (few) large marine embayments, such as northern Shark Bay (to the oceanic stock) and further south Cockburn Sound, Warnbro Sound and Owen Anchorage (to lower west coast populations) to recruitment with Snapper stocks off the west coast more broadly.

Snapper have a very broad diet and are able to shift prey species according to local availability. It is unclear what the effects of reductions in prey species/abundances due to temperature increases, cyclone related flood events, or habitat loss (e.g. seagrass beds in Shark Bay, Cockburn Sound) might have on Snapper. Adult Snapper are likely more resilient to the effects of climate change than juveniles. Juveniles typically inhabit shallower nearshore environments (e.g. northern Shark Bay, Cockburn Sound, King George Sound) and therefore are more likely to be impacted by increasing sea level and increasing water temperatures. There is a strong relationship between larval survival, water temperature and planktonic production. Pankhurst *et al.* (1991) assessed *C. auratus* larvae, which are relatively small and poorly developed at hatching, to be highly vulnerable to starvation in turbid sea conditions or during periods of low prey availability.

14.6 Ecosystem level interactions

The effects of climate change on the predators and prey of Snapper are unclear. There is strong anecdotal evidence from fishers in the Gascoyne region of increased predation by sharks in inshore waters (>100 m depth) during winter months in recent years. The consequences of a decline in abundances of prey species e.g. Blue Swimmer Crabs in inner Shark Bay or increased abundances e.g. Blue Swimmer Crabs along the south coast are unknown.

14.7 Additional stressors

The Snapper that comprise the various management units/biological stocks in WA are all regarded as fully exploited (with the exception of the Eastern Gulf stock in inner Shark Bay). Questions have been raised in relation to the impacts of climate change on the capacity of Snapper stocks to recover following periods of overfishing. There is possibly evidence of this in the Freycinet Estuary, where the environment is more extreme (wider range of annual temperature variation, elevated salinity, low nutrient levels) where the spawning stock appears to be taking longer to recover following a period of overfishing despite very conservative management in place for more than 10 years (Jackson 2007).

14.8 Critical gaps and level of uncertainty

It is critical that fishery monitoring programs that are currently in place are reviewed to ensure that sampling is able to provide data necessary to be able to investigate a range of climate related impacts into the future, e.g. seasonality of spawning, changes in size/age at maturity, changes in growth rates, recruitment variation, and stock structure. Changes in these key biological parameters will influence the results of stock assessments used in WA's Snapper fisheries.

More generally there is speculation on the consequences of ocean acidification on otolith formation in teleosts (e.g. Bignami *et al.* 2013). It is important to maintain linkages with workers in the biochronology area to follow the development of techniques that may allow us to use archived Snapper otolith collections (in WA these date to the late 1980s, that may provide a baseline to compare against in the future). There is a need to monitor changes in Snapper diet across the species range. There is a poor understanding of the factors affecting annual variation in recruitment and links with plankton production and larval survival. Linked with this is the need to improve understanding of the abundance of the earliest age classes in open waters off WA coast.

14.9 Future climate scenarios (2030/2060)

Under the various climate change scenarios there are likely to be both positive and negative consequences for Snapper in WA depending upon latitude. The predicted increases in SST are greatest in the northern areas of the range of Snapper. Reduced spawning success and recruitment due to warming of waters during winter spawning season in the north may be balanced by the potential for more successful and sustained spawning in cooler waters along south coast. Warmer waters may see increased predation from sharks in Gascoyne during winter while warmer conditions on south coast may see increased abundance in prey species e.g. Blue Swimmer Crabs. The predicted weakening of the Leeuwin Current (historically flows more strongly in autumn-early winter) may result in reduced dispersal of eggs and larvae from waters off Shark Bay to waters off Kalbarri and further to the south. Primary productivity is predicted to remain unchanged off the Gascoyne but to decrease further south and along the south coast with implications for the survival of Snapper larvae and subsequent recruitment in these regions.

14.10 Management implications

Snapper have been identified as highly sensitive to climate change and therefore assessed as a high risk species in WA (Part 1, Table 7.2.2.3). Snapper are currently managed spatially as six separate biological stocks or management units with different arrangements and commercial entitlement regimes in place in the Gascoyne, West Coast and South Coast bioregions. As climate change impacts these Snapper stocks/units into the future, noting that these effects have likely been/are occurring already, the respective management arrangements will need to adapt to meet sustainability and economic/social objectives.

The most immediate issue is that of the relationship between Snapper in the waters of the Gascoyne and northern zones of the West Coast. Partly in recognition of observed changes 'on the water' in recent years, there are questions being raised by the commercial sector in relation to the current management boundary between the Gascoyne and northern waters of the West Coast in relation to Snapper. There is an urgent need to investigate the linkages between the Gascoyne and northern zones of the West Coast Bioregion in terms of juvenile recruitment and adult movement patterns. This will need to include consideration of the role of LC during winter and the effects of change in strength/seasonality of peak flows in the future. Also in the Gascoyne, stock productivity in inner gulfs of Shark Bay that are the basis of an important recreational fishery may reach a critical point within timeframes being considered here. More generally, there is a need for closer monitoring of spatial patterns in commercial and recreational catches, catch rates, seasonal spawning patterns, and variation in individual growth in Snapper across all bioregions where it is a key target species.

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15.0 Australian Sardine (*Sardinops sagax*)

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The Australian Sardine, *Sardinops sagax* (Cuvier, 1828), also referred to as the Pilchard, is a member of the Family Clupeidae (the Sardines). The taxonomy of the species is yet to be fully resolved and the widely accepted view is that the genus *Sardinops* is mono-specific (Parrish 1989) although a more recent study suggests there may be 3 lineages: Southern Africa/Australia, Chile/California and Japan (Grant *et al.* 1998). The species has a wide distribution throughout most cool temperate and subtropical coastal waters (water temperatures 13-25°C) of the world, except the Mediterranean and North Africa. In Australia the species occurs throughout the southern half of the continent, from Shark Bay in WA around to Rockhampton in Queensland (Figure 15.2.2.1), including Tasmania and New Zealand. The Australian Sardine is a significant commercial species throughout its Australian distribution.

15.1 The fisheries

- Commercial catches are taken in Western Australia, Victoria, South Australia, New South Wales and by the Commonwealth Small Pelagic Fishery.
- In 2009–10 the total Australian catch was 40,700 t.
- In 2009–10 WA generated 6.5% of the Australian commercial catch.
- Recreational catch in this fishery is limited with none reported in the 2011 WA recreational boat survey.

The Australian Sardine (or Pilchard as still referred to in WA) is an important commercial species targeted by the West Coast (WCPSMF, see Molony *et al.* 2013a) and South Coast Purse Seine Fisheries (SCPSMF, see Molony *et al.* 2013b) (Fletcher and Santoro 2013). The fisheries have had a turbulent history with two mass mortality events in the late 1990's that reduced pilchard biomass by up to 70% and closed the fisheries for several years (Ward *et al.* 2012). Since this time, catches of Pilchards have slowly increased only in the SCPSMF but not returned to historical high levels of over 7,000 t recorded from 1986-97 (Molony *et al.* 2013b). The 2011/12 total catch of Pilchards in Western Australia were estimated at 2,410 tonnes (Fletcher and Santoro 2013).

Pilchards are one of the two main target species (the other is the tropical Scaly Mackerel (*Sardinella lemuru*)) in the WCPSMF but since the mass mortality events in the late 1990s dramatically reduced stock levels (Gaughan *et al.* 2000; Gaut 2000, Ward *et al.* 2012) catches have remained low, as fishing effort has not returned to previous levels. Various factors such as low demand, economics and less predictable patterns of abundance are attributed to low effort (Molony *et al.* 2013a). Total catches have further declined over the past few years from 139 t (2007) to 10 t (2009). Historically the fishery landed over 1,000 t of Pilchards per year from 1990-1998 with a high of almost 4,000 t in 1996. Currently the TAC of Pilchards in the WCPSMF for the fishery is set at 2,328 t.

In the SCPSMF recent annual catches of Pilchards are higher than in the WCPSMF and have been increasing over recent years, with 2,647 t taken in 2009/10 (Department of Fisheries 2011). This is well short of the historical high recorded in 1988 of 8,435 t. The fishery is managed in 5 zones with four of these allocated TACs allowing a combined annual catch of 5,683 t.

The recreational catch of Pilchards in WA is limited to fishers who collect their own bait and is negligble with none reported during the Statewide boat survey in late 2011 (Ryan *et al.* 2013).

15.2 Life history

15.2.1 Life cycle, age and growth

The Australian Sardine is a serial or batch spawner with asynchronous oocyte development, an extended spawning season and hence indeterminate fecundity. Spawning occurs in open coastal shelf waters during summer-autumn in SA (Ward *et al.* 2010), late winter–early summer in southern NSW, winter–spring in northern NSW (Stewart *et al.* 2011) and over two seasons of late winter and early autumn in southern WA (Fletcher *et al.* 1996). Spawning has been linked to water temperatures of between 14 and 21°C (see Ward *et al.* 2012 for summary).

The species has a relatively long larval phase of 1-2 months allowing for wide distribution of recruits by currents with passive advection from southern WA across the Great Australian Bight by the Leeuwin current possible in most years (Gaughan *et al.* 2001a). Juveniles have been found to occur in sheltered inshore nursery areas (Gaughan *et al.* 2001b, Rogers and Ward 2007). The species reaches maturity at 2-3 years of age and 10-15 cm in fork length (Fletcher 1991). The maximum reported size of 230 mm FL and age is approximately 8 years (Fletcher 1991).

Due to difficulties associated with interpreting and counting opaque zones in their otoliths the increment based age determination has been difficult for the species in WA, SA and California. Nevertheless ageing has been achieved through use of high readability otoliths and otolith weight. Growth rates and size have been shown to be higher in SA than other parts of Australia (Table 15.2.1.1), which has been attributed to upwelling at the mouth of the Spencer Gulf (Ward *et al.* 2010).

Table 15.2.1.1. Von Bertalanffy growth parameters for Australian Sardine in WA, SA and NSW.

Location	Sex	L_∞	K	t_0	Reference
WA (Albany)	♀ ♂	174 164	0.584 0.805	0 0	Fletcher and Blight 2000
SA	♀ ♂	212.9 203.2	0.38 0.42	-0.5 -0.5	Ward *et al.* 2010
NSW	♀ & ♂ combined	216	0.37	-0.28	Stewart *et al.* 2011

15.2.2 Distribution, habitat and environmental preferences

The Australian Sardine is a pelagic-neritic, schooling and strongly migratory species, which is widely distributed throughout coastal shelf waters of the entire southern half of the continent (Whitehead 1985). The overall stock displays a high level of genetic heterogeneity (Ward *et al.* 2012). A recent study using 3 complementary stock structure techniques (weight of evidence, otolith shape and otolith chemistry) has suggested the population structure of the Australian sardine is complex and consists of multiple sub-populations with various levels of overlap (Izzo *et al.* 2012). It identified at least 3 different regional Sardine groups on the east coast with sub-structuring within these. Previous studies in WA have identified 2 regional groups with sub-structuring within (Edmonds and Fletcher 1997; Gaughan *et al.* 2001c; Gaughan *et al.* 2002).

Thus overall the population structure in Australia can be divided into 6 regional groups (Figure 15.2.2.1). However, there are four genetic stocks identified in Australia (Ward *et al.* 2012).

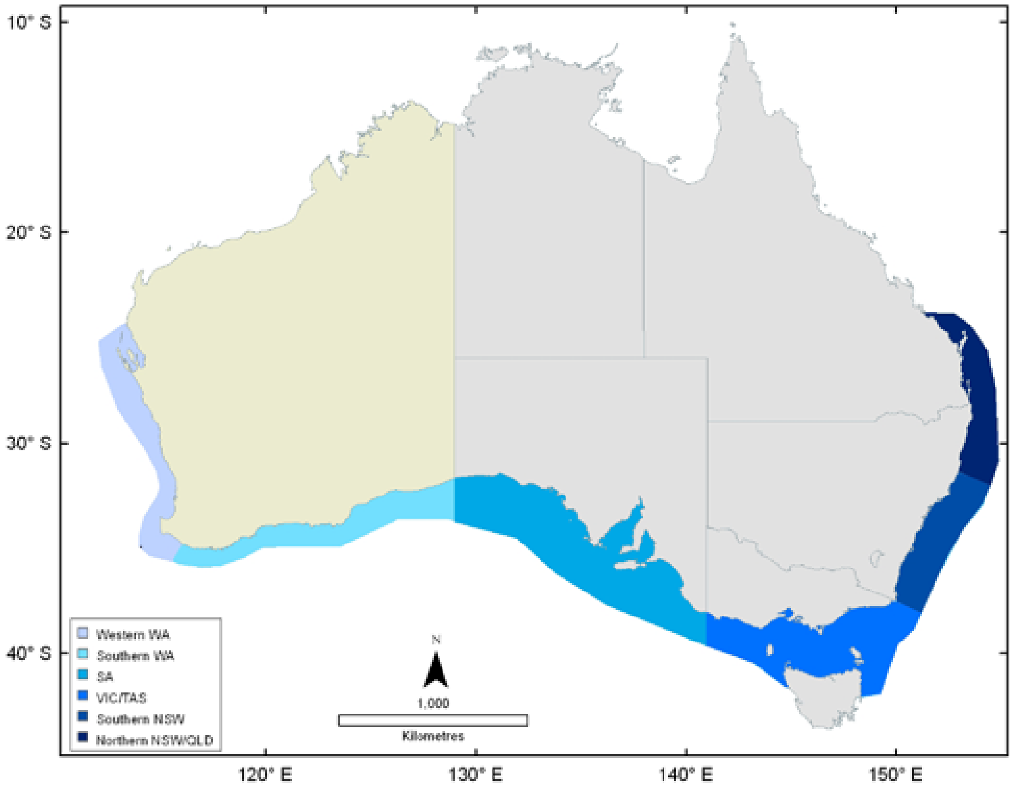

Figure 15.2.2.1. The distribution and current stock boundaries of the Australian Sardine.

15.2.3 Predators and prey

The Australian Sardine has two feeding modes; filter-feeding on micro-zooplankton and phytoplankton; and particulate feeding on macro-zooplankton. Juveniles tend to be more reliant on particulate feeding than adults, which can switch their feeding mode to target abundant items (van der Lingen 1994). Krill occurred in the greatest numbers of stomach contents of sardines sampled in SA along with other crustaceans (ostracods, euphausids, copepods), fish eggs, gelatinous zooplankton (salps) and plant material also present (Ward *et al.* 2008).

Sardines are an important prey item for a large number of predatory fishes, squid, seabirds and marine mammals. A review of information on diets and foraging patterns of key pelagic predators in SA waters (Ward *et al.* 2008) indicated that Australian Sardines were the primary prey of predatory fish species including Bronze Whaler Sharks (*Carcharhinus brachyurus*) and Tuna such as Southern Bluefin (*Thunnus maccoyii*), Albacore (*T. alalunga*), Australian Bonito (*Sarda australis*), and Skipjack (*Katsuwonus pelamis*). Other predatory fish species such as the Smooth Hammerhead (*Sphyrna zygaena*), Yellowtail Kingfish (*Seriola lalandi*), Australian Salmon (*Arripis truttacea*), Barracouta (*Thyrsites atun*), and Snook (*Sphyraena novahollandiae*) also consumed Pilchards but they were not the primary prey. Seabirds such as the Little Penguin (*Eudyptula minor*) and Crested Tern (*Sterna bergii*) were also shown to consume sardines while the New Zealand Fur Seal (*Arctocephalus forsteri*) and Short Tailed Shearwater (*Puffinus tenuirostris*) relied heavily on small pelagic fish but not specifically sardines. Sardines were not identified in the diet of the Arrow Squid (*Nototodarus gouldi*).

15.2.4 Recruitment

Recruitment fluctuations are thought to cause the large variations in abundance observed elsewhere in sardine populations. Such recruitment variability is not observed in Australia indicating a stable environment, albeit an oligotrophic or low productivity one. In SA recruitment success is linked to summer upwelling events at the time of spawning.

15.3 Current impacts of climate change

There are no known current impacts of climate change on the Australian Sardine. However, the catch of the species in the WCPSMF has not recovered since the virus in 1999 and there are anecdotal reports by fishers of less reliable schooling behaviour and abundance which may be due to warmer water currents on the west coast of WA. The catch composition of the fishery has shifted to a higher proportion of the more tropical Scaly Mackerel (*Sardinella lemuru*) which is likely attributed to warmer water temperatures.

Predictions of the impacts and adaptation responses of temperate small coastal pelagic species to general ocean warming and predicted strengthening of the East Australian Current are that species such Pilchards will see range contractions further to the south on both the east and west coasts. Meanwhile possible changes in productivity due to predicted increased coastal upwelling between Cape Otway and the Great Australian Bight may lead to increases in abundance of Sardines and Anchovy (Hobday *et al.* 2009). In addition a recent study has suggested the species are likely to undergo a southerly range shift of 192 km by 2055 in response to scenario A1B in the Special Report for Emission Scenarios (Cheung *et al.* 2012).

15.4 Sensitivity to change

In general small pelagic species such as the Australian Sardine are highly sensitive to change with high recruitment variability observed in species elsewhere (Hobday *et al.* 2009). Such recruitment variability is not observed in Australian waters but in general small pelagic fish species, which are short lived, highly fecund, with extended spawning periods and wide dispersal potential of larvae are able to respond quickly to change. The attributes of the species and particularly the link between spawning and environmental cues give the species a sensitivity score of 5.5 indicating it is of medium sensitivity to change (Part 1, Table 7.2.2.1). An important consideration is that spawning has been linked to water temperatures of between 14 and 21°C and this may restrict spawning success in the northern range of the population as water temperatures increase.

15.5 Resilience to change

As with many pelagic fish Pilchards are able to respond to changes in habitat suitability (e.g. temperature) by moving rapidly to remain within favourable conditions. There is some evidence of density dependence in growth after the mass mortality event (Gaughan *et al.* 2008) indicating the species can respond to available resources, although there is high interannual variability in growth. The latitudinal distribution of over 10° may assist the resilience of the overall population to the impacts of climate change.

15.6 Ecosystem level interactions

Australian Sardines are a key species for transfer of nutrients from primary producers to higher order predators, as highlighted above in section on predators. While the range of Pilchards may contract due to climate change, it is possible that the tropical Scaly Mackerel may fill the niche of a small pelagic species and thus continue supporting the ecosystem.

15.7 Additional (multiple) stressors

Mass mortality events in 1995 and 1998/99 spread through the entire Australian Sardine range (Gaut 2000) and in some areas were estimated to have killed over 70% of the spawning stock (see Ward *et al.* 2012). The mortalities were attributed to an exotic pathogen to which the Australian Sardines were naïve (Jones *et al.* 1997). Since this time stock levels have recovered dramatically in SA (Ward *et al.* 2010) and NSW (Ward *et al.* 2008) but to a lesser extent in WA where recovery was observed to be slower (Gaughan *et al.* 2004) and may be sensitive to fishing pressure (Murray and Gaughan 2003).

Current levels of fishing effort for Australian Sardines are considered to be sustainable in Australia (Ward *et al.* 2012). However in SA the catch is currently at the TAC level and the local Pilchard stock is considered fully exploited. Predicted declines in upwelling strength and duration as a consequence of climate change could put pressure on this stock in the central region of their distribution.

15.8 Critical data gaps and level of uncertainty

Critical gaps that need to be investigated are sensitivity of Australian Sardines to environmental variation including pH and temperature, particularly for early life history stages.

15.9 Future climate scenarios (2030/2060)

Pilchards are a cool temperate species likely to be negatively impacted by the projected climate change scenarios. The increase in water temperatures will restrict their range of suitable habitats (waters below 20° C). It is likely Pilchards will become less abundant on the West Coast Bioregion, as sea surface temperatures increase. The role of this species may be filled by the tropical Scaly Mackerel which is likely to extend its range southward under climate change scenarios.

The predicted weakening of the Leeuwin Current under future climate change scenarios will reduce the distribution of eggs and larvae of this serial batch spawner with a long planktonic duration which may have a detrimental effect on recruitment of the species.

15.10 Management implications

Pilchards were ranked as a medium-high risk of undesirable impacts due to climate change (Part 1, Table 7.2.2.3). Management will require continued monitoring of commercial catches in all zones and Bioregions. In particular, close attention should be paid to the commercial catch in the WCB where the negative effects of climate change are likely to occur. It is likely that a phase shift in the fishery to the more tropical Scaly Mackerel (*Sardinella lemuru*) will become permanent as shifts have occurred in the past during warmer periods of stronger Leeuwin Current.

Along with continued and potentially increased monitoring of commercial Pilchard catches, other monitoring should also be considered. Additional monitoring and research could include;

- Updating biomass estimates across the fishery and within each Bioregion
- Monitoring of age structure across the fishery and within each Bioregion
- Spatial patterns in size and age of commercial catches to identify changes in growth patterns.

15.11 Acknowledgements

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16.0 Tailor (*Pomatomus saltatrix*)

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Tailor, *Pomatomus saltatrix* (Cuvier, 1828), also referred to as Bluefish or Elf, is the single member in the Family Pomatomidae. The species has a wide distribution throughout most temperate and subtropical coastal waters of the world. In Australia it occurs as separate stocks on the lower half of both the east and west coasts. In WA its typical distribution ranges from Onslow to Esperance. Tailor is a significant recreational and commercial species throughout its Australian distribution.

- Commercial catches are taken in Western Australia, Victoria, New South Wales and Queensland.
- In 2009 the WA commercial catch was 25 t.
- It is a key recreational species. WA catch estimates are limited to a statewide survey in 2000/01 of 187 t. WCB boat based catch estimates of 13.75 t in 2011 (Ryan *et al.* 2013).

16.1 The fisheries

In WA, Tailor is a minor commercial species targeted by the Shark Bay Beach Seine and Mesh Net Fishery (SBBSMNF) and taken as bycatch in the West Coast Estuarine Managed Fishery (WCEMF) (Department of Fisheries 2011). The majority, 60–80%, of the commercial Tailor catch in WA is taken by the SBBSMNF. Historically the fishery landed over 40 t of Tailor from 1961–1967 with a high of 54 t in 1964. Since then catches have fluctuated between 14 to 38 t but in recent years have steadily declined from 38 t (2000) to 17 t (2009). The decline in Tailor catch has been attributed to local processing restrictions. The catches of Tailor in the WCEMF have been as bycatch in the Swan-Canning and Peel-Harvey estuaries. In the Peel-Harvey catches have fluctuated from 1-8 t over the past decade and were 4 t in 2009. In the Swan-Canning Tailor catches have declined to nil through licence buybacks with only a single operator remaining. Historically the catch in these two estuaries was up to 80 t in 1974.

Tailor is an important recreational species in WA although there are few estimates of the recreational catch. The only statewide recreational catch survey estimated the total recreational catch in 2000/01 to be 187 t (Henry and Lyle 2003). The survey indicated the majority of the catch, 87%, is taken by shore based anglers in the West Coast bioregion. Recent estimates for the boat based sector in WCB were 13.75 t with an equivalent number kept as released (Ryan *et al.* 2013).

16.2 Life history

16.2.1 Life cycle, age and growth

Tailor is a fractional spawner with asynchronous oocyte development, an extended spawning season and hence indeterminate fecundity. Spawning occurs in coastal shelf waters during winter/spring spawning in the north of their WA range which corresponds with the southerly flow of the Leeuwin Current and the summer/autumn spawning in the south of the range with the northerly Capes current (Lenanton *et al.* 1996). The eggs and larvae remain pelagic for 50 - 70 days allowing for a wide distribution by prevailing currents. The extended spawning period results in new recruits occurring along the Perth metropolitan coast in any month of the year with the peak over summer (Smith *et al.* 2012).

The juveniles form large schools in surface waters close to shore and in estuaries. They are voracious predators that grow rapidly reaching a size of up to 240 mm in their first year. The species reaches maturity at approximately two years of age and 300 mm in total length (Smith *et al.* 2012). The species can attain a size of over one metre in length and has been recorded to reach approximately 10 – 13 years of age throughout its distribution (Smith *et al.* 2012; Robillard *et al.* 2009). The majority of the catch in WA, Qld and NSW is two to four years of age (Smith *et al.* 2012; Fisheries Queensland 2011; Rowling *et al.* 2010).

The species has been regarded as notoriously difficult to age primarily due to difficulties associated with interpreting the first annual increment (Brown *et al.* 2003). These difficulties arise from the extended spawning periods observed in the species creating differing appearances of the first increment. Opaque bands are formed annually in Sept–Nov and generally subsequent zones in their otoliths are clearer and ages can be determined (Smith *et al.* 2012). Growth rates for the species have been shown to be higher in other parts of their global distribution than in Australia. Juanes *et al.* (1996) reviewed growth rates of global *P. saltatrix* populations and suggested three groupings. "Fast" growth occurred in north-eastern USA and north-western Africa, "medium" growth in Black Sea and eastern South America, and "slow" growth in South Africa, Mediterranean and Australian populations. These groups were associated with high, medium and low sizes at maturity and different von Bertalanffy growth parameters.

Table 16.2.1.1. von Bertalanffy growth parameters for Tailor in WA, eastern Australia and the USA.

Location	Sex	L_∞	K	t_o	Reference
WA	♀ & ♂ combined	595	0.46	-0.1	Smith *et al.* 2012
East Aust	♀ & ♂ combined	727	0.163	-0.41	Bade 1977
USA	♀ & ♂ combined	815	0.311	0.301	Robillard *et al.* 2009

Given its rapid growth, high fecundity and wide temperate distribution Tailor has been given an intrinsic vulnerability of 55, which is moderate (Cheung *et al.* 2007).

16.2.2 Distribution, habitat and environmental preferences

Separate stocks of Tailor are present on the east and west coasts of Australia (Nurthen *et al.* 1992), (Figure 16.2.1.1). It is suggested from otolith chemistry, time of spawning and growth data that multiple adult stocks are present within Western Australia (Edmonds *et al.* 1999). However, there is likely to be widespread gene flow among these separate stocks. In the USA and South Africa it is suggested there are 2 or 3 separate stocks each with different migratory behaviours including a northern stock that is migratory and a southern stock showing combinations of seasonally transient and resident behaviour. It is likely to be the case in Australia with evidence of highly migratory and residential individuals recorded (Smith *et al.* 2012).

Adult *P. saltatrix* are commonly found out to 40 metres depth and are often associated with offshore breaking reefs while juveniles and sub-adults are generally seasonally abundant in protected marine embayments and estuarine habitats (Potter *et al.* 1983; Hutchins and Swainston 1986; Young *et al.* 1999; Salerno *et al.* 2001; Lucena *et al.* 2002). All sizes are frequently encountered in the coastal surf zone, often in association with rocky outcrops on sandy beaches (van der Elst 1976).

The species usually occurs in water temperatures of 14–30°C with 20–26°C the preferential surface temperature for spawning.

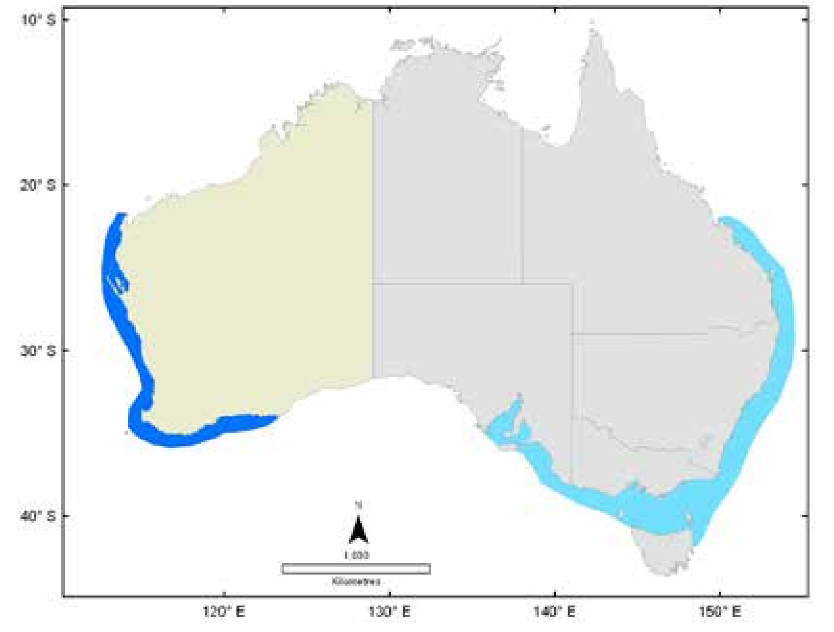

Figure 16.2.1.1. The Australian distribution of Tailor.

16.2.3 Predators and prey

Principal natural predators for *P. saltatrix* are other teleosts such as Mackerel (*Scomberomorus* sp.), Tuna (*Thunnus* sp.), Swordfish (*Xiphias gladius*) and Wahoo (*Acanthocybium solandri*) and Sharks (Mako, Long-Nosed Grey, Bull, Black Whaler). Lassiter (1962) found that *P. saltatrix* are cannibalistic and that they may be an important component of their own diet.

Tailor larvae undergo an ontogenetic shift in diet from zooplankton to a fish dominated diet. Fish prey become a substantial component of the diet when the larvae are about 40-60 mm in length. The change in diet from crustaceans (mainly copepods) to fish and crustaceans corresponds to the migration of the larvae from an oceanic habitat to inshore and estuarine waters (Marks and Conover 1993). In South Africa small individuals (100-300 mm) took a large number of mysids. The principal prey of all but the larger individuals (>500 mm) was schooling pelagic squid and fishes. The larger adults consumed a large proportion of demersal fish (Smale 1986).

16.2.4 Recruitment

Two distinct recruitment events for *P. saltatrix* are reported in most regions of their world-wide distribution. Able *et al.* (2003) suggest that the two *P. saltatrix* cohorts differentially utilise nursery habitats, with the summer cohort preferring oceanic environments whereas the spring cohort preferred estuarine conditions. The possible reasons are food availability and water temperature. Recruitment fluctuations are thought to cause the large variations in abundance observed with possible differential contribution of cohorts to adult stocks. Munch and Conover (2000) estimated the relative abundance of spring and summer-spawned juvenile cohorts from 1973 to 1995. Spring–spawned cohorts were numerically dominant in all but one of these years but in recent years the summer-spawned cohort has been dominant.

16.3 Current impacts of climate change

In WA there are anecdotal reports of range extension occurring in the species with increased Tailor abundance and recruits on the south coast with high abundance of juveniles reported in the Kalgan River near Albany (T. Leary *pers. comm.*). Elsewhere the impacts of climate change on the species such as in the Mediterranean has been to increase their distribution into waters where previously not recorded (Sabates *et al.* 2012). The increase in sea surface temperatures to above 21°C, which is the threshold for the presence of larvae has allowed the species to reproduce in the northwestern Mediterranean where they were not recorded two decades ago. It is suggested that the habitat available to temperate species such as Tailor may contract as warm water from the tropics extends further south (Hobday *et al.* 2009). As 20-26°C is their preferential surface temperature for spawning then the increase in water temperature off the lower west coast of WA (Pearce and Feng 2007) may affect their spawning behaviour, particularly in the northern and southern distribution of the population.

16.4 Sensitivity to change

The attributes of the species and particularly the link of spawning and migration to environmental cues give the species a sensitivity score of 5.5 indicating it is of medium sensitivity to change (Part 1, Section 7.2.2). Spawning in particular is reliant upon water temperature and recruitment strength has been correlated with salinity or northerly winds in Sept – Nov period (Caputi *et al.* 2010).

16.5 Resilience to change

Tailor are found over a wide latitudinal and temperature range throughout the world and their distribution extends from shallow inshore waters and estuaries to offshore waters of 40 m depth. Their latitudinal distribution is also spread over 10º in WA. They are a highly mobile migratory species with extended spawning seasons and their diet appears to be varied. Within Australia two separate genetic stocks exist and possibly multiple separate stocks of adult fish. These attributes suggest that Tailor are a resilient species to differences in environmental conditions and therefore change.

16.6 Ecosystem level interactions

As a voracious predator Tailor can have a substantial impact on the recruitment of other nearshore and estuarine fish species. This was demonstrated for Striped Bass (*Morone saxatilis*) in the Hudson River estuary of the US where the Bass recruitment was negatively correlated with Tailor abundance (Buckel *et al.* 1999). Thus high Tailor recruitment are likely to have detrimental impacts upon recruitment of other nearshore species.

16.7 Additional (multiple) stressors

Juveniles favour nearshore and estuarine environments and may therefore be influenced by land-based and anthropogenic impacts. Under current levels of commercial and recreational fishing effort Tailor are considered to be fully exploited on the east coast of Australia. The predicted shift in range to the south may lead to establishment of the species throughout the Great Australian Bight and subsequent genetic exchange between east and west coast populations.

16.8 Critical data gaps and level of uncertainty

Estimates of the total recreational catch of Tailor are limited to a single national phone diary based survey and as the majority are caught by shore based fishers the current surveys of boat based recreational fishers are only going to give a small proportion of the Tailor catch. Other critical gaps that need to be investigated are the sensitivity of Tailor to environmental variation including pH and temperature, particularly for early life history stages.

16.9 Future climate scenarios (2030/2060)

Tailor in the south of their WA range are likely to benefit from the projected climate change scenarios. Their relatively low age to maturity, fecundity and ability to rapidly move is likely to result in this species being able to capitalise on opportunities of expanding their range into suitable habitats (waters above 20°C). It is likely Tailor will be reported more often in the South Coast Bioregion and in greater numbers, as sea surface temperatures increase the range of suitable habitats. Tailor have a protracted spawning period largely dictated by water temperature and thus it is likely that the spawning period will extend in the WCB as water temperatures increase and food available continues.

However, in the north of their range spawning may be restricted under future climate change scenarios, particularly in the Gascoyne Bioregion as currently spawning appears to only occur in the cooler winter months when water temperatures are below 26°C. In addition the reduced Leeuwin Current predicted may reduce the distribution of the northern spawning recruits to southern parts of their range which currently relies on both local and distant recruitment.

If future climate change scenarios result in further range extensions of the species to the south on both east and west coasts of Australia this may result in the genetic mixing of the east and west coast Tailor populations which are currently separate genetic stocks. The results of such genetic mixing are unknown.

16.10 Management implications

Tailor are at a high risk of undesirable impacts due to climate change (Part 1, Table 7.2.2.3). Management will require continued close monitoring of catches by both sectors in all zones and Bioregions. In particular, close attention should be paid to the commercial catch in the Gascoyne Bioregion where the negative effects of climate change are likely to occur with possible flow on effects of reduced recruitment of Tailor to the WCB if spawning is restricted. In addition a reliable measure of the total recreational catch is required to manage and limit the expansion of the recreational fishery due to likely human population growth (e.g. 3 million people in Perth by 2050).

Along with continued and potentially increased monitoring of catches of Tailor by both sectors and recruitment monitoring in the Perth metropolitan area, other monitoring should also be considered. Additional monitoring and research could include;

- Development of biomass estimates across the fishery and within each Bioregion
- Development of shore based recreational catch estimates to track the total recreational catch for the species
- Monitoring of age structure across the fishery and within each Bioregion
- Investigation of the connectivity between the Gascoyne and West Coast Bioregions.

16.11 Acknowledgements

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17.0 Western Blue Groper (*Achoerodus gouldii*)

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Western Blue Groper, *Achoerodus gouldii* (Richardson 1843), belongs to the Labridae (Wrasses) and is endemic to southern Australia from about the Houtman Abrolhos Islands (28°30′S) to Port Phillip Bay, Victoria (145°E). It is caught by commercial and recreational fishers in Western Australia but is only a small part of catch elsewhere in its range.

17.1 The fisheries

- Western Blue Groper is caught by commercial, recreational and charter fishers.
- Most of the catch is taken in the South Coast Bioregion (SCB) of Western Australia (between 115°30E and the WA/SA border).
- Annual estimates of commercial catch in Western Australia are obtained from statutory logbooks.
- Periodic estimates of recreational catch are available.
- Charter sector catches are estimated annually (since 2002/03).

Achoerodus gouldii is caught primarily by the temperate demersal gill net and demersal long-line fisheries in Western Australia. In the West (WCB) and South Coast Bioregions (SCB), catch ranges of those fisheries between 2006/07 and 2012/13 were 14-18 t and 22-42 t, respectively (McAuley *et al.* 2010; McAuley and Sarginson 2011; Braccini *et al.* 2013). Annual catches of the open access commercial line fishery in the SCB have remained small between 2008 and 2013 (< 2 t per year; Norriss *et al.* 2013). Estimated catches by the West Coast Demersal Scalefish Interim Managed Fishery (WCDSIMF) and recreational and charter sectors in the WCB are very small, i.e. < 5 t total per year (see Sumner *et al.* 2008; Ryan *et al.* 2013; Department of Fisheries, unpublished data). In the SCB, the estimated numbers of *A. gouldii* retained by recreational fishers during 2011/12 was 393 individuals. Charter catches in the SCB have not been reported.

There are few data on catches of *A. gouldii* in South Australia and Victoria. However, less than 100 individuals were caught each year between 2008/09 and 2010/11.

A formal stock assessment of *A. gouldii* has not been conducted in the SCB (Norriss *et al.* 2013), however, a limited assessment will form part of a WANRM funded project to assess stock status of demersal indicator species in the SCB. This will be completed in 2015. Coulson *et al.* (2009) indicated that the species may have reached full exploitation levels, based on spawning potential ratio analyses. Assessments of demersal indicator species in the WCB demonstrated that overfishing was occurring (Wise *et al.* 2007; Fairclough *et al.* 2009), but a more recent assessment, after the introduction of significant management changes to reduce catches, has demonstrated the commencement of recovery of these species (Fairclough *et al.* 2014). As these indicators are considered to represent the entire suite of demersal species in the WCB, it is assumed the *A. gouldii* stocks have the same status.

17.2 Life history

17.2.1 Distribution, habitat and environmental preferences

Achoerodus gouldii is endemic to southern Australia from about the Houtman Abrolhos Islands (28°30′S), Western Australia to Port Phillip Bay, Victoria (145°E) (Hutchins and Swainston 1986). It is most abundant on the south coasts of Western Australia and South Australia (Coulson *et al.* 2009). *Achoerodus gouldii* typically uses reefs in protected inshore waters along the coast and around islands as a nursery habitat. As it increases in size, it moves to deeper, offshore reefs to about 40 m (Shepherd and Brook 2007; Gomon *et al.* 2008). Bryars *et al.* (2012) indicated that adult *A. gouldii* have a small home range relative to other temperate reef species.

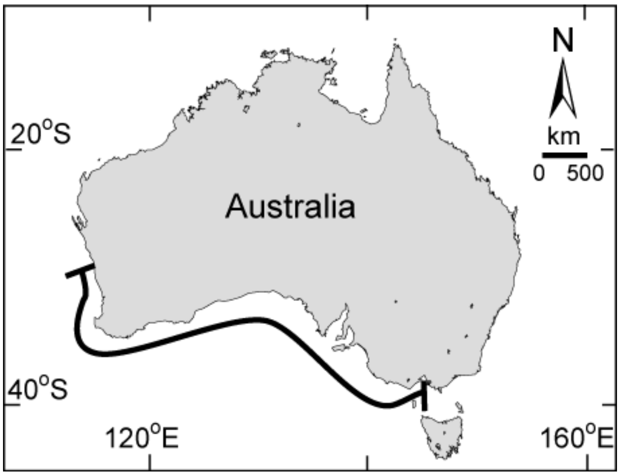

Figure 17.2.1.1. The distribution of *Achoerodus gouldii*.

17.2.2 Life cycle, age, growth and reproduction

Like many labrids, *A. gouldii* is a protogynous hermaphrodite, i.e. individuals commence life as females, mature as females and later change sex to males. This species can reach approximately 175 cm and 39 kg (Hutchins and Swainston 1986; Gomon *et al.* 2008). Its reported maximum age is 70 years (Coulson *et al.* 2009). On average, its females reach sexual maturity at 653 mm when they are 15–19 years old. Females change to male at about 821 mm and on average between 30 and 39 years (Coulson *et al.* 2009). See Table 17.2.2.1 for growth parameters. The rate of natural mortality estimated by Coulson *et al.* (2009) was 0.072 year^{-1} (0.022–0.180 year^{-1}) and 0.054 year^{-1} (0.021–0.09 year^{-1}) using the methods of Hoenig (1983) and Hall *et al.* (2004), respectively.

Achoerodus gouldii spawns predominantly between winter and spring (Coulson *et al.* 2009). Females produce multiple batches of eggs during the spawning season. Batch fecundity estimates for 12 females of *A. gouldii*, with lengths ranging from 530 to 850 mm and weights from 3 to 14 kg, respectively, ranged from 150,420 to 402,912 and produced a mean ± 95% CL of 256,484 ± 54,983 (Coulson 2008). Nothing is known of its larval biology, although this has been studied in its congener *A. viridis* (Leis and Hay 2004). There have been no studies of its stock structure.

As *A. gouldii* is protogynous, very long-lived and slow growing, with late maturity and sex change, its inherent vulnerability is considered extreme (Department of Fisheries 2011).

Table 17.2.2.1. von Bertalanffy growth parameters for *Achoerodus gouldii* based on (1) a common growth curve fitted to lengths at age of females, males and unsexed individuals and (2) separate curves fitted to lengths at age of females and males (where unsexed individuals were assigned by probability to either sex based on their colour). 95 % confidence intervals in parentheses where available. See Coulson *et al.* 2009 for analysis and other curves.

Curve		L_∞	K	t_o	r^2
Common		777 (766, 789)	0.10 (0.09, 0.11)	-0.65 (-0.90, -0.39)	0.84
Separate sexes	Females	682 (675, 692)	0.14 (0.14, 0.15)	0.06 (0, 0.1)	0.93
	Males	982 (952, 1013)	0.08 (0.07, 0.09)	-0.48 (-1.09, -0.14)	0.93

17.2.3 Predators and prey

Achoerodus gouldii consume invertebrates (Shepherd 2005). Small individuals feed on small epifaunal crustacea, bivalves and gastropods, while medium and large fish consume more large decapods, molluscs and echinoids (Shepherd 2005). Predators of *A. gouldii* are likely to be elasmobranchs and/or large piscivorous teleosts.

17.2.4 Recruitment

Coulson *et al.* (2009) demonstrated interannual recruitment variability from age structure data and indicated full recruitment to the fishery at 15 years.

17.3 Current impacts of climate change

There are no known existing impacts of climate change recorded for *A. gouldii*.

17.4 Sensitivity to change

Nothing is known of whether this temperate species is sensitive to change in environmental factors. As juveniles typically occur in shallow environments, they may be intolerant to increases in water temperature. Recent anecdotal reports suggested lower abundance of *A. gouldii* in shallow waters. Such water temperature changes may also influence invertebrate prey abundance. Changes to prevailing current strength may influence the extent of dispersal of eggs and larvae. The sensitivity of *A. gouldii* to environmental variation, including pH, temperature and extreme events are not known, particularly for early life history stages. Increased pH levels, reflecting ocean acidification, have been shown to affect otolith morphology of fish species, which is likely to influence hearing (Bignami *et al.* 2013). This may impact on the ability of larvae to settle in suitable habitats, if reliant on specific cues, e.g. reef noise.

17.5 Resilience to change

Achoerodus gouldii occurs in waters to 40 m across the continental shelf indicating a degree of robustness to a range of water temperatures.

17.6 Ecosystem level interactions

Achoerodus gouldii are reliant on invertebrates as a food source.

17.7 Additional (multiple) stressors

While the level of commercial fishing in the SCB is estimated annually, this has never been done for recreational fishing until 2011/12. Further investigation is underway to determine whether there are areas of high fishing pressure within the bioregion and thus the potential for localised depletion.

17.8 Critical data gaps and level of uncertainty

The sensitivity of *A. gouldii* to environmental variation including pH, temperature and extreme events is not known, particularly for early life history stages. Increased pH levels, reflecting ocean acidification, may affect otolith morphology and subsequently hearing ability (Bignami *et al.* 2013). This may impact on the ability of larvae to settle in suitable habitats, if reliant on specific cues, e.g. reef noise, and thus influence recruitment success. Sensitivity of the prey of *A. gouldii* to such variations is also not known. Mortality of prey could impact on food availability.

Data from the first survey of recreational fishing in the SCB requires further investigation to determine whether there are areas of high fishing pressure and thus potential for localised depletion of this species.

17.9 References

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