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Improving confidence in the management of the blue swimmer crab (*Portunus armatus*) in Shark Bay

PART I: Rebuilding of the Shark Bay Crab Fishery

FRDC Project No. **2012/15**

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Supplementary documents

This FRDC final report addresses three primary objectives, each of which is produced as a standalone document (FRDC 2012/015 Parts I, II and III).

- Part I : Rebuilding of the Shark Bay Crab Fishery
- Part II : Socio-economic significance of commercial Blue Swimmer crabs in Shark Bay
- Part III: Proceedings of the Third National Workshop of Blue Swimmer Crab (*Portunus armatus*)

Part I includes outcomes of objectives 1-3 (see Section 1.3, below), which addresses the research results of the stock rebuilding phase of the Shark Bay Crab Fishery and the development of a preliminary harvest strategy (DoF, 2015) for improved management of the stock. This report also includes results of concurrent research on the cause and impact of an extreme marine heat wave event along the Western Australian coast during the summer of 2010/11 on the initial stock decline and ongoing stock recovery. The marine heat wave event generated several State-wide research hubs investigating different aspects of its impact on fisheries stocks and oceanographic features. Therefore relevant research undertaken in regards to the Shark Bay crab fishery has been included in this report (Caputi et al. 2015a).

Part II covers objective 4 which was a socio-economic study of the blue swimmer crab fishery in Shark Bay undertaken by fisheries economists at Horizon Consultancy (Daley and Ingrid van Putten 2018).

Part III of this project (coordinated and edited by A. Chandrapavan) deals with Objective 5 of this study which was to host the Third National Workshop on Blue Swimmer Crab which took place 3-4 June 2015. In accordance with previous workshops, a standalone proceedings document is published (Chandrapavan 2018).

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Acknowledgments

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1 Executive Summary

1.1 Overview

This, and the accompanying Part II report, summarise the results of the research activities undertaken on the blue swimmer crab stock in Shark Bay by the Department of Fisheries, Western Australia, which were done in collaboration with commercial fishers, fishery managers and economic analysts between 2012 and 2016. The project also included hosting the Third National Workshop on Blue Swimmer Crab in June 2015 which involved 60 participants including researchers, managers and industry members from most Australian states. This was a very successful forum to share research findings, highlight challenges and exchange ideas on management strategies and increase industry collaborations (Part III).

Following the significant decline in abundance of the Shark Bay crab, *Portunus armatus,* stock identified early in 2012, a comprehensive research program was established and focused on examining the potential causes, including the key environmental factors that may affect the spawning stock, recruitment and adult survival, and also understanding the impact of the 2010/11 marine heat wave event in Shark Bay. During this study, the commercial fishery was closed in April 2012 for 18 months and re-opened in November 2013. The stock has since been in a recovering phase and not considered fully recovered. The research information gathered during this period has greatly assisted with the development of the management strategies that have been adopted since the decline. This project has led to improved understanding of the environmental factors that are associated with recruitment and other factors that may affect stock dynamics of this resource, and which are required by managers for developing suitable management arrangements. This includes providing the basis for the development of an appropriate Harvest Strategy for the sustainable use of this valuable resource (socio-economic study Part II), which was a key aim of this project.

The data collected through the fishery-independent trawl survey program has addressed some of the key knowledge gaps in the biology of *Portunus armatus* in Shark Bay. Peak spawning activity is considered to be during the cooler winter months in Shark Bay, and the peak abundance of 0^+ recruits is detected during February. This is about 9 months after peak spawning which indicates the cycle for blue swimmer crabs from spawning to harvesting is around 18 months. Detailed studies on the growth and reproductive biology of both male and female blue swimmer crabs were undertaken. The seasonal pattern of growth of blue swimmer crabs in Shark Bay was shown to differ from those in more temperate environments with the revised size at maturity for female crabs in Shark Bay now being larger (~20 mm) than estimated by de Lestang in 2003. This may have implications to current minimum legal size and industry voluntary commercial size limits, although the size at maturity is still remains well below the target commercial size.

The first biomass dynamics model for blue swimmer crabs was also developed from this study. This preliminary model allows managers to test current management strategies and the TACC settings and explore how stock recovery may respond to changes to these strategies. The risk-based weight of evidence assessment conducted for the current TACC setting and recovery trajectories indicated that, if commercial catch levels remain within recent catch levels of 300-371 t, which are well below the TACC of 450 t, there is still a 'Possible' likelihood (L3) of 'Major' stock depletion (C3) and this constitutes a medium risk level. If the catch levels increase such that they approach the current TACC, then the likelihood of major stock depletion increases to 'Likely' (L4) which would constitute a **high risk level** to stock sustainability. This level of risk is unacceptable and strong management measures need to be undertaken**.**

It appears that, under recent environmental conditions, the current levels of catch will not enable further stock recovery. If these conditions persist, such recovery cannot be achieved and further management measures will be required to protect the mature biomass.

Addendum

The above assessment of stock status was based on the weight of evidence of all available data up until the mid 2015/16 fishing season. Since the completion of this study, there has been a significant improvement in some of the stock indices. An increased mean catch rate of the residual legal biomass at the end of the 2015/16 season and significant improvements in the commercial catch and trap catch rates during the 2016/17 season had resulted in a change in the stock status to a **moderate risk level to stock sustainability based on a 450 t TACC**. This change to the stock status is further supported by the biomass dynamics model which now indicates a recovering stock trajectory under the current environmental conditions.

1.2 Background

As substantial increases in landings of blue swimmer crabs in Shark Bay between 2000 and 2010 caused stock sustainability concerns for management, the original need for undertaking this project was to better understand the biology of the stock and determine sustainable harvest levels. From 2008 onwards, there were signals of a decrease in mean commercial sizes and a decline in commercial trap catch rates while catches continued to increase beyond 800 t, and thus a plan to cap commercial catch levels was being discussed with Industry. However, the extreme marine heat wave event that occurred in summer of 2010/11 resulted in a recruitment failure and low adult survival in Shark Bay in late 2011. The aims of the project were therefore refined to investigate the reasons for this recruitment failure and to determine key biological parameters for blue swimmer crab in Shark Bay to enable sustainable management and harvest of crabs once a level of recovery was observed in this fishery.

1.3 Aims/objectives

1. To examine key drivers of the blue swimmer crab recruitment in Shark Bay, particularly environmental factors associated with low recruitment.

2. Develop and implement a stock rebuilding strategy.

3. Develop a harvest strategy for improved management of the stock.

4. Determine the socio-economic significance of the blue swimmer crabs to the commercial trap and trawl sectors in Shark Bay.

5. Host the Third National Workshop on Blue Swimmer Crab in 2015.

1.4 Methodology

Fishery-independent research trawls were undertaken at standard sites, four times a year over four consecutive years to sample the majority of the areas where crabs were known to occur within Shark Bay. The limitation from using trawls was that it was not possible to sample in shallow, structured habitats which can also contain crabs. It was, however, considered that regular sampling of the 58 trawl sites was considered to provide adequate spatial coverage (viz. 70% of the crab fishery) and produce a representative sample of the crabs within Shark Bay, including the non-trawl accessible areas. Trawling is also considered less biased than trapping and would yield sufficient information on recruitment, spawning and legal biomass that will address the project objectives and can be adopted for future monitoring of this stock.

The sampling design allowed standardised crab abundance indices to be developed for immature, mature, sublegal and legal-sized crabs for each time period. Water quality and biological samples were also collected during these trips. Modelling was employed to determine, growth, size of maturity and preliminary biomass estimates. Correlation analyses were undertaken to examine the relationships between water temperature and the available commercial catch rates and the November survey catch rates that had recorded crab data since 2001. The effect of the flooding events in 2010/11 were also examined.

1.5 Results/key findings

The expanded fishery-independent survey program established during this study sampled crabs during four survey periods in February, April, June and November over four consecutive years (2012-2016). The results included information on seasonal catch and catch rate of crabs at four different life stages (i.e. spawning, juvenile, sublegal and legal biomass), which was critical to our understanding of the crabs' life-cycle, peak spawning and recruitment periods, growth and the impact of fishing on the stock.

From this expanded monitoring program a number of key stock indicators were developed including indices of peak spawning biomass levels (June survey), peak recruitment biomass levels (February survey) and residual spawning biomass levels (November survey), which will facilitate the development of the Harvest Strategy for this fishery. The data indicate that during the closure period, the status of the stock had improved for all three biomass indicators but have since stabilised at the lower end of the historic range (based on the November survey) for the past three years under the catch levels of 300-371 t.

This study has also allowed the development of the first fitted growth curve for blue swimmer crabs in Shark Bay, characterised by high growth rates coincided during the cooler months. A key finding of this study was that the female size at maturity is likely to be around 110 mm CW, which is an increase from previous estimates around 92 mm and supports an increase in the minimum legal size limit from 127 mm CW to the current voluntary commercial size limit of 135 mm CW. The first estimates of batch fecundity revealed that larger females > 135 mm CW were twice as fecund (~ 1.5 million eggs) as females at 120 mm CW.

Environmental conditions play an important role during spawning and recruitment periods, and in Shark Bay high levels of recruitment have been associated with warmer than average winter SSTs and cooler than average summer SSTs. The heat wave event produced the hottest summer SSTs on record in Shark Bay in 2010/11 while the preceding winter (2010) was one of the coldest winters on record due to a change from El Niño conditions to a strong La Nina in late 2010. While the contribution of each individual event is unclear it is likely that both environmental events were major factors in the recruitment failure and subsequent stock decline in late 2011. During the current recovery phase, winter SSTs remain cooler than average while the summer SSTs have been more variable with some years warmer and others cooler than average. A long-term decrease in winter SST has been recorded based on satellite SST data since 1982 and a shift in the seasonal winter months has also been observed in recent years for Shark Bay with the peak winter month occurring 1-2 months earlier than historically. Once the SST is taken into account there is little evidence that the flooding event had a major effect on the stock abundance.

A preliminary biomass dynamics model was developed for the Shark Bay crab stock. Model estimates for virgin (unfished) mature biomass level for this stock was approximately 1319 t and an estimated maximum sustainable yield (*MSY*) of 666 t under normal environmental conditions and historical levels of recruitment. Model output suggests that the stock recovered partially to ~ 200 t (approximately 20% of unfished levels) during the closure of the fishery. However, stock recovery had stalled at this level since fishing resumed in 2013 under the current catch levels of 300-371 t and not increased to promote further stock recovery.

1.6 Implications for relevant stakeholders

The findings of this research program have already assisted in determining an appropriate rebuilding strategy for this stock. Furthermore the results will facilitate the development of a Harvest Strategy for the Shark Bay blue swimmer crab fishery.

The beneficiaries of this work are the Shark Bay commercial fishers (trawl and trap sectors), fishery managers and the Gascoyne community and others that participate in recreational crab fishing or purchasing commercially-caught product. The detailed information collated on environmental factors is useful for other natural resource interest groups within the Shark Bay region in light of climate change scenarios.

1.7 Recommendations

- Fishery-independent survey sampling of crab abundance and data collection of reproductive condition continue for at least three time periods (February, June and November) each year to enable development of a longer time series of data that is likely to be pivotal for annual stock assessments and for determination of an appropriate TACC. These data will provide the basis for determining a recruitment index (February survey) and a spawning index (June), while the long-running November scallop survey will provide valuable information on the deeper water crab stocks, which is an important component of the harvest strategy that will increase confidence in annual stock assessments and in determining an appropriate TACC.

- Ongoing monitoring of reproductive condition of crabs will enable longer term assessments of any further changes such as in the size of maturity and peak timing of spawning given the changes in the seasonal climatic conditions (i.e. decreases in winter water temperature and the extreme marine heat wave event).
- We recommend the continued collection of environmental data to inform likely consequences for spawning stock and recruitment success and to further attempt to combine this information with production modelling.

KEYWORDS: Blue swimmer crab, *Portunus armatus,* marine heat wave, recruitment, fecundity, growth, biomass dynamics model, Shark Bay, Western Australia, management.

2 Introduction

2.1 Development of the Shark Bay Crab Fishery

The Shark Bay blue swimmer crab (*Portunus armatus*, formerly *Portunus pelagicus*, Lai et al. 2010) stock is genetically heterogeneous from crabs stocks along the north coast of WA (Exmouth Gulf and Broome), and even more distinctive than crab stocks along the south-west coast of WA (Chaplin et al. 2001). It is unknown whether blue swimmer crabs in Shark Bay constitute a self-recruiting population with little immigration into, or emigration out of, the Gulfs and northern area of the Bay and between Shark Bay and neighbouring water bodies. Consequently, the stock has been managed independently of other crab stocks in the north of the State.

The Shark Bay crab resource is harvested commercially by the Shark Bay crab trap, the Shark Bay prawn trawl and Shark Bay scallop trawl sectors within the waters (all depths) of the Bay. The exploitation of this resource began with an exploratory fishing phase during the 1980s before an experimental trap fishery was established in 1998 to assess the potential for further expansion (Table 1, Figure 2.1). A comprehensive review of the experimental fishery in 2004 found crab stocks in Shark Bay to be healthy and more than adequate at the levels of exploitation applied at that time. This review recommended that the fishery was capable of further expansion since the stock did not display a strong annual cycle of depletion (Bellchambers et al. 2005). The fishery transitioned into an interim managed status in 2005 and fishers were allowed a total of 1500 traps/day, with only a maximum of 400 of the 1500 traps allowed to be used in the Eastern and Western Gulfs south of Cape Peron (Figure 2.2).

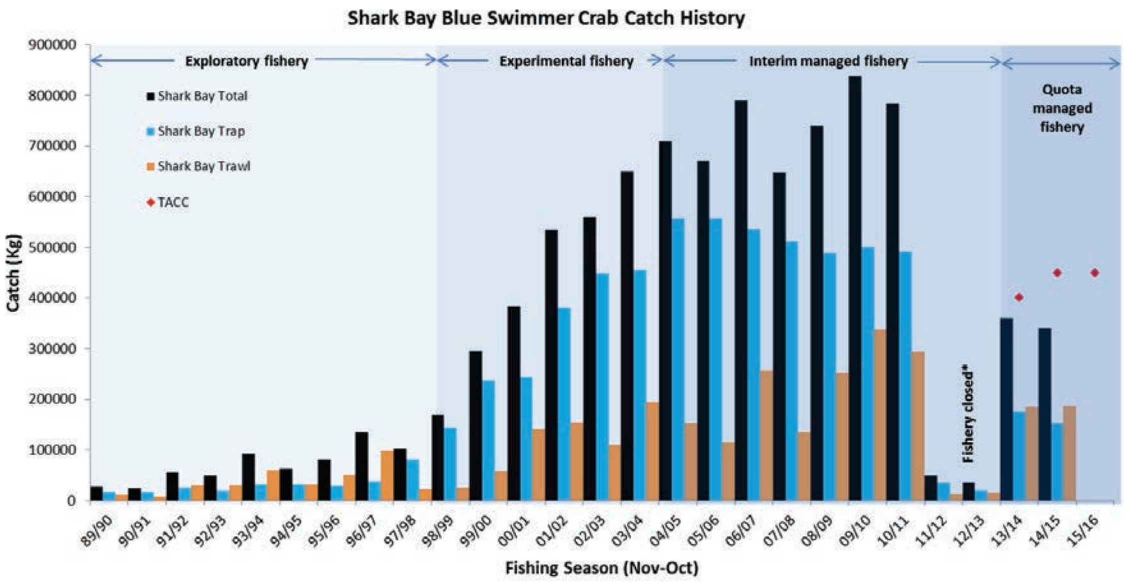


Figure 2.1. Commercial catch history for blue swimmer crabs in Shark Bay from 1989 to present. The fishing season is defined as 1 November to 31 October. The fishery closed between April 2012 and October 2013 and catches shown for 2012/13 were taken as part of an experimental fishing trial(*). Fishing resumed under a quota managed fishery in 2013 with a TACC (ie. for all commercial fishing sectors) of 400 t for the 2013/14 season and 450 t for the 2014/15 and 2015/16 seasons.

The management guidelines for the interim managed fishery set no temporal closures to commercial trapping, however fishers were restricted to pulling their traps only once in any 24-hour period (commencing at midnight) and spatial closures were implemented around Point Quobba and Carnarvon to minimise conflict with recreational fishers (Figure 2.2). Recreational crabbing is socially very important in Shark Bay, although this sector only takes around 2.4 t (Ryan et al. 2015). The statutory minimum legal size limit for blue swimmer crabs (as governed by the Fish Resources Management Regulations 1995 (FRMR)) is 127 mm (CW) (distance between the tips of the two lateral spines of the carapace), however commercial operators (trap and trawl) in Shark Bay voluntarily operate at 135 mm CW. The higher commercial size limit provides increased opportunity for the recreational sector to access crabs in Shark Bay, noting that recreational fishers adhere to the legislated 127 mm CW minimum size.

The Shark Bay prawn and scallop trawl fisheries have also historically retained blue swimmer crabs as a byproduct species of their fishing operations. Since 2000, the prawn trawl licensees have steadily increased their capacity to process and retain crabs, and the trawl-caught crab catches rose from 43 t in 2000 (15% of the total blue swimmer crab catch in Shark Bay) to 338 t in 2010 (41% of the total blue swimmer crab catch in Shark Bay), with crabs becoming an important economic component of the trawl catch (Harris et al. 2014). In 2010 there were five 300-trap licences and 29 trawl licences (18 prawn and 11 scallop) authorising fishers to take blue swimmer crabs in Shark Bay. The combined annual landings by all sectors had increased threefold from 297 t in 2000 (238 t by trap and 58 t by trawl), to its peak at 828 t in 2010 (490 t by trap and 338 t by trawl) (Figure 2.1). In this year, it was Australia's highest producing blue swimmer crab fishery with an estimated value of $5 million (Johnston et al. 2012).

This marked increase in annual landings, however, raised concern for managers and scientists regarding the stock's capacity to withstand further increases in fishing pressure. Thus a precautionary total allowable commercial catch (TACC) system was under consideration in 2011and capping catches at 700 t was discussed with the commercial fishing industry (Harris et al. 2014), along with an appropriate resource sharing arrangement between the three commercial fishing sectors that have access. An external review of the fishery in May 2011 (W. Sumpton. *pers comm*) also identified a number of knowledge gaps in the biology (natural mortality, peak recruitment and spawning biomass, movement patterns, biomass modelling) and stock structure, which needed to be addressed to determine a sustainable harvest level for this resource.

The Shark Bay crab resource also supports a small but regionally important recreational fishery. This sector is managed through a combination of input and output controls including a minimum size limit (127 mm CW) along with a bag and boat limits. The 2013/14 state-wide recreational fishing from boat surveys found only 4% of the state's blue swimmer recreational catches came from the Gascoyne region. The total number of blue swimmer crabs that were kept was 8 716 ± 2312 crabs which is approximately 2.4 tonnes by weight. Within Shark Bay, blue swimmer crabs were the most common invertebrate recreational species.

Table 1. Chronology of key changes in the history of the Shark Bay Blue Swimmer Crab Fishery. *Indicates changes that occurred during the course of this project

1980's	Exploratory phase of the crab trap fishery in Shark Bay, 450 hourglass traps were used by two licensees of the Shark Bay Beach Seine and Mesh Net Fishery (SBBSMNF) to be fished in the Western and Eastern Gulfs of Shark Bay.
1996	Review of the exploratory phase of the fishery, and consideration of further development of a dedicated crab trap fishery.
1998	The Carnarvon Experimental Crab Trap Fishery (CECTF) was established, with a voluntary minimum size limit of 135 mm CW. • 2 fishers in the SBBSMNF were granted a maximum of 200 traps each and allowed to fish the whole Bay • 3 new 200-trap endorsements were issued to fish in the northern grounds only
2001	Additional 100 traps were allocated to each of the 2 SBBSMNF fishers with only 200 traps of their 300-trap allocation allowed in the lower gulfs. Additional 100 traps were also allocated to the 3 CECTF exemptions. Total traps allowed were 1500.
2004	The Commonwealth Government assessed the fishery under the provisions of the *Environmental Protection and Biodiversity Conservation Act 1999* and accredited it for a period of five years allowing product to be exported from Australia. The fishery has been re-certified in 2015 and is due for re-assessment in 2025.
2005	The Shark Bay Crab Interim Managed fishery was formalised with existing management arrangements.
2010/11	Shark Bay experienced an extreme marine heat wave and flooding events during the summer of 2010/11 (November 2010 to March 2011). An external review of the Shark Bay crab fishery during May 2011 which made recommendations to limiting the catch until sustainable harvest levels could be determined. Significant stock decline observed during latter half of 2011 which led to exploratory fishing beyond the fishery boundary.
2012*	Voluntary closure of the fishery in April 2012 to both trap and trawl sectors. A dedicated fishery independent trawl survey program for crabs was established to monitor stock recovery as part of this FRDC project 2012/015.

	The fishery undergoes MSC pre-assessment evaluation. A formalised catch share allocation within the commercial sectors was made in June 2012; trap - 66%, prawn trawl – 33.8%, scallop trawl – 0.2%
2013*	Partial recovery of the stock prompts industry to seek a short-term commercial fishing trial in June 2013 which yielded commercially-acceptable catch rates. Commercial fishing resumed from November 2013 with a TACC of 400 tonnes for the 2013/14 season.
2014*	Stock continued to recover and a TACC of 450 tonnes was set for the 2014/15 fishing season.
2015*	Shark Bay Crab Managed Fishery formalised in November 2015 with a new management plan based on an ITQ system and with spatial zoning. A TACC of 450 tonnes was set for the 2015/16 fishing season.

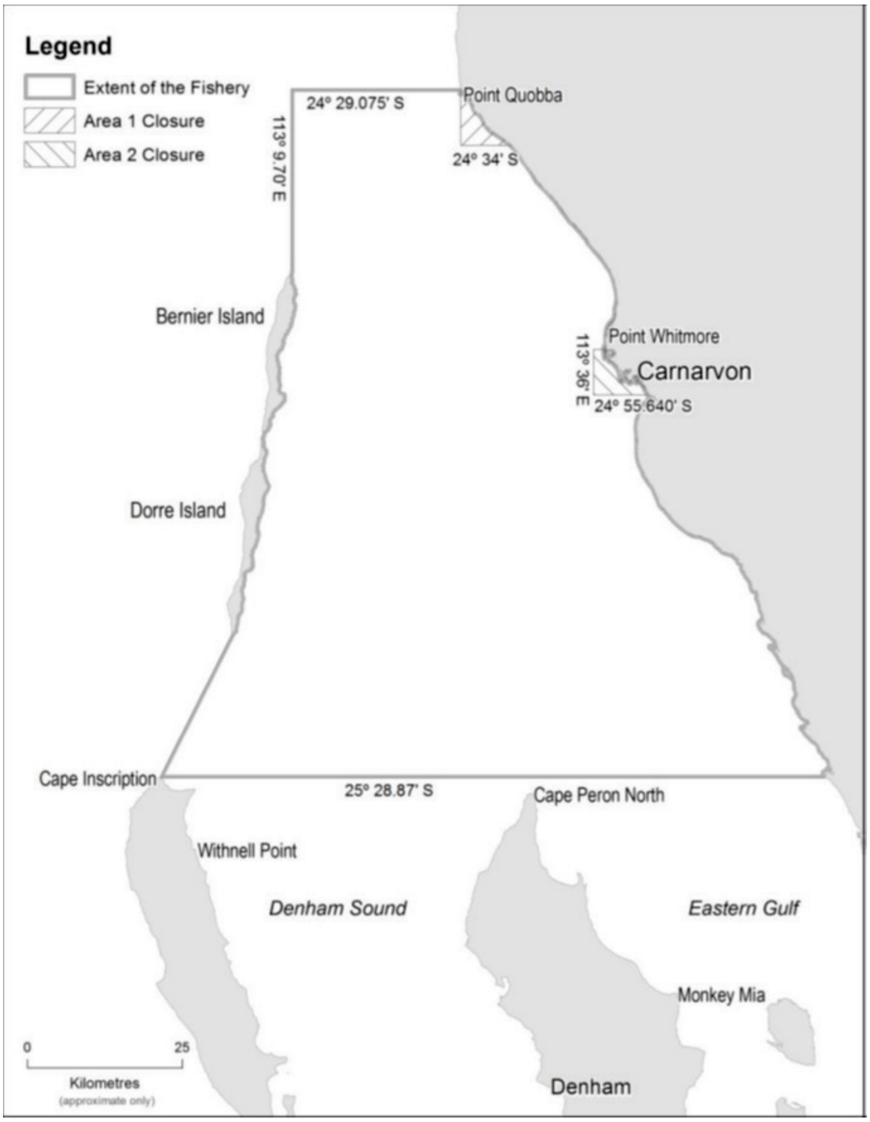


Figure 2.2. Map showing the boundary of the Shark Bay Crab Interim Managed Fishery. Two additional 200-trap exemptions allow for fishing in the western and eastern gulfs south of Cape Peron North

2.2 Marine heat wave event of 2010/11

During the summer of 2010/11 (November to March), the nearshore water temperatures along the Gascoyne and mid-west coast of Western Australia were 2-3°C higher than mean historical levels and within Shark Bay the temperatures even exceeded 5°C above average for brief periods. This extreme marine heat wave event, named the Ningaloo Niño, was the result of an alignment of interseasonal to interdecadal processes, which resulted in an earlier surge of the Leeuwin Current during the austral summer which was associated with high temperatures (Feng et al. 2013).

The monthly Reynolds Sea Surface Temperatures (SSTs) for the summer months over the past three decades show both the intensity and the regional (alongshore) variability of the heat wave (Figure 2.3a). The water was warmest at 2-3°C above the long-term monthly average for all the west coast locations in early 2011 while the south coast was about 1°C above average (Figure 2.3b). Elevated temperatures persisted into the summer of 2012/13 with Ningaloo, Albany and Esperance recording their highest summer temperatures.

The south flowing Leeuwin current is the dominant current off WA coast bringing warm tropical water southwards and usually flows strongly during the cooler winter months. Its strength is directly influenced by ENSO events and a strong Southern Oscillation Index (SOI) is associated with a strong Leeuwin Current (Figure 2.4). In the past, the major El Niño events (1982/83, 1987, early 1992 and 1997/98) are all associated with lower sea levels (weaker Leeuwin Current) and cooler water, while during the strong La Niña periods (1988/89, 1998–2000, 2008/09 and 2010–2012) higher sea levels indicated that the Leeuwin Current was flowing strongly and water temperatures were relatively high. There were occasions (such as 1994/95 and 1997) when the water was warmer despite lower sea levels and El Niño-like conditions, suggesting that other drivers such as air-sea heat flux (acting independently of the Leeuwin Current) also play an important role in influencing local ocean temperatures.

The Capes and Ningaloo Currents are wind-driven currents that flow northward inshore of the Leeuwin Current (largely during the summer months) and are associated with upwelling of cooler waters onto the continental shelf. When strong along-shelf (southerly) winds blow, these currents are enhanced and intrude into the western regions of Shark Bay, causing SSTs to drop 1–2°C in these intrusion areas of the Bay. The cooler water intrudes Shark Bay through the Naturaliste Channel (western entrance) and exits out the northern entrance when the event is relatively strong (Figure 2.2). Sea surface temperatures near Naturaliste Channel were consistently cooler than other areas of the Bay due to this flushing mechanism. Wind records from Carnarvon indicated that during the summer of 2010/11 the mean November-March southerly wind component was ~2 ms^{-1} lower than the long-term mean. Although this was just one of the factors contributing to the high SSTs experienced during the marine heat wave, it highlights the importance of the wind in controlling water temperatures in this shallow region.

Thus the marine heat wave event was associated with 1) an extremely strong La Niña event, 2) an accompanying strong Leeuwin Current and 3) an anomalously high heat flux from the atmosphere entering the ocean (Pearce and Feng 2013; Feng et al. 2013). The immediate and short-term effects on the marine biota were devastating, with massive mortality of fish and invertebrate species in some areas, range extension of some tropical species with sightings well south of their normal ranges, coral bleaching events, phytoplankton blooms and significant loss of seagrass habitats in some regions (Pearce et al. 2011). Those animals capable of moving and finding refuge from the heat wave effects probably survived, and short-term temperature "spikes" may have severely affected already stressed animals, e.g. by disrupting physiological processes (spawning, thermal regulation, moulting), and contributed to the observed mortality of some species.

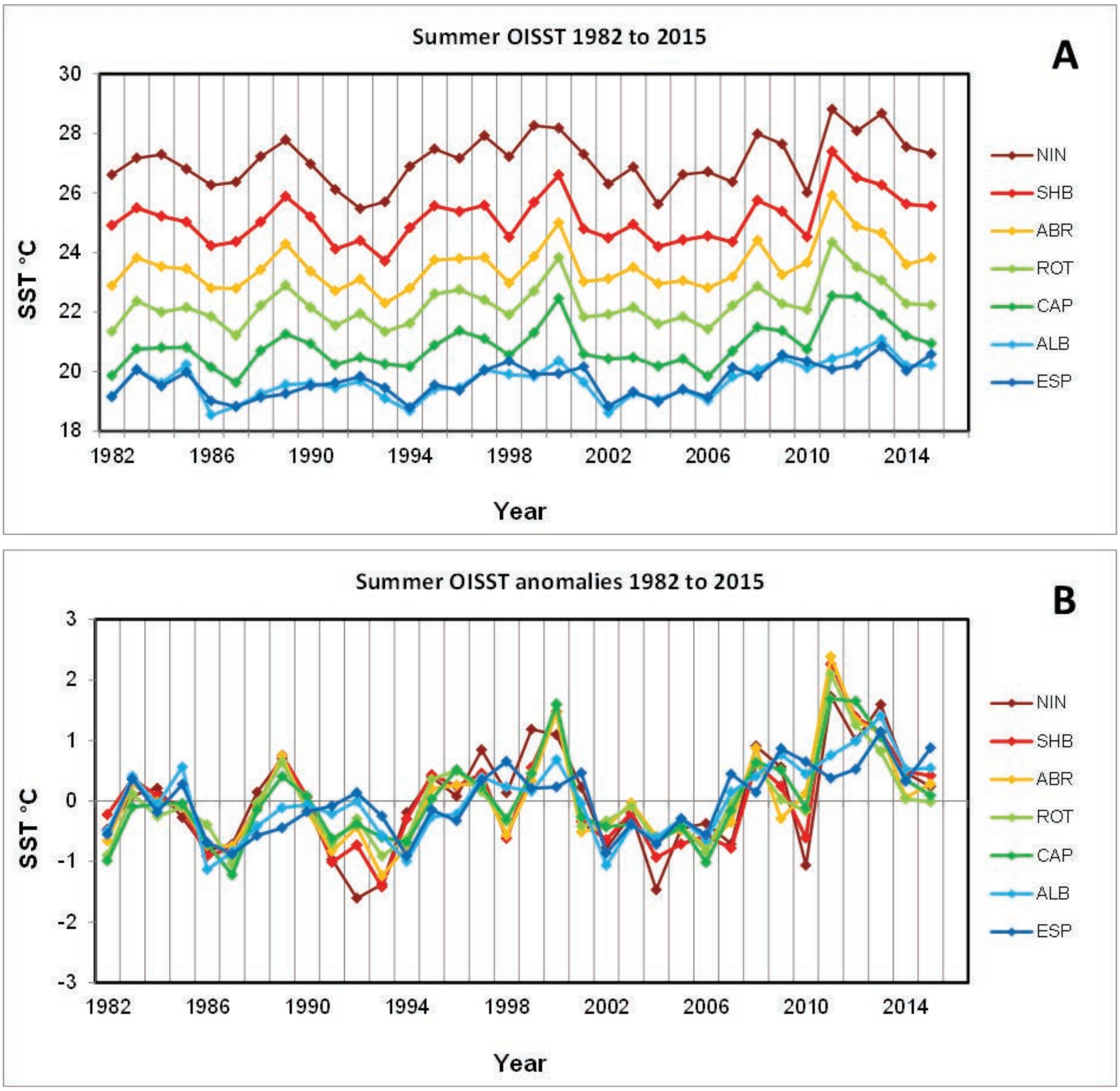


Figure 2.3. (A) Summer water temperatures from the Reynolds SST dataset for the 1-degree blocks off Ningaloo, Shark Bay, the Abrolhos Islands, Rottnest Island, the Capes region, Albany and Esperance and (B) Summer temperature anomalies from the long-term annual cycle (bottom). Summer is defined as January to March (location details in Caputi et al. 2015).

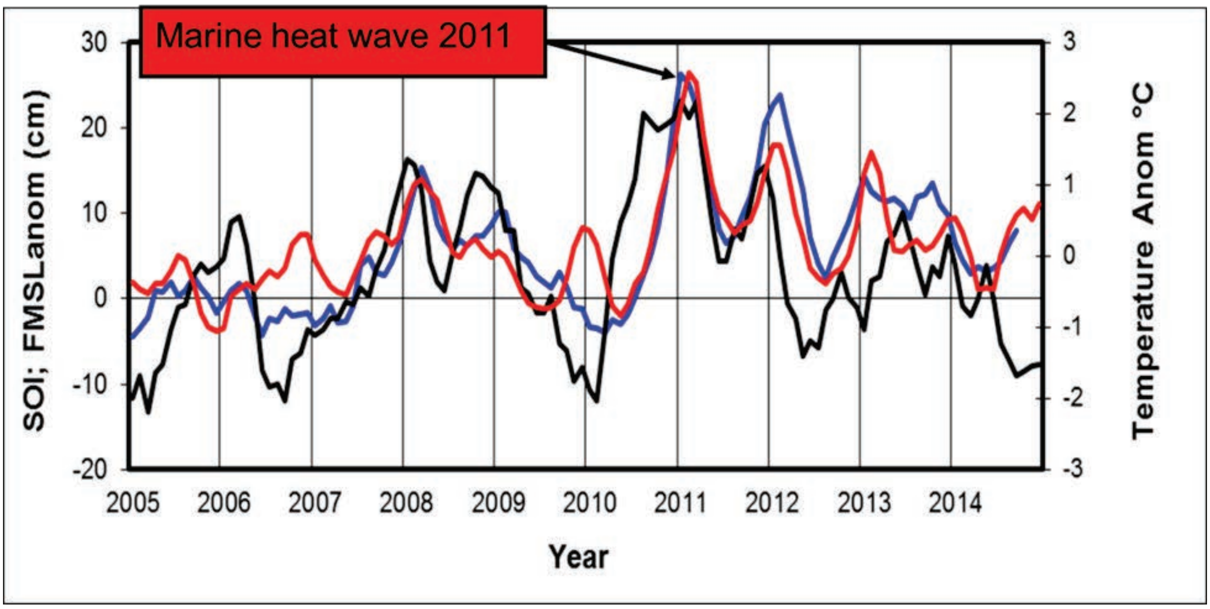


Figure 2.4. Monthly values of the Southern Oscillation Index (black), the Fremantle sea level anomaly (FMSLanom -- the difference between a monthly sea level value and the long-term average for that month, blue) and the sea surface temperature anomaly at the Abrolhos Islands (right axis, red) between 2005 and 2014. High values of the SOI indicate *La Niña* conditions and low values reflect *El Niño* conditions, while high sea levels indicate a strong Leeuwin Current. The record strength Leeuwin Current and record high temperatures in February/March 2011 constituted the unprecedented marine heat wave event.

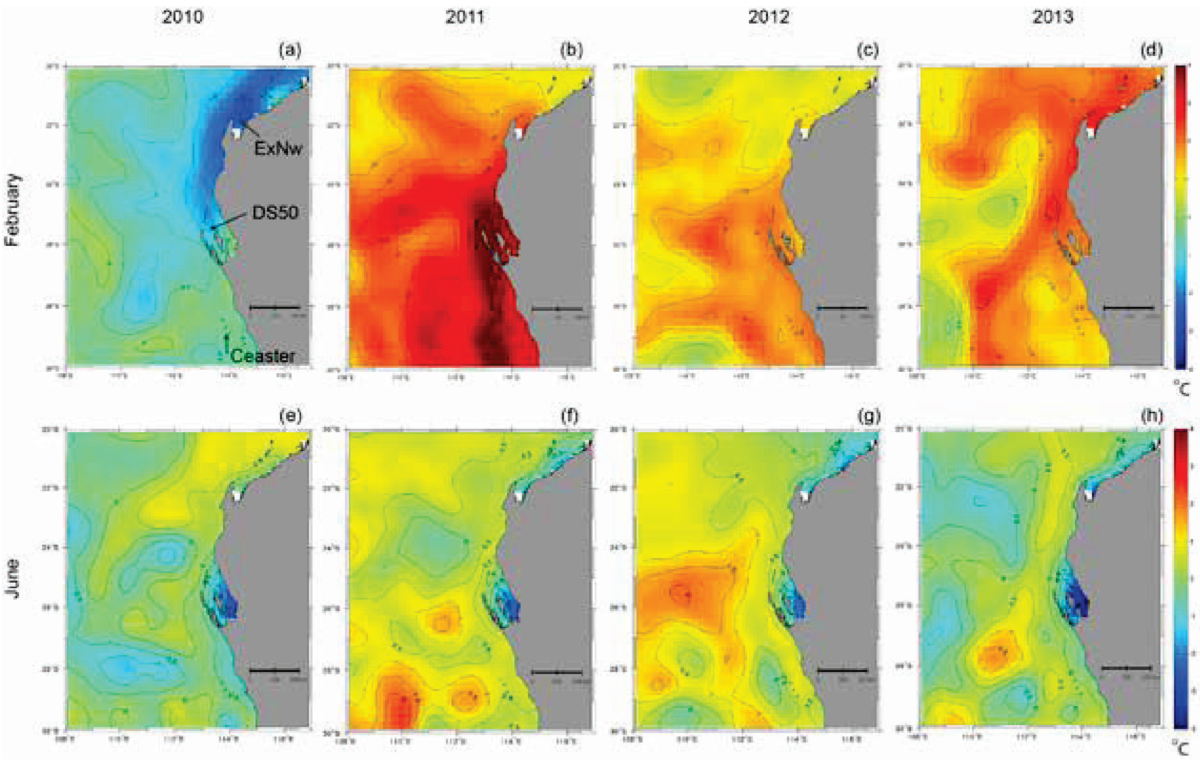


Figure 2.5. Monthly mean SST anomalies calculated from the ¼ degree (28 km) resolution OIv2 dataset. Colours represent degrees above/below the 1982-2012 mean temperatures for February (a-d) and June (e-h) and temperature contours are shown at 0.5 degree intervals (from Caputi et al. 2015).

Following the 2010/11 summer heat wave, summer SSTs continued to be higher than average during the following four summers (2011/12–2014/15) (Figure 2.3b, Figure 2.5 b,c,d). In association with these above average summer temperatures were below average winter temperatures between 2010 and 2013 (Figure 2.5 e-h). The reason that Shark Bay experienced these large deviations from mean temperatures is largely related to its enclosed geography and shallow depths, thus causing SSTs to be more affected by anomalous air-ocean heat fluxes. For this reason the shallowest, most isolated inner regions of the bay experience the most extreme SSTs where the highest temperatures within Shark Bay occurred during February 2011 and conversely during the winter in June 2013 were also the coldest temperatures at approximately 3 degrees below average (Figure 2.5h).

2.3 Other extreme weather events of 2010/11 summer

La Niña events usually lead to higher than average number of tropical cyclones, and higher than average rainfall, sometimes causing floods. During the 2010/11 La Niña, most of mainland Australia experienced significantly higher than average rainfall over the nine months from July 2010 to March 2011 and led to widespread flooding in many regions between September 2010 and March 2011 including Western Australia (Figure 2.6). Five out of a total of 10 tropical cyclones during the 2010/11 summer were in the severe category and an above average 29 systems developed into tropical depressions (Bureau of Meteorology, 2012).

The most severe and destructive system to hit the Gascoyne region around Shark Bay was during December 2010 when a tropical depression resulted in significant rainfall and caused major flooding of the Gascoyne River. Carnarvon's average December rainfall is 5.6 mm and its annual rainfall is 231 mm, but over the 2 days in December 2010, Carnarvon received 255 mm with some sites recording over 300 mm (Bureau of Meteorology, 2011). Three of the five river gauging stations along the Gascoyne River recorded the highest flood levels on record ranging from 7.63 to 15.53 m. Carnarvon was declared a natural disaster zone from this single event and this situation only worsened in the following months with ongoing cyclone activity in the region.

During January 2011, Tropical cyclone *Bianca* (reached category 4) brought heavy rainfall to the southern Gascoyne region. Carnarvon recorded a January rainfall of 62.4 mm compared to an average of 12 mm. This was followed by further two typical cyclones during February 2011, Tropical Cyclone *Carlos* (reached category 3) and Tropical Cyclone *Dianna*. The cloud band associated with these systems generated heavy rainfall in the inland Gascoyne region with minor flooding events (Bureau of Meteorology, 2011).

Shark Bay is an inverse estuary characterised by high rates of evaporation and minimal freshwater input and so the estuary can become more saline and denser than the outside oceanic waters. Thus there is a bottom outflow of denser saline water from the Bay and surface inflow of less saline ocean water (reversed density gradient and flow pattern). Only during the occasional flooding events in the region and at times of extreme weather events as experienced during the 2010/11 summer, will result in tonnes of freshwater being discharged from the Gascoyne catchment river systems over a short period. Some of the Gascoyne River monitoring stations recorded up to 3.9 million megalitres of discharge during the 2010/11 summer and broke record levels to date (Western Australia Department of Water). Flood plumes of red silt were visible from space (Figure 2.6 left) and an estimated 5.6 million tonnes of suspended sediment had likely entered Shark Bay (Waddell et al. 2012). The level of disruption to the salinity regime in the inshore regions of the Bay from the freshwater discharge is not known and in the absence of any *in situ* data logger information we can only speculate that some displacement (probably larger sized crabs) and/or mortality (juveniles) occurred.

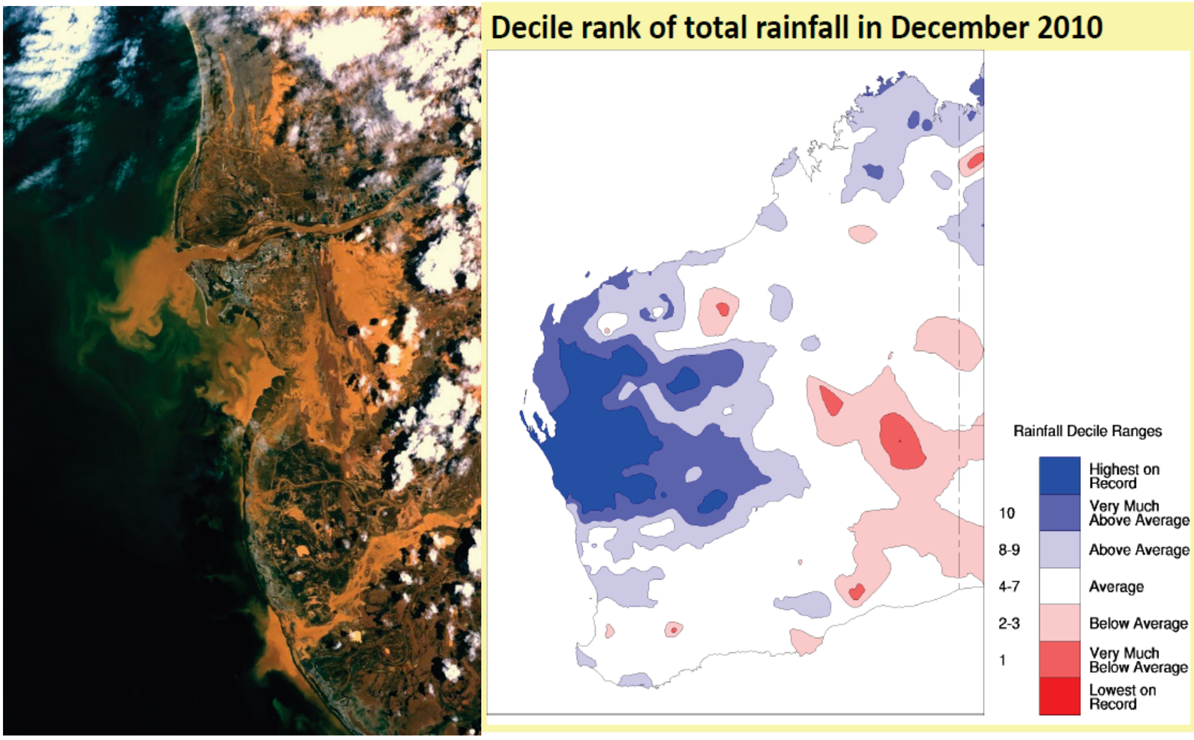


Figure 2.6. Satellite image to the left showing Gascoyne River mouth (and Wooramel River in the south) sediment plumes on 22 December 2010. (Image processed and enhanced by Landgate, Satellite Remote Sensing Services). Map to the right shows the Gascoyne region of Western Australia receiving record high rainfall during December 2010 (Bureau of Meteorology, 2011).

2.4 Stock decline and closure of the fishery

The impact of the marine heat wave event on the Shark Bay crab stock was not immediately identified as the trap sector and especially the trawl sector produced higher than average monthly catches during the first half of 2011 (Figure 2.7). In late 2011 however, the monthly commercial catch and catch rates of crabs declined to historically low levels. The prawn trawl fishing season began in March 2011 and boats landed above average monthly crab catches of 50 to 90 t until June 2011, followed by a marked drop in monthly catches from August to October 2011 after which the prawn season closed (Figure 2.7a). The trap fishery also caught above-average catches during March-May in 2011 and then catches started to decline from

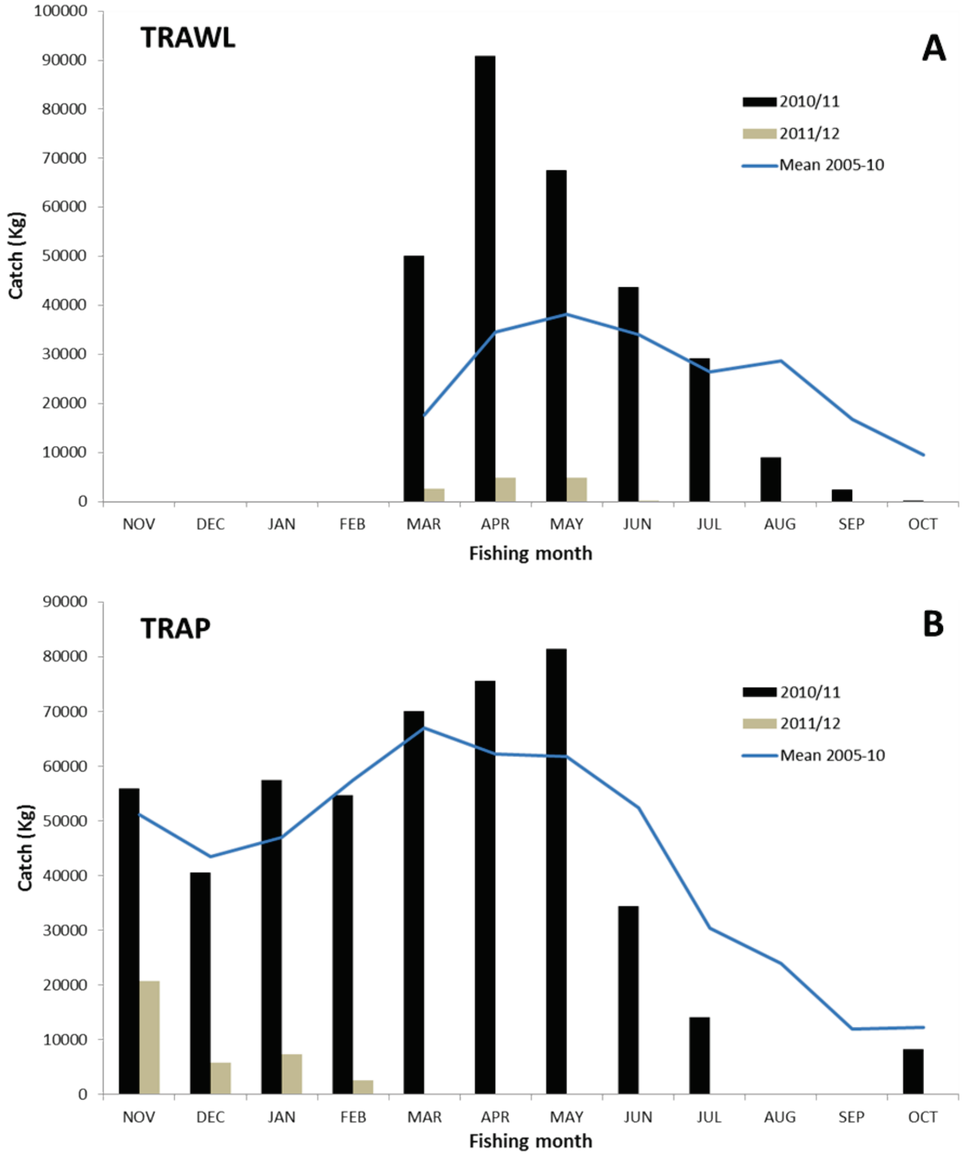


Figure 2.7. Historical mean monthly crab landings by the trawl (A) and trap (B) sectors (blue line) compared to monthly catches taken after the marine heat wave event (2010/11 and 2011/12 fishing seasons).

June onwards. When the trap season began in November 2011, catches were less than the historical mean, and less than 5 tonnes overall had been landed by February 2012 (Figure 2.7b). The annual fishery-independent scallop trawl survey in November 2011 confirmed the widespread decline in crab abundance within the trawl grounds of Shark Bay as well some exploratory fishing outside the Bay (Chandrapavan et al. 2013).

Markedly lower catches from June 2011 onwards suggested that recruitment had been detrimentally affected by the effects of the heat wave and/or the flooding events from the summer of 2010/11. The winter prior to the heat wave was the coldest on record which may have affected the spawning cycle. Furthermore, the high level of fishing pressure in the years prior to 2011 may have contributed to the stock decline and reduced its resilience to adverse environmental events. Thus the combination of all these factors rather than individually may have contributed to the stock decline that was observed. This prompted a voluntary industry-agreed closure of the commercial fishery in April 2012 including no retention of crabs by the prawn trawl sector (as scallop trawl fishery was also closed in 2012) to assist in stock recovery.

2.5 Resumption of fishing

Since 2012, during this study period, the Shark Bay crab stock had recovered partially to allow for commercial fishing to resume (discussed in detail in Section 6.5.2) and to also apply management changes that were already under consideration prior to the closure. In response to resource sharing issues, a Ministerial decision was made in June 2012 (while the fishery was closed) on a formalised resource allocation model which allows for the trap sector to retain 66% of the TACC, the prawn trawl sector to retain 33.8% and the scallop trawl sector to retain 0.2% of the TACC. These allocations were based on historical catches by each sector (for the years 2007-2011). Further approval was given by the Minister to progress this fishery to be Fully Managed with the development of a new Management Plan that would incorporate an Individual Transferable Quota system of entitlement to apply across all three commercial sectors in Shark Bay. This came into effect at the beginning of the 2015/16 fishing season. The fishery continues to operate with a 12 month fishing season (November – October) with a newly defined fishing boundary and spatial zoning (Figure 2.8).

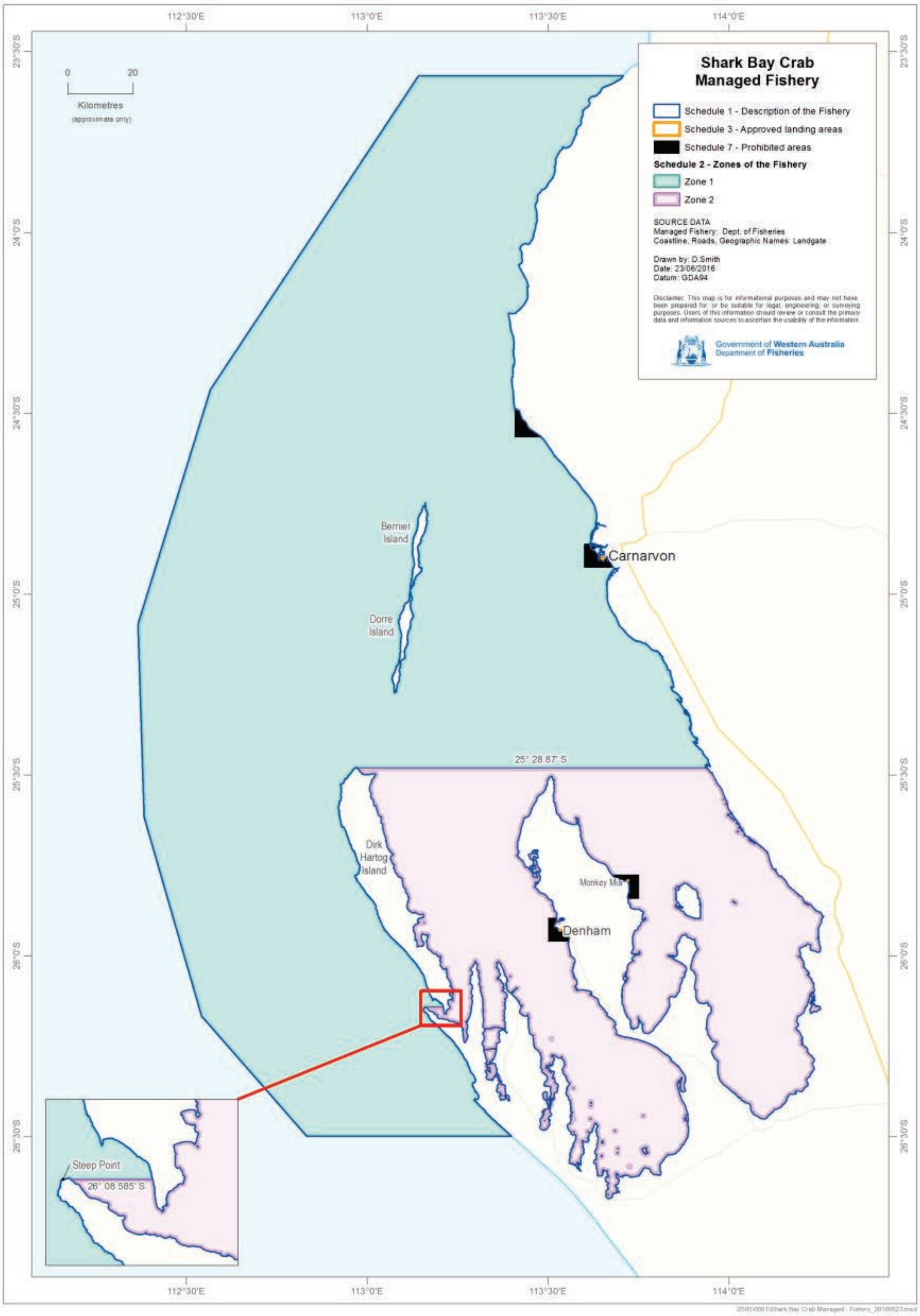


Figure 2.8. Map showing the boundary of the new Shark Bay Crab Managed Fishery. Zone 1 includes the waters of Shark Bay out to the 150m isobaths excluding the waters of the Inner Gulfs, and Zone 2 includes only the Inner Gulfs (western and eastern gulfs). Trapping will be permitted in all waters of the fishery except closed waters. When operating with trawl gear, the permitted fishing area will remain the same as the existing permitted fishing grounds within the Shark Bay Prawn and Shark Bay Scallop Managed Fisheries.

3 Objectives

The commencement of this study coincided with the closure of this fishery after the stock collapse in late 2011. To achieve stock recovery and for improved management of the resource, the goal of this study was to increase our understanding of the status and population dynamics of blue swimmer crabs within Shark Bay by achieving the following objectives;

1. To examine key drivers of the blue swimmer crab recruitment in Shark Bay, particularly environmental factors associated with low recruitment
2. Develop and implement a stock rebuilding strategy
3. Develop a harvest strategy for improved management of the stock
4. Determine the socio-economic significance of the blue swimmer crabs to the commercial trap and trawl sectors in Shark Bay
5. Host the Third National Workshop on Blue Swimmer Crab in 2015

4 Methods

4.1 Study area

Shark Bay is located 800 km north of Perth, Western Australia (between latitudes 24^{o} 30' S and 26^{o} 00' S), and covers an area of approximately13 000 km^2. Shark Bay is the largest marine embayment in Australia and supports the most extensive and diverse seagrass meadows in the world (Walker, 1989). This embayment, which is of great significance to the recreational and commercial fishing sectors and the conservation sector, was added to the World Heritage List in 1991 (Francesconi and Clayton, 1996).

Shark Bay is an inverse estuary formed by an elongate chain of three islands; Dirk Hartog, Bernier and Dorre Island (Nahas, 2004) (Figure 4.1). The southern half of the embayment is divided by the Peron Peninsula into the Eastern and Western Gulfs, characterised by narrow inlets and basins. The embayment is for the most part relatively shallow, with an average depth of 9 m and deepest depth at 29 m in the north (Francesconi and Clayton, 1996). Shark Bay has a semi-arid climate, characterised by mild winters (mean minimum/maximum temperatures of 11/24 ^{o}C) and hot, dry summers (mean min/max temperatures of 21/33 ^{o}C) punctuated by infrequent cyclones. Mean annual rainfall is low, ranging from 200 mm in the west of the Bay to 400 mm to the east.

The hydrology of Shark Bay is influenced by the Leeuwin Current which carries warm, low saline water southward down the WA coast. Substantial exchange of oceanic water in the northern waters of Shark Bay occurs through the broad Naturaliste and Geographe Channels, while a lesser exchange occurs in the Western Gulf through the narrow South Passage. Extensive meadows of seagrass in the lower gulfs further restrict water movement. Currents slow as the water passes over these meadows, causing increased deposition of suspended sediments that over time have produced large sedimentary banks (Francesconi and Clayton, 1996). The most significant sedimentary bank is the Faure Sill, which greatly inhibits the outflow of dense, haline waters from Hamelin Pool maintaining a hyper-saline environment in the lower half of the eastern gulf (Francesconi and Clayton, 1996). The limited exchange of oceanic water, minimal freshwater input and high evaporation rates has resulted in Shark Bay containing three distinct water body types: oceanic (salinity of 35–40 ‰) in the northern waters and upper gulf regions, metahaline (40 –56 ‰) in the middle gulf regions and hypersaline (56 –70 ‰) in the lower gulfs. These distinct salinity regimes influence habitat and species distribution, resulting in three different biotic zones within Shark Bay (Francesconi and Clayton, 1996).

4.2 Commercial fishing

Crab fishing is permitted across all the waters within Shark Bay (excluding specific exclusion zones for recreational activity and protection of sensitive habitats), however there are spatial and access restrictions that apply to different sectors and license holders (Harris et al. 2014). Trawling usually occurs between the depths 16 and 40 m (Figure 4.2), while trap fishers utilise all depths.

Prior to 2011when the fishery was primarily under effort controls, commercial trap fishers submitted statutory monthly catch records that include total crab catch and an estimate of fishing effort (days fished per month and mean number of traps used per day in that month) in a given fishing area. The majority of the trap-based crab catches (87%) were landed from the central and northern Shark Bay regions with 8% from the Eastern Gulf, and 5% from the Western Gulf (Harris et al. 2014). A voluntary logbook system was introduced in 2003 which provided some additional information on seasonal and spatial fishing patterns and intensity (Harris et al. 2014). When fishing resumed in 2013 the fishery was primarily managed with a TACC and fishers required to complete a catch disposal record for unload of catch.

Both prawn and scallop fishers provide statutory daily catch and effort records that focus on the primary target species and retained byproduct (including blue swimmer crabs). This information provides an estimate of daily catch and total hours trawled for each fishing period and fishers usually record a latitude and longitude position and the catch of target species (prawn and scallops) for each trawl. However, non-target species such as blue swimmer crabs are aggregated over each night's fishing. Retained crab catches may be variable during the season depending on the abundance of the target species and crab prices paid to the boat. The trawl effort is targeted towards prawns (and/or scallops) rather than crabs, so fishing effort cannot be accurately apportioned to crabs.

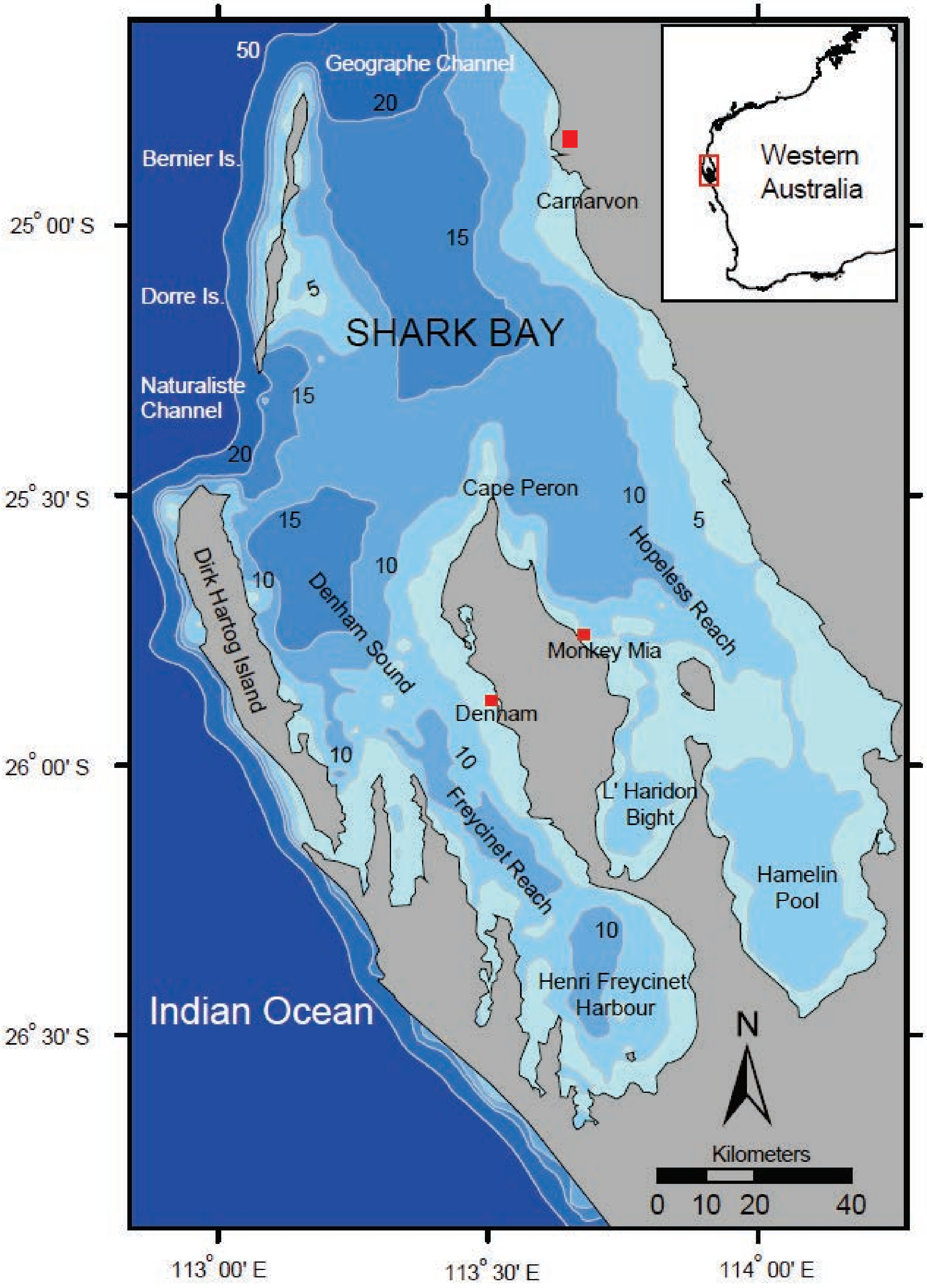


Figure 4.1. Bathymetry map of Shark Bay showing the 5, 10, 15 and 20 metre depth contours. (Sourced from Kangas et al. 2012).

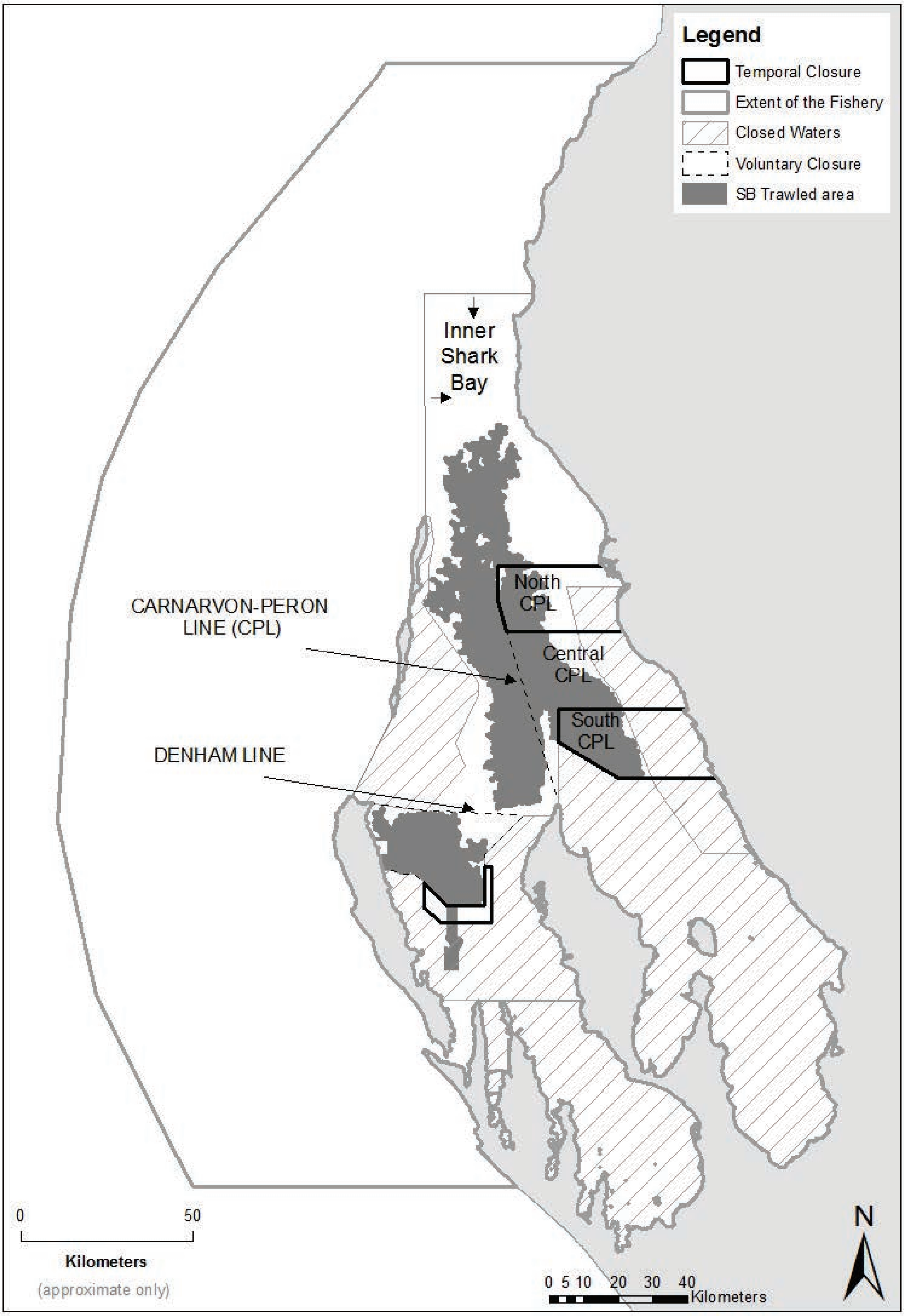


Figure 4.2. The main boundaries of the Shark Bay Prawn Managed Fishery, Inner Shark Bay, North CPL, Central CPL, South CPL, trawl closures, permitted trawl area (extends out to the 200m isobath) and the shaded area represents the general fishing grounds of the prawn and scallop fleets (combined) when in operation.

4.3 Stock monitoring

4.3.1 Trap monitoring program

A commercial trap monitoring program (fishery-dependent) for the trap sector was in place between 2000 and 2011, and was conducted by Departmental research staff to collect crab catch rate and size composition data. This data collection occurred up to three times per year (March-May, July-August, October-December) over 2-4 days in areas where the commercial trap fleet was operating (Harris et al. 2014). During the fishery closure period (April 2012 to November 2013), this program became a fishery-independent trap survey from 2012 to mid-2013 but then ceased due to the following challenges: 1) commercial traps were designed to allow small sized (juvenile) crabs to escape and therefore could not provide recruitment information; 2) the difficulty in comparing measureable units between capture data from traps and trawls to assess stock status; and 3) cost of chartering commercial boats during the closure. Given these challenges and differences in data between the sampling methods (see Appendix C. Trap vs Trawl catch comparison), developing an accurate index of spawning stock and more importantly recruitment, a fishery-independent trawl-based survey was considered far more effective than trap surveys despite the spatial and depth limitations of using trawls.

4.3.2 Annual November trawl survey program (2002 – present)

An annual fishery-independent scallop trawl survey program has been underway in Shark Bay since 1983 and is conducted during November of each year with up to 82 sites being sampled in the West CPL and Denham Sound regions (Figure 4.4). Since 2002, information relating to crab abundance, catch rates (number of crabs per nautical mile), size composition, sex and breeding condition were also recorded. Although this survey was designed to cover key scallop fishing grounds and did not encompass the primary crab trap fishing grounds, it did provide valuable data on crab abundance which reflected the stock at a consistent time and space. Crab stock information continues to be collected from this survey and became the basis of a dedicated crab trawl survey program in 2012.

4.3.3 Expanded fishery-independent crab trawl survey program (2012-present)

An expanded dedicated fishery independent survey program for blue swimmer crabs in Shark Bay was designed and implemented in April 2012. This survey included approximately half the number of sites sampled on the West CPL grounds during the annual November survey with additional sites to the east of the Carnarvon Peron Line (a management line for the prawn trawl fishery) that were part of the dedicated prawn surveys (North CPL, Central CPL and South CPL) (Figure 4.4). New sites were also added to extend the sampling to the south east region of the Bay to identify crab recruitment areas (East Peron Nursery). Denham Sound was however excluded due to historically low commercial crab catch rates from this region compared to the rest of the Bay but continued to be surveyed during November for its scallop and crab abundance. Although survey sites are restricted by the trawlable areas of the Bay, the sampling sites cover the main commercial fishing grounds of both the trap and trawl sectors, and thus the areas where most (~70%) of the crab catches are landed by these sectors

(Figure 4.3). Note also that, although the trap and trawl fishing area extends a considerable distance above the northern-most sampling site (see Figure 4.3), only a marginal (< 2%) amount of the total catch comes from this area. The February (and April) surveys provide an assessment of the juvenile (0^+) abundance but it does not sample very small (< 30 mm) 0^+ recruits.

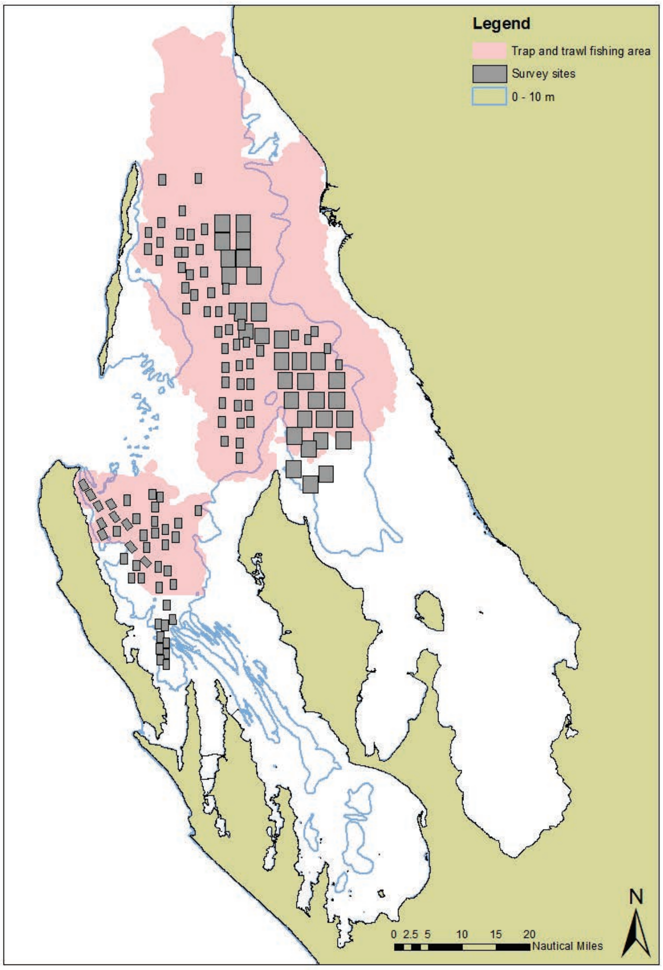


Figure 4.3. Map showing the main commercial fishing grounds of the trap and trawl sectors (from log book data) combined (pink), overlayed with the survey sites sampled during the fishery-independent crab survey program and the annual November survey program. The 10 m depth contour is shown to approximately define the trawlable areas of the Bay. The larger squares represent the areas where the historic prawn surveys were 30 min. duration and the smaller squares where the scallop surveys were 20 min.

The fishery-independent crab survey program included sampling during the months of February, April, June, and November from 2012 to the present and undertaken during the third phase of the lunar cycle (i.e. third quarter). The survey is undertaken over six to seven nights on the research vessel (RV) Naturaliste using a twin otter trawl gear (two nets, each with six-fathom (10.9 m) headrope length) with 50 mm mesh in the panels and 45 mm in the cod-end. Trawling is undertaken at night, commencing at dusk and the duration of each trawl is 20 minutes. The trawl period begins when the trawl gear starts to fish and winches cease paying out until the commencement of retrieving the trawl gear.

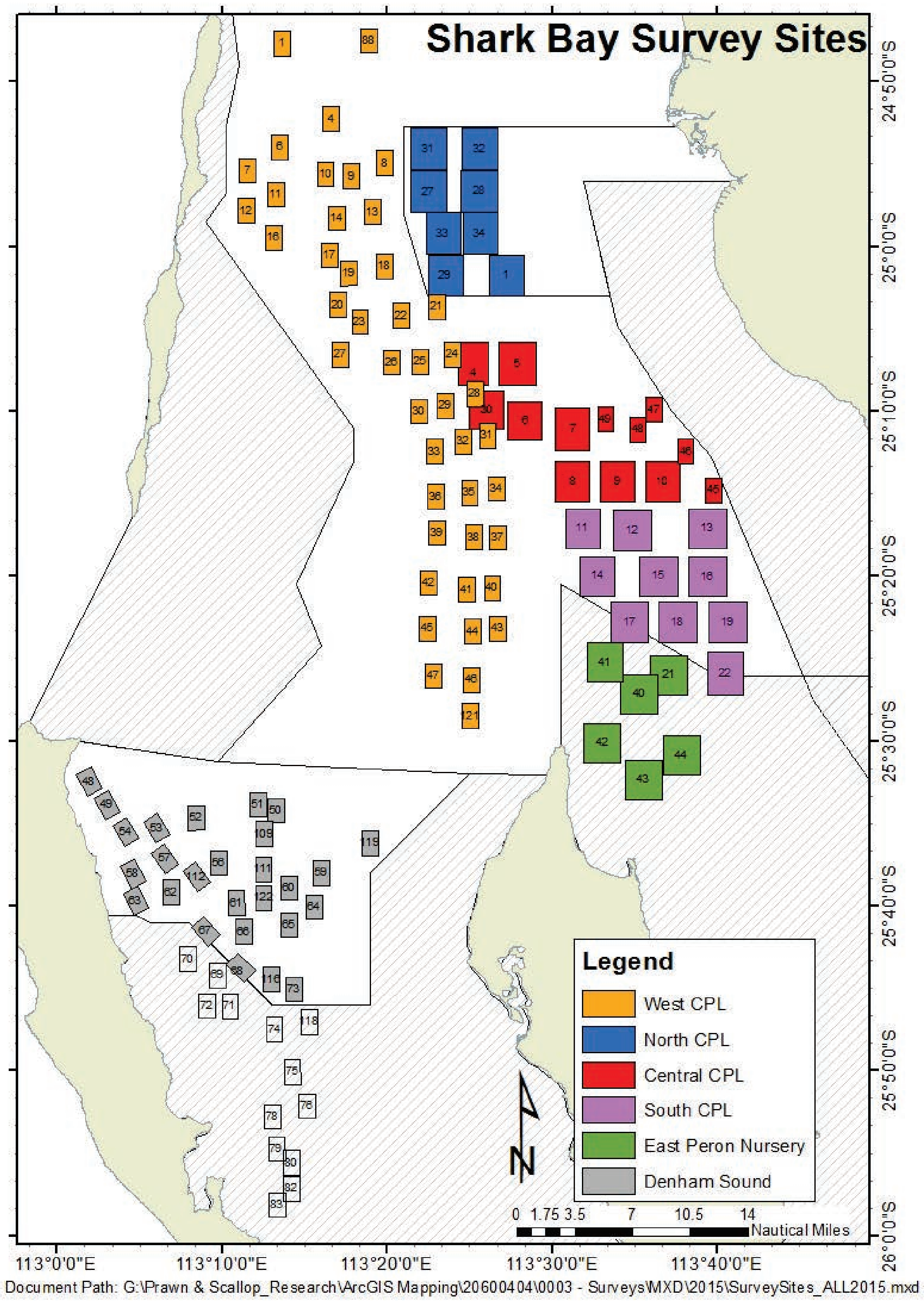


Figure 4.4. Standardised crab trawl survey sites in the North CPL (blue), Central CPL (red), South CPL (purple), East Peron Nursery (green) and West CPL (orange) regions of Shark Bay during the months of February, April, June and November. The non-coloured sites in the West CPL and all the sites in the Denham Sound region are additional sites that are sampled during the annual November survey program. Additional sampling took place in February 2015 in the Denham Sound region (grey sites).

Processing the catch from each trawl involves recording the total numbers of male, female and berried (ovigerous females) crabs from the port and starboard cod-ends. Based on initial visual inspection of the landed catch on the sorting table, if the total number of crabs was less than ~200, then all crabs were measured to the nearest mm CW (the distance between the tips of the two lateral spines of the carapace measured to the nearest mm). If the total number of crabs was between ~200 and 500, then only the crabs from the port side cod-end were measured. Note that a preliminary analyses undertaken in 2012 showed that when the total numbers of crabs from both nets were between 200-500, the abundances of crabs caught by the port and starboard-side nets did not differ significantly (DoF, unpublished data). Thus, the catch from one of these nets can be used as a representative subsample of the total catch from both nets. If, however, the total number of crabs was between 500 and 2000 crabs, the catch from one of the nets (which is always well mixed) is further subdivided to provide a sample of approximately 200 crabs. If the number of crabs exceeded 2000, individuals crabs are selected randomly (i.e. in a haphazard manner) from the catch on the sorting tray and placed into baskets (i.e. "milk" crates), a process which is repeated until all of the catch is in baskets. The sizes of the crabs in one of the baskets is then measured, and the weight of that basket is compared to the total weight of all baskets to estimate the total abundance of crabs from the catch in that shot. Note that prior to placing crabs in a crate, that crate is first placed on a scale and the weight re-zeroed, thereby ensuring that the weight of each crate, and any variation in weight among crates was taken into account.

At selected sites, measurements of surface and bottom water temperature, salinity and pH were taken using the YSI sampling unit (Professional Plus multi-parameter instrument, YSI Incorporated, Ohio, USA, 2011) (Figure 4.5). During June 2015, a handheld meter (Cond 330i) was used instead to collect surface temperature and salinity data.

Additional sampling sites were at times added during these surveys to sample for other species and thus provided additional crab abundance and water sampling opportunities. These included selected sites in Denham Sound (shown in grey in Fig 4.4), Freycinet sites, which are located further south into the reaches of Western Gulf, and Eastern Gulf sites, which are located south of the East Peron Nursery sites (Figure 4.5).

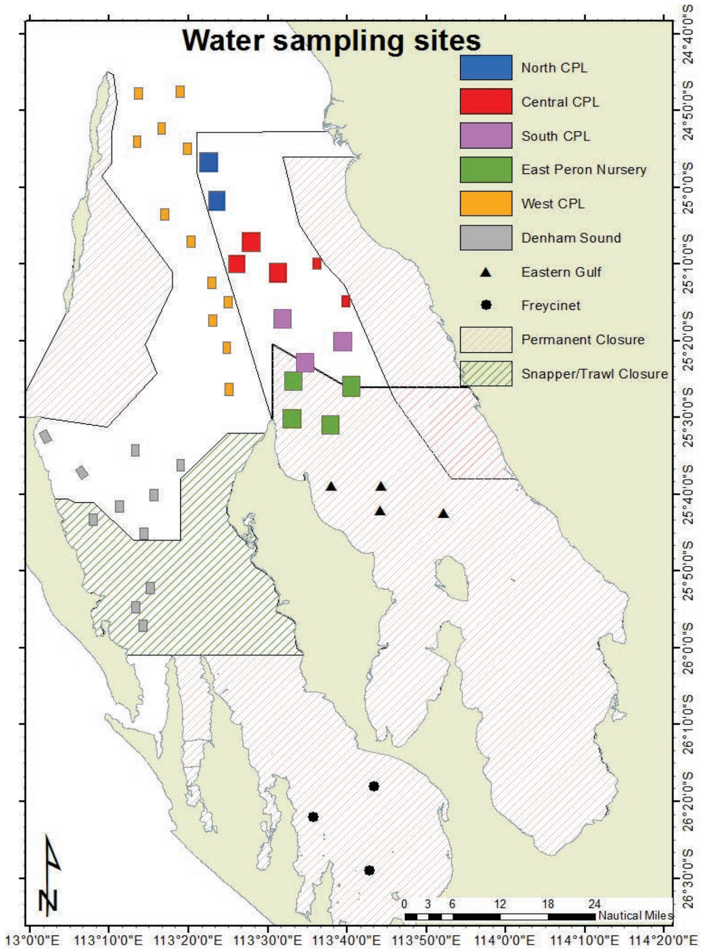


Figure 4.5. Selected survey sites where water quality sampling was undertaken. Additional survey opportunities allowed water sampling further into the reaches of the Eastern Gulf (▲) and Western Gulf (Freycinet).

4.4 Reproductive biology

A key management tool used to provide a level of protection to the breeding stock involves setting the commercial legal size limits well above the size at sexual maturity (SOM). Previous SOM estimates for Shark Bay by de Lestang et al. (2003a) indicated that, on average, males mature at 97 mm CW and females at 92 mm CW. This study re-estimated the size at maturity for males and females by using the same methods to assess if there was evidence of any temporal shift given the considerable environmental and stock changes that have occurred over the past 10 years. This study is also the first to examine the relationship between batch fecundity and size to better understand the reproductive biology of *P. armatus* in this fishery.

4.4.1 Estimates of size at the onset of maturity (SOM)

A total of 1380 female crabs were collected from the fishery independent trawl surveys during November 2011 (45), April 2012 (328), June 2012 (441), November 2012 (152), February 2013 (280) and April 2013 (134). Females were classified as sexually immature or mature based on the shape and looseness of the abdomen flap as per de Lestang et al.

(2003a). The abdominal flap of immature (juvenile) females is triangular in shape and after undergoing the pubertal moult, it changes to an oval shape and the flap becomes loose and free from the cephalothorax allowing for copulation to occur (Figure 4.6a).

For males, maturity was estimated based on the external appearance of the testes and the vas deferens using a sample of 567 males collected during surveys undertaken in February 2014 and April 2014. For this analysis, the gonads were categorised as immature (testes and vas deferens were not visible or opaque and loosely coiled) (Figure 4.7a) or mature (testes and vas deferens are enlarged, white and highly coiled) (Figure 4.7b) based on the external appearance of the vas deferens (de Lestang et al. 2003a).

4.4.2 Logistic regression analyses

Logistic regression was used to determine the carapace width (CW) at which 50% (CW_{50}) and 95% (CW_{95}) of female and male crabs were mature. The logistic equation used to relate the probability, P, of individuals being mature given its CW was

$$P = 1/(1 + \exp\{-\ln[(19)(CW - CW_{50})/(CW_{95} - CW_{50})]\}$$

On the basis of its CW, the likelihood of the jth crab being mature or immature was calculated as P_j or 1 - P_j, respectively. Setting $X_j = 0$ if the jth crab was immature and $X_j = 1$ if the crab was mature, the overall log-likelihood, λ , was calculated as

$$\lambda = \sum_j \{X_j \ln P_j + (1 - X_j)\ln(1 - P_j)\}$$

The logistic equation was fitted by maximizing this log-likelihood using SOLVER in Microsoft Excel. The data were randomly resampled and analysed to create 500 sets of bootstrap estimates of the parameters of the logistic equation.

Maturity data from an earlier study by de Lestang et al. (2003a) were made available for this study to enable statistical comparisons of the two studies for a detailed examination of evidence for any temporal shift in the maturity of *P. armatus* in Shark Bay. Estimates of SOM by de Lestang et al. (2003a) were based on samples collected between 1998 and 2000 from four inshore sites (Herald Bay, Monkey Mia, Denham and Nanga Bay) using a combination of beach seine, trawl and trap sampling methods. In this study, however, the maturity estimates are derived solely from fishery-independent survey trawl data.

A consideration made when comparing the maturity data sets from the two studies was that the maturity data by de Lestang et al. (2003a) was re-analysed by Smith et al. (2004), which led to the conclusion that maturity estimates for female blue swimmer crabs are likely to be biased if based on trap data. As discussed by those latter authors, this would reflect individuals of a given size caught (passively) in traps having a higher probability of being mature than caught using other (active) gears, associated with sex-related behavioural differences influencing catchability. While this is an entirely valid hypothesis, examination of the maturity data available from the study of de Lestang et al. (2003a) indicated that, if a very small number of data points (i.e. 2 or 3) for crabs around the size at maturity were omitted from the analysis, the differences in estimates of mean size of females at maturity between the trap data vs seine and trawl data would no longer be significant. It should be noted that, the sample sizes in the available data set from the study of Smith et al. (2004) differed slightly to those reported in the paper and as a consequence, we could not replicate the exact results in that former study.

The maturity data collected in this study were compared with the maturity data from de Lestang et al. (2003a) firstly, by all fishing methods, and secondly, by combining the seine and trawl data. In each case, the comparisons involved fitting maturity curves fitted under all four possible parameter sets, i.e. (I) a common curve for the two data sets (2 parameters), (II) separate curves with a common CW_{50} and separate CW_{95} values (3 parameters), (III) separate curves with a common CW_{95} and separate CW_{50} values (3 parameters) and (IV) separate curves with separate CW_{50} and CW_{95} values (4 parameters). Likelihood ratio tests (Cerrato, 1990) were employed to compare the 2 and 3 parameter models with the 4 parameter model to determine which of these, if any, was not significantly different from the 4 parameter model. For each comparison, the test statistic was calculated as twice the difference between the log-likelihoods obtained by fitting the alternative models. The hypothesis that the data sets from the two time periods could appropriately be represented by the simpler of the two models being compared was rejected at the $\alpha = 0.05$ level of significance if the above test statistic exceeded $\chi^2_{\alpha}(q)$, where q is the difference between the number of parameters for the two models (Cerrato, 1990). The model selected on the basis of these tests was the simplest model that, in the statistical sense, provided the best description of the data. The new estimates of SOM from re-analysis in this study have been incorporated in the stock indices (see sections 5.4 and 5.3) and in the estimation of biomass using swept area analysis (see Section 5.7) and also in the biomass dynamics modelling (see Section 5.8).

4.4.3 Batch fecundity analyses

Based on the egg staging categories typically described for blue swimmer crabs (de Lestang et al. 2003a), the reproductive development of ovigerous (egg bearing) females was categorised into three stages based on the level of embryonic development, which can be assessed macroscopically based on the egg mass colour. Egg mass of bright yellow colour was Stage 1 (high volume of yolk) (Figure 4.6b), yellow-grey colour indicated Stage 2 (Figure 4.6c) and dark grey colour (yolk fully absorbed) for Stage 3 (Figure 4.6d). Assuming there is no substantial egg loss during the incubation period from Stage 1 to spawning, fecundity estimates can be based on any berried stage. However, to be consistent with methods from previous studies (de Lestang et al. 2003a), analysis was based on the early stage berried (i.e. Stage 1) females.

A total of 33 ovigerous females of Stage 1 embryonic development (bright yellow eggs) (Figure 4.6b) with undamaged egg masses were collected from trawl surveys during June 2013 (11 berried females) and November 2013 (22 berried females), when the highest number of berried females were encountered. The whole egg mass was removed from the pleonal flap by detaching it at the base of the pleopods. The egg mass was pat dried to remove as much moisture as possible and weighed to the nearest 0.001g on an electronic balance. From each egg mass, five replicate ~ 0.01 g subsamples were taken and weighed.

The numbers of eggs within each subsample were recorded and the egg diameter measured under a stereo microscope (Figure 4.8). For each crab, the number of eggs in each replicate subsample (of known weight) was calculated and used, in combination with the total weight of the gonad, to provide five estimates of the batch fecundity (i.e. total number of eggs within the egg mass) for that individual.

Initial inspection of the data indicated that the relationship between batch fecundity (BF) and carapace width (CW) could possibly be described adequately by a linear relationship, i.e. ($BF = a\,CW + b$). To confirm whether this was the case, the fit of the linear relationship was compared with that of a power relationship, i.e. $BF = a\,CW^b$ (based on their respective values for r^2). The relationships were fitted using R Statistical Software package (R Core team, 2013) employing a weighted least squares regression. Noting that five replicate egg mass subsamples were taken from each crab, the mean number of eggs for each crab and associated variance (i.e. from the five subsamples) was calculated. Differences in the precision of the mean estimates of batch fecundity among the 33 crabs was accounted for by weighting, for each crab, the squared residual between the observed mean batch fecundity (i.e. across the five replicates) and the expected batch fecundity, according to the variance for the observed mean. That is, the sum of squared residuals was calculated as

$$\sum_{j=1}^{n} \frac{\left(\bar{y}_j - \hat{y}_j\right)^2}{\sigma_j^2}$$

where $\bar{y}_j$ and $\hat{y}_j$ are the calculated observed mean batch fecundity and the expected batch fecundities for the jth crab, respectively, and σ_j^2 is the variance associated with the observed mean batch fecundity for that crab. When fitting both the linear and power relationships, the errors were assumed to be additive and normally distributed.

where n is the number of crabs used in the fecundity analysis (i.e. 33), $\bar{y}_j$ and σ_j^2 are observed mean batch fecundity and variance (for the five replicates) for the jth crab, and $\hat{y}_j$ is the expected batch fecundity for that crab based on either the linear or power relationship between batch fecundity and size. When fitting both the linear and power relationships, the errors were assumed to be additive and normally distributed.

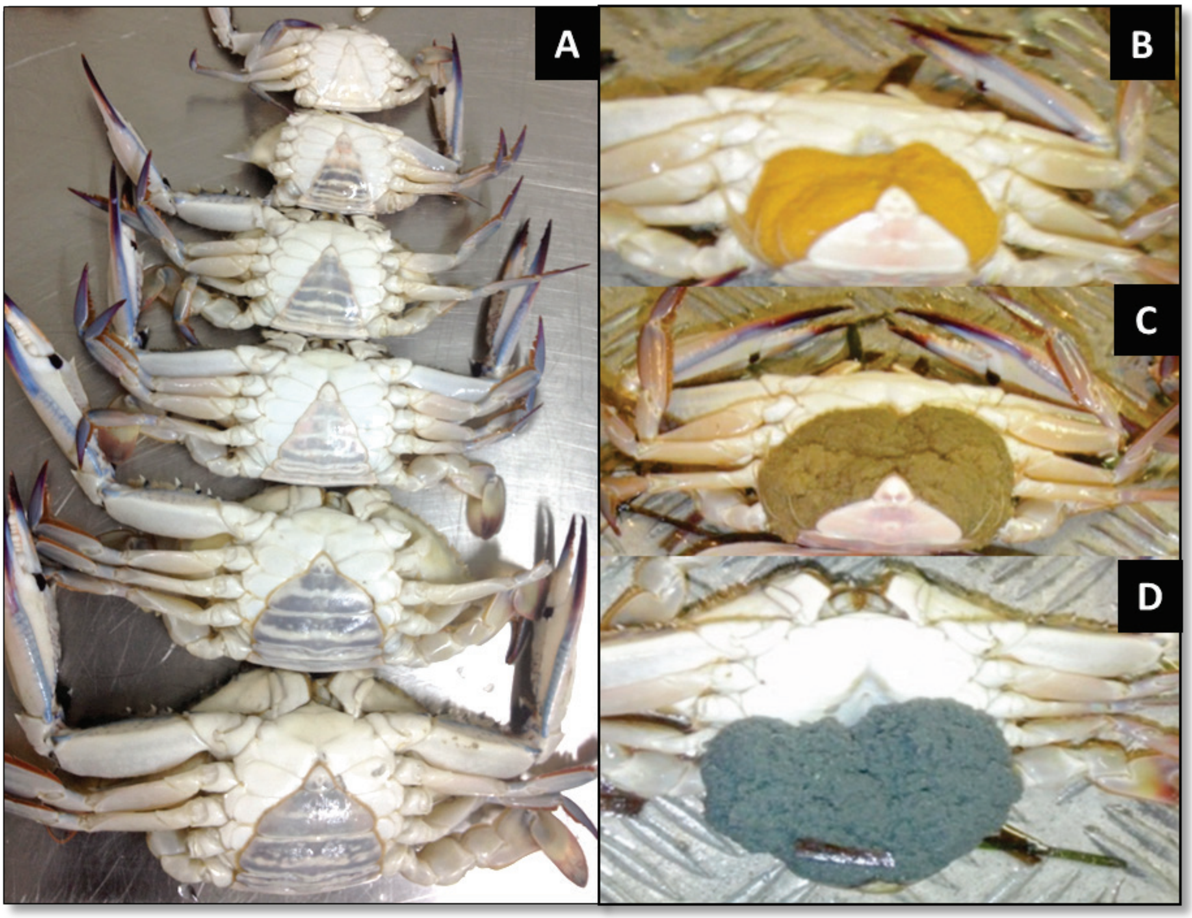


Figure 4.6. (A) Change in the shape of the abdominal flap from the triangular shaped immature females (top) to the oval shaped mature female (bottom). Embryonic development during (B) Stage 1, bright yellow egg mass (C) Stage 2, yellow-grey egg mass and (D) Stage 3 dark grey egg mass, in ovigerous females.

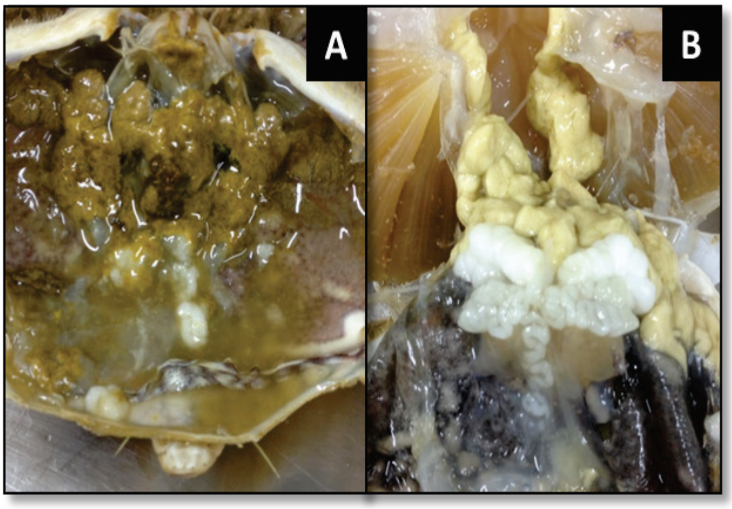


Figure 4.7. (A) An example of an immature male crab showing no visibly developed testes or van deferens; (B) An example of a mature male crab with well-developed testes and vas deferens that are enlarged, white and highly coiled.

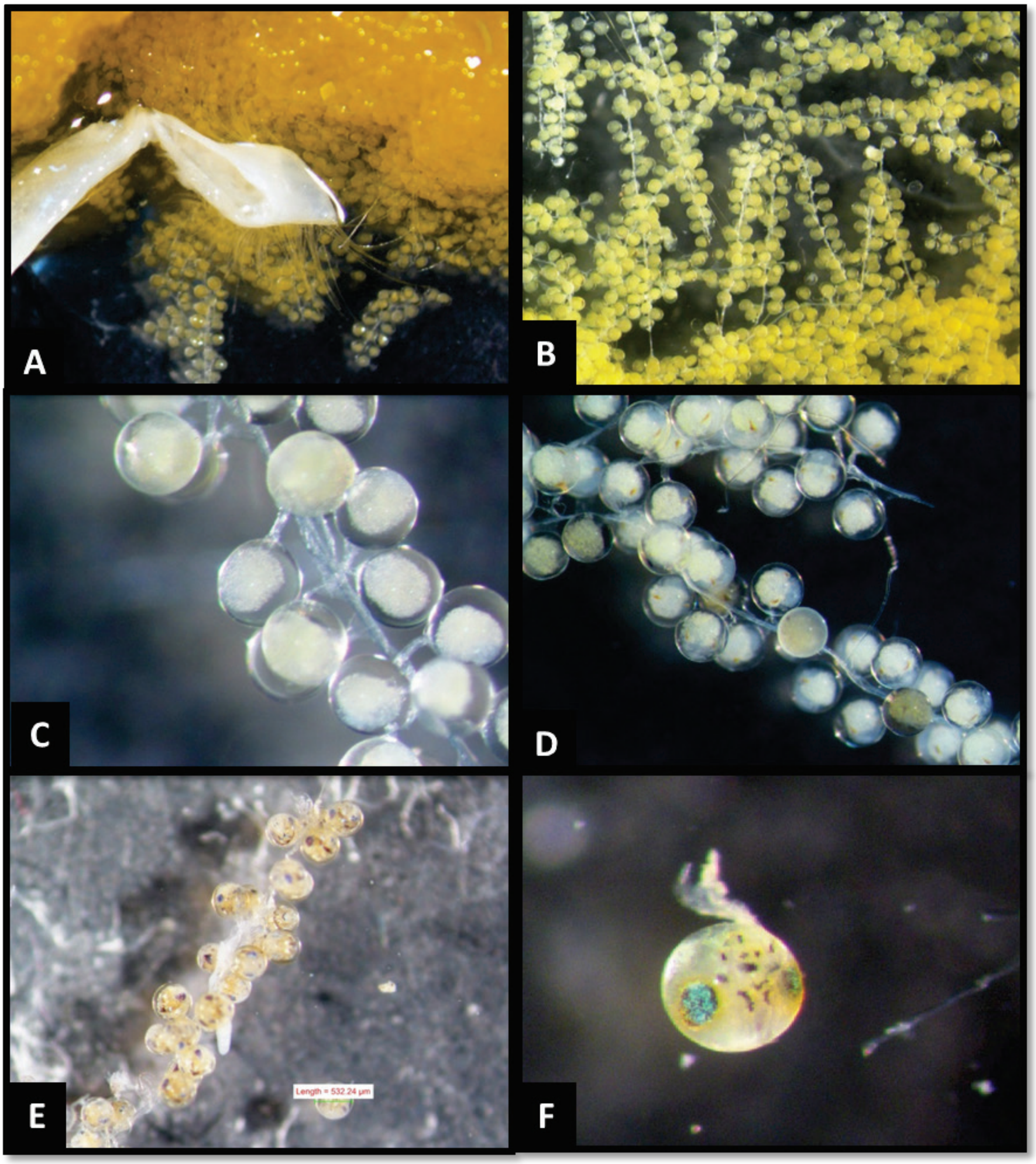


Figure 4.8. (A) Egg bearing setae on the pleopod of a Stage 1 ovigerous female. (B) Individual strands of setae detached from the pleopod. (C) Stage 1 yellow (colour from the yolk sac) eggs individually attached via a stalk to the setae (D) Stage 2 yellow-grey eggs with eyespots now present (E) Stage 3 grey eggs with discernible eyespots and chromatophores. Diameter of a single egg is shown to be 532.24 µm (F) A detached stage 3 egg.

4.5 Estimation of crab biomass using swept area analysis

4.5.1 Overview of analysis

The fishery-independent crab trawl survey data collected between April 2012 and June 2015 were used in a "swept area analysis" to provide estimates of biomass for the crab population in Shark Bay. The swept area analysis involved calculating a mean crab density expressed in terms of weight (i.e. kg/nm^2), together with its uncertainty, and multiplying the estimate by a specified area within Shark Bay. Estimates of biomass were calculated for crabs belonging to five catch categories; total biomass (crabs of all sizes), legal biomass (males and females ≥135 mm CW, excluding berried females), spawning biomass (mature females crabs based on the size at maturity estimates determined in this study (i.e. all females and ≥110 mm), mature biomass (all females ≥110 mm and all males ≥105 mm), sublegal biomass (110 mm ≤ females < 135 mm; 105 mm ≤ males < 135 mm), and juveniles (immature crabs, females < 110 mm and males < 105mm).

Biomass estimates of each crab category was based on two spatial area calculations; Area A (657 nm^2) representing the crab stock encompassing the survey region and Area B (1604 nm^2) representing the crab stock within the commercial fishing grounds of the trap and trawl sectors where majority of the crabs are harvested, i.e. the fished area (Figure 4.9). Area A encompasses all standard survey sites (excluding Denham Sound), and does not cover the full extent of the fished area. Area B encompasses the majority of the historic and current trap and trawl commercial fishing grounds (determined from commercial logbook data which indicate that 70% of the catch comes from the area covered by the survey).

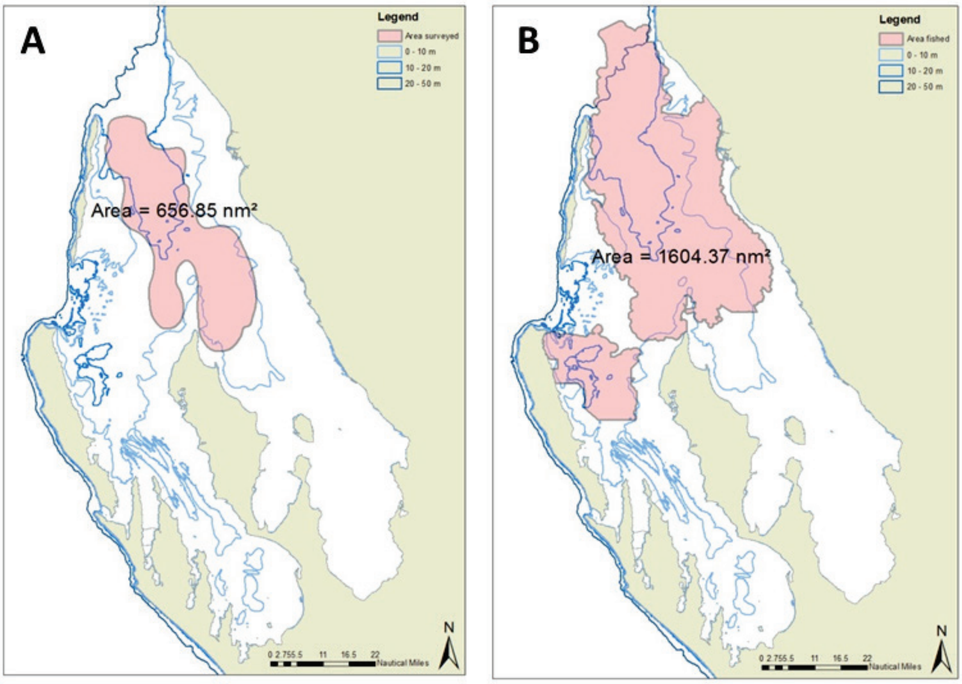


Figure 4.9. Maps of area calculations for estimates of total biomass A) fishery independent crab survey sites, B) current and historical crab fishing areas derived from logbooks.

4.5.2 Conversion of length measurements to weights

As the fishery independent survey trawl data for crabs are recorded in terms of numbers rather than weights, the first step of the analysis involved estimating the weight of each crab in each sample from its size (using a weight-length relationship), to allow calculation of the weight of all crabs in each sample, for a given category. The following sex-specific equations relating crab weight, W , to carapace width, CW, were used

$$\text{Females: } \ln W = 3.12018 \ln CW - 10.0843$$

$$\text{Males: } \ln W = 2.96434 \ln CW - 9.27173$$

where ln refers to the natural logarithm.

Values for the swept area (nm^2) of each trawl undertaken at each site in each survey, A, were calculated as

$$A = 2HVTF$$

where V is the velocity of the trawl over the ground when trawling ($nm\ h^{-1}$),T is the time spent trawling (h), H is the length of the head-rope (0.00592 nm, = 36 ft) and W is the fraction of the head-rope length that is open (0.81). Note that the trawl surveys for crabs in Shark Bay employ twin trawl nets. The overall weights of each category of crab, i.e. all crabs, legal size crabs, mature crabs, and undersize crabs, and value of A for each sample were then used to estimate the density of crabs per square nautical mile.

4.5.3 Distributional assumption for crab density data

The mean densities (by weight) of crabs recorded in trawls were calculated assuming that the densities of crabs among the individual trawls have a delta-lognormal distribution. This distribution, which combines a lognormal distribution for the positive values, together with an additional probability mass at zero, was considered appropriate given that 1) the distributions for the values of density were skewed, and approximately lognormal and 2) that, for the various size categories of crabs considered (immature, mature, sublegal, legal) a value of zero was often recorded at several sites within a survey.

4.5.4 Alternative statistical approaches for calculating biomass

Two alternative statistical approaches for estimating mean density based on the assumption of a delta-lognormal distribution (i.e. an analytical approach and a parametric resampling approach) were used to confirm that the two statistical methodologies produced consistent results.

1) *Analytic approach*

The mean and associated 95% confidence limits of a delta-lognormal distribution may be calculated analytically employing a modification of the Cox method, designed to calculate the mean of a lognormal distribution (Fletcher 2008). Applying this modification, if Y is said to have a delta-lognormal distribution for which $P(Y > 0) = \pi$ and $X = \{lnY|Y > 0\}$ with,

$X \sim N(\mu_x, \sigma_x^2)$, then it can readily be shown (Aitchison, 1955) that the expected value of Y is given by $\mu_Y = \pi \exp(\mu_X + \frac{\sigma_X^2}{2})$. The confidence interval for μ_Y can be calculated by first calculating a confidence interval for $\theta = \ln(\mu_Y) = ln\pi + \mu_X + \frac{\sigma^2}{2}$. An estimate of θ is given by $\hat{\theta} = \ln p + \bar{x} + \frac{s_X^2}{2}$ An estimate of the variance of $\hat{\theta}$ is given by:

$$V\left(\hat{\theta}\right) \approx \frac{\left(\hat{d}-\hat{c}\right)\left(1-\hat{c}\hat{d}\right)-m\left(1-\hat{c}\right)^2}{m\left(1-\hat{c}\hat{d}\right)^2} + \frac{s_X^2}{m} + \frac{s_X^4}{2(m+1)}$$

where $\hat{c} = (1-p)^{n-1}$ and $\hat{d} = 1 + (n-1)^p$.

Assuming approximate normality for $\hat{\theta}$, a back-transformed 95% confidence interval for μ_Y is given by $\exp\left\{\hat{\theta} \pm 1.96\sqrt{V\left(\hat{\theta}\right)}\right\}$ (Fletcher 2008).

The estimate of total biomass is thus given by $\hat{B} = T\hat{\theta}$, and the associated lower and upper limits of the 95% confidence interval are given by $T\left(\hat{\theta} - 1.96\sqrt{V\left(\hat{\theta}\right)}\right)$ and $T\left(\hat{\theta} + 1.96\sqrt{V\left(\hat{\theta}\right)}\right)$ respectively.

2) *Parametric resampling approach*

Alternatively, an estimate of the biomass of crabs in the trawl area may also be obtained using a parametric resampling approach and assuming a delta-lognormal distribution. For this analysis, 10,000 random values of P^*, the proportion of sites within each survey, with non-zero abundances, and 10,000 random values for the mean of the log-transformed non-zero densities in transects, $\bar{x}^*$, were drawn from binomial and normal distributions, respectively. The values of $\bar{x}^*$ were drawn using the equation

$$\bar{x}^* = \bar{x} + SE.r$$

where $\bar{x}$ and SE are the mean and standard error of the non-zero values respectively, and *r* is a random normal variate. Each value of $\bar{x}^*$ was then back-transformed and corrected for bias, using the equation

$$E_{corr} = E_{uncorr}.\exp(0.5.\sigma^2)$$

where E_{corr} is the bias-corrected estimate following back-transformation, E_{uncorr} is the back-transformed value of $\bar{x}^*$, and σ^2 is the variance of the log- transformed values. Each of the 10,000 values of E_{corr} was then multiplied by one of the 10,000 values of P^* to produce 10,000 estimates of mean density. These, in turn, were multiplied by the assumed value representing the area of the stock to obtain 10,000 estimates for the biomass of crabs in that area, at the time of a given survey. The point estimate and lower and upper 95% confidence limits for crab biomass, for each survey, were taken as the median, 2.5 and 97.5 percentiles, respectively, of the 10,000 biomass values.

4.6 Modelling growth of *P. armatus* in Shark Bay

In the absence of a reliable ageing technique for individual crabs, growth is usually estimated from monthly length frequency (LF) data. Previous growth analyses for *P. armatus* in Western Australia by de Lestang et al. (2003b) involved a two-stage process. In the first stage, the means and standard deviations of the length modes present in samples were estimated independently for samples collected in different months using "mixture analyses", assuming that each of the length modes were normally distributed. Likelihood-ratio tests were used to ascertain whether one, two or three modes were present in the data for each month, with the result that, for any month, either 1 or 2 length modes were considered to be present. In the second stage, an age was assigned to each of the length modes in each month using an assigned birth date for crabs. A seasonal growth curve (Hanumara and Hoenig 1987) was then fitted to the estimated mean lengths at each age. Although de Lestang et al. (2003b) was able to fit growth curves to length composition data for *P. armatus* from Cockburn Sound, Peel-Harvey Estuary and Leschenault Estuary crab stocks, due to lack of signal in the data, this was not possible for Shark Bay.

In the current study, length frequency data were only available for the months of February, April, June and November for crabs captured using otter trawl gear. Visual inspection of the length frequency data revealed the presence of two modes (0^+ and 1^+ age cohorts) in some months and most clearly during November (see Figure 5.11). Unlike that of de Lestang et al. (2003b), the modes in the current data, when traced through time, exhibited a clear growth signal which may reflect the different sampling gears (trawling vs trap and seine netting) and/or spatial differences in sampling between the two studies. Consistent with previous growth analyses for blue swimmer crabs in Cockburn Sound, it was assumed that crabs in Shark Bay also attain a maximum age of 2 years and that growth exhibits a seasonal pattern. Although it is likely that at least a small number of crabs live for more than 2 years (particularly if there has been a period of several years of low or no fishing pressure), it would not have been possible to distinguish such animals from other age groups from length frequency data alone.

Growth analysis in the current study involved a single stage rather than two-stage process for fitting the growth model (fitted separately by sex) to 4000 crabs, i.e. with 1000 individuals being randomly sampled from the length frequency data collected during each calendar month, i.e. February in 2013-15 surveys, April in 2012-15 surveys, June in 2013-14 surveys and November in 2012-14 surveys. As the numbers of crabs in November, in particular, were relatively low compared with other months, limiting the samples to 1000 random crabs ensured that all months were well represented in the growth analysis. The values for the mean lengths of crabs for each length mode, in the length frequency data for each month, are described by a seasonal growth curve, rather than (as in the previous study) determined from the results of independent mixture analyses. In contrast to previous analyses, for which a separate standard deviation was estimated for each length mode in each month, the current model assumed a common value for the standard deviation for all of the length modes in all months. The model employed in the current study has an additional parameter for each month defining the relative contributions of crabs belonging to the 0^+ and 1^+ age cohorts in each month. Note that, although it is assumed that two cohorts are potentially present in each month, the relative abundance of one of the two cohorts could potentially be estimated as zero.

Benefits of the current modelling approach include that the number of parameters that need to be estimated has been greatly reduced and this approach allow better estimation of uncertainty associated with the growth parameter values and mean lengths at age. One assumption in the current model that may require further consideration is the use of a single standard deviation for the mean lengths at age for all cohorts, and whether it would be beneficial to estimate separate standard deviations for different age cohorts and/or for different months. Note also that the current model does not follow the growth of particular cohorts, but rather estimates the mean size at age across the full sampling period. In future, there may be a benefit in modifying the current approach to model the growth of individual cohorts, which may lead to improved growth estimates and allow for investigations of temporal growth changes.

The growth of blue swimmer crabs is described using the seasonal growth curve of Somers (1998). From this equation, the expected length of the j^{th} crab L_j, is

$$L_j = L_\infty \left\{ 1 - exp\left[-k \left(t_j - t_0 + \frac{C}{2\pi} [S(t_j) - S(t_0)] \right) \right] \right\}$$

where t_j is the age of the j^{th} crab, L_∞ is the asymptotic length (mm), k is the von Bertalanffy growth coefficient and t_0 is the age of the crab with a length of zero. In Somer's model, $S(t_j) = sin[2\pi(t_j - t_c)]$ and $S(t_0) = sin[2\pi(t_0 - t_c)]$, where C is the seasonality amplitude parameter (which is constrained in the model to be between 0 and 1) and t_c is a parameter that determines the time of year at which growth is at a maximum or minimum, i.e. it acts to shift the growth curve to the left or right to align with the actual seasonal pattern of growth. The decision to use the seasonal growth curve of Somers (1998) rather than that of Hanumara and Hoenig (1987) was based on experience gained from fitting a wide range of seasonal growth models to data for a species of fish (*Pelates octolineatus*) (N. Hall, *pers. comm.*). This revealed that, at least for *P. octolineatus,* optimisation for the curve of Somers (1998) was more robust than for several other seasonal growth models. That is, the optimisation procedure yielded exactly the same estimates for the growth parameters for the Somers (1988) curve regardless of the specified initial values for those parameters, which was often not the case with other growth curves (N. Hall, *pers. comm.*).

The probability of a crab, of age a belonging to length class i, was calculated as

$$\psi_{a,i} = \int_{L_i}^{L_{i+1}} f_a(L) dL$$

where L_i and L_{i+1} are the lower and upper bounds of length class i, respectively, and where $f_a(L)$ is the value of the normal probability density function for a crab of age a with length L, calculated using a constant standard deviation over all ages, i.e. $L \sim N(\mu_a, \sigma^2)$. That is,

$$f_a(L) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[\left(\frac{-L-\mu}{2\sigma^2}\right)^2\right]$$

It is assumed that, at any time of year, any crab is potentially one of two ages, i.e. that any crab would potentially belong to either the 0^+ year old cohort, or the 1^+ year old cohort. It is necessary, for the analysis, to calculate both of the two possible ages for each crab. Assuming peak spawning is during the winter/spring months in Shark Bay (see Section 5.4.4), a mean birth date of 1 August, the age (in years) of the j^{th} crab if it belonged to the 0^+ cohort, (a_j^{0+}), and if it was caught between January and August, a_j^{0+}, was calculated as

$$a_{j,0+} = (m_j + 4)/12$$

If a crab of the 0^+ cohort was captured between September and December, then

$$a_{j,0+} = (m_j - 8)/12$$

For corresponding months, the ages of crabs belonging to the 1^+ cohort, a_j^{1+}, was calculated in the same manner as above for 0^+ crabs, but adding 1 year to the calculated age.

The negative log-likelihood, λ, associated with the fit of the model to the length frequency data, was calculated as

$$\lambda = \sum_{j=1}^{N} \log_e\left\{\left[f_{a_{j,0+}} \phi_{a_{j,0+}}\right] + \left[f_{a_{j,1+}}(1 - \phi_{a_{j,0+}})\right]\right\}$$

where N is the number of crabs, $f_{a_{j,0+}}$ and $f_{a_{j,1+}}$ are the values of the normal probability density function for the j^{th} crab if it belonged to the 0^+ or 1^+ cohorts, respectively, and $\phi_{a_{j,0+}}$, is the probability of the crab belonging to the 0^+ cohort. Note that the value of $\phi_{a_{j,0+}}$ is the same for all crabs caught in the same month, i.e. the values of $\phi_{a_{j,0+}}$ are estimated model parameters for each month. The model was implemented in AD Model Builder (Fournier et al., 2012) and was fitted to the data by minimising the negative log-likelihood.

The instantaneous rate of change of growth was also calculated by the derivative of $L(t)$ as:

$$L'(t) = L_\infty k\left[1 + C\cos\left(2\pi(t - t_0)\right)\right]\exp(-k\left\{\text{t} - t_0 + \frac{C}{2\pi}\left[\sin\left(2\pi(t - t_c)\right) - \sin\left(2\pi(t_0 - t_c)\right)\right]\right\}$$

to examine how the growth rate changes through the year in relation to seasonal variations in water temperature in Shark Bay.

4.7 Marine heat wave effect on Shark Bay crab stock

The effect of the marine heat wave on the Shark Bay stock has been documented in a separate FRDC project (see details in Caputi et al. 2015a) and only incremental results from ongoing analysis have been included in this report. The effect of the heat wave was examined using statistical analyses between monthly SST within Shark Bay and the available crab abundance indices. Since daily *in situ* measurements were not available for Shark Bay for extended time periods, satellite-derived continuous daily SSTs from the NOAA OIv2 dataset from 1982 onwards at ¼ degree (~28 km) resolution was used for analyses (Reynolds et al. 2007). The mean monthly SST was examined for nine locations in Shark Bay (Figure 4.10) showing similar results and so only 3 sites (sites SWcar, North Peron and East Gulf) were selected to be averaged as they represent the main area where the crabs generally occur. The abundance indices examined in the statistical assessment for the Shark Bay crab fishery were;

(i) standardised catch rate of legal-size crabs obtained from fishers' monthly returns by financial year taking into account month and location of fishing

(ii) standardised catch rate of legal sized crabs from the annual November trawl survey program (2002 - 2015)

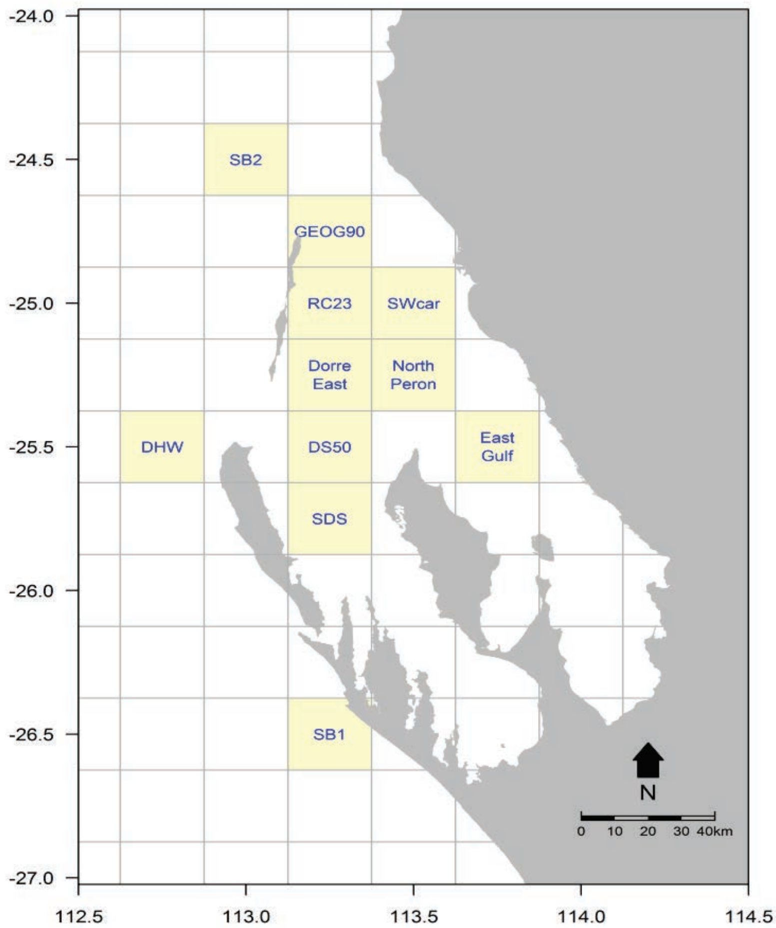


Figure 4.10. Map of Shark Bay region in ¼ degree blocks (~28km). The eight locations inside the Bay and the three locations outside the Bay have been used for various SST profiles.

4.8 Biomass dynamics model of Shark Bay crab stock

4.8.1 Selection of catch rate data

The available time series of catch and catch rate data to which the biomass dynamics model described below could potentially be fitted were:

1) The November fishery independent trawl survey data of mature biomass for female (≥ 110 mm CW) and male crabs (≥ 105 mm CW), combined, sampled between 2002 and 2015 (excluding 2007), noting that the values of 110 and 105 equate to the estimates, derived in this study, for the L_{50} at maturity. Note, data for legal-sized crabs (≥ 135 mm) crabs were also available from these surveys but it was considered more appropriate to link the "production equation" of the Schaefer biomass dynamics model applied in this study to mature biomass (rather than legal biomass, which represents a component of the mature biomass – see discussion).

2) The commercial annual trap catch rate time series data (1989/90 to 2014/15).

Although the commercial trap catch rate data is available from 1989/90, the fishery was exploratory and thus only part of the stock was being fished during the early years. Likewise, as the fishery was expanding between 1995 and 2004, it was considered that only the commercial trap catch rates reported after 2005 could potentially represent a reliable index of abundance. As the fishery was closed in 2012 and, when the fishery was re-opened in November 2013, the management regime changed from an input (effort) controlled fishery to an output (quota) controlled fishery, the commercial trap data between 2012 and 2015 were not comparable to the commercial trap data prior to 2011. In addition, it is well known that trap catch rates are likely to be influenced by a range of other factors affecting catchability of crabs in traps, such as behaviour of crabs around traps (e.g. male-female interactions), differences in trap design, and other issues such as high-grading by fishers.

A preliminary comparison of the November trawl survey legal crab catch rates with the commercial trap catch rates for legal sized crabs in November, revealed inconsistent trends (Figure 4.11). For example, while the survey catch rates declined progressively between 2008 and 2011, the trap catch rates remained relatively steady between 2008 and 2010 and then declined precipitously in 2011. One possible explanation for this difference is due to hyper-stability of the commercial trap catch rates, i.e. associated with commercial fishers being able to maintain high catch rates for several years, despite declining overall population abundance, by targeting areas of highest crab abundance. Although commercial trapping does cover a broader area than that covered by the fishery independent trawl survey sites, as trapping extends into more inshore/shallower areas, during November, effectively all of the trap effort is focussed in the central part of Shark Bay covered by the fishery independent trawl survey sites (Harris et al. 2014, Figure. 52). This was also shown to be true for November of 2010, i.e. when the survey trawl and commercial trap catch rates became particularly divergent with a relatively high trap catch rate and very low survey trawl catch rate (Harris et al. 2014, Fig. 52). The more offshore distribution of commercial trapping in November probably reflects higher abundances of legal sized crabs in those areas at that time of year (see Figure 5.10).

Given that the commercial trap catch rates eventually declined to such a low level triggering a fishery closure, it seems highly likely that the population abundance would have been declining for some period of time prior, consistent with the trend exhibited by the November trawl survey data. Therefore, the November fishery independent survey trawl data were considered to provide the most reliable index of crab abundance in Shark Bay, and was the only time series of catch rate data to which the model was fitted.

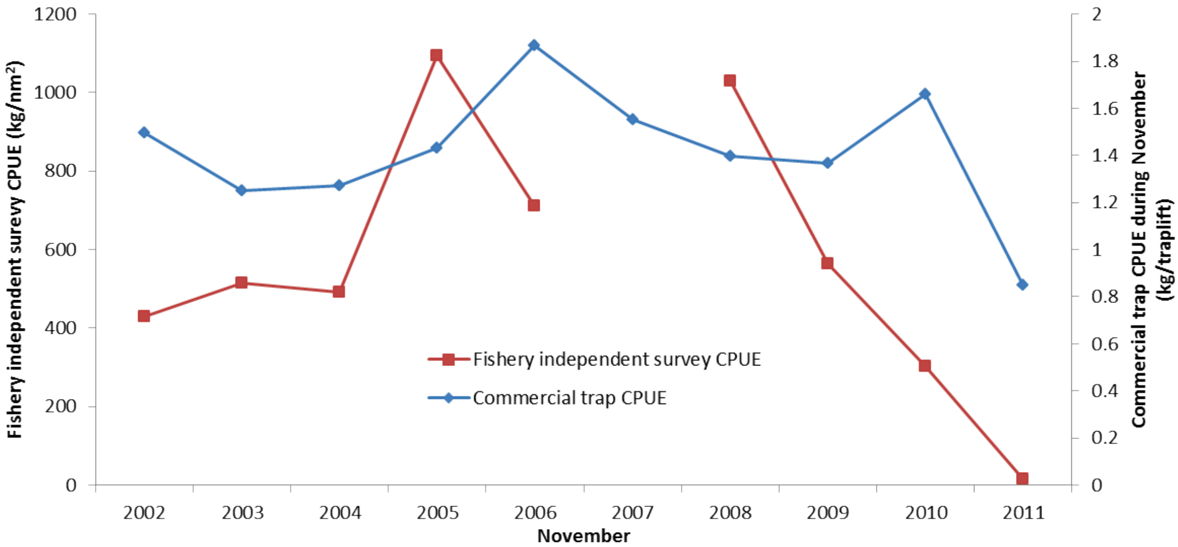


Figure 4.11. Comparison of nominal commercial trap catch rates during the month of November and the annual November trawl survey catch rates of legal sized crabs. Note that beyond 2011, the fishery was closed for 18 months and then recommenced under quota management (rather than using effort controls).

It should be noted that the sites covered by the long term November trawl survey program do not represent the full spatial coverage of the fishery. However, the fact that the majority of both the commercial trap and trawl crab catch is taken from the West CPL grounds (i.e. west of the Carnarvon Peron Line) lends support to the view that the survey data are likely to 'track' the overall Shark Bay crab population biomass (at the end of a fishing season) and, hence, provides a reliable index of abundance for this stock. From 2012 onwards, the November survey was also expanded to include new sites to the east of the CPL. As the addition of the new sites did not markedly change the catch rate values (see Figure 5.36), and as the focus of the modelling outputs are for the more recent years, the decision was made to use the full available data series for the recent period rather than continue solely with the data series based on the restricted sites.

Finally, note also that the timing of the November survey corresponds to the end/start of the fishing season, when overall crab abundance is typically at its lowest. However, as the timing is consistent from year to year, it was considered reasonable to assume that the annual trend in stock abundance in November would be consistent and proportional to the overall annual trend in stock abundance.

4.8.2 Preliminary biomass dynamics model

A preliminary biomass dynamics model (Haddon 2011) was developed for the Shark Bay crab stock. The model was fitted to the November fishery independent trawl survey data of mature-sized crabs (≥ 110 CW for females and ≥ 105 mm CW for males), to estimate the annual trend in exploitable biomass over the history of the fishery, maximum sustainable yield (*MSY*), and the likely level of stock biomass in the 2015/16 season given a specified catch for that year.

Applying the classic Schaefer (1954) production equation, B_{t+1}, is the mature biomass at the beginning of year $t+1$, and calculated as

$$B_{t+1} = B_t + rB_t\left(1 - \frac{B_t}{K}\right) - C_t$$

where B_t is the mature biomass at the start of year t, r is the intrinsic rate of population increase, K is the population carrying capacity, and C_t is the recorded catch in year t. $\hat{U}_t$, the estimated catch rate in year t, is calculated as

$$\hat{U}_t = qB_t$$

where q is the catchability coefficient, estimated as a model parameter.

Note that the biomass in the first season (1989/90) was assumed to equal *K*.

The model was fitted in AD Model Builder (ADMB) and the model parameters (*r*, *K*, and *q*) were estimated by minimising the negative log-likelihood, λ, calculated as

$$\lambda = 0.5n\log_e 2\pi + 0.5\sum_t \log_e\left(\sigma_{1,t}^2 + \sigma_2^2\right) + 0.5\sum_t \left[\left(\log_e\left(U_t\right) - \log_e\left(\hat{U}_t\right)\right)^2 / \left(\sigma_{1,t}^2 + \sigma_2^2\right)\right]$$

where U_t and $\hat{U}_t$ are the observed and expected catch rates, respectively, $\sigma_{1,t}^2$ is the variance associated with U_t, calculated outside the model, and σ_2^2 is the additional variance associated with the "model", estimated as a model parameter. An estimate of the maximum sustainable yield was calculated as

$$MSY = \frac{rK}{4}$$

Estimates of uncertainty for the model parameters, annual values of stock biomass and MSY were calculated from their asymptotic standard errors, estimated by ADMB when fitting the model.

Note that the model was fitted to annual catch rate data for mature crabs caught in the November fishery independent surveys between 2002 and 2015, and to annual catch data between the 1989/90 season and 2014/15 season (i.e. where a season starts on November 1 and ends on October 31). The model was also used to assess how different levels of future catch (0, 100, 200, 300, 400 and 450 t) would be likely to influence the level of mature biomass of crabs in the 2016/17 season (noting that 450 t is equivalent to the TACC set for the 2015/16 season).

The resultant estimates for biomass values and their associated standard deviations were produced by ADMB. A 60% confidence limits for the estimated biomass in 2016/17 were calculated using the estimated standard deviation and applying a Z-score of 0.85, where $\alpha =$ 0.4. Using a 60% confidence implies that there is an 80% probability that the actual biomass (as estimated by the model) lay above this limit.

5 Results

5.1 Estimates of size at onset of maturity (SOM)

As found by Smith et al. (2004), the mean size at maturity, CW_{50}, estimated for females using the maturity data collected by de Lestang et al. (2003a), differed depending on method of collection (Figure 5.1a-c). The estimate of CW_{50} for females from the current study (Figure 5.1d) was 110 mm CW. This estimate was 18 mm greater than the 92 mm CW estimate by de Lestang et al. (2003a) based on the combined data from trap, seine and trawl methods. This current estimate is 24 mm greater than that estimated using only trap data by Smith et al. (2004), and 14 mm greater than that estimated using seine/trawl data also by Smith et al. (2004).

The size of the smallest mature female caught in this study at 89 mm CW was also considerably larger than that recorded in the earlier study (61 mm CW). The plot for the proportion of mature female crabs in successive length categories show that the relationship between maturity and size can be described well by a logistic curve (Figure 5.1d). Comparisons of the logistic curves fitted separately to the data from the former and current study (using either the trap or seine/trawl data for the earlier study) highlight that the relationships differ substantially. The amount of maturity data available from the current study is much greater than that collected during the former study (Figure 5.1e-f). Thus, when a common curve is fitted to the maturity data from both studies and compared with the curves fitted separately to each data set, the common curve is most similar to the separate curve estimated from the current data set. The trends in proportions of ovigerous females in successive length categories were similar to those for mature females (data not shown), indicating that the size at which female crabs in Shark Bay typically attain physiological maturity is similar to that at which they first breed and become ovigerous.

Comparisons of the current and historical female maturity data involved statistically comparing four alternative models, i.e. (I) common curve for the two data sets (2 parameters), (II) separate curves with a common CW_{50} and separate CW_{95} values (3 parameters), (III) separate curves with a common CW_{95} and separate CW_{50} values (3 parameters) and (IV) separate curves with separate CW_{50} and CW_{95} values (4 parameters). The likelihood ratio tests comparing models fitted to the current maturity data with the historic trap maturity data demonstrated model IV (4 parameters) provided significantly better fits to those data than model I ($p<0.001$; 2 parameters), model II ($p<0.01$; 3 parameters) or model III ($p<0.001$; 3 parameters). Thus, the estimates for CW_{50} and CW_{95} differed significantly between the two data sets. Likelihood ratio tests comparing the current maturity data with the historic seine/trawl maturity data demonstrated that, although models I (2 parameters) and model II (3 parameters) differed significantly from the 4 parameter model ($p<0.001$ for both comparisons), model III (separate CW_{50} values and a common CW_{95} value) did not differ significantly ($p>0.05$) from the 4 parameter model. Thus, the estimates for CW_{50} but not CW_{95} differed significantly between the two studies, when using seine/trawl data for that earlier study. In summary, regardless of the data used from that earlier study (trap vs seine/trawl), the comparisons demonstrated that the mean size at which female crabs attain maturity (CW_{50}) has changed over time.

The estimate for CW_{50} of 105 mm CW, derived in this study for male crabs caught during fishery independent trawls (Figure 5.2), is also considerably higher than the value of 97 mm CW derived by de Lestang et al. (2003a) based on a combination of trap, seine and trawl data. Note that as the original raw data were not available for males from that study, it was not possible to make statistical comparisons between models fitted to the current and historic male maturity data sets.

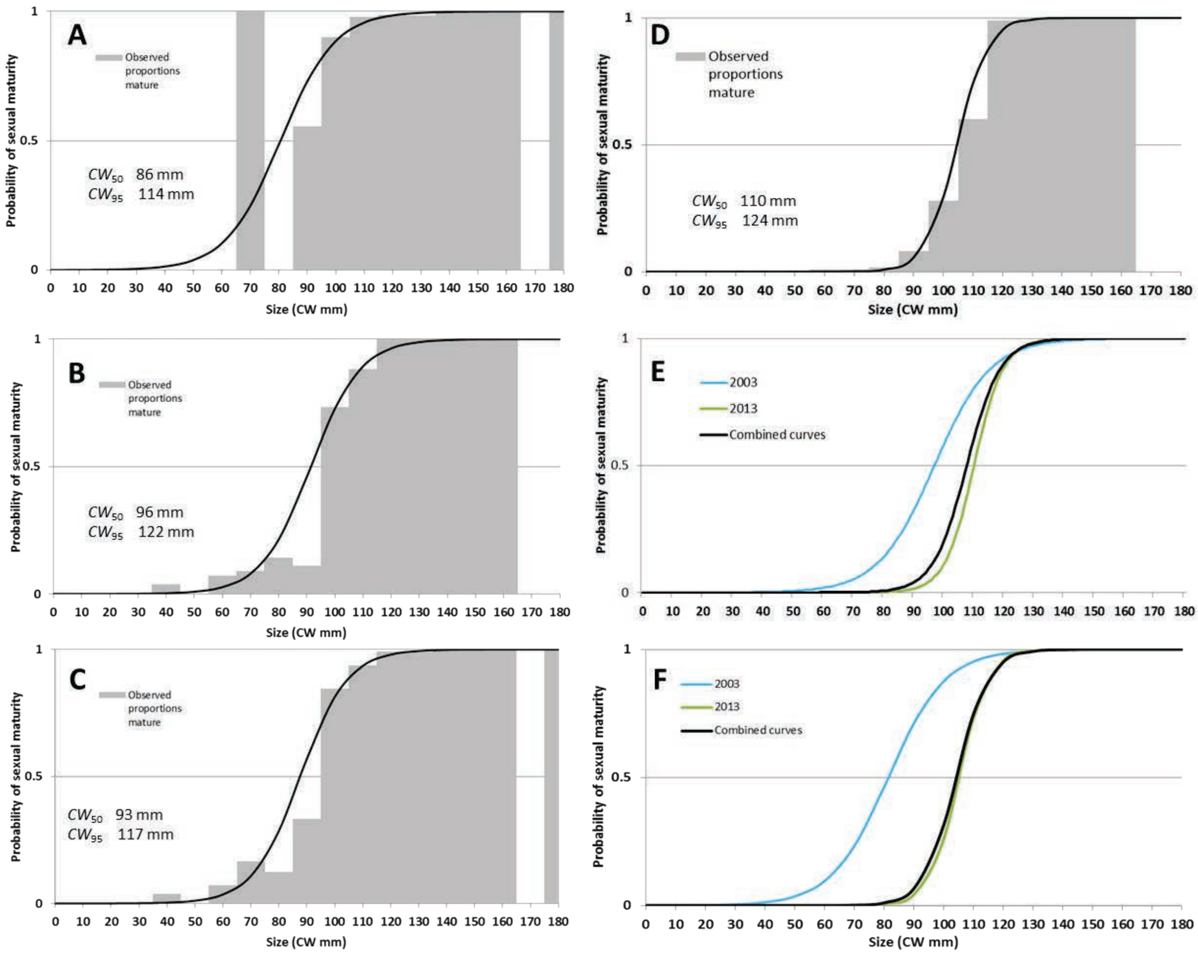


Figure 5.1. Logistic relationships between the probability of female maturity and carapace width for crabs in Shark Bay based on current data (this study) and/or historic data (de Lestang et al., 2003a), namely for (A) historic trap data (*n*=275) (B) historic seine and trawl data (*n*=257), (C) historic trap, seine and trawl data (*n*=532), (D) current fishery independent trawl data (*n*=1380), (E) historic trap vs current trawl data vs combined data and (F) historic seine/trawl vs current trawl data vs combined data. In A-D, the curves have been plotted over the observed proportions of mature females in successive length classes.

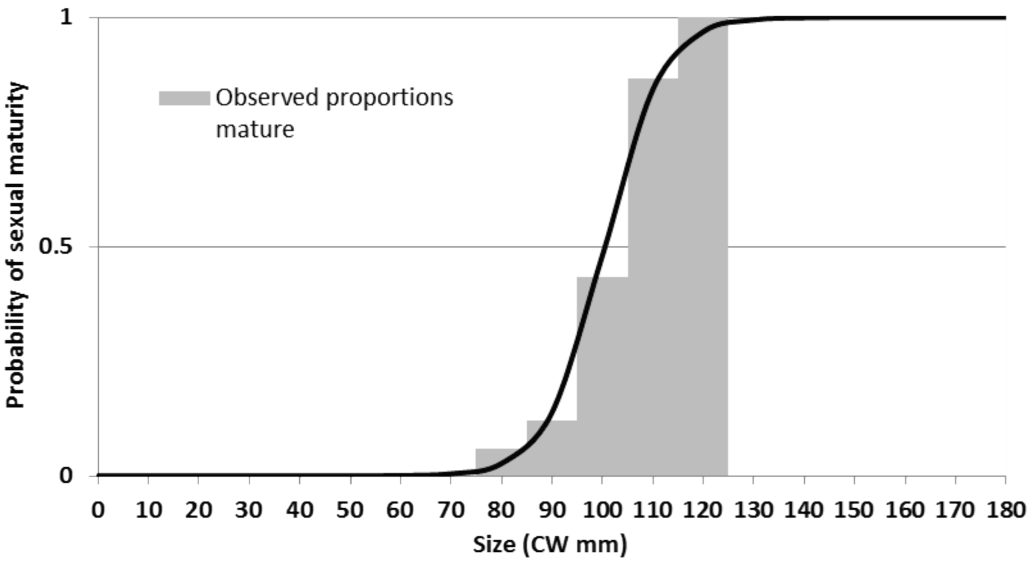


Figure 5.2. Logistic relationship between the probability of male maturity (based on external inspection of the gonads) and carapace width for crabs in Shark Bay based on fishery independent trawl data collected in this study (*n*=567). The curves have been plotted over the observed proportions of mature males in successive length classes.

5.2 Batch fecundity of *Portunus armatus* in Shark Bay

The fitted linear relationship between batch fecundity (BF) and carapace width (CW) was

$$BF = 18.38CW - 1470$$

The fitted power relationship between BF and CW was

$$BF = 0.0004595CW^{2.972}$$

The fit of the linear curve to the batch fecundity-carapace width data was marginally better (r^2 = 0.927) than that of the power curve (r^2 = 0.922) (Figure 5.3). The patterns of residuals associated with the two fitted curves were very similar (data not shown). Applying weighted least squares regression when fitting a linear relationship to the batch fecundity-carapace width data resulted in the slope of the line being slightly less than was the case when it was fitted applying unweighted least squares regression (Figure 5.4). The linear relationship fitted using weighted least squares was considered most appropriate as it takes into account the uncertainty in the means and thus this fit is described as,

$$BF = 14.78CW - 1132$$

The number of eggs per batch ranged from 306,162 for a crab 93 mm CW to 1,322,260 for a crab 150 mm CW (Fig 5.3). In general, legal-sized females (> 135 mm CW) carried 2-3 times the number of eggs of sublegal-sized females. The diameter of early Stage 1 eggs (yellow) ranged between 380 - 485 µm. For comparison, a smaller number of later Stage 3 eggs (grey) were also measured, the diameters of which ranged between 520-550 µm.

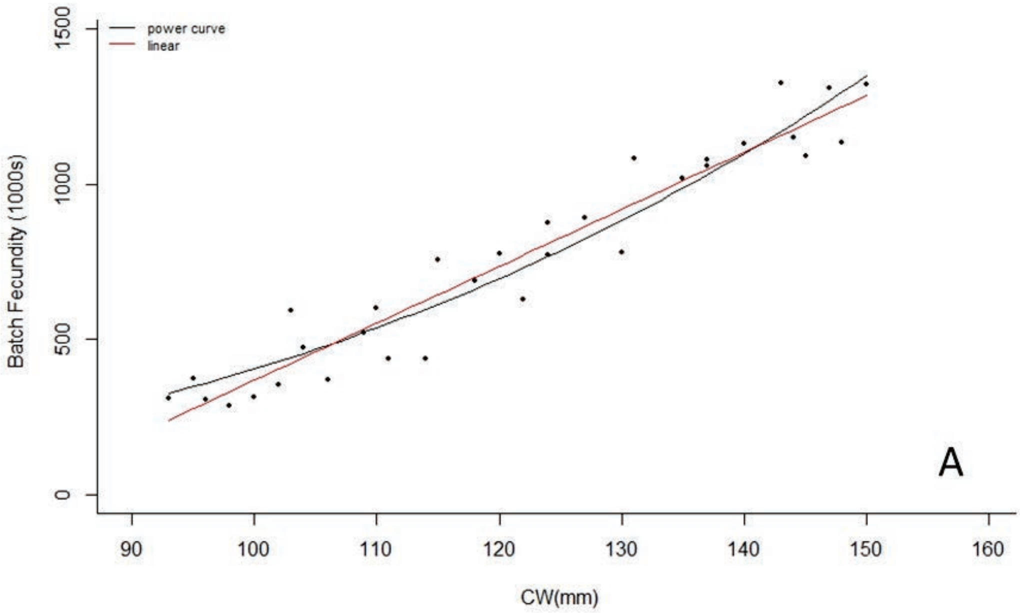


Figure 5.3. Relationships between batch fecundity and CW (mm) for 33 female crabs in Shark Bay, described by a linear regression (red line) and by a power function (black line). Note that, for this initial comparison, the relationships were derived using standard least squares regression.

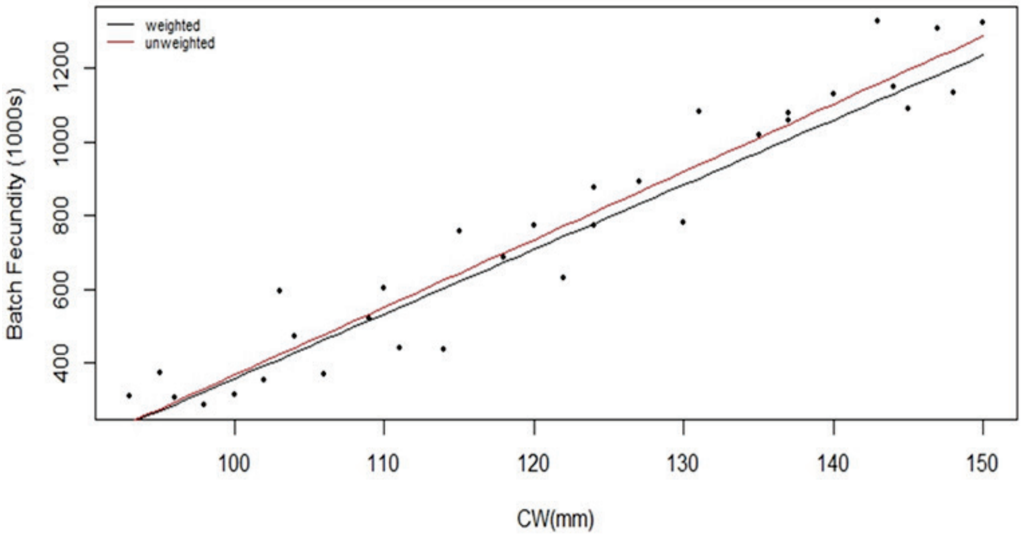


Figure 5.4. Comparison of the linear relationships between estimated batch fecundity and measured carapace width (mm) for 33 female crabs in Shark Bay fitted using weighted (black line) and unweighted (red line) least squares regression.

5.3 Annual November trawl survey program

The mean catch rates of crabs on the West CPL ground during November have varied between 2637 and 12879 crabs/nm^2 between 2002 and 2010 and declined below 500 crabs/nm^2 during 2012 and 2013. Catch rates have since increased and remain between 3000 to 4000 crabs/ nm^2 in the last two years of the current stock recovery phase (Figure 5.5).

The time series of LF data show a shift in the model classes in the years before and after the heat wave (Figure 5.6). Prior to November 2011, a single cohort of crabs with a modal range of approx. 130-135mm CW was present on the West CPL ground where there was equal proportions of sublegal and legal sized crabs and a high proportion of berried females. Both 12 (2011) and 24 (2012) months after the heat wave, there was low abundance of all sized crabs. The catch composition of the crabs during the recovery phase has been highly variable, with a high abundance of crabs during 2013 dominated by sublegal crabs, followed by a bi-modal distribution in the catches observed during 2014 and catches during November 2015 distribution profile most similar to 2010. One notable difference in the LF distributions for the recovery phase has been the lower catch rates of berried females compared to historical years (Figure 5.6).

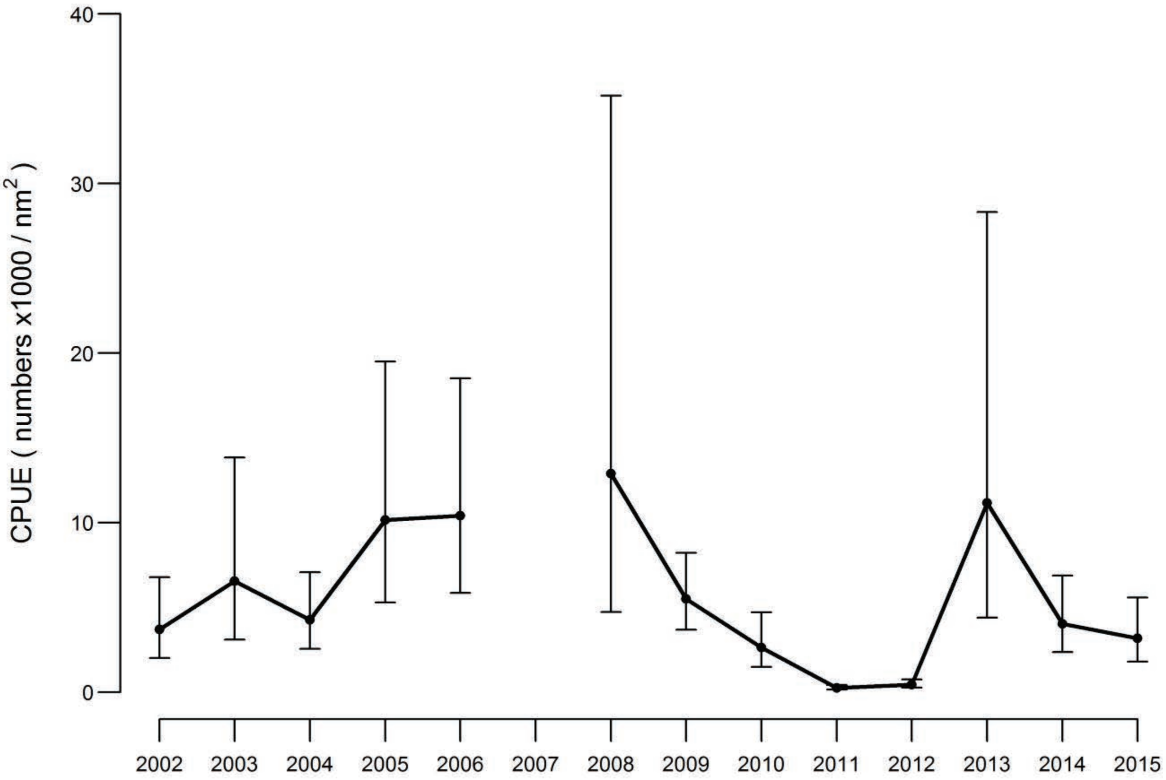


Figure 5.5. Standardised mean (± 95%CI) catch rate of all crabs captured during the November fishery independent surveys on the West CPL grounds (the non-coloured and orange coloured sites from West CPL, see Figure 4.4) between April 2002 and 2015. The 2007 survey was excluded as catch data was compromised by severe weather conditions and incomplete sampling.

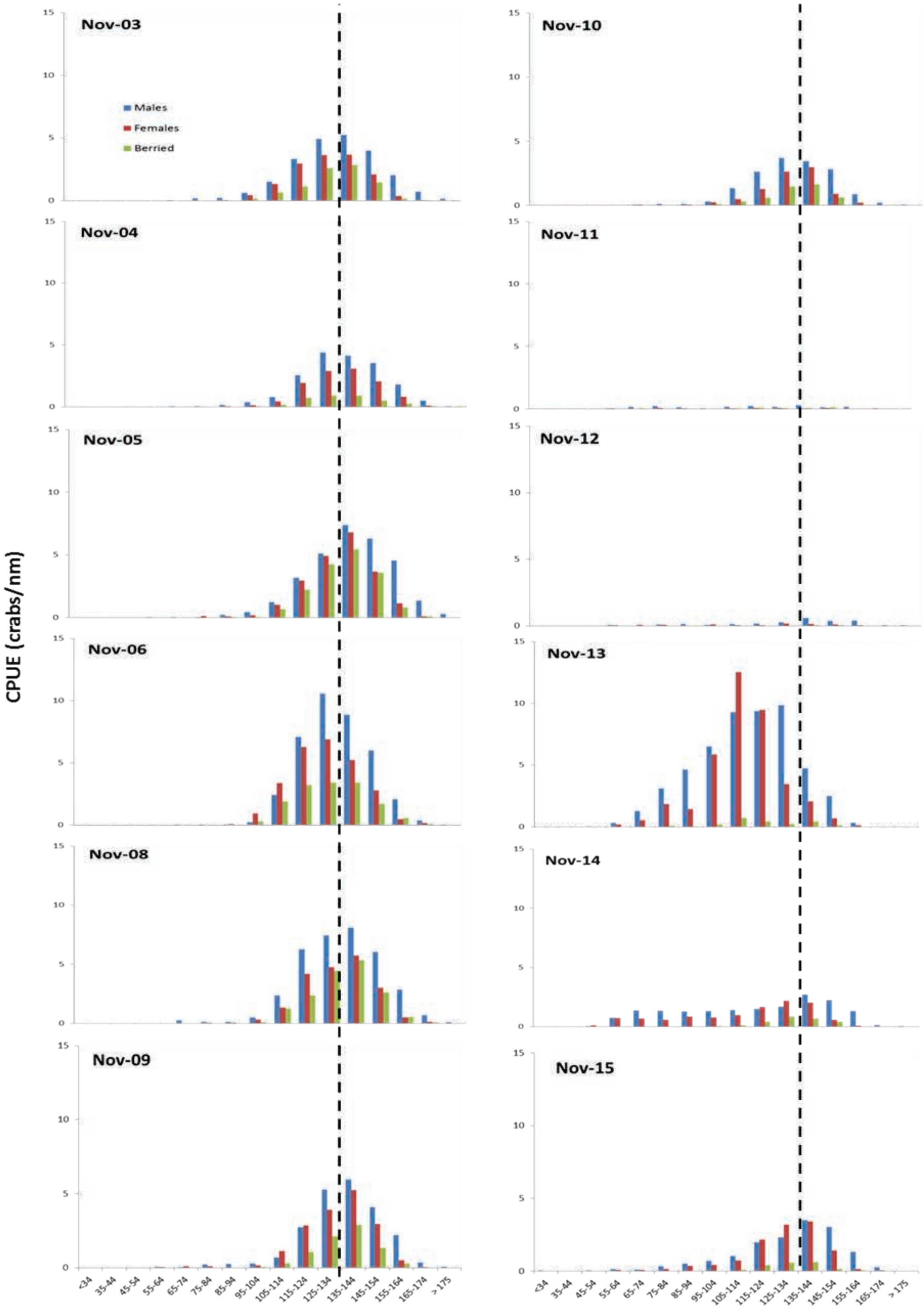


Figure 5.6. Length frequency of trawl captured crabs (crabs/nm) on the West CPL fishing grounds during the annual November Shark Bay surveys between 2003 and 2015 (excluding 2007). Vertical broken line indicates legal size limit of 135 mm CW.

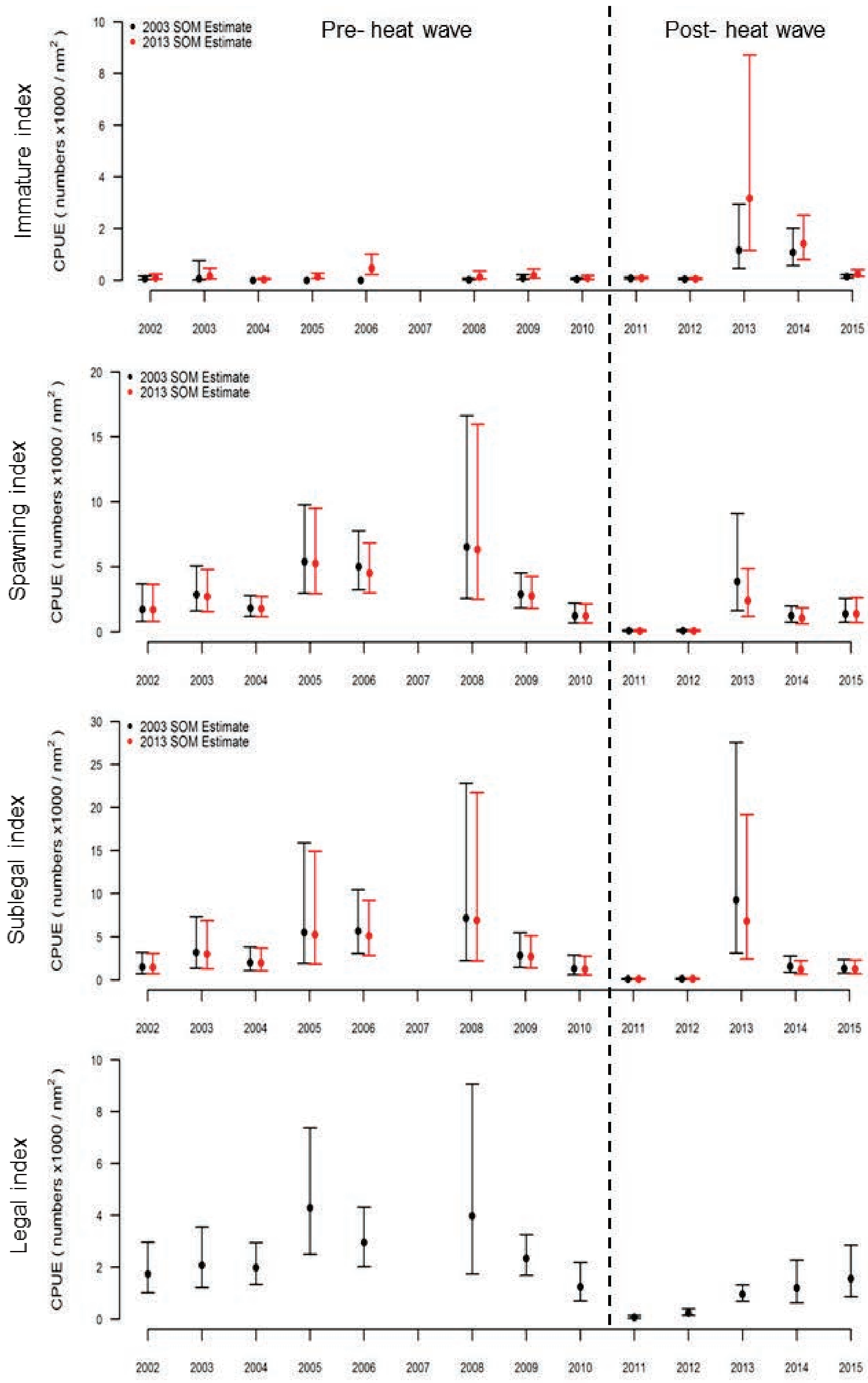


Figure 5.7. Standardised mean catch rates (± 95%CI) of spawning (mature females), immature, sublegal and legal, and biomass (based on 2003 and 2013 SOM estimates) derived from the annual November trawl survey dataset (between 2002 and 2015, excluding 2007) on the West CPL fishing grounds. The dotted line separates the pre and post-heat wave years.

Catch rates of spawning, sublegal and immature biomass did not differ markedly for the differing SOM estimates on which they were based (Figure 5.7). Catch rates of immature crabs, which represent juvenile recruitment, were very low across all the years except during 2013 and 2014. Trends in the sublegal and spawning catch rates were very similar, both showing a recovery during 2013 but catch rates remain within the lower range of the pre-heat wave years for 2014 and 2015. Catch rates of legal crabs on the West CPL grounds are most representative of the residual biomass after a 12 month fishing season. When commercial fishing resumed in November 2013, catch rates had increased from the low levels in 2011 and 2012 and within the historic range, and has increased further during 2014 and 2015 (Figure 5.7).

5.4 Fishery independent (expanded) crab trawl survey program

The expansion of the fishery independent trawl survey program to cover fishing grounds to the east of the CPL and additional survey periods during February, April and June, provided seasonal and temporal patterns in crab abundance and distribution as well as information relating to peak recruitment and spawning periods.

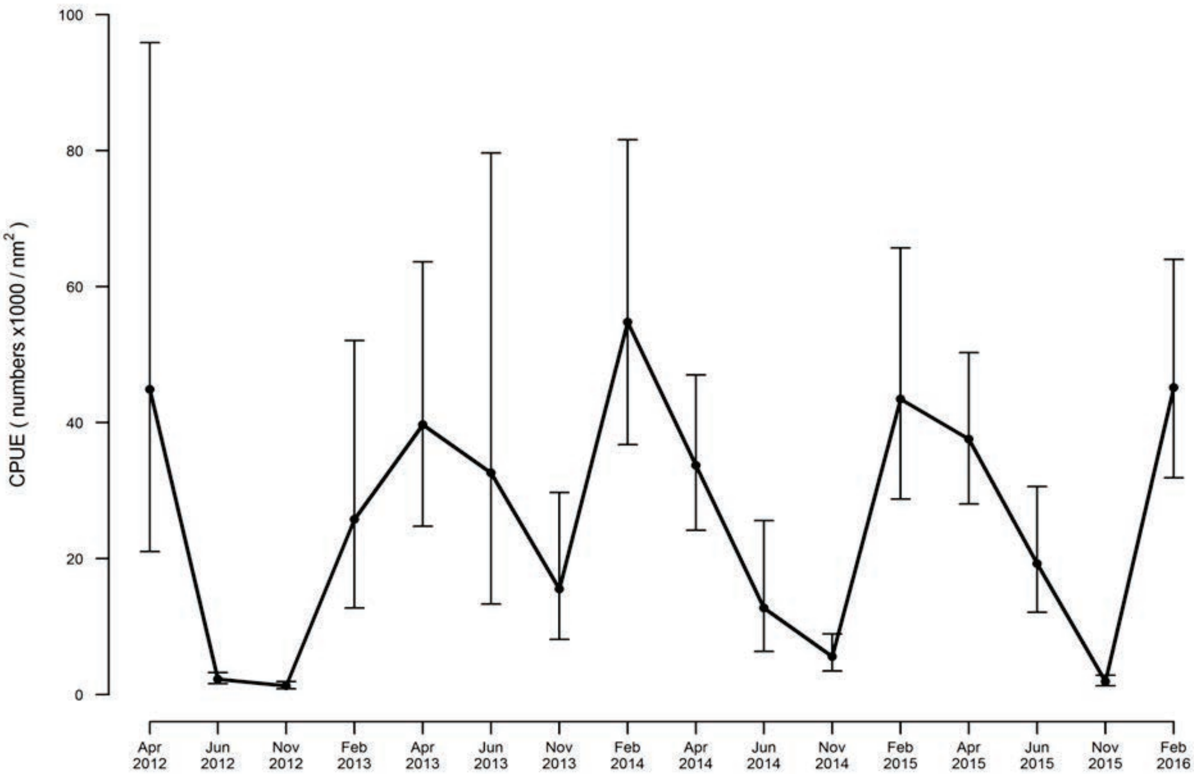


Figure 5.8. Standardised mean (± 95% CI) catch rates of crabs captured from fishery independent crab trawl surveys (coloured sites from West CPL, North CPL, Central CPL, South CPL and East Peron Nursery grounds, see Figure 4.4) between April 2012 and February 2016.

Seasonal trends in mean catch rates of crabs showed the highest abundance of crabs occurred in February or April between 2012 and 2016 with lower abundances during June, and the lowest during the November survey (Figure 5.8). The 95% confidence limits associated with the estimated mean value for catch rate were often very broad, particularly in those months when overall abundance was high. In such months, the abundance of crabs differed considerably among sites with, on occasion, their numbers at adjacent sites differing by up to 5000 individuals. In regards to the spatial distribution of crab abundance, crabs were found across all of the sites sampled in each of the four survey periods but at differing densities (Figure 5.10). During November, when the abundance of crabs is the lowest overall, their distribution was more on the West CPL and sites on the central region of the Bay. A few months later during February when the crab abundance is usually at its highest, their distribution switches more to the to the grounds to the central Bay region and East of the CPL (Figure 5.10)

The sex ratio of the sampled catch also followed a seasonal pattern with males always being the most abundant in November (> 50%) and then decreasing progressively in February, April and June, when females were always most abundant (Figure 5.9). This trend was observed throughout the fishery closure period and also when fishing resumed in 2013. Male domination of the catch was also observed in the long term November data series. The 95% confidence limits for the calculated sex ratios are very small, and thus the survey data provide precise information on the sex ratios of crabs caught by trawling at different times of the year.

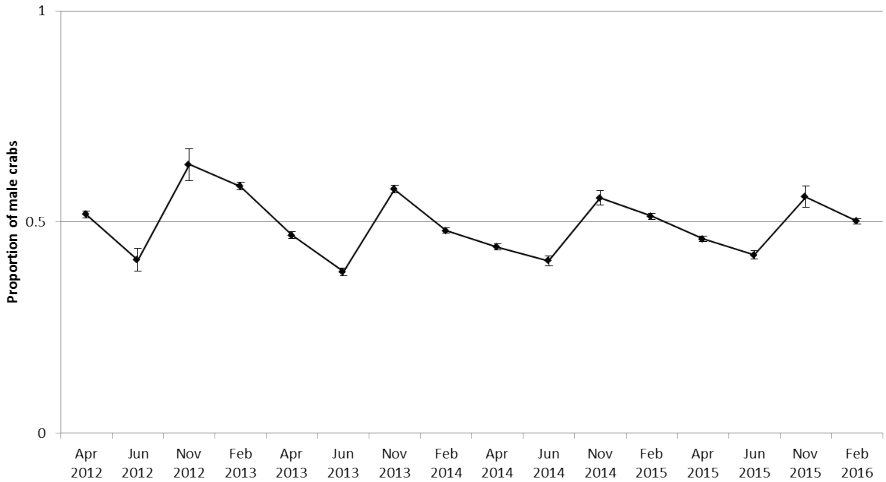


Figure 5.9. Proportion (±95% CI) of male crabs from fishery independent crab trawl surveys between April 2012 and February 2016.

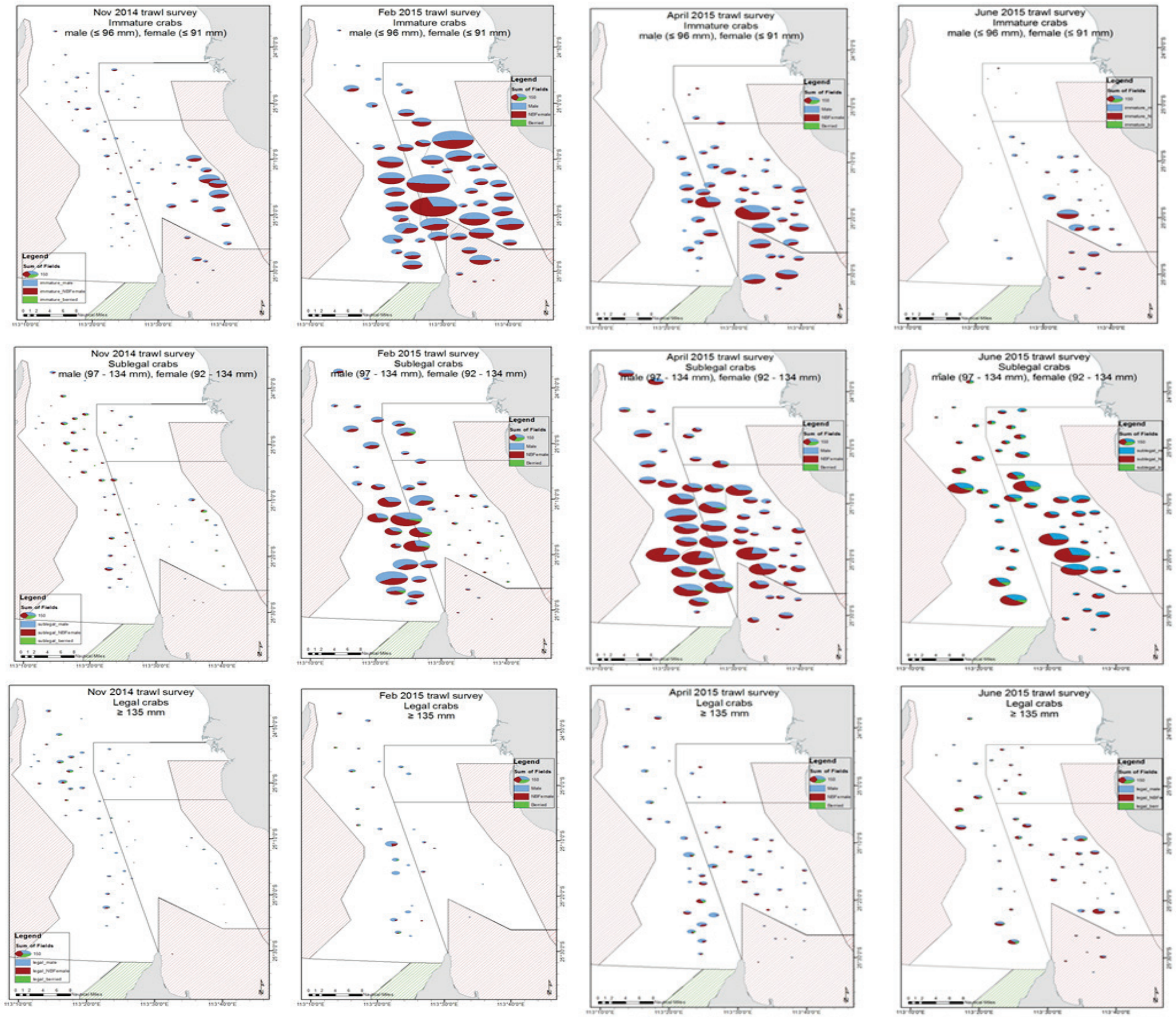


Figure 5.10. Seasonal trends in the spatial distributions of the catch rate of immature (top), sublegal (middle) and legal-sized crabs (bottom) during November 2014 (left) and February 2015 (right). Blue - males, red - females and green - berried females.

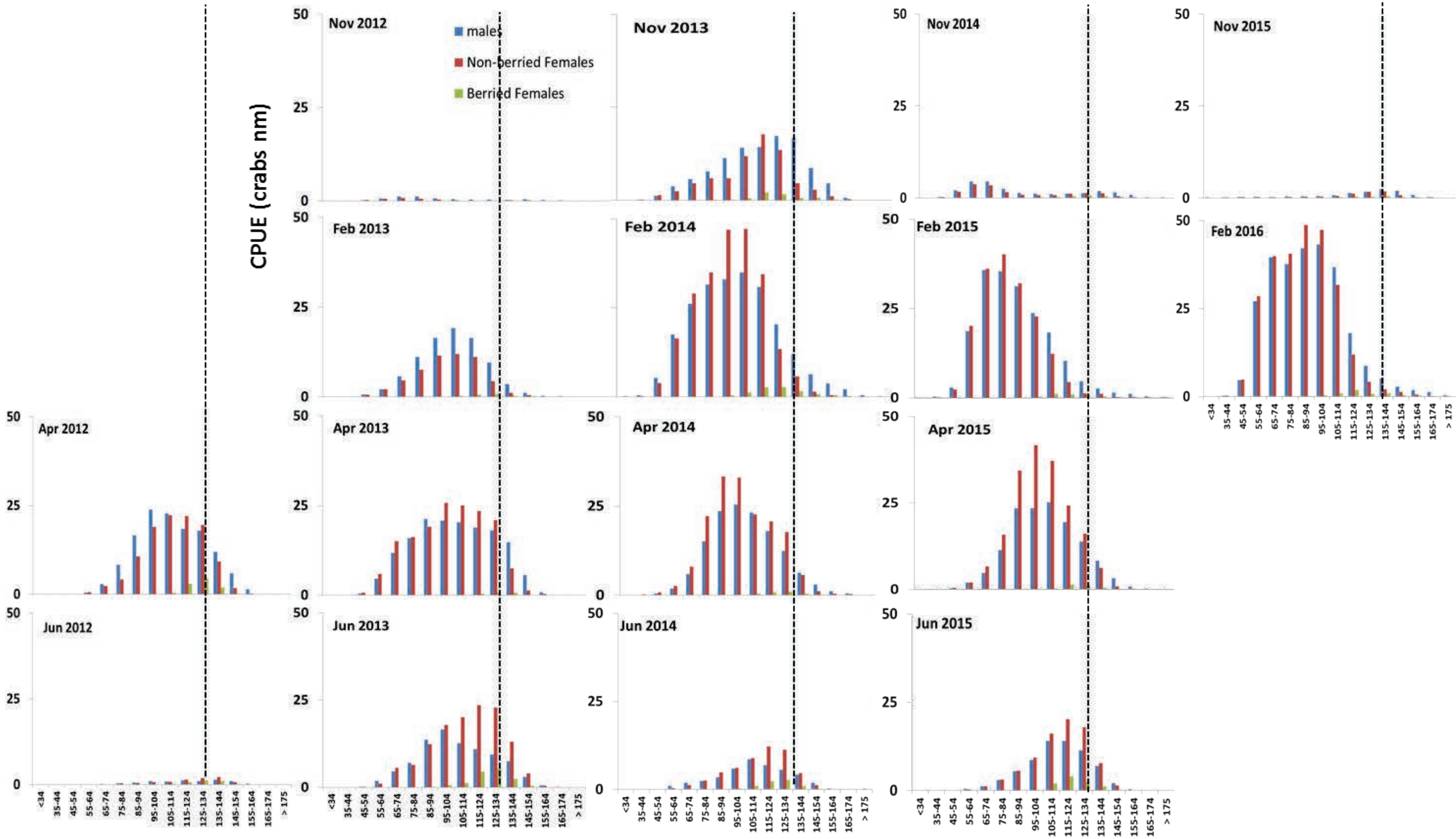


Figure 5.11. Length frequency distributions (mm CW) of trawl captured crabs between November 2012 and February 2016 across all survey sites during the fishery-independent crab trawl surveys indicated on Figure 4.4. Broken vertical line indicates the legal (commercial) size limit of 135 mm CW.

The length frequency (LF) distributions of the sampled catch from these surveys (Figure 5.11), are predominantly represented by a single cohort, although two cohorts representing 0^+ and 1^+ aged crabs were observed during November 2014. Due to the rapid growth of crabs during their first year of life, the single modal class is present and this is most likely a mixture of crabs from different spawning periods but also crabs of differing growth rates. Across all months, approximately 80% of the catch is dominated by sublegal sized crabs (< 135 mm CW) but crabs of sizes from 29 to 200 mm CW were sampled from these trawl surveys. One way to separate these age classes is to use their size of maturity as cut-offs to assess catch rates of juveniles, sublegal and legal sizes crabs. These are described in detail below.

5.4.1 Immature crab biomass

Immature crabs from 29 mm CW were captured during all four surveys periods although the peak catch rates generally occurred during the February survey (Figure 5.12), and catch rates gradually decrease towards November. The very large 95% CI around these catch rates indicate the large site variation in abundance. Immature crabs were captured across all the survey sites in Shark Bay, but the East Peron Nursery, South CPL and Central CPL grounds consistently recorded the highest catches (Figure 5.10). These sites are also adjacent to the extensive inshore seagrass habitats on the eastern side of the Bay where juvenile crabs are thought to recruit from. Immature crabs captured on the West CPL grounds maybe recruiting from seagrass habitats on the western regions of the Bay but this is difficult to confirm with the current survey design/limitations.

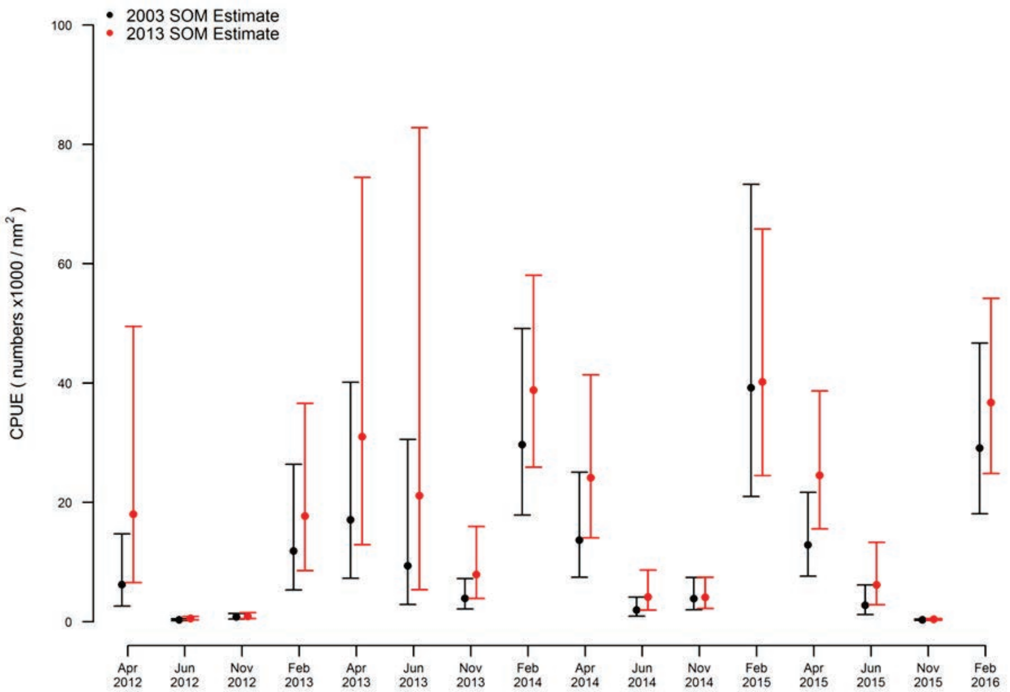


Figure 5.12. Standardised mean (± 95% CI) catch rate of immature crabs based on the 2003 SOM estimates (females < 92 mm and males < 95 mm CW) and 2013 SOM estimates (females < 110 mm and males < 105 mm CW) from the fishery independent crab trawl surveys program between April 2012 and February 2016.

5.4.2 Sublegal crab biomass

A large proportion of the catch composition was made up of sublegal sized crabs. Catch rates of sublegal crabs increase from November and usually peak during April. Catch rates based on the new SOM estimates were slightly lower than 2003 SOM estimates due to the size of maturity estimates being increased by approximately 20 mm (Figure 5.13). The LF distributions show a shift in the modal size range from 75-95 mm CW during February to 95-114 mm CW during April for males and females (Figure 5.11). Between April and June, the modal size range increases to 115-135 mm CW and this may also be moult associated given the approach of the mating season in the following months.

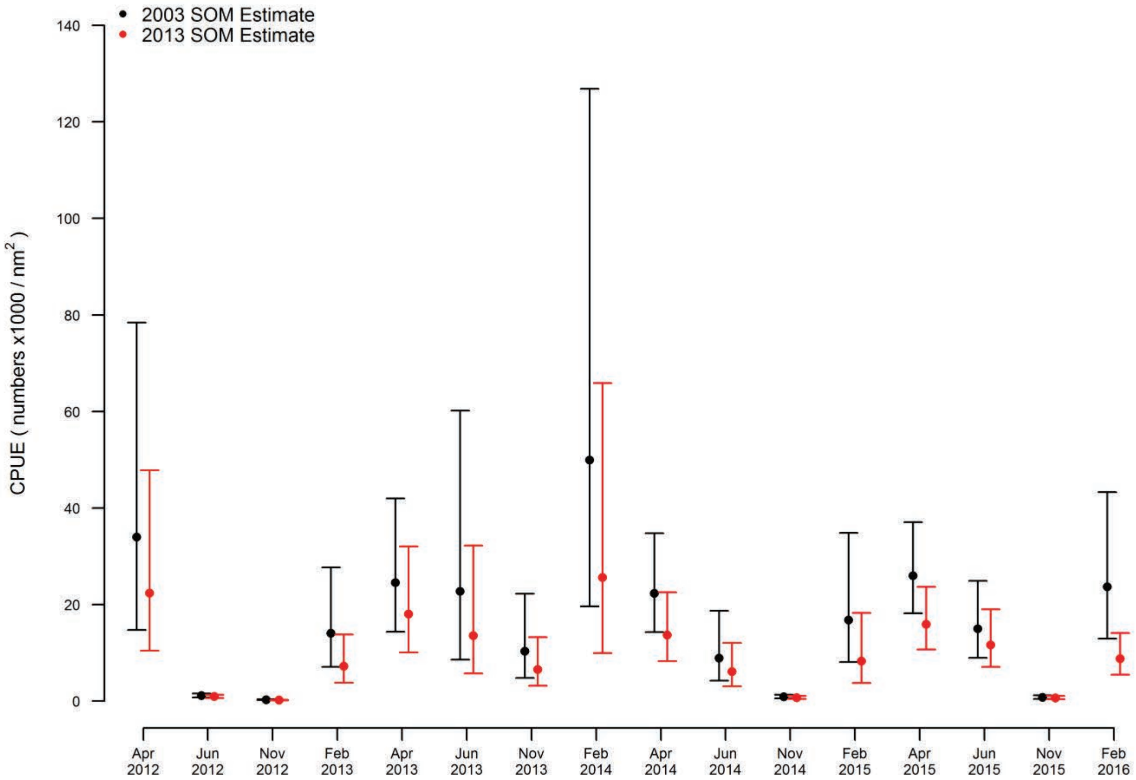


Figure 5.13. Standardised mean (± 95% CI) catch rate of sublegal sized crabs according to the 2003 SOM estimates (97≤ males < 135mm; 92 ≤ females < 135 mm CW) and 2013 SOM estimates (105≤ males < 135mm; 110 ≤ females < 135 mm CW) from the fishery independent crab trawl surveys program between April 2012 and February 2016.

5.4.3 Berried females

Ovigerous (berried) females were captured during all four trawl survey months with the lowest catch rates during November and highest catch rates usually in June, although high catch rates did occur during April and sometimes in February (Figure 5.14). The proportion of ovigerous females (of all stages) were generally less than 5% (as a % of all females captured) during February and April and increased to 10% during June and November (excluding June 2012) (Figure 5.15a). In contrast, the annual November fishery independent trawl survey program undertaken on the West CPL grounds shows a slightly different trend. Between 2002 and 2011, the proportion of ovigerous females have ranged between 20 to 50%, which is markedly higher than 2–20% observed during post-heat wave years since 2012 (Figure 5.15b). Berried females generally ranged from approximately 90 to 160 mm CW with modal class values of 125-135 mm CW. Approximately 22% of berried females are legal sized and the majority (78%) of berried females were sublegal sized females. Ovigerous females were captured across all the survey sites, but generally in highest abundances in the central regions of Shark Bay, particularly from survey sites adjacent to the CPL which are the deepest regions of the Bay with sandy substrates which females require for successful egg extrusion (Sumpton et al. 1994).

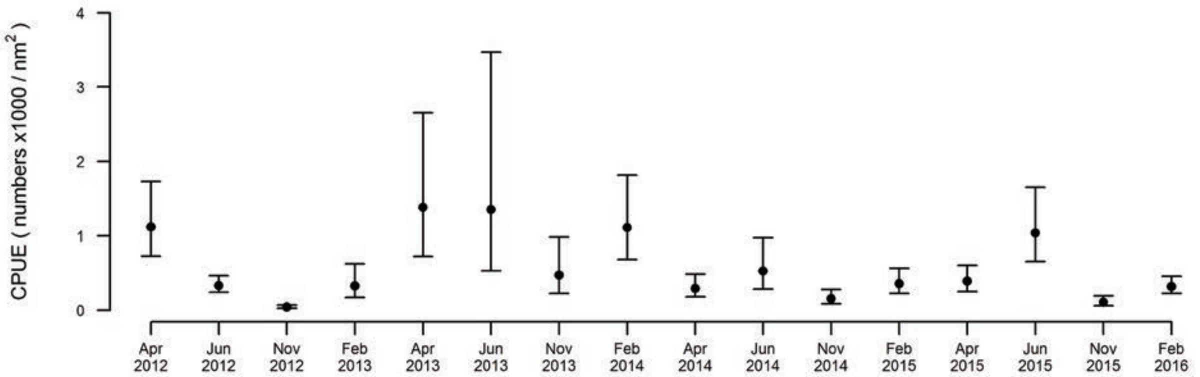


Figure 5.14. Standardised mean (± 95% CI) catch rate of berried female crabs from the fishery independent crab trawl surveys program between April 2012 and February 2016.

5.4.4 Spawning biomass

Seasonal trends in the spawning (mature females) catch rates show the lowest catches rates during November and the highest/peak catch rates during April and/or June (Figure 5.16). Given the catch rates of berried females usually peak during the June survey, the June spawning is considered to provide the most appropriate estimates of peak spawning biomass levels in Shark Bay while noting that lower levels of spawning does occur in other months. Given peak recruitment is during the February survey, approximately 7-8 months later, this further supports the cooler months in Shark Bay as the main spawning period.

The lowest spawning catch rate was during June 2012 at 200 kg/nm^2 and this increased to 1789 kg/nm^2 during June 2013 while the fishery was closed for stock recovery. Peak spawning catch rates have remained below this level for the 2014 (592 kg/nm^2) and 2015 (1394 kg/nm^2).

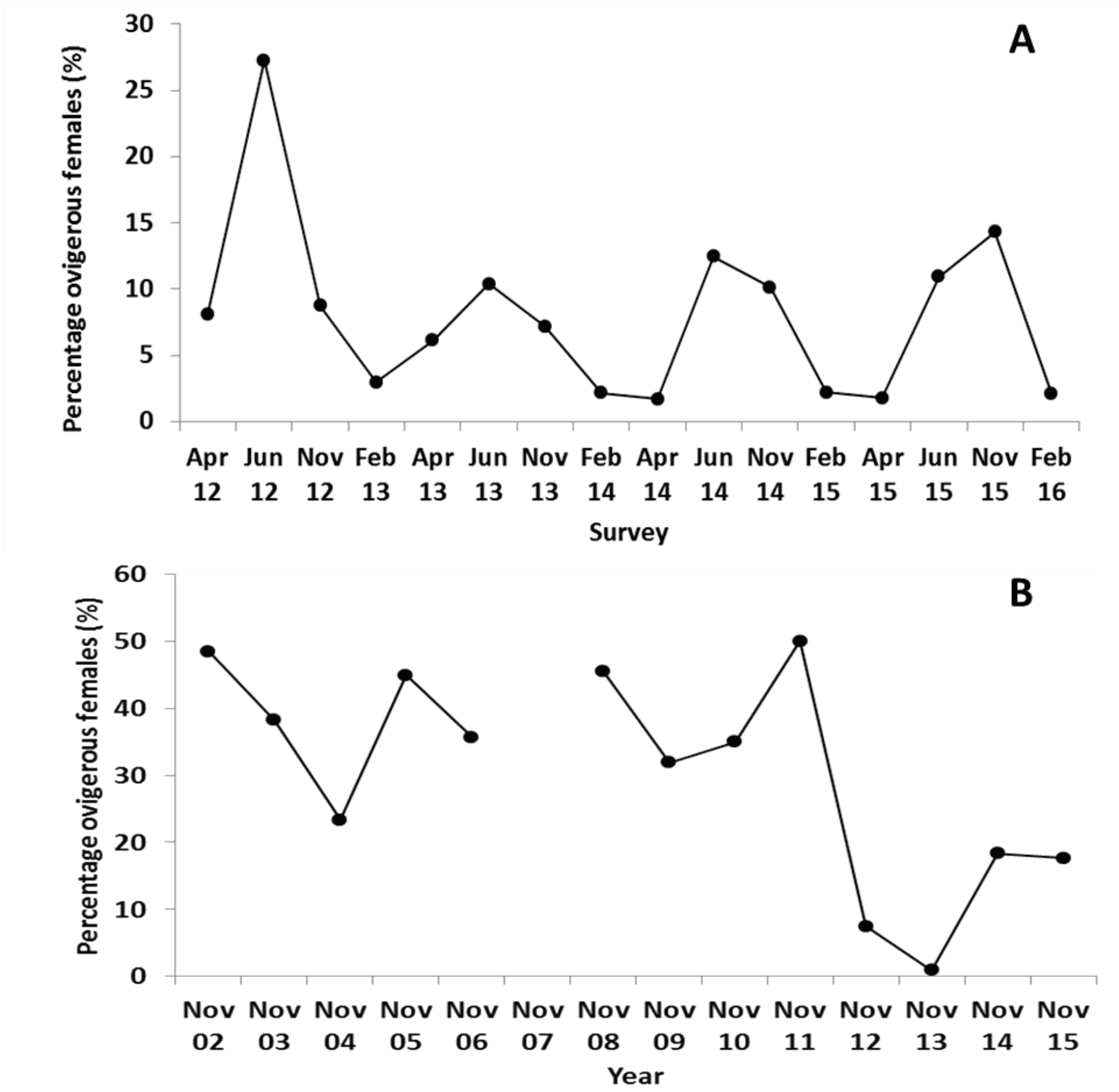


Figure 5.15. Percentage of ovigerous females from the (A) fishery independent crab trawl survey program between April 2012 and February 2015 and from the (B) annual November trawl surveys on West CPL grounds only.

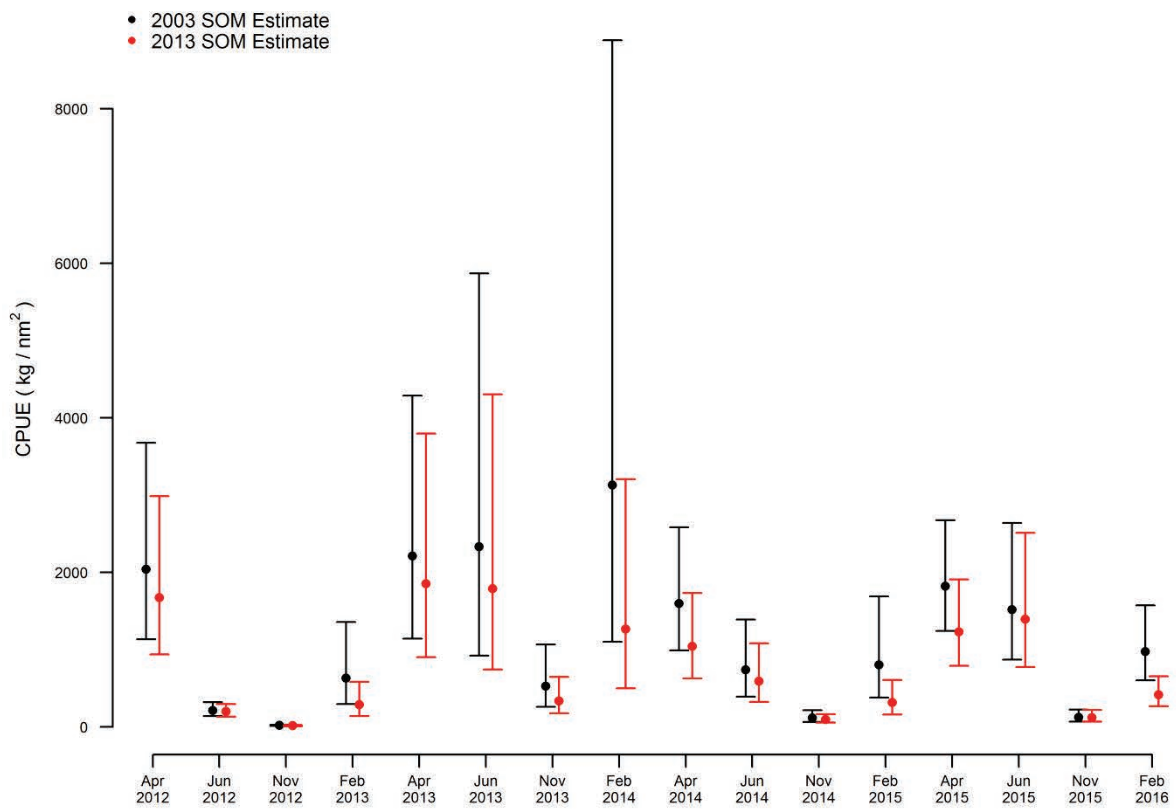


Figure 5.16. Standardised mean (± 95% CI) catch rate of spawning crabs (mature females) according to the 2003 SOM estimates (92 mm CW ≤ females) and 2013 SOM estimates (110 mm CW ≤ females) from the fishery independent crab trawl surveys program between April 2012 and February 2016.

5.4.5 Legal crab biomass

Catch rates of legal crabs are usually highest during April and June and lowest during November, although there are annual variations due to different rates of depletion and recruitment into this size class (Figure 5.17). When commercial fishing resumed in November 2013, approximately 371 tonnes (TACC of 400 tonnes) of legal sized crabs were harvested in the following 12 months and legal catch rates declined from 2 386 crab/nm^2 (February 2014) to 563 crab/nm^2 (November 2014). During the following season when approximately 341 tonnes were harvested, catch rates declined from 2 146 crab/nm^2 during April 2014 to 780 crab/nm^2 during November 2015 (Figure 5.17). Legal sized crabs were found evenly distributed across all the survey regions with no distinct seasonal or spatial trends (Figure 5.10), and this may reflect the highly mobile nature of the larger adult crabs. They represent the lowest proportion of the all the size classes but are also subject to fishing mortality and likely higher natural mortality.

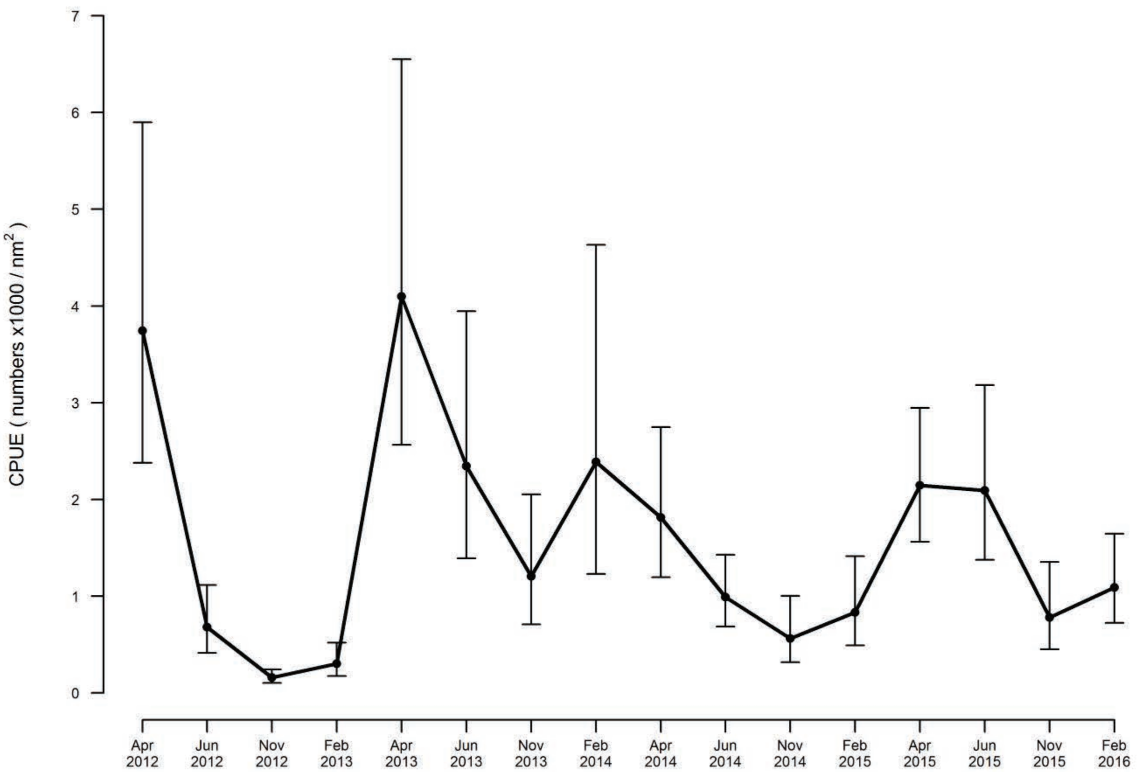


Figure 5.17. Standardised mean (± 95%CI) catch rate of legal sized crabs (≥ 135 mm CW) from the dedicated crab trawl survey program between April 2012 and June 2015. Note the resumption of commercial fishing from November 2013 onwards.

5.5 Modelling the growth of *Portunus armatus* in Shark Bay

Overall, the length frequency data exhibit very similar trends for the two sexes. For both sexes, the length-frequency data collected in November show prominent, but overlapping modes where the smaller of the two modes peaks at ~ 70 mm CW, whereas the larger mode peaks at about 120 mm CW (Figure 5.18, Figure 5.19). Although the length-frequency plots for February, April and June appear to be represented by two modes, these are largely overlapping and thus not very distinct.

The parameters estimated by the model describing the relative proportions of the two cohorts indicate that, for males, the 0^+ cohort was most abundant in the trawl catch in all months except during November, when the abundance of 1^+ crabs was greater (55%) (*cf* Table 2; Figure 5.19). For females, the trends differed in that the 0^+ cohort dominated the trawl catch (≥ 62%) only in February and April, whereas the 1^+ cohort was most abundant in June and November (≥ 59%) (*cf* Table 2; Figure 5.18).

The similarity in the length frequency plots for the two sexes (Figure 5.18, Figure 5.19) is paralleled in the similarity of the estimated growth curves for females and males (Figure 5.19). The estimated values for the standard deviation associated with the growth curves for both females and males were relatively large (Table 2), reflecting the substantial variation in lengths within each cohort. This is also shown, for example, in the fact that the estimates for the mean length at age 2 years (i.e. the assumed maximum age of crabs in the sample (121 mm CW for females and 128 mm CW for males) are well below the observed maximum carapace widths in the samples (175 mm CW for females and 190 mm CW for males).

The sex-specific seasonal growth curves provided good visual fits to the length-frequency data collected for each sex, particularly in February and November (Figure 5.18, Figure 5.19). According to the growth model, the mean lengths of the 0^+ and 1^+ cohorts in November were 73 mm CW (4 months old) and 122 mm CW (16 months old), respectively, for males, and 70 mm CW (5 months old) and 115 mm CW (16 months old) respectively, for females (Figure 5.20). By February, the mean length of the 0^+ and 1^+ cohort had increased to 88 and 124 mm CW (i.e. 8 and 20 months), respectively for males and 87 and 119 mm, respectively for females. The sizes of the two cohorts of crabs of each sex in April and June had only increased marginally (~ 2-3 mm).

When the model is fitted, the curves fitted to the length frequency data essentially describe the probability that a crab, at a specified length, belongs to either the 0^+ or 1^+ cohort at a particular time of year. Thus, to visualise the likely spread of lengths-at-age, random numbers were used to assign each crab a putative age, based on the assumed birth date (for all crabs of August 1), its date of capture and its probability of belonging to the 0^+ and 1^+ cohorts given its length (i.e. as estimated by the model). As is evident from the plots and consistent with the length-frequency distributions, there is a large degree of overlap in the sizes of 0^+ and 1^+ crabs (Figure 5.21).

Both the seasonal curves and instantaneous growth rates indicate that, at least during the period of data collection, growth began to increase when water temperatures were declining (April/May) and was most rapid when water temperatures were at their minima (July/August). Growth began to decline when water temperatures started increasing (August/September) and was very minimal when water temperatures at their maxima (February/March) (Figure 5.20-Figure 5.22). On average, throughout each year in 2010-2014, water temperatures (SSTs) ranged between ~21-26 °C (Figure 5.22). The instantaneous rate of growth, as would be expected, was most rapid early in life (Figure 5.20- Figure 5.22).

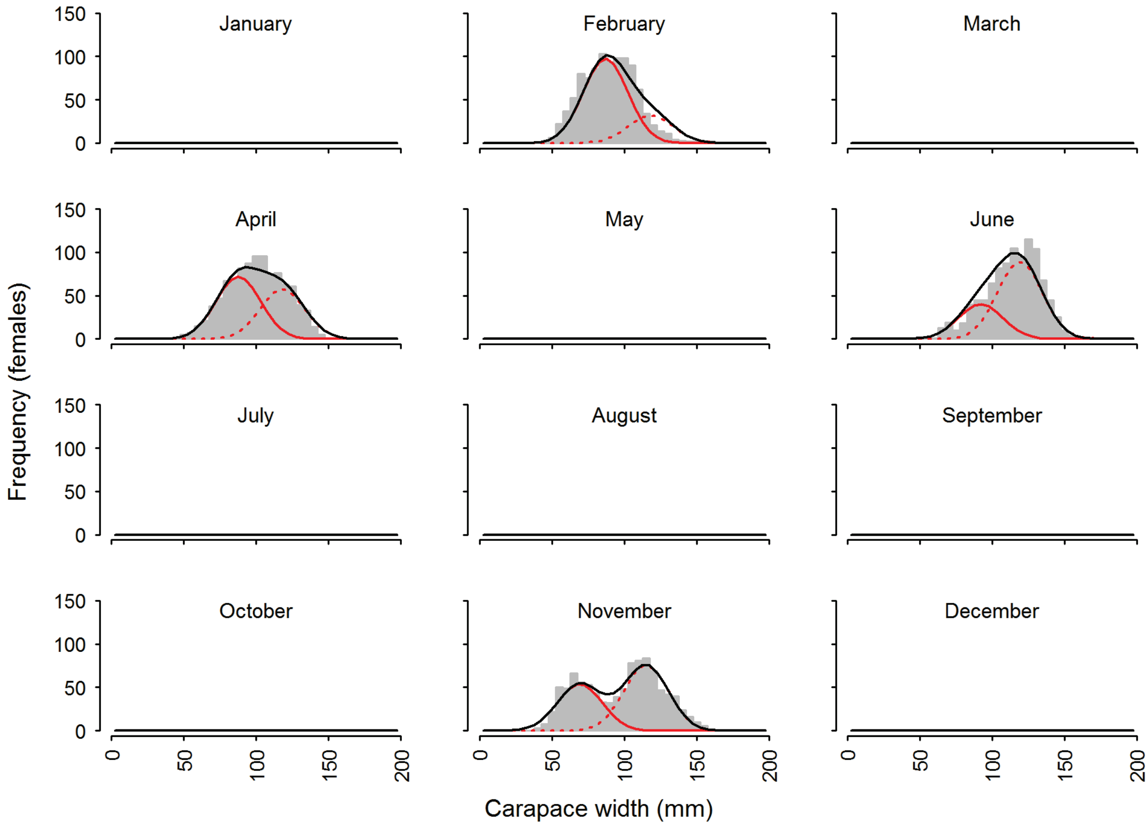


Figure 5.18. Observed monthly length-frequency distributions for female blue swimmer crabs in Shark Bay (grey bars). The expected monthly distributions for 0^+ (solid red lines) and 1^+ year old (dotted red lines) females are derived by fitting a seasonal growth curve to the observed length-frequency data. The overall fits of the model to the monthly distributions (i.e. combined expected distributions for the two cohorts are also shown (black lines).

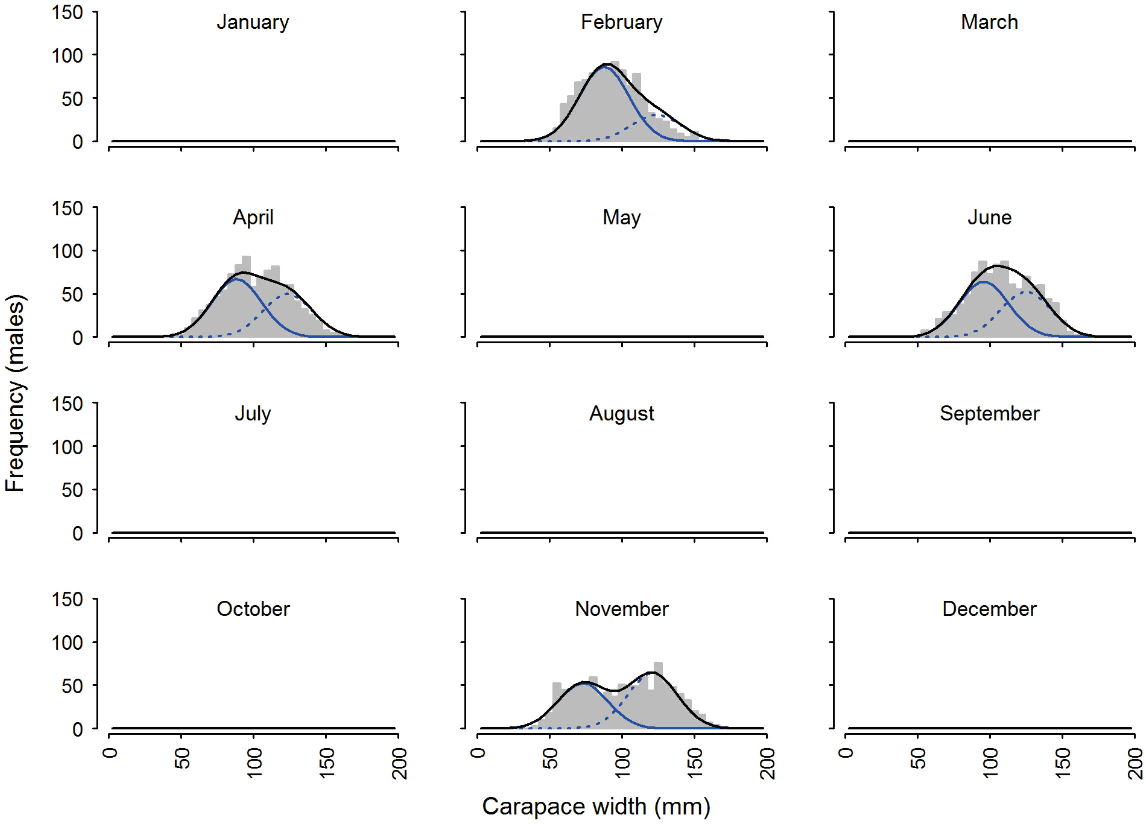


Figure 5.19. Observed monthly length-frequency distributions for male blue swimmer crabs in Shark Bay (grey bars). The expected monthly distributions for 0^+ (solid blue lines) and 1^+ year old (dotted blue lines) males are derived by fitting a seasonal growth curve to the observed length-frequency data. The overall fits of the model to the monthly distributions (i.e. combined expected distributions for the two cohorts are also shown (black lines).

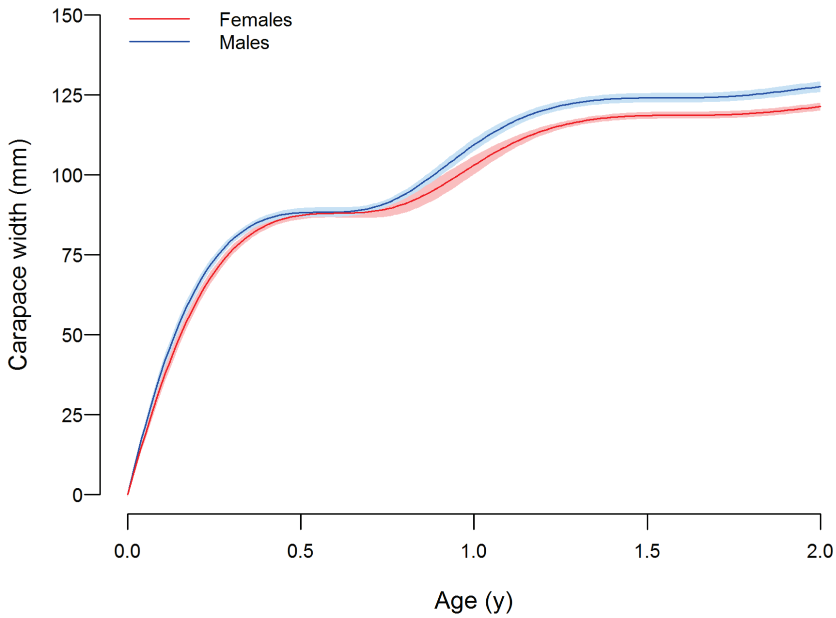


Figure 5.20. Seasonal growth curves for female and male (± 95% CI) blue swimmer crabs in Shark Bay.

Table 2. Estimates of the parameters (and associated 95% CL) of the seasonal growth model fitted to length-frequency data for blue swimmer crabs in Shark Bay. $\boldsymbol{CW_{\infty}}$, mean asymptotic carapace width; $\boldsymbol{k}$, von Bertalanffy growth coefficient, $\boldsymbol{t_0}$, hypothetical age at length zero, $\boldsymbol{C}$ and $\boldsymbol{t_c}$ parameters associated with seasonality in growth rate; $\boldsymbol{\sigma}$, common standard deviation for the lengths in all cohorts; $\boldsymbol{\phi_{0+}}$, parameters defining the proportion of crabs belonging to the 0^+ and 1^+ age cohorts, in months (m) for which there are length-frequency data. *NLL*, negative log-likelihood; *n*, overall sample size, *i.e.* number of crabs.

Parameter	***MALES***			***FEMALES***		
	Estimate	(low 95%CL)	(hi 95%CL)	Estimate	(low 95%CL)	(hi 95%CL)
CW_{∞} (mm)	131.3	129.0	133.6	125.3	123.0	127.6
k (year^{-1})	1.79	1.66	1.92	1.73	1.54	1.92
t_0 (years)	0.00	0.00	0.00	0.00	0.00	0.00
C	1.00	1.00	1.00	0.98	0.81	1.14
t_c	0.06	0.04	0.08	1.11	1.08	1.13
σ (mm)	17.05	16.43	17.66	15.34	14.82	15.87
$\phi_{0+}^{\mathrm{m}=2}$	0.85	0.81	0.89	0.91	0.88	0.95
$\phi_{0+}^{\mathrm{m}=4}$	0.62	0.57	0.68	0.59	0.54	0.65
$\phi_{0+}^{\mathrm{m}=6}$	0.57	0.51	0.62	0.22	0.16	0.27
$\phi_{0+}^{\mathrm{m}=11}$	0.45	0.41	0.49	0.41	0.37	0.44
NLL	18316.0			17772.4		
n	4000			4000		

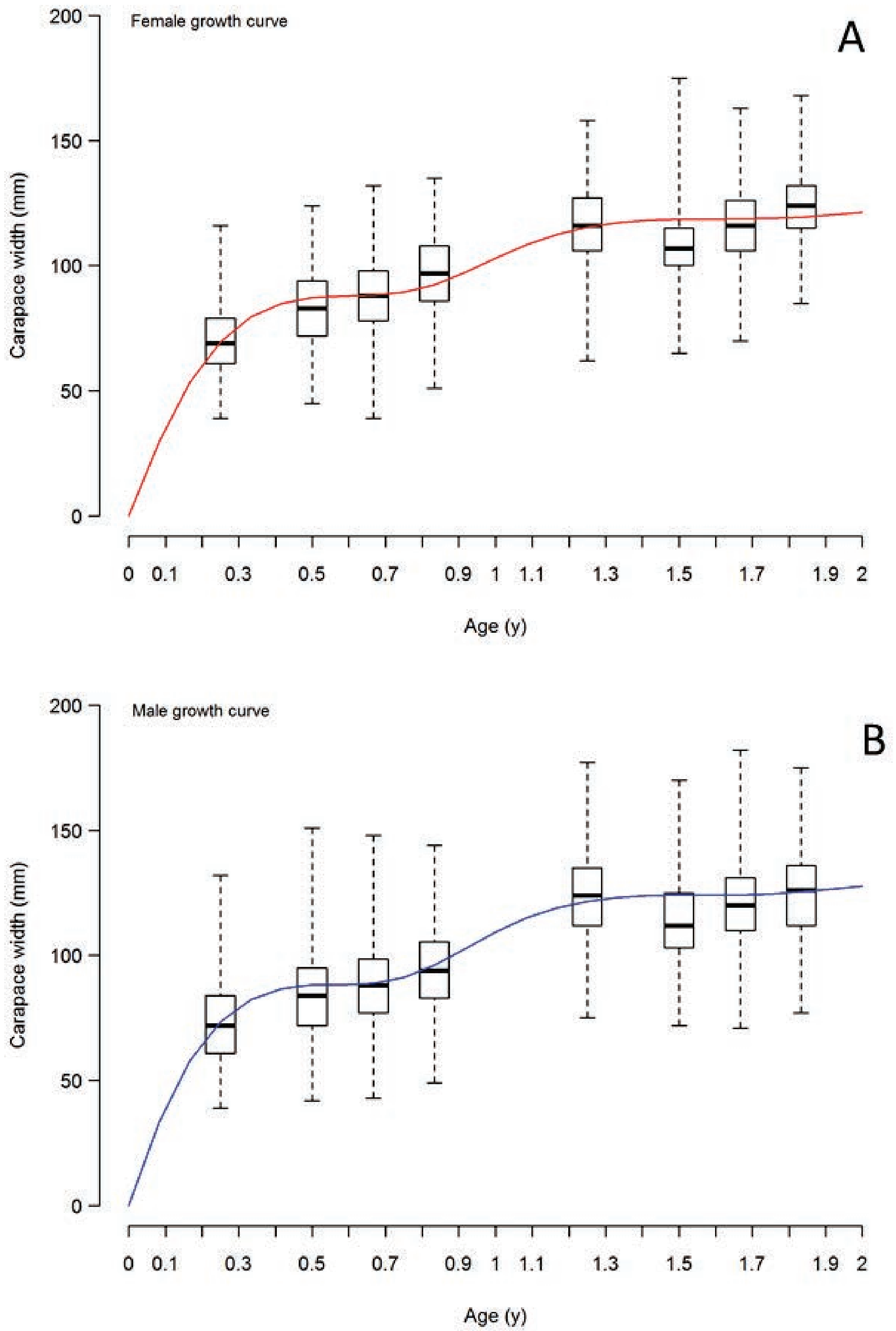


Figure 5.21. Estimated seasonal growth curves for (A) female and (B) male blue swimmer crabs in Shark Bay (blue line) plotted together with the lengths of crabs with randomly-assigned ages based on their probabilities, given their lengths, of belonging to either the 0^+ and 1^+ cohort (as estimated by the growth model). The 25th and 75th percentiles of the lengths of crabs at each randomly assigned age are represented by the lower and upper bounds of each box, respectively, and the minimum and maximum lengths as the lower and upper whiskers, respectively. The median values of the lengths are represented by dark lines within the boxes.

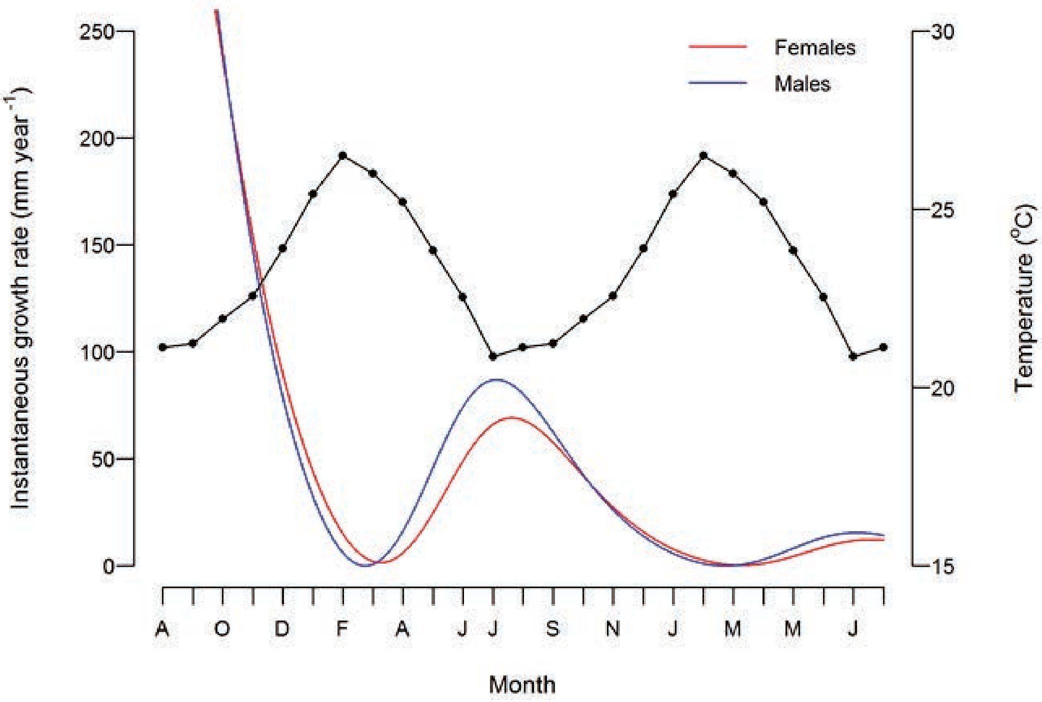


Figure 5.22. Instantaneous rates of growth (mm year $^{-1}$) of male (blue) and female (red) *P. armatus* in Shark Bay. The mean monthly sea surface temperatures in Shark Bay between 2010 and 2014 (solid line) are also shown.

5.6 Sea surface temperature (SST) data for Shark Bay

5.6.1 Stock-environment relationships

Detailed results of the correlation of SST data with abundance indices (standardised commercial catch rates and fishery-independent trawl catch rates of legal sized crabs) are published in Caputi et al. 2015a and 2016.

The analysis identified two key SST periods for which statistically significant correlations with commercial catch rates existed; 1) the first period was the summer months January to March (heat wave period) where there was a negative correlation with commercial catch rates, 2) the second was the autumn/winter months April to August when peak spawning is expected to occur and this showed a positive correlation with SSTs. The multiple regression relationship based on the SST during these two periods, January–March (SST13) and April–August (SST48) of the previous year resulted in a multiple correlation of 0.92 (R^2 = 0.85, $F(2,9)$ = 25.9, $p < 0.001$) with the SST in each of the periods significant ($p < 0.005$) (Figure 5.23):

$$\log_e\left(CPUE_{t/t+1}\right) = -0.296 - 0.148SST13_t + 0.196SST48_{t-1}$$

The results of this analysis suggests that warm temperatures during the autumn/winter spawning period are beneficial to recruitment, however warm temperatures during the juvenile phase in the summer months when the crabs are mainly in the shallow water areas appears to have a negative effect. This suggests that the major cause of the low recruitment to the fishery in 2011/12 was likely a combination of a very cool winter in 2010 followed by the heat wave in the summer of 2010/11. The winter SSTs since 2010 have returned to within historic ranges although remaining at the lower end of this range. Summer SST in 2011/12 and 2012/13 have remained above average though lower than the record high level of 2010/11, and SST returned to average levels in 2014/15 and 2015/16. Predicted commercial catch rates for the past three seasons are shown on Figure 5.25, as actual commercial catch rates are no longer reliable and do not accurately reflect stock abundance. Poor trap logbook data, high-grading of crabs and high reduced effort in the trap sector due to quota trading has precluded further analysis of commercial trap catch rate data.

The effect of the heat wave on the crab stock was also examined using the annual November trawl survey data of legal crab catch rates. The analysis suggested that SST in the previous summer, November to February, was negatively correlated with the (log-transformed) catch rates of legal crabs in November thus indicating a negative effect of warm temperature during this period (Caputi et al. 2015a). This analysis was updated to include the recent (2013-2015) survey catch rates with similar results as before (R^2= 0.73, p<0.001) (Figure 5.24):

$$\log_e\left(CPUE\right) = 33.752 - 1.083SST$$

This suggests that above average recruitment requires cooler summer temperatures which are likely to produce higher catch rates of legal crabs in the following summer when they start to recruit to the fishery (the reason the fishing season is set from November to October). The low catch rate during 2011 clearly shows the significant stock decline and progressive improvements in the stock abundance reflected in the following years up to 2015. The lowest abundance of crabs across the Bay in any one year is observed during the November survey however it is proportional to the overall annual stock levels. The effects of fishing effort (or crab landings) on the November index needs to be further investigated.

Once the SST effect is taken into account in the above assessment there is little evidence to suggest that the flooding event in 2010/11 had a significant effect on recruitment but it is important to continue to monitor and assess the effects of this environmental effect as well as other changes that are occurring in the system such as changes in the seagrass habitat.

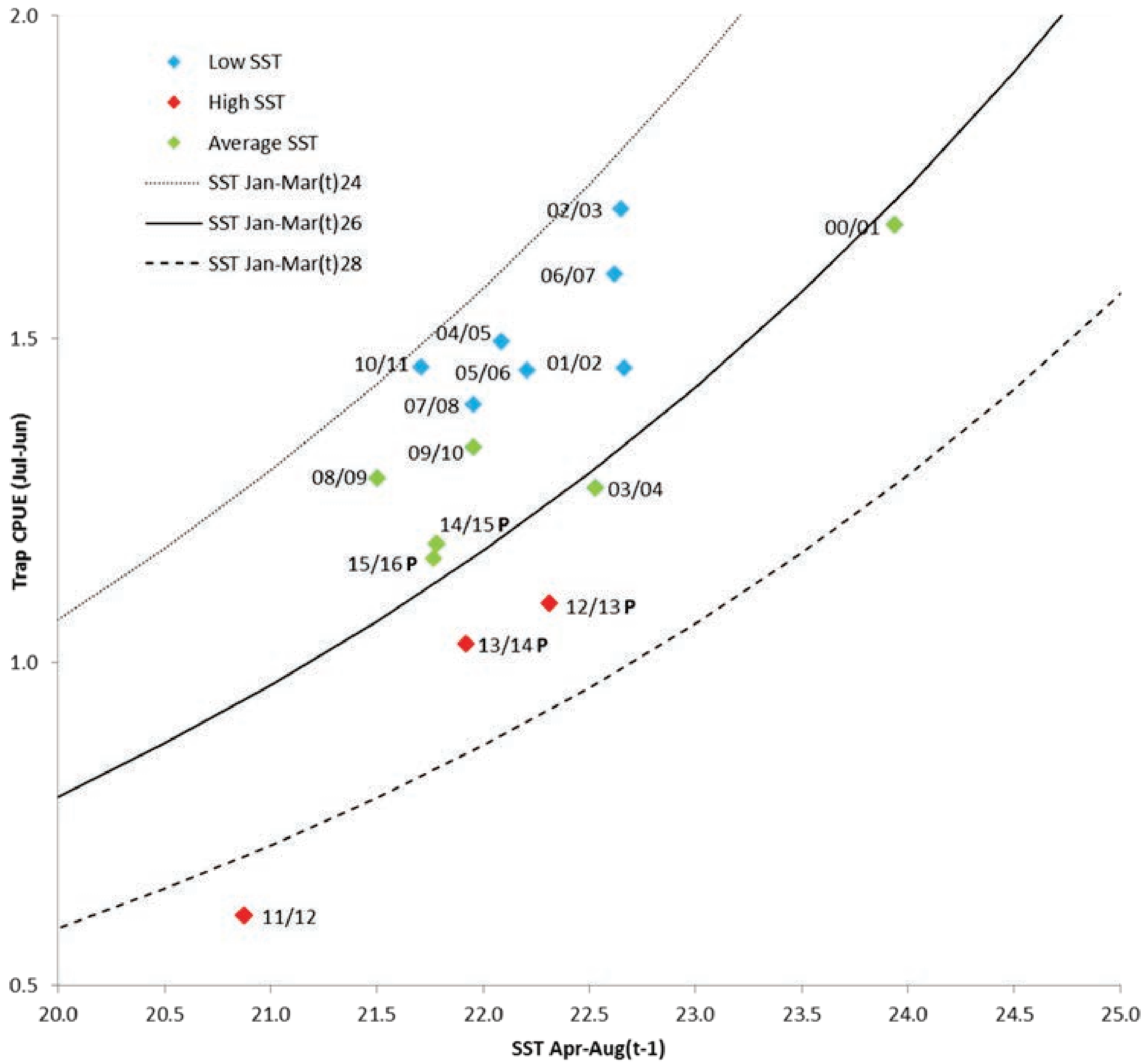


Figure 5.23. Relationship between standardised annual commercial trap crab catch rate (year t/ t+1) and mean SST during January-March (t) and April-August (t-1). The year shown indicates that of the commercial catch rate with the January-March SST also plotted. The analysis is based on the years (00/01 to 11/12). Predicted catch rates for the following 12/13 (as no fishing), 13/14, 14/15, 15/16 seasons are also shown (P). (Modified from Caputi et al. 2015a).

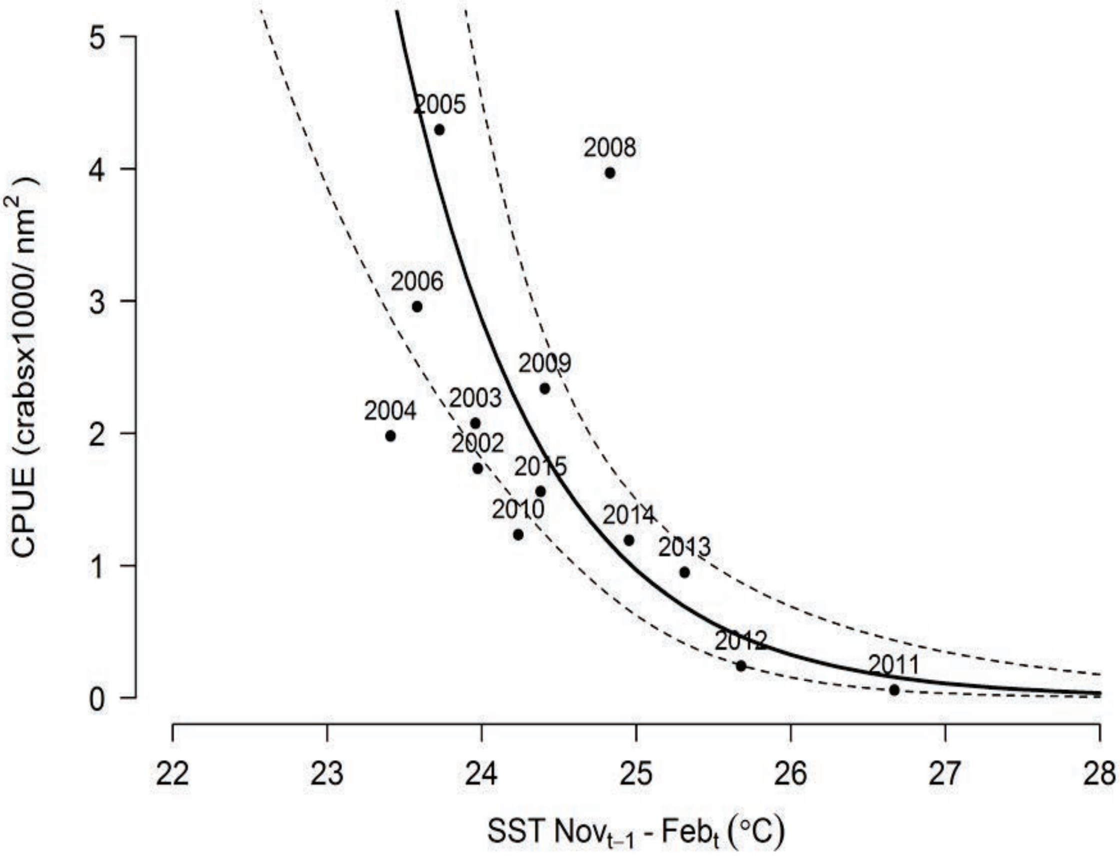


Figure 5.24. Relationship between November trawl survey legal crab catch rate (year t) and mean SST during November (t-1) - February (t) with 95% CL. (Modified from Caputi et al. 2015a). Survey data is not available for 2007.

5.6.2 Post heat wave SST profiles

The historical mean monthly SST profiles for Inner Shark Bay and Denham Sound regions show the coolest winter period as August to October with a SST range of 20.5 – 21.5 °C, and the warmest summer period as February to May with a SST range of 24 – 26 °C (Figure 5.25). During 2010, SSTs were cooler than the average from February onwards and reached their lowest temperature during July at 20.04 °C in Inner Shark Bay, well ahead of its typical winter period, and from September 2010 the SSTs rapidly increased to above average temperatures peaking during February 2011 at approximately 29 °C. Since 2011, there has been a notable shift in the winter period in Shark Bay with the coolest SSTs occurring earlier between June and July and also on average being cooler by approximately 2°C. This phenomenon is not present outside Shark Bay and thus appears to be related to other factors such as wind stress and direction within Shark Bay (Y. Hetzel, *pers comm*.). The summer SSTs have been returning to the historical average with 2016 being cooler than the average and showing a similar profile to 2010 (Figure 5.25, Figure 5.26).

The SSTs anomalies indicate more clearly that the months associated with peak spawning period for blue swimmer crabs in Shark Bay, April to August, have been cooler than the average since 2002, with record low SSTs in 2010 and in 2016. However this trend is not present for the region Outside Shark Bay (Figure 5.26) with no long term cooler than average winter trends. The SST anomalies also show 2012 and 2013 being warmer than the historical average both inside and outside Shark Bay, however 2014 and 2015 were more closer to the average while 2016 summer being cooler than the average (Figure 5.26).

5.6.3 *In situ* water sampling

In situ water sampling undertaken during the trawl surveys provided both complementary information to the SST satellite data for Shark Bay and supplementary information in terms of salinity and pH profiles of the Bay. There were very little difference between the mean bottom and surface temperatures across all the survey months, except during June 2014 when the mean bottom temperature of 18.4°C, was lower than the surface temperature of 19.1°C (Figure 5.27). The mean surface temperature for June 2015 was also much higher than June 2014 (Figure 5.27). Temperatures during the months of November and April appear to be the least variable among the sites, while February and June showed much greater variation among sites, which is likely due to other factors such as winds and tides. In comparing the *in situ* surface temperatures with monthly SST data, there were no large differences detected with the exception of June 2014 where the SST reading of 22.3°C was much higher than the *in situ* surface temperature reading of 19.1°C. The mean bottom salinity was either similar or higher than surface salinity and ranged from 34 to 44 (Figure 5.28). Both the bottom and surface salinity readings for April 2015 showed the highest variation among sites. There were no notable differences between bottom and surface pH readings but there were annual variations, particularly the pH for April and November 2014 which were much lower than 2013 and 2015 readings (Figure 5.29).

Using the temperature and salinity data collected from each site across all the surveys between November 2012 and June 2015, the temperature-salinity signature profiles of the body of water sampled were plotted to understand the differences in the characteristics of the water masses both seasonally, spatially and in some instances annually. The spatial trends in the bottom and surface temperature-salinity signature of the different survey areas are shown for the months of November, February, April and June in Figure 5.30 and Figure 5.31. In general, there were very minimal differences in the temperature-salinity signatures between the different survey areas within Shark Bay, indicating a generally well-mixed water masses between West, North Central and South CPL regions. The East Peron Nursery region which is furthest to the south was slightly separated by its higher salinity characteristics, particularly during June. The Eastern Gulf region, which was only sampled during April, is more distinct due to its higher salinity profile of up to 47 (Figure 5.30C). The Denham Sound region during November shared a similar profile to the northern Shark Bay region (Figure 5.30A, Figure 5.31A), indicating a strong mixing of the water masses during this time of the year but Denham Sound was distinctly cooler during February (Figure 5.30B, Figure 5.31B). The surface temperature salinity signatures were similar to those at the bottom indicating strong vertical mixing, except during June (Figure 5.31D) when some stratification was apparent. Annual differences in the surface water mass signatures were also apparent between June 2014 and June 2015 (circled).

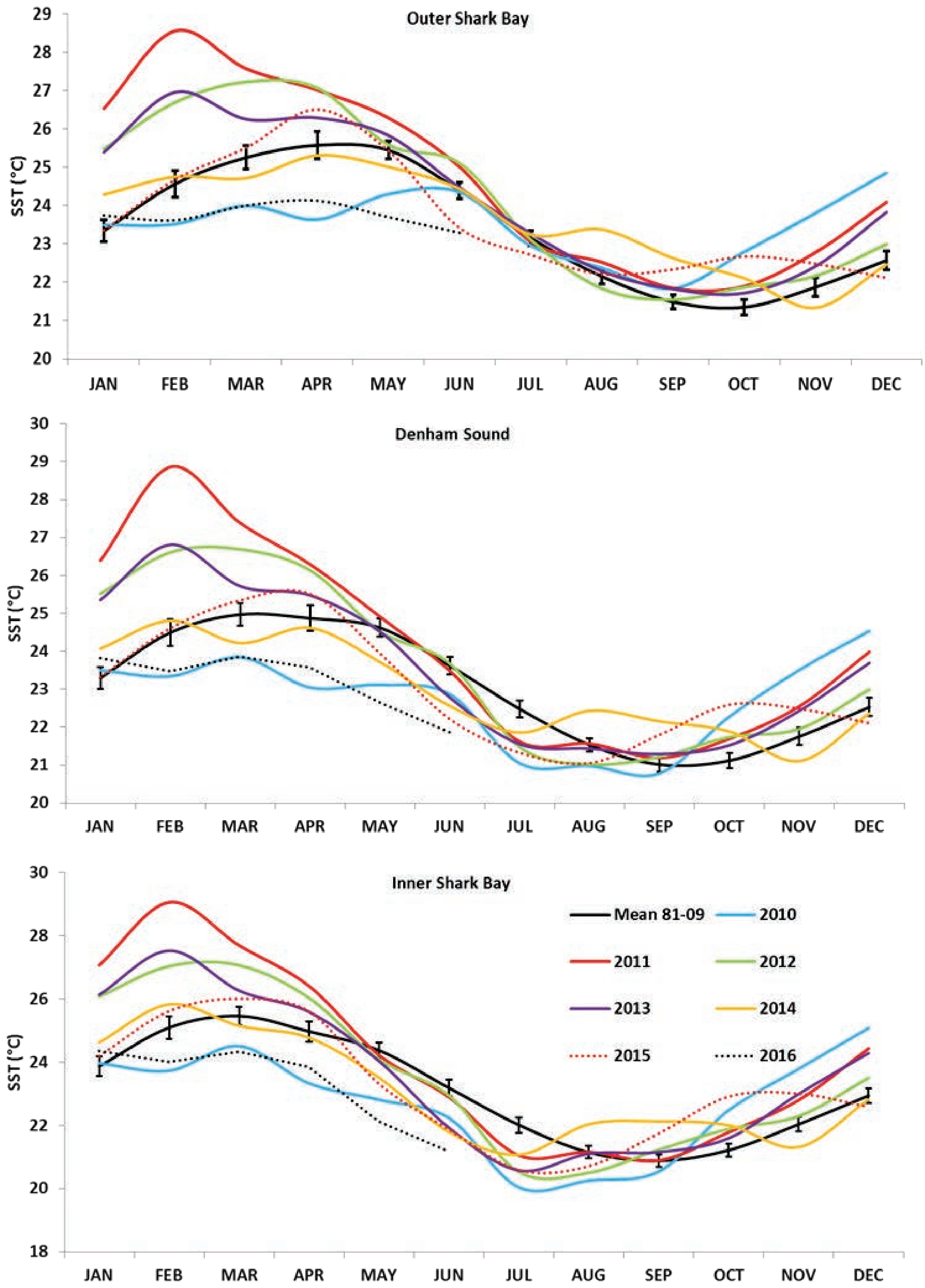


Figure 5.25. Comparison of the historical (pre-heat wave) mean monthly SST (mean ± 95% Prediction Limits) (1981 – 2009) and the mean monthly SST for 2010, 2011, 2012, 2013, 2014 and 2015 (post- heat wave years) Outer Shark Bay (sites DHW, SB1 and SB2 from Fig 4.10), Denham Sound (sites DS50 and SDS from Fig 4.10) and Inner Shark Bay (sites GEOG90, RC23, SWcar, Dorre East, North Peron and East Gulf from Fig 4.10) regions.

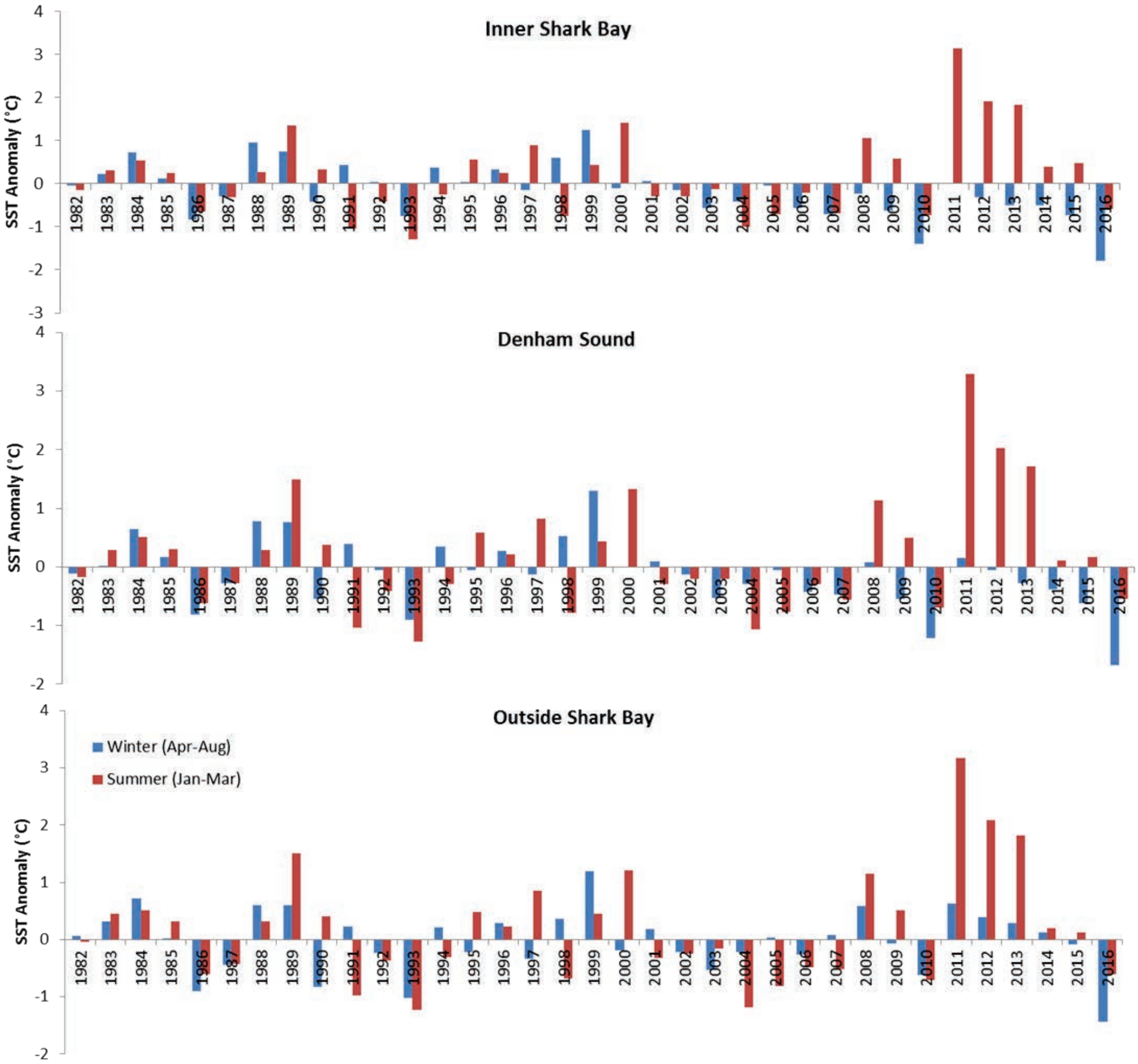


Figure 5.26. Mean winter (April to August) and summer (January to March) SST anomalies for inner Shark Bay, Denham Sound and outer Shark Bay regions from 1982 to 2016, calculated against the 1982 – 2009 means (representing pre-heat wave years).

The seasonal trends in the temperature-salinity signature profiles of the different sampling areas are shown in Figure 5.32, Figure 5.33 and Figure 5.34. The West CPL region shows a salinity range between 34 and 37 for all months and transitions from 27°C in February to 18 °C in June (Figure 5.32). The southern sites of West CPL were much cooler during February 2015 (circled) compared with the rest which may be due to an intrusion of the Capes Current through the Naturaliste Channel entrance. November 2012 was distinctly separated from the other November readings by the lower salinity signature of this water mass. The water masses in the Gulf regions were distinctly different both spatially and seasonally with Denham Sound showing a warmer signature profile during February than November. The Eastern Gulf regions showed a large variation in their salinity signature profile which may be influenced by differing evaporation rates. The seasonal trends in the signatures observed for North, Central and South CPL were very similar (Figure 5.33, Figure 5.34) and should be considered as one water mass body, and there was some overlap in their signatures with that of the East Peron Nursery region (Figure 5.34).

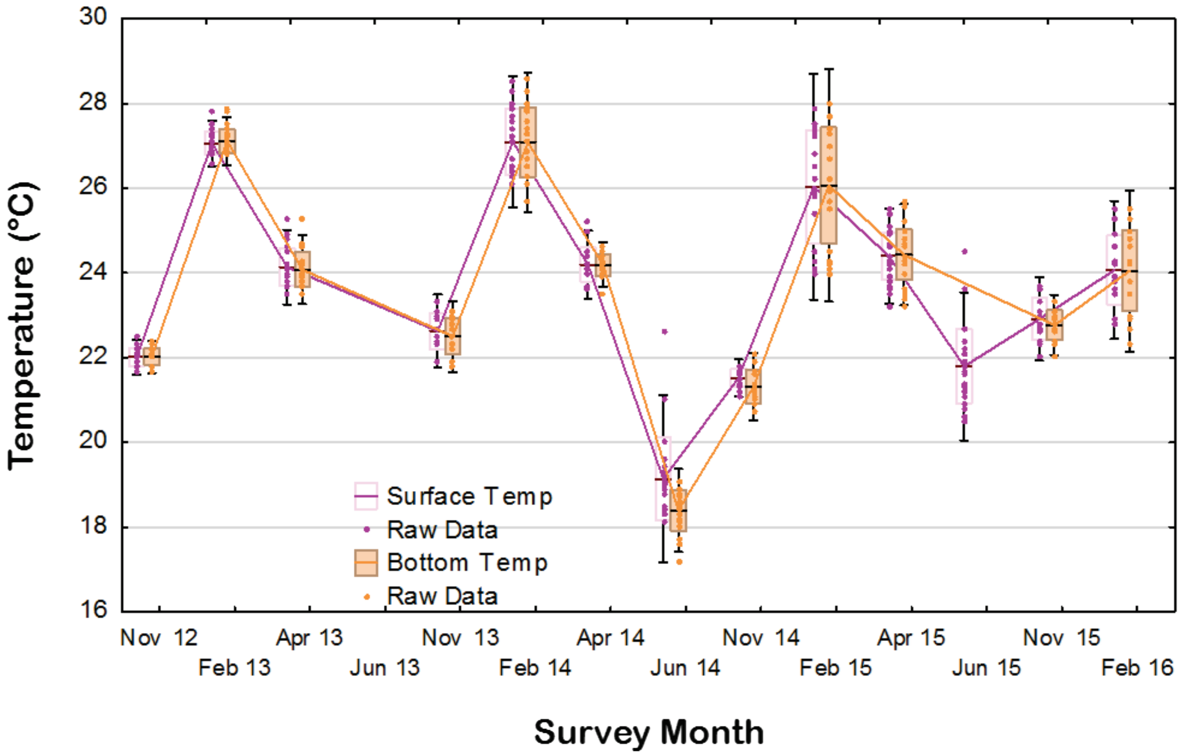


Figure 5.27. Box plots of mean surface and bottom temperatures during the fishery-independent crab trawl surveys from November 2012 to February 2016. The box represents 1 SD and the whiskers represent 2 SD overlayed with raw data. Note no temperature readings taken during June 2013 and no bottom temperatures taken for June 2015.

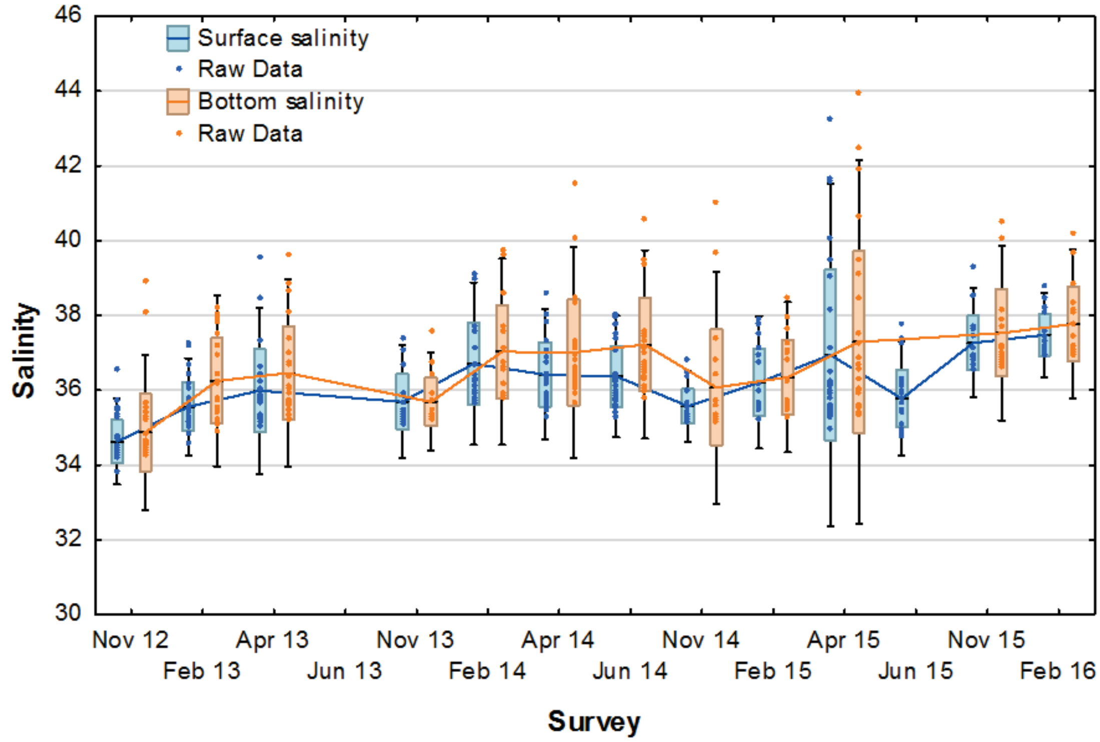


Figure 5.28. Box plots of mean surface and bottom salinity for surveys during the fishery-independent crab trawl surveys from November 2012 to February 2016. The box represents 1 SD and the whiskers represent 2 SD overlayed with raw data. Note no temperature readings taken during June 2013 and no bottom temperatures taken for June 2015.

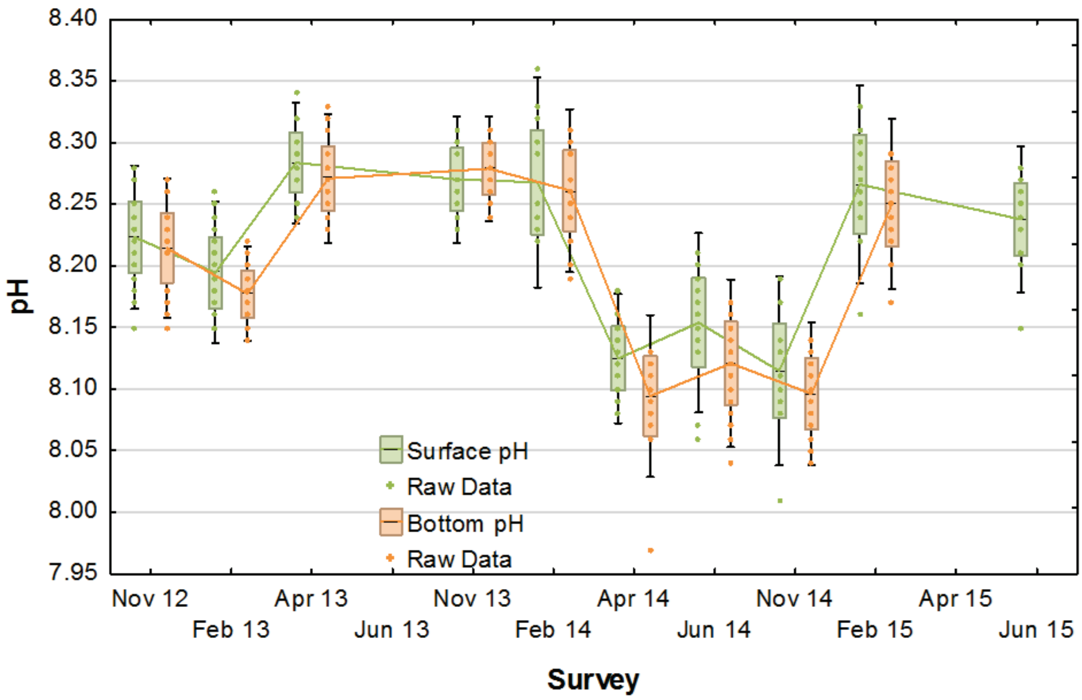


Figure 5.29. Box plots of mean surface and bottom pH for surveys from November 2012 to June 2015. The box represents 1 SD and the whiskers represent 2 SD overlayed with raw data. Note no pH readings taken during June 2013 and April 2015 and no bottom pH taken during June 2015. No pH readings taken after June 2015.

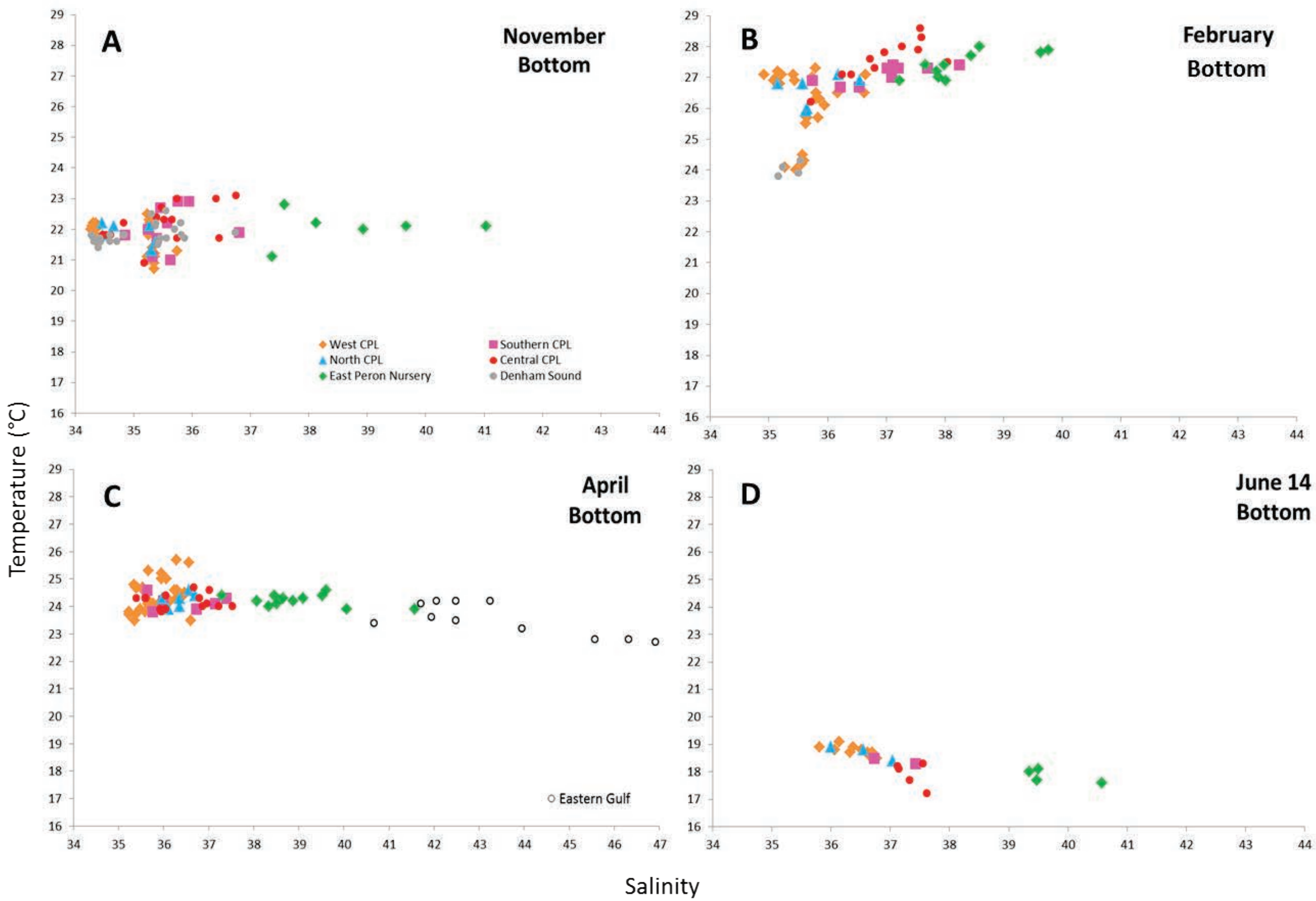


Figure 5.30. Spatial trends in the bottom temperature and salinity signature of the water bodies within the survey sites from November 2012 - June 2015. Note there were no bottom readings available for June 2013 and June 2015. Water sampling in the Eastern Gulf sites only occurred during the April surveys.

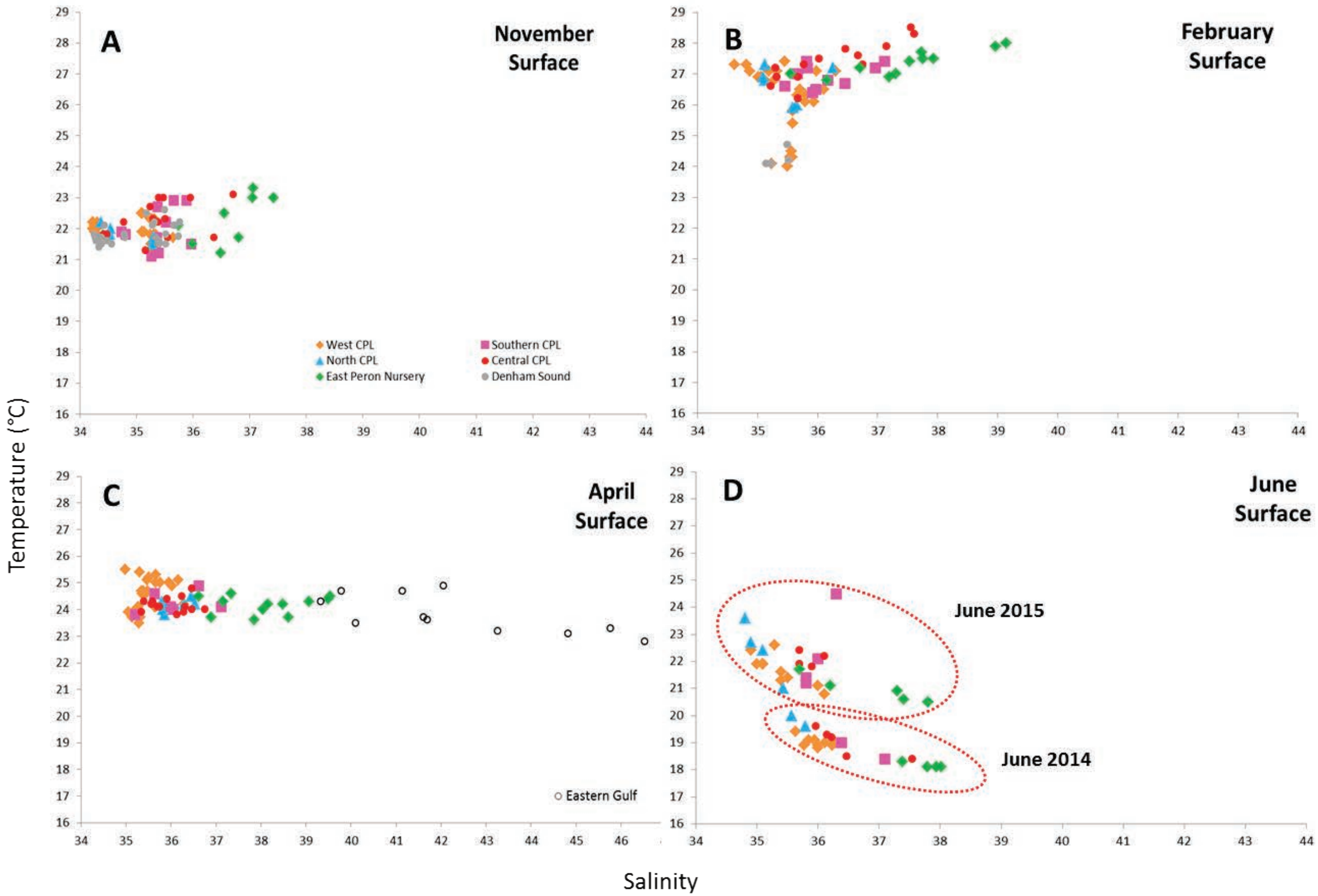


Figure 5.31. Spatial trends in the surface temperature and salinity signature of the water bodies within the survey sites from November 2012 - June 2015. Note there were no surface readings available for June 2013. Water sampling in the Eastern Gulf sites only occurred during the April surveys.

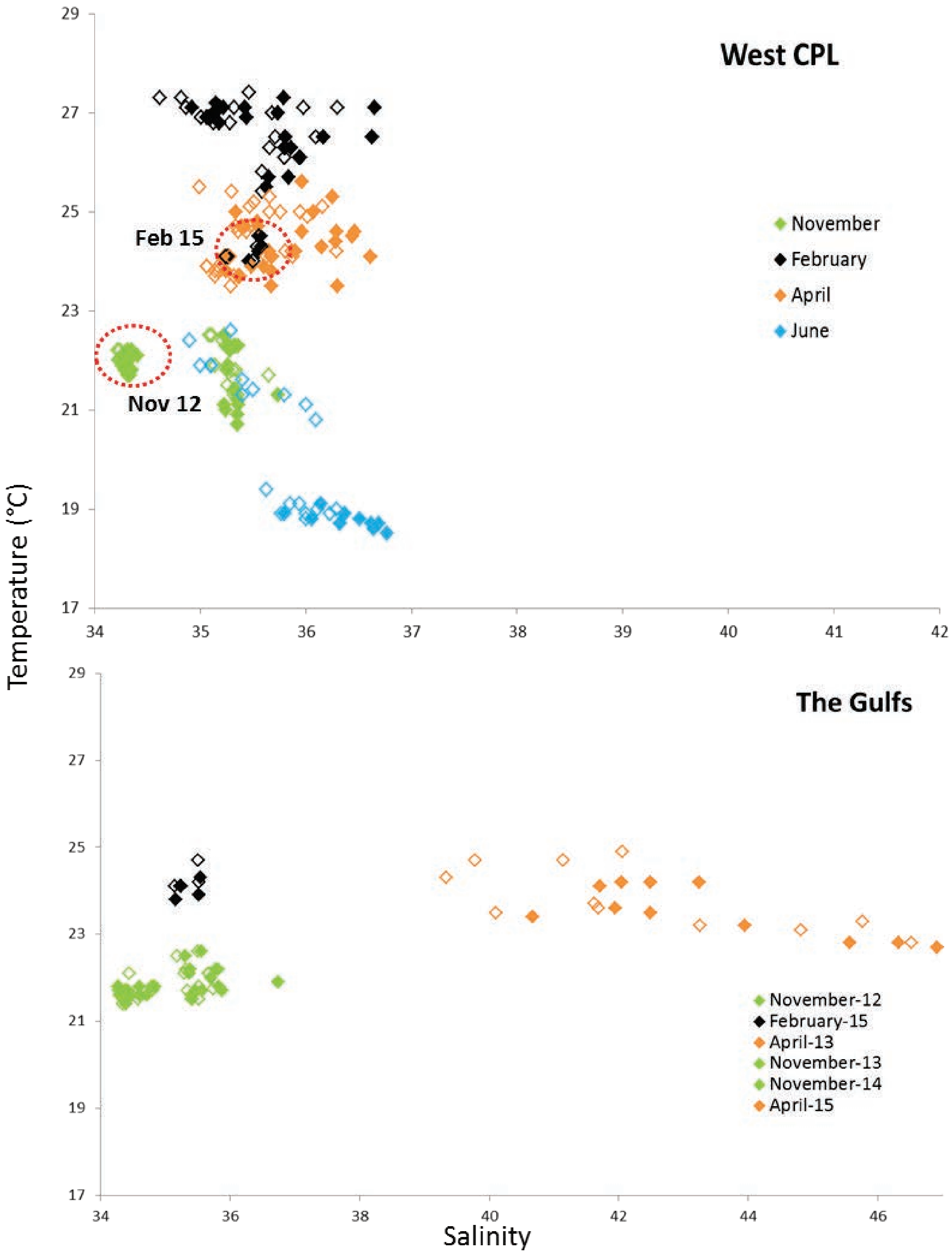


Figure 5.32. Seasonal transitions in the bottom (filled) and surface (non-filled) temperature and salinity signatures of the water bodies in the West CPL and the Gulfs (Denham Sound, Freycinet Estuary and the Eastern Gulf) regions from November 2012 to June 2015.

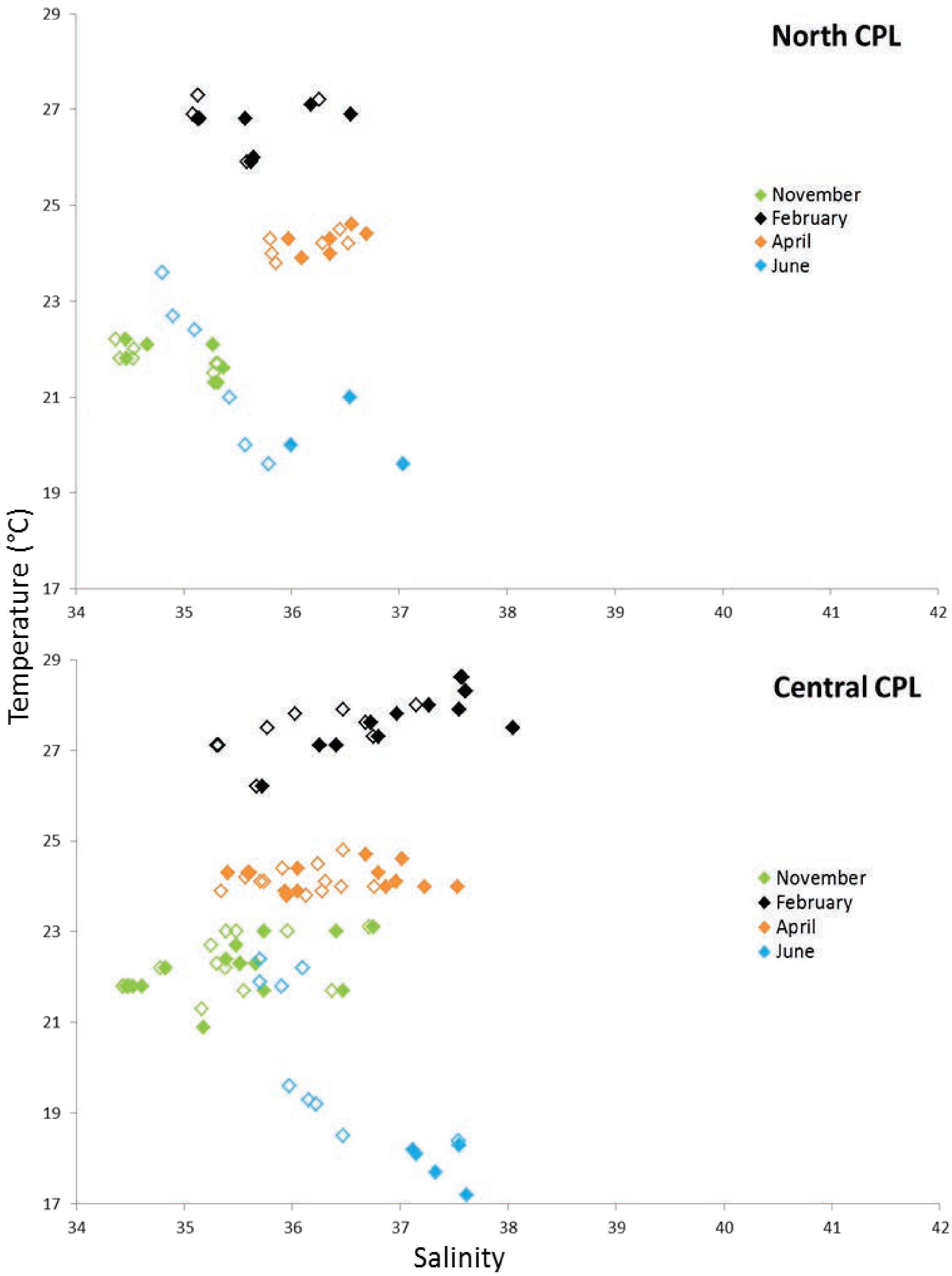


Figure 5.33. Seasonal transitions in the bottom (filled) and surface (non-filled) temperature and salinity signatures of the water bodies in the North CPL and Central CPL regions from November 2012 to June 2015.

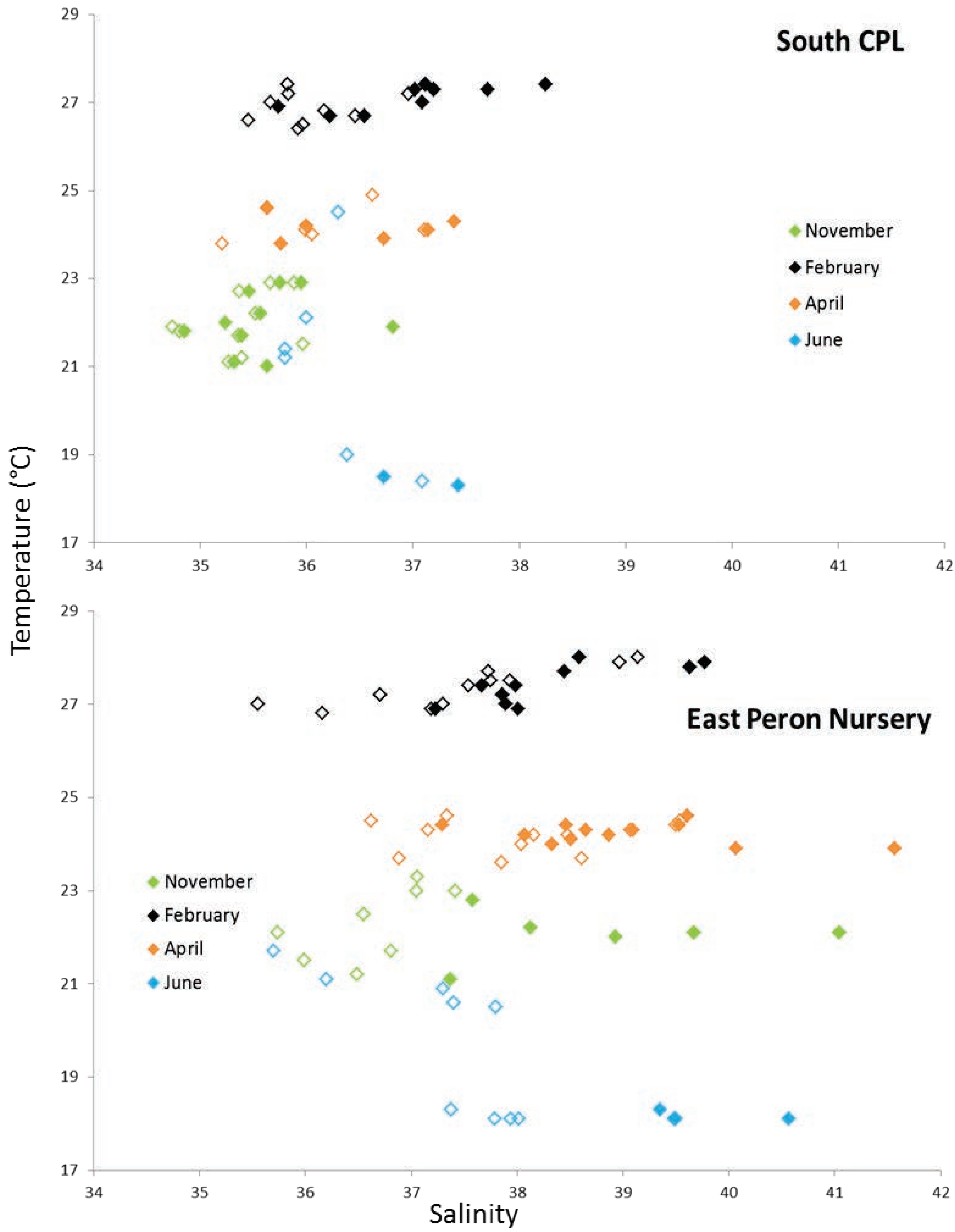


Figure 5.34. Seasonal transitions in the bottom (filled) and surface (non-filled) temperature and salinity signatures of the water bodies in the South CPL and East Peron Nursery regions from November 2012 to June 2015.

5.7 Biomass estimates using swept area analysis

Biomass estimates using swept area analysis were determined for the catch categories of juvenile, sublegal, spawning, mature and legal crabs based on two different area calculations within Shark Bay (Figure 5.35). Estimates for Area A were generally higher than Area B, however for most months the estimates within the confidence limits. Area B is considered to be most representative as it encompasses the majority of the trap and trawl commercial fishing grounds and therefore the following biomass trends are described only for Area B.

Peak spawning biomass levels during the June surveys showed 131 t during 2012 and this increased to 1175 t during 2013. Spawning biomass levels has remained < 2000 t since fishing had resumed (Figure 5.35) in November 2013. Similarly, juvenile (immature) biomass level during February 2013 was 651 t and increased to 1444 t in 2014. Highest juvenile biomass levels have been < 1500 t during 2015 and 2016. Sublegal crabs dominated the catch composition and peak biomass levels usually occur during April and ranged between 1000 and 2000 t, except during 2014 when peak levels were detected during February at 2166 t. The timing of recruitment and moulting tend to influence when peak abundances are detected in these surveys. The highest abundance of legal biomass was during April 2013 at 600 t, when the fishery was closed. Since fishing had resumed in November 2013, peak legal biomass levels (ie. in June) are approximately around 300 t (Figure 5.35).

Biomass estimates during November were also determined based on the annual November fishery independent survey catch rates from the West CPL grounds. These estimates were compared to biomass estimates from the expanded fishery-independent survey catch rates from 2012 onwards (Figure 5.36). Juvenile biomass levels had been very low during November prior to 2012, but increased to 332 t in 2013. Estimates based on data collected during the expanded survey were much higher at 907 t and are indicative of greater abundance of small crabs on the sites to the east of the CPL. Estimates of spawning and sublegal biomass levels appear to be within the lower range of the historical biomass levels and no marked differences in estimates are apparent between the two survey programs. Estimates of legal biomass levels in 2014 were similar to the level in 2010 at approximately 480 t and estimates based on the expanded survey program are lower, which may reflect the higher abundance of legal crabs found on the west CPL ground during November (Figure 5.36).

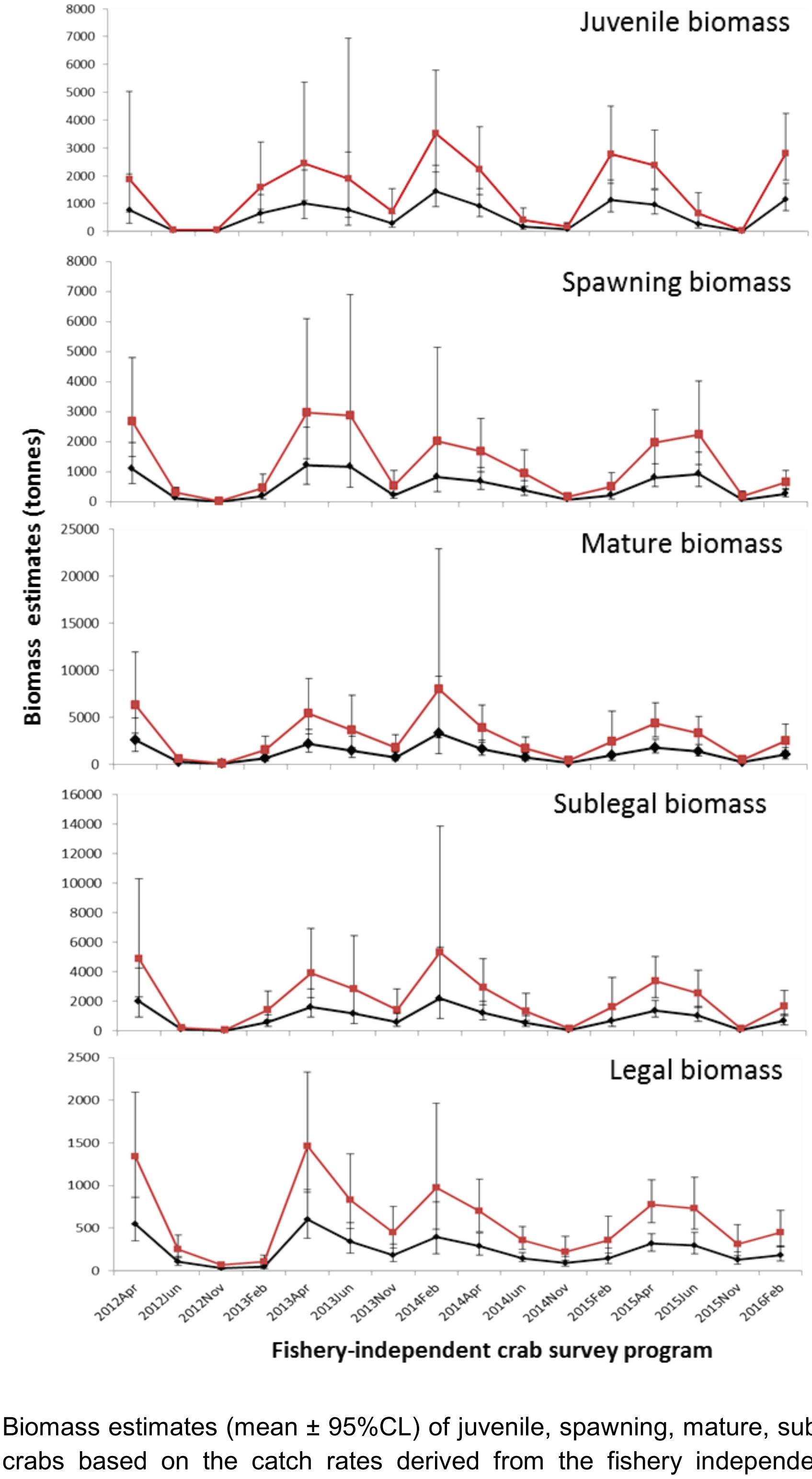


Figure 5.35. Biomass estimates (mean ± 95%CL) of juvenile, spawning, mature, sublegal, and legal crabs based on the catch rates derived from the fishery independent trawl survey program (April 2012-February 2016). Estimates are provided for Area A (area within Shark Bay which encompasses all the standard surveys sites excluding Denham Sound) (black) and Area B (area within Shark Bay, which encompasses the majority of the trap and trawl commercial fishing grounds both historically and recently) (red).

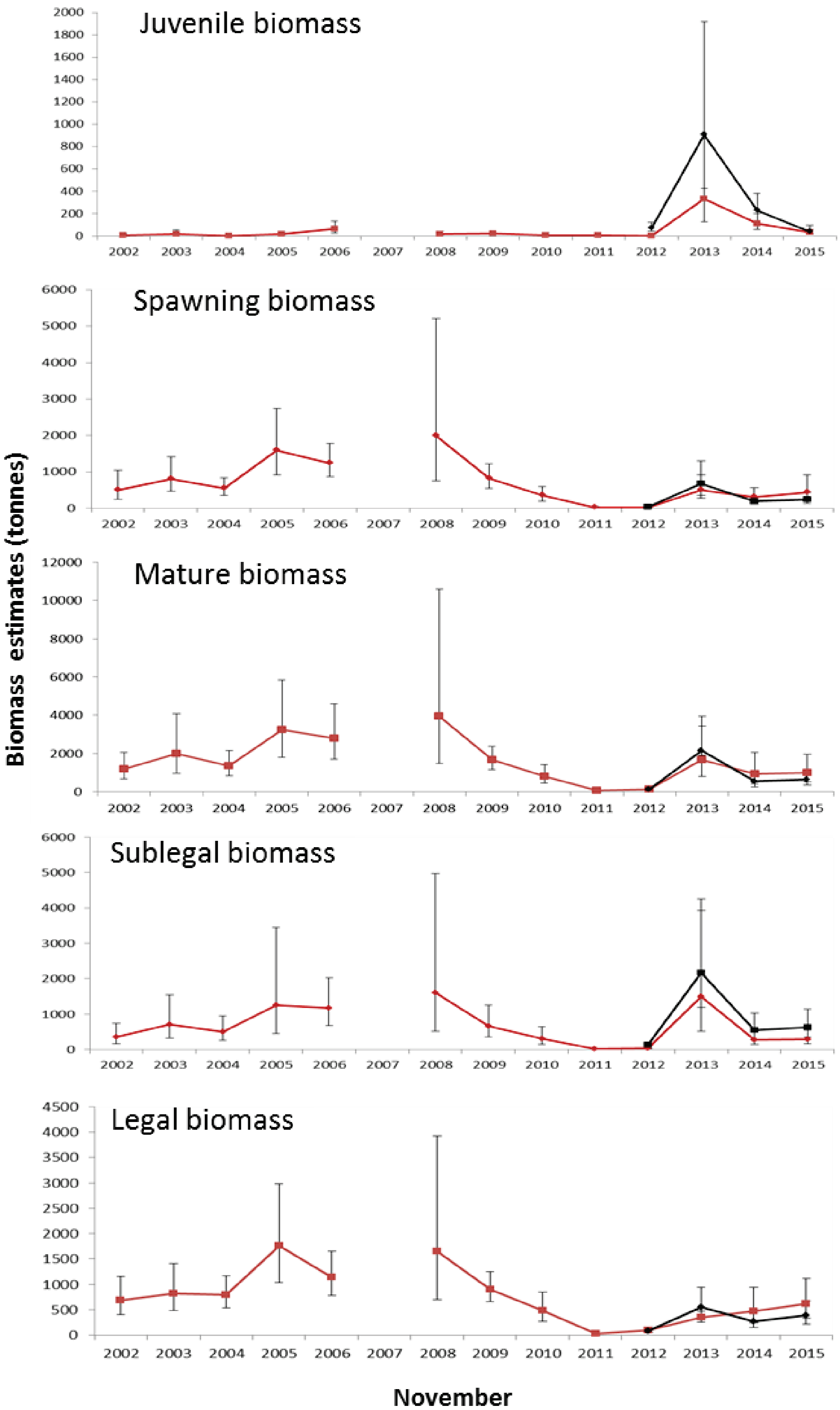


Figure 5.36. Biomass estimates during November (mean ± 95%CL) of juvenile, spawning, sublegal, mature and legal crabs calculated for Area B (area within Shark Bay which encompasses majority of the trap and trawl commercial fishing grounds both historically and recently). Estimates derived from the annual November survey on the West CPL grounds are shown in red and estimates based on the expanded standard sites (West and East CPL sites) of the fishery independent crab survey program are shown in black.

5.8 Biomass dynamics model of Shark Bay crab stock

The model provided a reasonable (visual) fit to the observed November survey catch rate data for mature sized crabs, i.e. the natural logarithms of the observed and expected catch rates exhibited similar trends. This view is supported by the expected catch rates falling within the 95% confidence limits for the observed catch rates. The logged values for the catch rates remained relatively stable at ~ 6-7.5 kg nm^2 prior to 2011/12 before declining markedly to a minimum of 3.6 kg nm^2. They then increased and remained between 5.8 - 7.0 kg nm^2 during 2013-2105 (Figure 5.37).

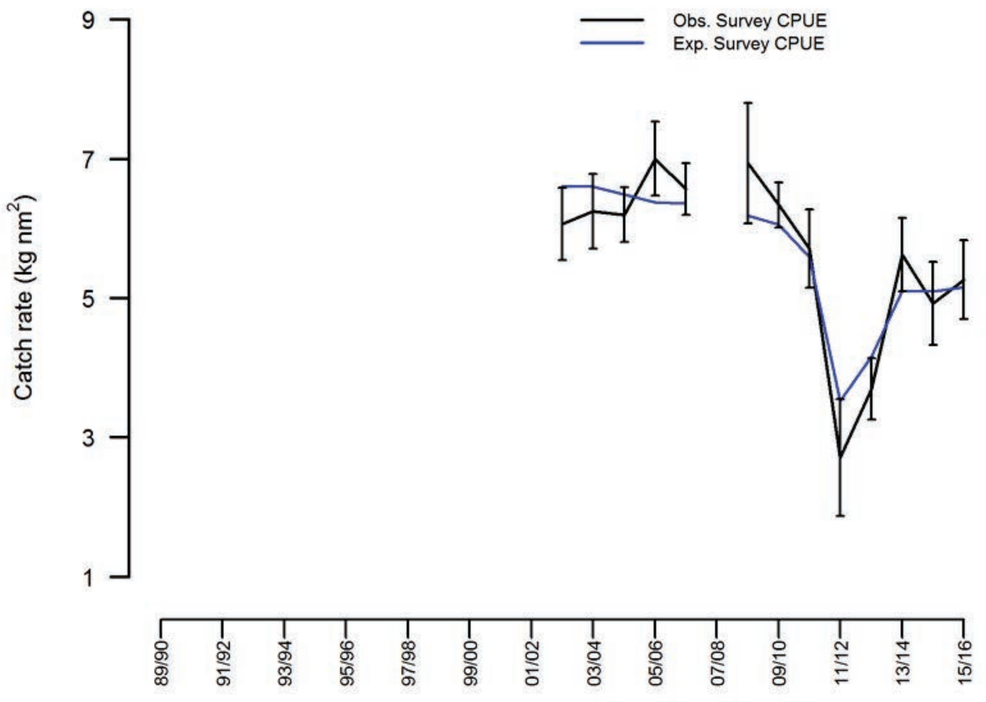


Figure 5.37. Natural logarithms of the annual observed and expected catch rates for mature-sized crabs (females > 110 mm CW and males > 105 mm CW, based on 2013 SOM estimates). The observed catch rates represent crab catches from the annual November trawl survey program.

The history of the Shark Bay crab fishery has been discussed with respect to four management phases, namely an early exploratory phase of low catches and effort (1989-1998), an experimental phase of increasing effort and catches (1999-2004), an interim managed phase when catches increased further followed by a significant stock decline and fishery closure (2005-2012), and lastly the current stock rebuilding phase under quota management (2013-2016). As expected, the estimated biomass changed little throughout the exploratory fishing phase due to minimal catch and effort, i.e. it remained at around the estimated unfished level (B_0 of 1319 t) (Figure 5.38; Table 3). Also as expected, the biomass declined progressively during the experimental ("expansion") phase, and by 2005 it is estimated to have declined to 56% of the unfished level (i.e. still above MSY). During the interim managed phase, when catches had increased to their highest levels in the history of the fishery and above the estimated MSY of 666 t, the estimated biomass continued decreasing progressively until 2010, after which it fell precipitously to its lowest level (43 t) in 2011. During the current quota managed phase of the fishery the estimated biomass increased incrementally during the period when the fishery was closed. However, following the re-opening of the fishery, when the catch quota was set between 400 - 450 t each year and noting that the catches actually taken in those years were lower than the quota at 370 t in 2013/14 and 341 t in the 2014/15 season, the estimated exploitable biomass has remained steady at the relatively low level of ~200 t (Figure 5.38).

Table 3. Parameter estimates from the biomass dynamics model for the Shark Bay crab stock. CL denotes confidence limit.

Estimated parameters	Estimated value	Lower 95 % CL	Upper 95 % CL
q (catchability)	1.62	0.92	2.42
K (carrying capacity or virgin biomass, B_0)	1319 t	919 t	1644 t
r (population growth rate)	2.02	1.42	2.75
MSY	666 t	643 t	693 t

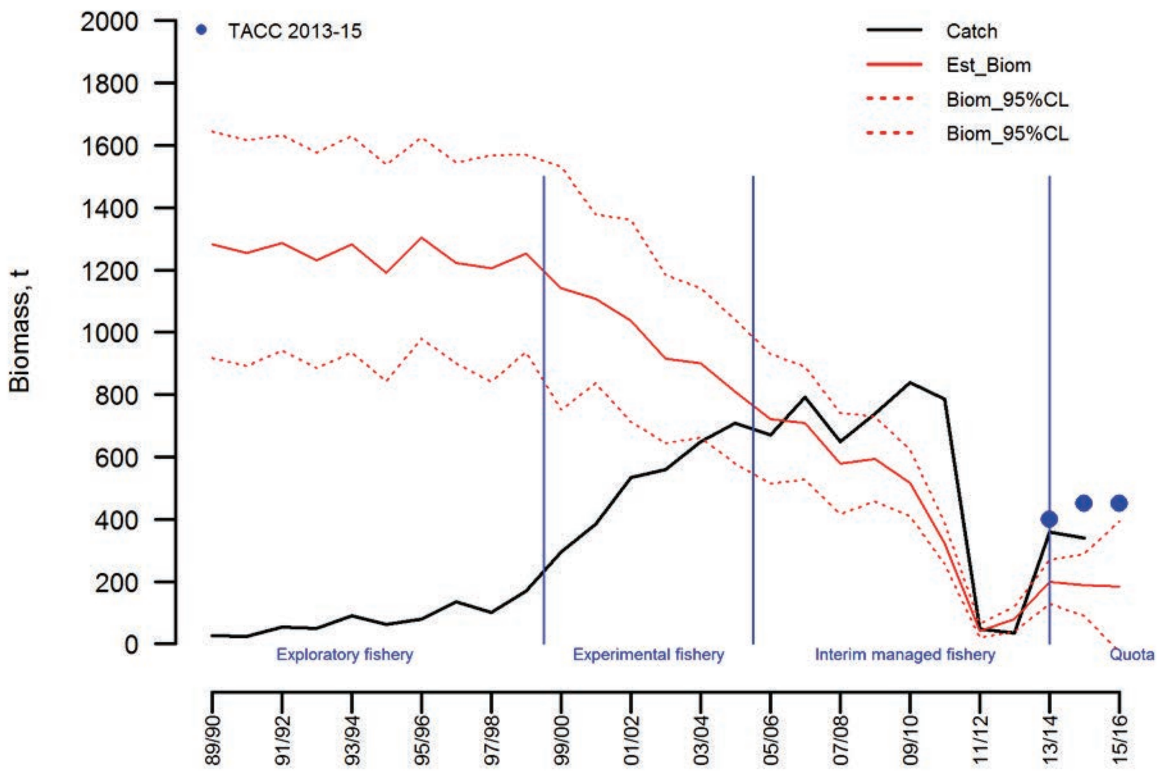


Figure 5.38. Estimates of mature biomass (±95% confidence limits) (red lines) between 1989 and 2016. The estimate for 2015/16 assumes that in the current year, 400 t is caught from the 450 t TACC. The annual catches (black line) taken over the history of the Shark Bay crab fishery are shown with the different management phases of the fishery (blue text/lines). Also presented are the TACC levels (blue dots) set for the 2013/14 season (400 t) and the 2014/15 and 2015/16 seasons (450 t).

6 Discussion

This study has established a detailed fishery-independent trawl sampling program for monitoring blue swimmer crab stock abundance alongside an environmental monitoring program to investigate impacts of key environmental factors on stock abundance, particularly recruitment. The sampling program has helped to confirm that the data produced from the annual fishery-independent trawl sampling in November in the earlier years are still of value for providing information on stock abundance, despite some key limitations in terms of spatial coverage and lack of information for other times of the year. The seasonal data provided by the new fishery independent sampling program were also invaluable for deriving key biological information for this stock on growth and reproductive biology, as well as being useful for informing a preliminary assessment model. The fishery-dependent commercial trap catch rates provided a useful time series prior to the closure, however the time series since the closure has not been comparable because of the move to a TACC and the changes in the pattern of fishing. In addition, options are provided for future management and for setting an annual sustainable TACC. Ultimately, this project has led to improved understanding of stock dynamics required by managers when developing plans to ensure the sustainable use of this resource.

6.1 Life cycle and biology

6.1.1 Growth

This is the first study to have described the growth of individuals of blue swimmer crabs in Shark Bay. In a previous study, de Lestang (2002) collected size composition data for this species in Shark Bay employing a combination of fishing gears including seine netting, trapping and trawling. Although de Lestang (2002), and later, de Lestang et al. (2003a) were able to fit good growth curves to size composition data collected for blue swimmer crabs in several other stocks in temperate Western Australian estuaries, there was insufficient signal in the Shark Bay data (i.e. to trace size cohorts through time) to be able to fit a reliable curve (S. de Lestang, *pers. comm.)*. The progress made in this study in being able to fit a growth curve was primarily due to the presence of a clearer growth signal in the size composition data collected during the current fishery independent trawl survey program. Several possible explanations could be proposed for the different levels of signal in the data from the two study periods including: 1) that the fishery-independent sampling regimes differed, with a greater area coverage in the current study, 2) the decision in this study to restrict the size composition data used for growth analysis to survey trawl data, and 3) potential differences in biology associated with temporal changes in environmental conditions, such as water temperature (e.g. spawning may have been more protracted historically and prior to the heat wave, leading to more even recruitment of juveniles throughout the year, which would mask the growth signal in the data).

The results of the growth analysis demonstrate that, at least during recent times, the seasonal pattern of growth of blue swimmer crabs in Shark Bay differs markedly from those in more temperate environments. Thus, in Shark Bay, the growth rate of crabs are at their maximum when temperatures are at their minima, whereas in temperate environments, such as in Cockburn Sound and the Peel-Harvey and Leschenault estuaries, growth is greatest during the warmer summer months (de Lestang et al. 2003b), and on the basis of the growth curve plots, appears to peak around December. Furthermore, growth of crabs in the subtropical environment of Shark Bay is minimal in the warmest months of the year, and again the reverse is true for this species in temperate environments. Despite this marked difference in the time of year when growth rate peaks, growth is greatest in Shark Bay at water temperatures of ~21-22^{o}C in winter, which is about the same as that for Cockburn Sound in December (Johnston et al. 2011) This therefore suggests that there may be an underlying optimal temperature range for growth of around 22^{o}C for *P.armatus*. The indication that growth in subtropical Shark Bay is least in the warm period of the year differs from the results of Lloyd-Jones et al. (2016) for blue swimmer crabs in subtropical south-eastern Queensland, where growth was found to be greatest in March and least in the cool winter period.

6.1.2 Spawning period

Ovigerous (berried) females were captured in Shark Bay during each of the four survey months (February, April, June and November) indicating that some spawning activity occurs year round. However, the proportions of berried females in catches were generally higher during the cooler months, suggesting that spawning activity is more concentrated during that cooler period. Harris et al. (2014) also identified the winter period as a time of increased spawning activity. Spawning during the cooler autumn/winter months coincides with low winds and generally more stable atmospheric conditions in the Bay, which are likely to be favorable for larval retention (Kangas et al. 2012). The conclusion that spawning activity is not relatively constant through the year, at least in recent years, is supported by the presence of modes in the length composition data used for modelling growth. For growth modelling, the date of August 1 was assumed to correspond to the time of peak spawning. On that basis, the abundant 50-100 mm CW cohort sampled by trawling in February would be ~ 6 months old. Sumpton et al. (1994) observed similar seasonal trends with higher catch rates of juvenile crabs between November and February in Moreton Bay, Queensland. Note that little is known about the factors that influence larval development, including larval retention rates within the Bay, except that, generally, eggs develop and settle within 10-18 days (Harris et al. 2014).

6.1.3 Maturity

The size at maturity analyses undertaken in this study demonstrated that, on average, female crabs in Shark Bay now attain maturity at a larger size (~20 mm) than estimated by de Lestang et al. (2003a) based on a combination of seine, trap and trawl data, and also, to a lesser degree (~9 mm) by Smith et al. (2004) who restricted the maturity data collected by de Lestang et al. (2003a) to seine and trawl data. The key reason(s) for this apparent change in size at maturity is not fully clear, although the results of this study suggest that it does not simply reflect differences between sampling gears used in the two studies. In particular, the results demonstrated that regardless of whether the current maturity data were compared with historical seine, trawl and trap maturity data, or just historical seine/trawl maturity data, the current estimates for the mean size at maturity still differed significantly from the historical estimates. Thus, although it is recognised that maturity estimates derived using trap data can potentially be biased (Smith et al. 2004), this does not fully account for the observed change in size at maturity. Another possible contributing factor to the different maturity estimates between the two studies is differences in the spatial locations. In the historical study, sampling was limited to four nearshore sites in a restricted part of the Bay (upper eastern and western gulfs), compared with >50 sites in the current study covering a much larger region of the Bay (e.g. including deep water areas) that is commercially fished. Therefore, although it is possible that there has been a change in biology of crabs in Shark Bay, i.e. with crabs now attaining maturity at a larger size, given the spatial differences in sampling between the two studies, this cannot be determined with any confidence. Note also that the larger mean size at maturity of males recorded in this study compared with that recorded by de Lestang et al. (2003a) may also be due to differences in the spatial extent of sampling. Given the much broader spatial coverage of sampling, it is concluded that the maturity estimates derived in this study are more representative of the current stock of crabs in Shark Bay. As preliminary analysis of maturity data for blue swimmer crabs in Cockburn Sound indicates that size at maturity has varied considerably over time (unpub. data), it may be important to monitor changes in size at maturity of crabs in Shark Bay, particularly under the changing environmental conditions being observed.

To ascertain whether size at maturity changed temporally, and if it will continue to change in the Shark Bay crab stock, would require continued sampling using a similar sampling regime as undertaken in this study combined with reporting of information on maturity status. The estimates for size at maturity determined in this study for female crabs were based on subsamples of crabs from the fishery-independent trawl surveys for which maturity status were recorded for all crabs measured. As the maturity status of females is easily determined, based on external appearance, it would be readily possible to record maturity status of all individual crabs caught during surveys. This would enable the maturity status for each sampled crab to be used in the calculation of mature abundance indices, rather than (as used for this study), a cut-off value based on estimates of the typical size at maturity (e.g. 110mm CW for females and 105 mm CW for males). The sensitivity of the results to these alternative methods of calculating those indices could then be explored.

Reliable estimates of size at onset of maturity are important for management as they are often used as a basis for setting minimum commercial size limits and can influence the estimates of egg production that are used in stock assessment and harvest strategies. Thus, minimum size limits are often set above the SOM to ensure that, on average, females breed at least once before recruiting into the fishery. On the basis of the results of this and former studies on crabs in Shark Bay, the current minimum commercial size of 135 mm is about 25 mm above the average size at maturity, thereby providing at least some protection to the breeding stock. In addition, as commercial fishers tend to prefer catches of male rather than female crabs due to differences in marketability, this would be expected to provide further protection to females.

On the basis of the growth curves, the time of year when spawning activity is greatest (winter) corresponds to the period of fastest growth. On average, crabs in Shark Bay attain maturity at around 12 months and, during winter, grow by about 25 mm (~1 moult cycle) within 1-2 months. Thus, as at least some fishing for crabs by both sectors occurs during winter, typically, mature crabs are only protected from fishing by the current minimum size limit for a relatively short duration. As this size limit has been applied to the Shark Bay crab stock well before it declined in 2011, the level of protection afforded by this management measure, on its own, is insufficient to prevent a future stock decline. Supporting this view is the fact that, despite a similar minimum size measure for the crab stock in Cockburn Sound, that stock has now experienced multiple declines and fishery closures (Johnston et al. 2011).

An important question in relation to assessment of crab stocks is their resilience to fishing pressure. Prior to the experience of stock declines in Cockburn Sound and Shark Bay, there was a view that blue swimmer crab stocks in Western Australia were relatively resilient to fishing pressure. That view was, in part, based on the results of per recruit modelling for the Cockburn Sound crab stock (Melville-Smith et al. 2001), suggesting that, even under heavy fishing pressure and low ages/sizes at first capture, eggs per recruit would remain relatively stable, and that substantially reducing the size at first capture (below the existing MLL) would be expected to increase yield (but that such sizes were not marketable). In a recent re-examination of this issue, presented for the National Blue Swimmer Crab Workshop (Chandrapavan 2018), it was shown that the conclusions resulting from per recruit analysis are sensitive to the assumption of constant recruitment, i.e. by definition, per recruit analysis does not allow for the possibility that fishing can impact on recruitment by reducing spawning biomass. When the traditional per recruit model was extended to incorporate a stock-recruitment relationship, it was shown that blue swimmer crabs may be far more vulnerable to fishing pressure than previously considered depending on the steepness of the stock-recruitment relationship, i.e. degree of dependence of recruitment on stock size. In the case of Cockburn Sound, the existing data on the relationship between recruitment and stock size suggest a low value for the steepness parameter of the stock-recruitment relationship, i.e. that recruitment is closely linked to stock size and thus, that heavy fishing is likely to impact on recruitment (de Lestang et al. 2010). Currently, there are insufficient data to determine the pattern of the stock-recruitment relationship for crabs in Shark Bay, and thus, it would be appear prudent to assume that the stock-recruitment relationship is similar to that for crabs in Cockburn Sound, and that heavy fishing can impact on recruitment.

6.1.4 Fecundity

The relationship between batch fecundity and size determined in this study for crabs in Shark Bay is the first available for this stock. On average, the batch fecundities of legal-sized females were about twice those of sublegal sized (mature) females which indicates that legal-sized females, depending on their abundance, may make an important contribution to overall egg production. It may also be possible that legal-sized crabs produce more batches than sublegal mature crabs (de Lestang 2002), which would infer that legal-sized crab make an even more important contribution to egg production. In this regard, it may be relevant that the preliminary per recruit modelling for crabs in Cockburn Sound (Melville-Smith et al. 2001) indicated that the legal mature biomass of crabs in that system represented the majority (about 2/3) of the total mature biomass of that stock (*unpub. data*). If this situation pertains to the crab stock in Shark Bay, this would indicate that fishing pressure, if sufficiently heavy, can substantially reduce the overall reproductive capacity of that stock. The fecundity relationship determined for Shark Bay is now available for future modelling work. Given that there is evidence of at least some spawning activity of Shark Bay crabs in all months of the year, based on the results of this study and de Lestang et al. (2003a), it would be of interest to ascertain whether egg quality (as indicated by egg diameter measurements) varies throughout the year, and thus whether larval survival is likely to be greater at a particular time of year.

6.1.5 Recruitment

Monitoring of juvenile recruitment (pre-recruits) of crabs in Shark Bay is likely to be useful for stock assessment and management (Caputi et al. 2014). Firstly, quantifying recruitment may enable prediction of subsequent catches of legal-sized crabs. Secondly, over time, these data may be used in combination with indices of spawning stock abundance to derive a stock-recruitment relationship, which in turn, can be used to understand whether current spawning stock levels are sufficient for good recruitment (i.e. as a basis for management) and/or understanding impacts of environmental variables on recruitment variations about the stock-recruitment relationship. Thirdly, low recruitment levels provide an early warning that management may be required to sustain stocks levels. For blue swimmer crabs, which have a very short life cycle, this can be very important because the population age composition provides a very limited "buffer" from the combined effects of low recruitment and stock depletion through fishing.

The results of the fishery-independent sampling program indicate that relatively small (modal length of ~75 mm) 0^+ juveniles are typically most abundant in November and then dominate the catch in February, and to a lesser extent, in April. Although the seasonal indices of recruitment showed that the timing of peak catches of 0^+ recruits can vary among years, typically, the greatest abundance of 0^+ recruits was recorded during February surveys. Thus, the February survey is likely to be the most important for monitoring abundances of 0^+ recruits. Further analyses of the fishery independent trawl catches showed that the spatial distribution of 0^+ recruits in February was variable among years, with very low abundance west of the CPL pre-2012, but abundances of recruits being widespread throughout all of the trawl grounds during 2014-15. Thus, it is important that there is sufficient spatial distribution of sites in any future fishery-independent trawl sampling in Shark Bay to detect differences in spatial distribution of juvenile recruitment.

One aspect that should be noted in relation to using the fishery-independent trawl sampling to monitor recruitment is that such sampling does not capture the very small (<30 mm) early 0^+ recruits that occupy shallow, nearshore seagrass beds. Although it is possible to sample crabs of this size by alternative methods, i.e. seine netting, as shown by de Lestang (2002), and would provide a greater period before reaching legal size from a management perspective, such sampling would be very resource intensive. Furthermore, monitoring of early 0^+ recruits using nearshore seine netting would not necessarily be more informative than monitoring older 0^+ recruits by trawling, as higher and more variable natural mortality of early 0^+ recruits could result in a very weak relationship between early 0^+ juveniles and future abundance of legal-sized crabs. From a stock assessment and management perspective, and one of the lessons learned from the heat wave experience, it is critical that the juvenile recruitment abundance is observed early enough to be taken into account in the management settings.

Although sampling crabs in nearshore seagrass habitats would be too resource intensive, given the high dependence of early 0^+ juvenile crabs on seagrasses, any information that could be obtained on temporal changes in the distribution/quality of seagrass in Shark Bay would be valuable for understanding factors impacting on crab recruitment. Indeed, there is evidence that the period when the crab stock in Shark Bay declined coincided with a substantial loss (Caputi et al. 2013) of seagrass habitat within the Bay, which may have contributed to the subsequent recruitment failure recorded in 2012. It may thus be noteworthy that a study has recently commenced aimed at monitoring changes in seagrass habitats (and its effect on prawn recruitment) in Exmouth Gulf (north of Shark Bay) using a combination of ground surveys and satellite monitoring.

6.2 Future stock monitoring

The data collected through the fishery independent trawl survey program has addressed some of the key knowledge gaps in the biology of *P.armatus* in Shark Bay, however the survey does have limitations. Firstly, blue swimmer crabs are highly mobile on the sea floor, through the water column and even on the surface "hitching a ride" on outgoing tidal currents (*pers. obs.*). Trap fishers often set their traps along depth contours to increase catchability as they believe crabs move along these gradients. Validation of these movement patterns and ranges may be possible with acoustic tagging instead of conventional T-bar tags which have been largely unsuccessful in the past (Bellchambers et al. 2005). Secondly, trawling is considered a least-biased sampling method for crabs but assessing catchability is difficult and likely influenced by a suite of factors such as the effects of water temperatures, moulting and reproductive cycles, weather conditions and even by moon phases on crab behaviour and movement. These influences as well as the general patchiness of distribution, are likely reflected in the high variability in catch rates between sites, where adjacent sites differed by several orders of magnitudes. Therefore the resulting catch rates are confounded by a number of factors that are difficult to separate, and assessing the individual effects is almost impossible in the wild and difficult to replicate under laboratory conditions. Thirdly, a common criticism of trawl based surveys is the limitations on the spatial and depth coverage and, in Shark Bay, there are extensive areas that are not able to be trawl surveyed, in particular the inshore areas with depths <10 m. Nonetheless, a large proportion of the Bay where the majority (~70%) of the commercial crab catches are made is covered by the survey sites (see Figure 4.3). These surveys are costly and resource intensive but still able to deliver the information of all aspects of the life cycle including a good proxy for overall recruitment.

The National Blue Swimmer Crab Workshop (Chandrapavan 2018) identified the bias in sampling methodology as a common issue across all crab fisheries in Australia and the majority of research programs rely on trap sampling (commercial or fishery independent) for stock assessment. In Shark Bay, trawl sampling has been adopted as the primary fishery independent measure and therefore our results are not directly comparable to those of other jurisdictions.

6.3 Impact from the marine heat wave

The Shark Bay crab fishery produced one of the highest catches on record immediately before the summer heat wave in 2010/11 summer but the overall abundance of all sized crabs dropped rapidly by mid-2011 indicating a recruitment decline for the 2011/12 season. High summer temperature (January – March) greater than 26.5°C, during the juvenile phase (5-8 month old) of the crabs' life cycle showed a negative effect on recruitment. Average (25 - 26.5°C) to low (< 25°C) summer temperatures were associated with high catches for the following year thus indicating positive recruitment (Caputi et al. 2015a). The mean winter (April to August) temperature that preceded the heat wave summer was 20.9°C, and high catches are associated with years when winter temperatures were at least above 21.5°C. Warmer autumn/winter temperatures appear to be optimal for spawning success and beneficial to recruitment. In the south-west coast fisheries where water temperature is cooler than Shark Bay, spawning usually occurs in the summer. Therefore the low recruitment to the fishery in 2011/12 and subsequent stock decline was likely a combination of a very cold winter in 2010 followed by the summer heat wave over 2010/11 (see Figure 6.1b).

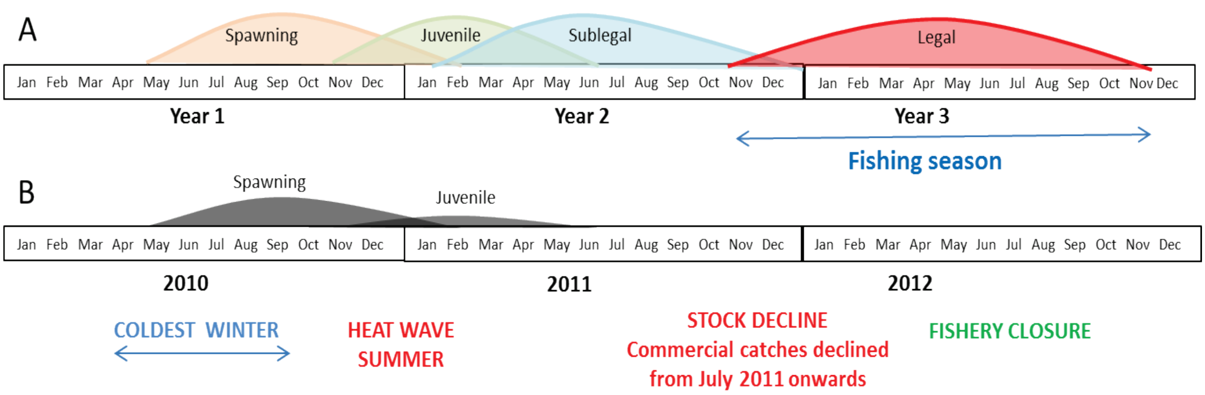


Figure 6.1. (A) A typical life cycle timeline of blue swimmer crabs in Shark Bay where the peak spawning period (orange) is over the winter months, followed by peak juvenile recruitment (green) period in the following summer months. Crabs reach maturity approximately 12 months after spawning (blue) and enter the fishery soon after (red). The crab fishing season in Shark Bay is from 1 November to 31 October. (B) Timeline showing the recruitment decline from the coldest winter temperatures recorded during the peak spawning period in 2010, followed by the summer heat wave event over 2010/11. This resulted in a very low sublegal cohort during 2011 and subsequent low commercial catches in late 2011, thus triggering a voluntary closure of the fishery in 2012.

Summer temperatures have returned to average levels after two consecutive warmer than average summers in 2011/12 and 2012/13. Despite a cooling winter temperature trend inside Shark Bay, the mean winter temperatures during 2011-15 were not as cold as during 2010, although the 2016 winter was the coldest recorded. The improvements in the overall survey catch rates since 2012 support the improving seasonal temperatures returning to within historical ranges, however the longer term trend since 1982 suggests Shark Bay is in the midst of a changing climate.

An important component of Shark Bay's circulation is driven by the large salinity gradients that create bottom outflows of dense hypersaline waters (Kangas et al. 2012). The temperature-salinity signatures of the water masses examined in this study are consistent with the general hydrodynamics of Shark Bay. Monitoring water chemistry and temperatures during surveys is now routinely undertaken and serves as additional data to complement satellite-derived information. The relationship between these outflows and larval dynamics in terms of flushing is not known.

6.4 Shark Bay under a changing climate

The marine heat wave event in the summer of 2010/11 has been described as a unique Ningaloo Niño event due to the unusual alignment of intra-seasonal to inter-decadal processes, resulting in an unseasonable surge of the Leeuwin Current and the extreme warm condition in the austral summer of 2010/11 (Feng et al. 2013). The summer heat wave and the cooler winter that preceded the heat wave appear to be part of two long-term climate trends in Shark Bay. One is the warming summer trajectory and the second is an unusual cooling winter trend for Shark Bay. Investigations are currently underway to understand the winter temperature phenomenon in the Shark Bay region (Y. Hetzel, *pers. comm.*). It appears to be related to anomalous synoptic conditions causing stronger, drier, more easterly winds blowing over the Bay and cooling the shallow areas that are furthest from the oceanic channel entrances. Preliminary analysis suggests the cooling may be linked to a southward shift in the subtropical high-pressure ridge (STR) (Y. Hetzel, *unpub. data*). During the summer months, the ridge is located to the south of the continent and the high pressure systems along the ridge tend to suppress cold frontal activity such as rainfall, temperature and wind and instead dry, stable conditions persist. As winter approaches, the STR moves northward over central Australia allowing for cold fronts associated with low pressure systems to bring colder south-westerly winds and showery conditions into southern Australia. In Shark Bay, the occurrence of moist/weak onshore winds associated with cold fronts appears to be linked to warmer than normal SST, whilst strong and dry easterly winds from the continent associated with southward shifts of the STR may lead to increased cooling. The southward movement of the high pressure ridge has been documented to be closely linked to decreased winter rainfall and less frequent cold fronts in the southwest of the State (England et al. 2006). This trend suggests that these colder winters in Shark Bay may persist in the future.

The impact of the long term warming summer temperatures and the potential impact of the cooling winter temperatures on the spawning cycles and subsequent recruitment levels will require continued stock and environmental monitoring for a stock-recruitment-environment relationship to be developed. The current variation in stock abundance and environmental conditions in the Shark Bay crab stock provides a unique opportunity for a case study. This study has revealed that inside Shark Bay, winter is becoming cooler and may have shifted forward by a few months in recent years and this may impact on the spawning cycle by contracting spawning to those months most suitable for spawning or shifting the peak timing of spawning. The marked decrease in the percentage of berried females present during the annual November trawl surveys (on the West CPL grounds) since the heat wave compared to historical years maybe evidence of this change.

Knowledge gaps remain on the larval dynamics of blue swimmer crabs and their survivorship and resilience under different environmental conditions. Outside of Shark Bay, however, the south west coast of WA has been classified as one of 24 global warming hotspots (Hobday and Pecl, 2013) and identified as a hotspot of water temperature increases in the Indian Ocean with a $1^{o}C$ increase over the past 40 years (Pearce & Feng 2007), and particularly during the austral autumn/winter period (Caputi et al. 2009). The observed impacts of changing climatic conditions on different crab stocks around Australia, and this current study highlights Shark Bay as not only a hot spot of global warming influence, but the environmental trends within Shark Bay are different to those off the WA coast with a cooling trend in winter in Shark Bay compared to a warming winter trend off the WA coast (Caputi et al. 2016). Hence, understanding climate variability and forecasting potential impacts on a stock is a key concern for both industry and fisheries managers. Survey information, particularly a measure of pre-recruits, allows for early detection of potential changes in abundance and provides the capacity for managers to respond in a timely and precautionary manner (and consistent with well-defined harvest control rules as set out in the harvest strategy). These were the lessons learnt from the Shark Bay crab stock decline and the knowledge gained from this study should improve the confidence and timeliness in the management of this fishery

6.5 Developing a harvest strategy

6.5.1 Harvest strategy (prior to 2011)

The Shark Bay crab stock, prior to the stock decline in 2012, was not managed under a formal harvest strategy but rather through the monitoring of commercial catch and trap catch rates, stock indices from the commercial trap monitoring program and the annual November fishery independent trawl survey program. Crab catches increased rapidly from < 100 t to 500 t during the experimental fishery years (1998-2004) from increased effort and efficiencies by the trap sector, while further increases in catches of up to 828 t occurred during the interim fishery years (2005-2010) due to increased crab retention by the trawl sector (see Figure 2.1). In the years leading up to the stock decline in 2012, there was no clear evidence of stock depletion given commercial trap catch rates remained above the threshold reference level of 1 kg/traplift (Figure 6.2) suggesting no risk from recruitment overfishing. However spawning stock levels (catch rates of sexually mature females and berried females) measured during the annual November trawl survey program were in decline since 2008 (although still within historical ranges) (Figure 6.3) indicating a possible risk to stock sustainability. In light of conflicting evidence and increasing catches, further research was deemed critical to address key knowledge gaps in the biology and stock dynamics to better assess stock status and make informed management decisions. A capping of the catches at 700 t was proposed and consultation with industry stakeholders was occurring in 2011. However the timing of this management action coincided with the marine heat wave event over the summer of 2010/11 and subsequent stock decline in 2012.

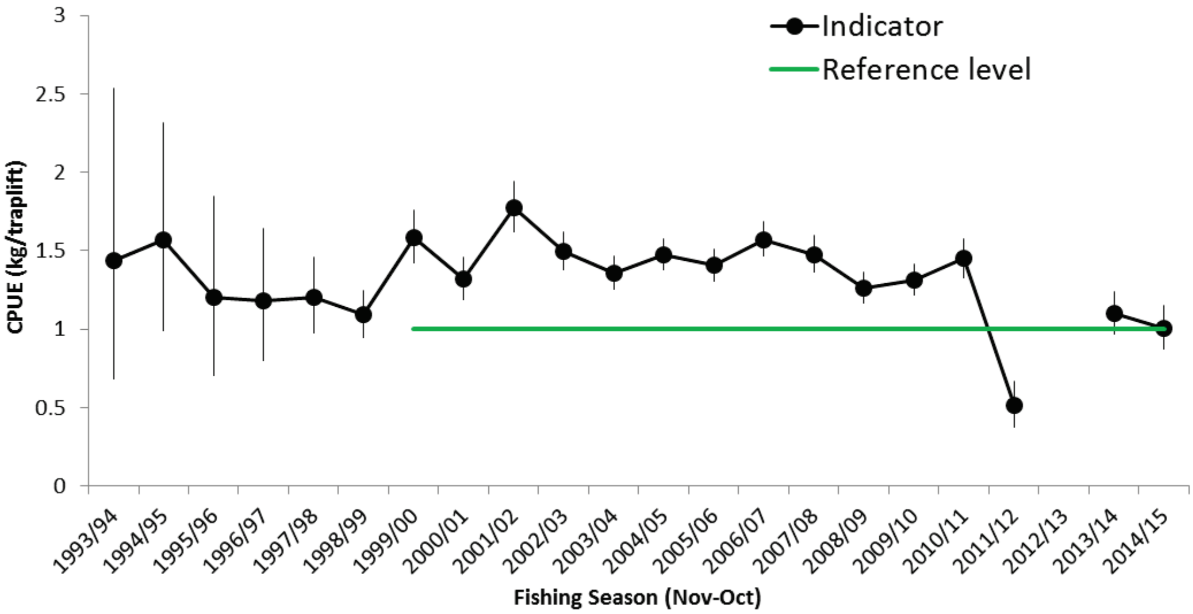


Figure 6.2. Standardised crab catch rate (kg/traplift) from the commercial trap fishery showing the historical threshold reference level of 1kg/traplift. Note the fishery was closed for the 2012/13 season.

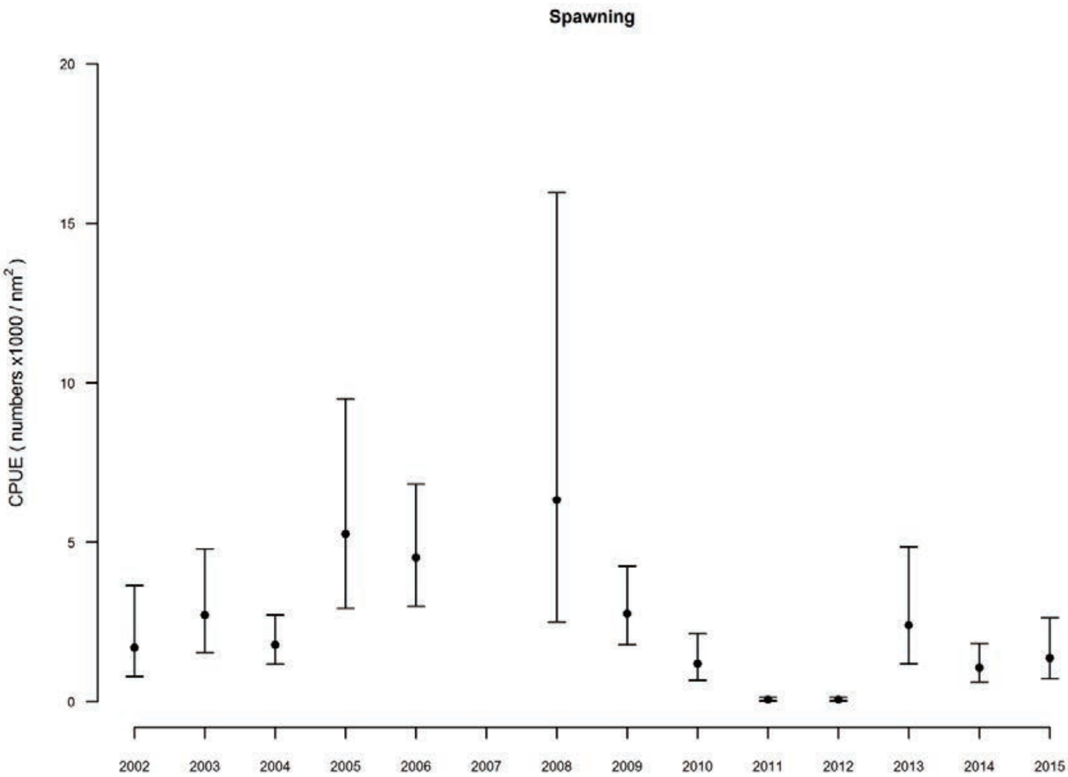


Figure 6.3. Standardised mean catch rates (± 95%CI) of spawning (mature females) biomass (based on 2013 SOM estimates) derived from the annual November trawl survey dataset (between 2002 and 2015, excluding 2007) on the West CPL fishing grounds.

6.5.2 Stock rebuilding strategy (2012-present)

Following the voluntary closure of the Shark Bay crab fishery to commercial fishing in April 2012, an expanded (spatially and temporally) fishery-independent crab trawl survey program for blue swimmer crabs was developed to monitor the recovery of the crab population. As trawling in Shark Bay was shown to catch a wide size range of crabs, this enabled monitoring of the abundances of different components of the stock, i.e. immature crabs (juvenile recruitment levels), sexually mature female crabs (a proxy for spawning stock levels), sublegal (component of the stock not vulnerable to fishing/retention) and legal crabs (exploitable component of the stock). Thus the expanded trawl survey enabled the identification of peak recruitment and spawning periods, which were less clear from the annual November trawl survey data alone. As the trawl survey sites covered (~60-70%) key crab stock abundance within the fishery, this also provided detailed information on the areas where recruitment and spawning was most concentrated. During the first year of monitoring, crabs were largely confined to the fishing grounds east of the CPL, however by mid-2013, crab catches had increased substantially across the Bay, and strong cyclic seasonal patterns in catch rates and catch compositions were evident during 2014 and 2015. Following the closure, the survey data were crucial for demonstrating that the stock had begun to rebuild.

The decision to re-open the fishery in 2013 was largely based on evidence of stock rebuilding from increasing overall catch rates including recruits, combined with the results of a commercial fishing trial in June 2013 (allowing 20 t catch to be taken by each sector), which recorded trap catch rates of legal-sized crabs similar to those experienced in years prior to the stock decline. After consultation with industry, a TACC was set at 400 tonnes for 2013/14 (based on half the historical maximum catch), with several review points throughout the 2013/14 season allowing potential revisions to the TACC level depending on the results of further stock monitoring. The TACC was increased to 450 t for the 2014/15 season based on the following considerations;

During the 2013/14 season, commercial fishers achieved most of their quota (371 t out of 400 t) demonstrating a level of stock recovery had been achieved. The underachievement of the quota was largely attributed to non-stock related issues such as greater targeted effort on other species and quota leasing decisions rather than insufficient stock abundance. Despite the landings of 371 t of crabs in 2013/14, the survey recruitment index during February 2014 survey had increased to 38,790 crabs/nm^2 from 17,722 crabs/nm^2 in February 2013. This suggested that a small increase in the TACC of 50 t was relatively low risk. The following year, the recruitment index during February 2015 was similar to 2014 at 40,164 crabs/nm^2, and this was a key consideration for leaving the TACC at 450 t for the 2015/16 fishing season.

In comparison to the 2011 above-average water temperatures during the summer months, the water temperatures in 2012 and 2013 were closer to the historical ranges although they were still warmer than the long-term summer average temperatures. The winter water temperatures are however showing a cooling trend and its impact on recruitment is yet to be fully understood. Thus, it was considered likely that the probability of successful spawning and recruitment had increased due to improved environmental conditions from the heat wave summer but still not favourable for optimal recruitment outcome.

Presently, the Shark Bay crab stock is considered to be in a stock rebuilding phase and developing well-defined performance/reference levels from the research generated from this current study is envisaged to be priority during the next management phase. Biologically meaningful stock indices of spawning and recruitment are now available from the expanded fishery-independent trawl survey program, however the limited time series of these data means they are not yet appropriate for setting reference levels. The annual long term November trawl survey data series also provides stock indices, in particular a spawning index for the end/start of a fishing season, which could also be considered for developing reference levels. However, given the biomass dynamics modelling is based on the November index of mature crabs, development of model-based approaches for assessing stock biomass and recovery could provide a basis for developing better defined stock recovery/sustainability targets.

6.5.3 Implications of model-based results for stock assessment

Preliminary biomass dynamic modelling was undertaken to complete a quantitative assessment of stock status and to provide management options. The results help facilitate the refinement of the rebuilding strategy for the fishery, which is consistent with Department's policy on recovering stocks, i.e. that "*the recovery plan for the stock should establish what are the explicit short-term performance levels that would represent an appropriate rate of recovery consistent with the vulnerability and productivity of the species involved plus the dynamics of the fishery*" (DoF, 2015). Ultimately, this means that the rebuilding strategy for the Shark Bay crab stocks should explicitly define what constitutes an appropriate level of stock recovery, the time frame for achieving that level of recovery, and would identify the uncertainties and risks associated with the rebuilding strategy.

The results of the biomass dynamic modelling for the Shark Bay crab stock are broadly consistent with the previous understanding with respect to changes in stock status, i.e. they indicate during 2011, there was a very marked decline in spawning stock biomass and that subsequently, the stock has partially recovered following 18 months of closure. Further, the modelling also suggests that, in the years leading up to the 2011 decline, landings had risen to unsustainable levels of fishing (i.e. exceeded levels that produced catches in excess of *MSY* for several consecutive years), resulting in reductions in mature biomass. While recruitment failure and the associated decline in stock abundance in 2011 can largely be attributed to the marine heat wave event of 2010/11, managers were concerned about the heavy fishing pressure in the years prior to 2011. However the November survey data indicated that the stock prior to the recruitment failure was within historic range. Finally, the indication from the modelling is that the recovery of the stock has stalled since the resumption of fishing in 2013/14. The earlier onset and cooler winter water temperature phenomenon identified for inner Shark Bay is likely to be impacting the spawning/recruitment cycle, although a longer time series of data is needed to fully determine the nature of the stock-recruitment-environment relationship.

Lastly, the model helps with forecasting the impact of next season's catch on the biomass one year out. For example, mature biomass estimates for the 2016/17 fishing season can be modelled for hypothetical values of catch of 0, 100, 200, 300, 400 and 450 t achieved during the 2015/16 season (Figure 6.4). The results of these projection analyses indicates a full closure (i.e. 0 catch) may increase the mature crab biomass to a mean biomass level of 500 t, while a catch level of 300 t may result in similar biomass levels observed in 2014 and 2015, that is, no further increase in the stock. More importantly, the model suggests that a catch of 400 t or greater, under normal environmental conditions, markedly increases the risk of a stock decline. The modelling approach explores, through single-year model projections, likely biomass outcomes resulting from different levels of catch and represents one method that could be of benefit for the TACC setting process. An additional benefit of this type of model-based approach is that it allows exploration of the likely effects, on future stock status, of different levels of fishing on stock recovery. Furthermore, validation of model outputs can be assessed each year through the comparisons of the model projection of spawning biomass for the year ahead with the model estimates from incorporating that fishing season's catch (total achieved) and the November survey catch rate data. For example, the model projections based on differing catch levels (Figure 6.4) can be compared with actual model estimates in November when the total catch from the 2015/16 season is known along with the November survey catch rate data.

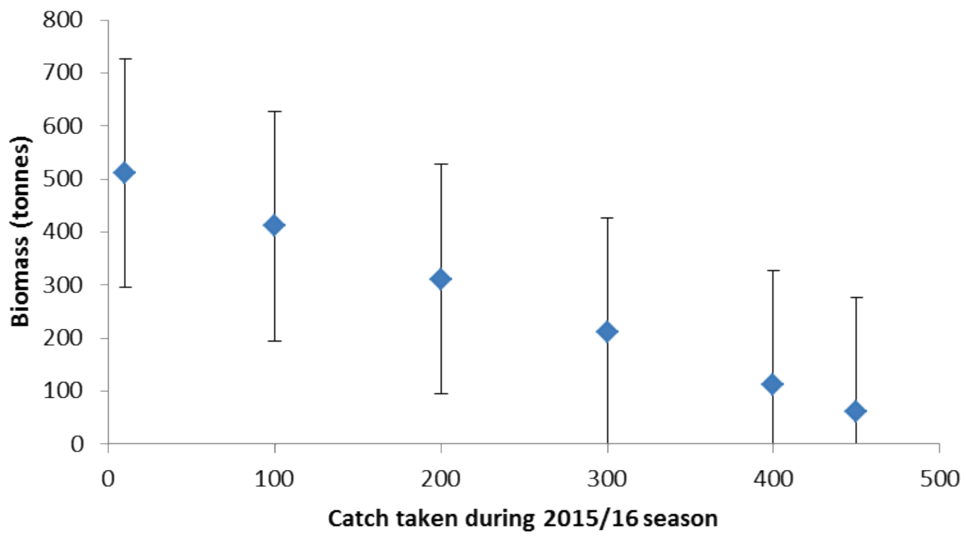


Figure 6.4. Model projections of mature biomass (±60% confidence limits) available at the beginning of the 2016/17 fishing season for alternative scenarios of catch achieved during the 2015/16 season.

Although the biomass dynamic modelling presented is of value, the results are based on limited data as well as being subject to some strong modelling assumptions. In terms of data, the annual November fishery independent survey time series is relatively short (13 years), and it is assumed that the sampling undertaken provides information that is representative of the Shark Bay crab population, and that the annual trends in crab abundance in November reflect the trends expected for other months of the year. More years of fishery independent data during other months is required to further test this assumption. However, despite this limitation, over the course of the time series, catch rates declined markedly and then began to increase, thus providing a good “signal” in the data for modelling changes in abundance.

In terms of modelling assumptions, biomass dynamic models are relatively simple models which, unlike more complex integrated models, pool a range of biological processes such as growth, recruitment and mortality into a single production function (Haddon, 2011). In contrast, more complex assessments tend to model these processes more explicitly, through incorporating more data, which potentially, enables the dynamics of the population being modelled to be better described (depending on the amount and quality of biological and fishery data available). The biological information on crabs collected during this study, i.e. on growth, size at maturity etc., can be used if, in future, a more sophisticated population model should be developed for the Shark Bay crab population, i.e. to provide a more realistic representation of the dynamics of the population. This would be useful as there is an issue with the current model in that it is not possible to account for the fact that fishing is only concentrated on a proportion of the mature stock. That is, fishers operate according to a minimum legal size (135 mm CW) that is well above the size at which crabs typically mature (~110 mm CW). Thus, potentially, the dynamics represented by applying the traditional Schaefer surplus production equation (as in this study) does not adequately describe the response of the stock to exploitation. However, the annual trends in the November fishery independent survey catch rates for the exploitable vs mature components of the stock are virtually the same (Figure 5.7), which provides some indication that the fishery impacts similarly on these two components of the stock. To model both the proportion of the population that is mature but not exploited and that which is both mature and exploited would require the development of an alternative, more complex model. To assess whether such additional model complexity is needed to provide reliable model assessments and predictions would require detailed analysis.

Finally, it is also important to recognise that environmental factors have been shown to play an important role in influencing population dynamics through changes in recruitment. In this study, attempts were made to incorporate the influence of temperature on recruitment within the model, by linking annual winter and/or summer temperatures to the production function (data not shown), i.e. as warmer winter temperatures and cooler summer temperatures are considered favourable for recruitment. Incorporation of temperature improved the model fit marginally (i.e. a slightly lower negative log-likelihood) but likelihood-ratio tests did not detect a significant difference. Given the results provided earlier (see Section 5.6.1), it would appear likely that if recruitment could be modelled explicitly, then temperature would be found to be a significant factor.

6.5.4 Assessing current risk status of stock

In assessing the overall stock status and inherent vulnerability to fishing of the Shark Bay crab stock, a risk-based assessment using a weight of evidence approach has been applied taking into consideration all the historical and current commercial catch data, fishery independent survey data, life-history traits, environmental conditions and model outputs. The lines of evidence are based on the available research data both prior to biomass decline and also during the current rebuilding phase. The Department's ISO 31000 based risk assessment framework (Fletcher, 2015, see Appendix D 13.4) has been used to determine the most appropriate combinations of consequence and likelihood to determine the overall current risk status of the stock as presented below.

Table 4. Summary of lines of evidence used to assess risk to sustainability of the Shark Bay crab fishery. Note the following stock assessment was done using data up to August 2016.

Category	Lines of evidence
Catch	Historically, the landed catches of crabs increased rapidly from < 100 t to 500 t from increased effort by the trap sector during this fishery's experimental phase (1998-2004). During the crab fishery's interim management phase (2005-2010), landed catches further increased up to a peak of 828 t from increased retention of crabs by the trawl sector. In 2011/12, extreme environmental conditions during 2010/11 resulted in a severe recruitment decline and the stock was severely depleted and it was closed to commercial fishing. Since reopening in late 2013 under quota management, the catch levels achieved have been below the TACCs by 7% during 2013/14 (371 out of 400 t) and by 24% during 2014/15 (341 out of 450 t) (Figure 2.1). The current catch level for the 2015/16 season is approx. 222 t and anticipated to only reach 300 t by end of season. Catch levels consistently below quota levels may indicate that the abundance of the stock is significantly lower than anticipated. **This line of evidence suggests the current level of stock recovery may not be sufficient to support the current quota setting at 450 t.**
Effort	The levels of effort (traplifts, days and months fished) currently being applied by the trap sector are considerably lower than historically used. Reduced trap effort levels are also influenced by leasing arrangements with the trawl sector, which may indicate that the abundance is not sufficient to economically utilise the available effort. Changes in trawl effort for crabs are under investigation. **This line of evidence is consistent with the abundance being lower than anticipated and not sufficient to support the current quota setting at 450 t.**
Effort distribution	There has been no expansion in the traditional crab fishing grounds by either sector, however a contraction in the areas fished by the trap sector is evident from the log book data. Distribution of effort has reduced from historical years and this is may reflect reduced effort levels (fishing days and months). **As there is evidence of contraction to the effort distribution, this is also consistent with the current crab abundance being lower than historically.**
Catch rates	Commercial catch rates are currently based only on the trap sector until reliable trawl based catch rates for crabs are available. Historically, the average CPUE was 1.32 kg/traplift (2005-2010), and since fishing resumed, the average CPUE is 0.92 kg/traplift (2013-15) (). Although these catch rates represent different management systems, given the TACC is not achieved for the past three seasons, the lower CPUEs reflect a combination of lower abundance, but also changes in marketability/economics and quota leasing arrangements. **Reduced trap catch rates indicate lower abundance, while the leasing of quota to the trawl sector further reflects the need to optimise economic output.**
Vulnerability (PSA)	Blue swimmer crabs are short lived (max 3 years) and in Shark Bay they mature at around 12 months and start to recruit into the fishery between 12 and 18 months of age. With a productivity score of 1.17 and susceptibility score of 2.36,

	the derived PSA score is 1.93. **This level of vulnerability indicates a low risk to stock depletion.**
Index of spawning biomass Index of recruitment biomass	There are currently two measures of spawning stock levels; 1) The annual November fishery-independent trawl survey data series (since 2002) indicates the residual spawning biomass levels have increased since the stock depletion in 2011/12 and are now at the lower level of the historical range (Figure 6.3). 2) The expanded fishery-independent trawl survey data series has been providing an index spawning biomass during the peak spawning period in June (since 2012) (Figure 5.16), and this indicates an increase in spawning biomass when the fishery was closed and the improved levels achieved in 2013 have been maintained (i.e. no increase) for the following years between 2014 to 2016. The February fishery-independent survey provides an index of recruitment (juvenile) biomass levels (Figure 5.12). Recruitment increased considerably from 2013 to 2014 while the fishery was closed for stock rebuilding, however recruitment levels have since stabilised between 2014 and 2016. **These lines of evidence indicate that the spawning stock and recruitment levels have both partially recovered but have stabilised since fishing resumed in 2013. Under the current environmental conditions and fishing levels, no further increase in stock recovery is evident.**
Environmental factors Climate change	Shark Bay experienced the coldest winter SSTs on record prior to the hottest summer SSTs on record between 2010 and 2011, which is considered to have led to a significant recruitment decline in 2012. Water temperatures in Shark Bay have since returned to within historical ranges however cooler than average winter and warmer than average summer temperatures have been identified as a unique phenomenon that persists within Shark Bay (Figure 5.26). These trends are unfavourable for recruitment as warmer winter and cooler summer SSTs have been associated with the highest commercial catches in Shark Bay. Blue swimmer crabs are ranked "high risk" under the current climate change scenario impacting the WA coastline. **Recruitment levels in Shark Bay may currently be limited by the prevailing environmental conditions, which could be limiting or reducing the rate of further stock recovery.**
Biomass dynamics modelling	Biomass dynamics modelling indicates the current mature biomass levels to be close to 20% of the unfished level and recovery of the stock to have stalled after fishing resumed in 2013 (Figure 5.38). The modelling provided a point estimate for MSY of 666 t for this stock (assuming average environmental conditions), which suggests that the fishery was operating unsustainably with catches up to 823 t in the years leading up to the 2011/12 stock decline. The 1-year model projection analysis using different catch levels, suggests that the current catch levels of about 300 t may result in the current level of mature biomass level being maintained, and catch levels near the TACC of 450 t is likely to have a negative impact on the level of available mature biomass and pose an increased risk to stock sustainability. **Model outputs indicate that a stock depletion of mature biomass is likely to occur if catch levels near the TACC of 450 t are achieved and that the current level of mature biomass is likely to be maintained with catches around 300 t.**

Shark Bay Crab risk matrix

Consequence (stock sustainability) Level	Likelihood					Risk Score
	L1 Remote (<5%)	L2 Unlikely (5-30%)	L3 Possible (30-50%)	L4 Likely (50-90%)	L5 Certain (90-100%)	
C1 Minimal (Measureable but minor levels of depletion of fish stock)						n/a
C2 Moderate (Maximum acceptable level of depletion of stock)						n/a
C3 High (Level of depletion of stock unacceptable but still not affecting recruitment level of the stock)				X (Based on catch levels 300-371 t)	X (Based on the TACC of 450 t)	12 -15
C4 Major (Level of depletion of stock are already or will definitely affect future recruitment potential level of the stock)			X (Based on catch levels 300-371 t)	X (Based on the TACC of 450 t)		12 -16
C5 Catastrophic (Permanent or widespread and long-term depletion of fish stock, close to extinction levels)						n/a

In considerations of all the lines of evidence, the four most reliable indicators of stock status are the spawning stock and recruitment levels measured from fishery-independent survey, catch and fishing effort, trends in sea surface temperature data, and the results of the biomass dynamics modelling. Stock reference levels have not yet been formally developed for this fishery based on any of the above lines of evidence, but this is planned over the next 6-12 months with industry consultation as part of developing a formalised harvest strategy. Therefore, the indicators are used to assess the overall risk to stock sustainability under the current catch levels and also assessed if catch levels reach the current TACC of 450 t.

C1 (Minimal Stock Depletion): – Not Plausible. All the lines of evidence are consistent with there having been a greater than a minimal level of stock depletion in recent years.

C2 (Maximum Acceptable Depletion): – Not Plausible. All the lines of evidence are consistent with there having been a greater than a moderate level of stock depletion in recent years.

C3 (Unacceptable Depletion): **L4/L5** – Trends in recruitment and spawning biomass have been stable/similar for the past three years with the current spawning biomass estimates at the lower end of the historic range. The biomass modelling also indicate mature biomass levels of ~ 200 t being maintained under the current catch levels and the current below-average environmental conditions for good recruitment.

- This indicates there is a Likely(L4) likelihood of a high level of depletion to stock level occurring even by maintaining the current catch levels of about 300-370 t, with environment being the major driver of the maximum level of recruitment;
- It is Certain (L5) likelihood there will be a high level of stock depletion if catch levels are close to the current TACC levels of 450 t.

C4 (Unacceptable Depletion): **L3/L4**– All the lines of evidence support a major risk to stock sustainability with the current catch levels and environmental conditions. Maintaining the current stock recovery levels also means the stock is vulnerable to a major stock depletion if it is to experience any adverse environmental condition/s in the future (e.g. another heat wave event).

- There is a Possible (L3) likelihood of major depletion in stock level under current catch levels and environmental conditions.
- There is a higher (Likely (L4) likelihood) consequence of a major depletion to stock sustainability if environmental conditions worsen to impact on recruitment and the catch levels move towards the current TACC of 450 t and further reduce spawning stock levels.

C5 (Catastrophic) – Not plausible under current circumstances.

Summary of stock status and potential risk to stock sustainability (at August 2016)

The risk assessment indicated that if the catch levels remain between 300-371 t371t, there is a possible likelihood of major stock depletion, and if the catch levels increase beyond this range such that they approach the current TACC levels of 450 t, then there is a likely likelihood of major stock depletion. This constitutes a **High risk level** to stock sustainability, which is unacceptable and strong management measures need to be undertaken**.** The current level of catch and current environmental condition does not indicate that further stock recovery can be achieved unless further measures are undertaken to increase the protection of the mature biomass.

Addendum

The above assessment of stock status was based on the weight of evidence of all available data up until the mid 2015/16 fishing season. Since the completion of this study, there has been a significant improvement in some of the stock indices. An increased mean catch rate of the residual legal biomass at the end of the 2015/16 season and significant improvements in the commercial catch and trap catch rates during the 2016/17 season had resulted in a change in the stock status to a **moderate risk level to stock sustainability based on a 450 t TACC**. This change to the stock status is further supported by the biomass dynamics model which now indicates a recovering stock trajectory under the current environmental conditions.

7 Conclusion

All of the project objectives were met except the development of a formalised harvest strategy, which is currently under development as a result of the outcomes of this study. Significant knowledge gaps relating to the biology of *P. armatus* in Shark Bay and the status of the crab stock have been addressed through this project, which will better inform future management directions. Stakeholders will now have a greater understanding of stock dynamics and the influence of the environment and fishing levels on stock recovery.

Objective 1: To examine key drivers of the blue swimmer crab recruitment in Shark Bay, particularly environmental factors associated with low recruitment

This objective has been met, but requires ongoing monitoring and assessment. Environmental conditions such as sea surface temperatures play an important role in spawning and recruitment where negative impacts have been shown to be related to colder than average winters and warmer than average summers. These conditions were identified as being the major factor contributing to the low stock abundance and apparent recruitment failure which resulted in the closure of the fishery in 2012. This study has also identified the recent shift in the timing of cool 'winter' water temperatures and the reduction in the mean temperatures over winter months as being unique to the waters within Shark Bay. Since the stock collapse, Shark Bay has experienced different combinations of cooler than average and warmer than average seasonal temperatures than historically and the resulting recruitment levels under these new conditions are being measured to assess overall stock recovery. The other key driver of recruitment is spawning stock levels, which was likely to already have been in decline prior to the heat wave from unsustainably high catch levels. Current spawning biomass levels appear to have stabilised at the lower end of their historical range since the re-opening of the fishery. At current levels of spawning stock, environmental conditions still appear to be the major driver affecting recruitment but greater protection to the spawning stock is required to promote further stock recovery.

Objective 2: Develop and implement a stock rebuilding strategy

Objective 3: Develop a harvest strategy for improved management of the stock

These two objectives were partially achieved. The stock monitoring strategy, when implemented in 2012 (after the closure of the fishery) did not define a certain time frame for full recovery to be achieved. This has largely been due to the uncertainties relating to the environment but also the limited data available on stock status at that time. The Shark Bay crab stock is currently in a stock recovery phase and current stock status suggests that commercial catch levels need to be reduced and/or environmental conditions need to further improve for greater recovery to be achieved.

The current stock assessment, based on the research data collected during this project is more informative and reliable to enable a formal harvest strategy for Shark Bay crab stock to be developed in consultation with industry and other stakeholders.

Objective 4: Determine the socio-economic significance of the blue swimmer crabs to the commercial trap and trawl sectors in Shark Bay

This objective has been achieved. The impact of the fishery closure for both the trap and trawl sectors has been significant. Fishing businesses (particularly in the trap sector) currently struggle with low volume and prices. In addition, supply chains have adapted by value adding the product in Australia, but low volume and high factory capital and operating costs means some product is now processed overseas. This reduces the demand for local labour and reduces flow-on benefits for the Shark Bay regional area in Western Australia. This combination of factors place significant pressure on the viability of the fishery in the longer term. An economically sustainable crab fishery requires greater catches (higher TACC), lower vessel costs, or higher prices for the crab product (or a combination of these). At a business level, both horizontal and vertical integration can achieve economies of scale and thus affect the price structure and profitability. Obviously the cost structure for the trawl and trap fishery are entirely different and the prawn catch can cross-subsidise the crab catch in the trawl sector, which is not the case in the single species trap sector. However crab catches remain an important component of the trawl fishery's value, particularly in recent years when there has also be a downturn in the scallop catches which have been another important part of the trawl catch.

Objective 5: Hosting the Third National Workshop on Blue Swimmer Crab in 2015

This objective has been achieved. The workshop highlighted the high number of managed blue swimmer crab fisheries across Australia and the varying management strategies and monitoring programs within each jurisdiction. The underlying mechanism for state-wide differences largely arose from the difference in the stock biology, physical location of the stocks, availability of resources and funding, stakeholder involvement and the political drivers within each State.

8 Implications

Both the managers and industry stakeholders have greatly benefited from the outcomes of this study in providing a better understanding of the biology, environment and fishery dynamics of the crab stock both historically and also into the future. The ongoing recovery of the Shark Bay crab stock is now monitored through a series of stock indicators to understand the influence of the environment and the different catch levels on the stock sustainability. In particular, indices of spawning stock and recruitment levels are now annually monitored through fishery-independent surveys to provide timely advice on setting appropriate catch levels (TACC) 12 months in advance. This TACC setting process is still in its infancy and will be reviewed regularly as more data are gathered and with further analyses. The information gathered in this study will be an important component of the formal harvest strategy being developed and the TACC setting process.

There have been significant changes to the social and economic circumstances of fishers as a result of the stock collapse and the current recovery phase under a quota management system, based on a risk-based weight of evidence assessment. The long term implications of these changes will be more evident in the future.

The National workshop greatly benefited all sectors related to capture, processing, marketing, research and management of blue swimmer crabs in Australia and provided valuable insight into the different management strategies adopted by each State while all facing similar challenges, in particular climate change.

9 Recommendations

For the Shark Bay crab fishery, we put forward the following recommendations:

- That collection of fishery-independent survey sampling of crab abundance and reproductive condition continue for at least three time periods annually (February, June and November) to enable development of a longer time series of information that may be pivotal for annual stock assessments and in determining an appropriate TACC. These will provide the basis for determining a recruitment index (February survey), a spawning index (June), while the long-term annual November survey provides valuable information on the deeper water crab stocks that is an important component of the harvest strategy.
- Shark Bay has been identified as being a sensitive region to inter-annual climate variability, and thus SST data (both satellite derived and if possible *in situ* sampling) should continue to be routinely monitored to assess ongoing changes in seasonality, long-term trends and there likely impact on recruitment and spawning.
- The revised estimates of size at maturity from this study support the current voluntary size limit of 135 mm CW and not the legal size limit of 127 mm CW. Managers should consider amending the Management Plan to reflect this change.
- Monitoring reproductive condition of crabs will enable longer-term assessments of potential for change due to changing climate such as decreases in winter water temperature.
- Ongoing improvements to the preliminary biomass dynamics model are essential to improve the reliability of its estimates of mature biomass as one of the indicators of stock recovery.
- Development of a formal harvest strategy incorporating the key stock indicators identified in this study to form the basis of well-defined references levels and control rules.
- The "Third National Workshop on Blue Swimmer Crab" highlighted how valuable such workshops are for providing a forum to engage scientists, managers and industry members involved with blue swimmer crabs in Australia and, for timely exchanges, the next workshop should be held in 2020.

10 Further development

This project successfully established a fishery-independent survey program that is now able to provide an index of spawning and recruitment biomass levels for the Shark Bay crab stock. This information is critical for the development of a stock-recruitment-environment relationship given water temperatures play a major role in the recruitment dynamics of crabs in Shark Bay. A robust model requires a long-time series of data and continuing data collection should therefore remain a high priority for at least five years.

The development of a formal harvest strategy for the Shark Bay crab stock is currently underway with industry/stakeholder consultation in line with the Departmental Harvest Strategy policy for recovering stocks (DoF, 2015). The survey program and biomass dynamic model should be important components of this strategy.

11 Extension and Adoption

Research progress and outcomes have been conveyed to industry and other stakeholders throughout the project's duration including presentations at annual management meetings, conferences and workshops.

The research recommendations and management implications arising from this study have been discussed regularly with managers. Formal consultation with industry members will also be held. For example, the size at maturity estimates from this study support the adoption of the current voluntary commercial size of 135 mm CW as the legal commercial size limit. The survey data and biomass dynamic model have also been an important part of the TACC setting process.

There was also general support from the broader scientific community and industry stakeholders for the continuation of the workshop series to be held approximately every five years. This may pave the way for a national body or association for blue swimmer crab science and management in the future.

12 Project coverage and material developed

At the commencement of this project, a media release (attached) was provided to radio and newspaper media on 27 September 2012 and an interview was aired during the WA ABC rural report and Country Hour on the 27th September 2012.

LISTEN TO THE INTERVIEW AT: http://mpegmedia.abc.net.au/rural/regions/201209/r1010662_11374860.mp3

During July 2015, Dr Arani Chandrapavan attended the "Mid-Year Meeting of The Crustacean Society" in Sydney and presented the current study titled "*The rise, the fall and the recovery of the Shark Bay blue swimmer crab fishery.*

13 Appendices

13.1 Appendix A. Intellectual property

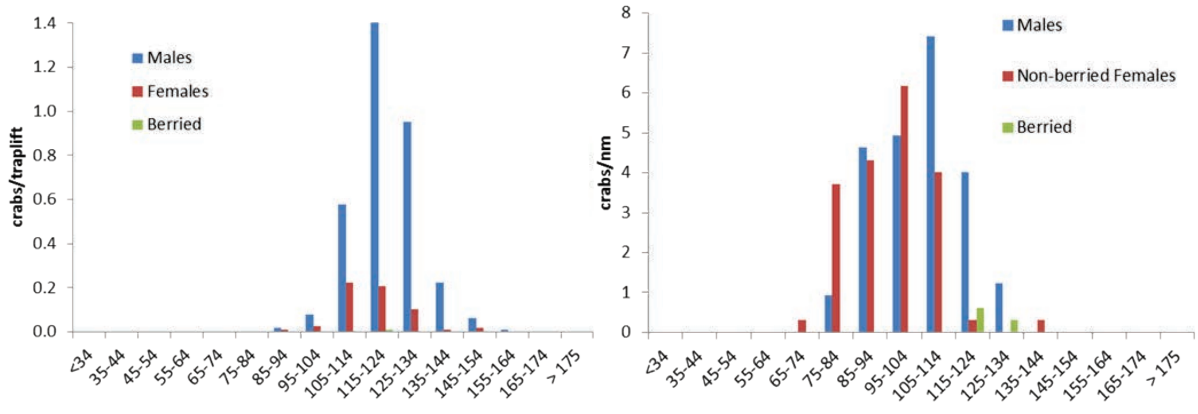
There is no intellectual property associated with this research report and it is not anticipated that any patents will arise from this project.

13.2 Appendix B. List of Staff

Principal Investigator:	Dr Mervi Kangas
Co-Investigators:	Dr Nick Caputi
	Dr Danielle Johnston
Research Scientist:	Dr Arani Chandrapavan
Statisticians:	Dr Ainslie Denham
	Dr Alex Hesp
Research Officers:	Errol Sporer
	Sharon Wilkin
Technical Staff:	Nick Breheny
	Inigo Koefoed
	Dean Meredith
	Marie Shanks
	Jessica Hommelhoff
	Chris Giles
	Adam Eastman
	Chris Marsh

13.3 Appendix C. Trap vs Trawl catch comparison

Preliminary data analysis on the comparison of adjacent trap and trawl survey sites during February 2013. Approximately 125 traps (24 hour soak time) were set in the regions overlapping sites 26, 27, 30, 33 and 36 on West CPL grounds (refer to Figure 4.4). The trawl survey was undertaken on 5th Feb 2013 and the trap survey between 12 - 13th February 2013.



Length frequency distributions and related catch composition data from trap (left) and trawl (right) methods from overlapping survey regions in Shark Bay.

Table of total number of crabs caught, sex ratio and proportion of immature, sublegal and legal crabs caught by traps(left) and trawl (right) in February 2013

TRAP SURVEY	TRAWL SURVEY
125 traplifts	3.24 nm distance trawled
Total catch = 496	Total catch = 140
Males = 85%, Females = 15%	Males = 54%, Females = 46%
Immature = 0.6 %	Immature = 32 %
Sublegal = 91 %	Sublegal = 67 %
Legal = 8 %	Legal = 0.7 %

There was a marked difference in the total crab catch, with greater number of crabs from trapping than trawling. However, the catch composition data revealed large differences in the sex ratio with only 15% of females retained in traps compared to 46% from trawling. As expected, the proportion of juvenile crabs (< 95 mm CW) was <1% in traps compared to 32% in the trawls and also in contrast, the proportion of legal sized crabs (> 135mm CW) was greater from the traps at 8% compared to 0.7% in the trawls. Sublegal sized crabs dominated the catches in both methods. Movement, catchability and behavioural aspects of crabs in and around trawl and trap gear has not been investigated in Shark Bay. But these confounding factors are likely to influence survey results. Crabs are highly mobile and the eight days between trials could result in crabs moving out of the survey region in response to food, predator or environmental stimulus. Depletion experiments on crabs in the past have not been successful in Shark Bay due to the low abundance of crabs in the area selected for depletion experiments which were not targeted on crab populations.

13.4 Appendix D. Consequence, Likelihood and Risk Levels (based on AS 4360 / ISO 31000) considered in the Department's Risk Assessment Framework

CONSEQUENCE LEVELS

1. Minimal – Measurable but minor levels of depletion of fish stock
2. Moderate – Maximum acceptable level of depletion of stock
3. High – Level of depletion of stock unacceptable but still not affecting recruitment level of the stock
4. Major – Level of depletion of stock are already (or will definitely) affect future recruitment potential level of the stock
5. Catastrophic – Permanent or widespread and long-term depletion of key fish stock, close to extinction levels

LIKELIHOOD LEVELS

1. Remote – Never heard of but not impossible here (< 5 % probability)
2. Unlikely – May occur here but only in exceptional circumstances (> 5 %)
3. Possible – Clear evidence to suggest this is possible in this situation (> 30 %)
4. Likely – It is likely, but not certain, to occur here (> 50 %)
5. Certain – It is almost certain to occur here (> 90 %)

Consequence × Likelihood Risk Matrix		Likelihood				
		Remote (1)	Unlikely (2)	Possible (3)	Likely (4)	Certain (5)
Consequence	Minimal (1)	1	2	3	4	5
	Moderate (2)	2	4	6	8	10
	High (3)	3	6	9	12	15
	Major (4)	4	8	12	16	20
	Catastrophic (5)	5	10	15	20	25

Risk Levels	Description	Likely Reporting & Monitoring Requirements	Likely Management Action
1 Negligible	Acceptable; Not an issue	Brief justification – no monitoring	Nil
2 Low	Acceptable; No specific control measures needed	Full justification needed – periodic monitoring	None specific
3 Medium	Acceptable; With current risk control measures in place (no new management required)	Full Performance Report – regular monitoring	Specific management and/or monitoring required
4 High	Not desirable; Continue strong management actions OR new / further risk control measures to be introduced in the near future	Full Performance Report – regular monitoring	Increased management activities needed
5 Severe	Unacceptable; Major changes required to management in immediate future	Recovery strategy and detailed monitoring	Increased management activities needed urgently

13.5 Appendix E. References

Aitchison, J. 1955. On the distribution of a positive random variable having a discrete probability mass at the origin. Journal of the American Statistical Association. 50:901–908.

Bellchambers, L.M., Smith, K.D. and Harris, D. 2006. An assessment of the blue swimmer crab fishery in Geographe Bay, Fisheries Research Report No. 158, Department of Fisheries, Western Australia, 40p.

http://fishnet/library/publications/frr158.pdf

Burnham, K.P. and Anderson , D.R. 2002. Model selection and multimodel inference: A practical information-theoretic approach.

Bureau of Meteorology. 2011. Monthly weather review Western Australia December 2010. Australian Government, Bureau of Meteorology.

Bureau of Meteorology. 2012. Record-breaking La Niña events : an analysis of the La Niña life cycle and the impacts and significance of 2010-11 and 2011-12 La Niña events in Australia. http://www.bom.gov.au/climate/enso/history/ln-2010-12/

Caddy, J.F. and Mahon R. 1998. A short review of precautionary reference points and some proposals for their use in data-poor situations. FAO Fisheries Technical Paper 379.

Caputi, N., de Lestang, S., Feng, M. and Pearce, A. 2009. Seasonal variation in the long-term warming trend in water temperature off the Western Australian coast. Marine and Freshwater Research 60: 129-139.

Caputi, N., G. Jackson and A. Pearce. 2013. The marine heat wave off Western Australia during the summer of 2010/11 – 2 years on. Fisheries Research Report No. 250, Department of Fisheries, Western Australia, 40pp.

Caputi, N., Feng, M., Pearce, A., Benthuysen, J., Denham, A., Hetzel, Y., Matear, R., Jackson, G., Molony, B., Joll, L. and Chandrapavan, A. 2015a. Management implications of climate change effect on fisheries in Western Australia. Part 1. Environmental change and risk assessment. FRDC Project No. 2010/535. Fisheries Research Report No. 261. Department of Fisheries, Western Australia. 176pp

Caputi, N., Feng, M., Pearce, A., Benthuysen, J., Denham, A., Hetzel, Y., Matear, R., Jackson, G., Molony, B., Joll, L., and Chandrapavan, A. 2015b. Management implications of climate change effect on fisheries in Western Australia. Part 2. Case studies. FRDC Project No. 2010/535. Fisheries Research Report No. 261. Department of Fisheries, Western Australia. 156pp

Caputi, N., Kangas, M., Denham, A., Feng, M., Pearce, A., Hetzel, Y. and Chandrapavan, A. 2016. Management adaptation of invertebrate fisheries to an extreme marine heat wave event at a global warming hot spot. Ecology and Evolution. 6 (11): 3583-3593.

Cerrato, R. M.1990. Interpretable statistical tests for growth comparisons using parameters in the von Bertalanffy equation. Canadian Journal of Fisheries and Aquatic Sciences. 47**:** 1416–1426.

Chaplin, J., Yap, E.S., Sezmiş, E. and Potter, I.C. 2001. Genetic (microsatellite) determination of the stock structure of the blue swimmer crab in Australia. Fisheries Research and Development Corporation, FRDC project 98/118.

Chandrapavan, A., Johnston, D., Sporer, E.S., O'Donoghue, S. and Cyers, C. 2013. Shark Bay Blue Swimmer Crab Fishery Status Report. In: *Status Reports of the Fisheries and Aquatic*

Resources of Western Australia 2012/13: The State of the Fisheries eds. W.J. Fletcher and K. Santoro, Department of Fisheries, Western Australia, pp. 158-163.

Chandrapavan A. 2018. Improving confidence in the management of the blue swimmer crab (Portunus armatus) in Shark Bay. Part 111. Proceedings of the Third National Workshop on Blue Swimmer Crab *Portunus armatus.* FRDC Project No. 2012/15. Fisheries Research Report 285. Department of Fisheries, Western Australia.

Daley, R and van Putten I. 2018. Improving confidence in the management of the blue swimmer crab (Portunus armatus) in Shark Bay. Part 11. Socio-economic significance of commercial blue swimmer crabs in Shark Bay. FRDC Project No. 2012/15. Fisheries Research Report No. 284. Department of Fisheries, Western Australia.

de Lestang. 2002. Biology of the blue swimmer crab, *Portunus pelagicus* (Linnaeus), in Western Australia. PhD Thesis. Murdoch University.

de Lestang, S., Hall, N.G. and Potter. I.C. 2003a. Reproductive biology of the blue swimmer crab, *Portunus pelagicus* (Decapoda: Portunidae) in five water bodies on the west coast of Australia. Fisheries Bulletin 101:745–757.

de Lestang, S., Hall, N.G., and Potter, I.C. 2003b. Do the age compositions and growth of the crab *Portunus pelagicus* in marine embayments and estuaries differ?. Journal of the Marine Biological Association of the UK, 83: 971 – 978.

de Lestang, S., Bellchambers, L.M., Caputi, N., Thomson, A.W., Pember, M.B., Johnston, D.J. and Harris, D.C. 2010. Stock-Recruitment-Environment Relationship in a *Portunus pelagicus* Fishery in Western Australia. In: Kruse GH, Eckert GL, Foy RJ, Lipcius RN, Sainte-Marie B, Stram DL, Woodby D (eds.), Biology and Management of Exploited Crab Populations under Climate Change. Alaska Sea Grant, University of Alaska Fairbanks.

doi: 10.4027/bmecpcc.2010.06.

Department of Fisheries (DoF). 2011. Resource Assessment Framework (RAF) for finfish resources in Western Australia. Fisheries Occasional Publication No. 85. Department of Fisheries, WA.

Department of Fisheries (DoF). 2015. Harvest strategy policy and operational guidelines for the aquatic resources of Western Australia.. Fisheries Management Paper, Department of Fisheries, Western Australia. No. 271**;** 44pp

England, M.H., Ummenhofer, C.C., Santoso, A., 2006. Interannual rainfall extremes over southwest Western Australia linked to Indian Ocean Climate Variability. Journal of Climate 19: 1948-1969.

Feng, M, McPhaden, M.J, S.-P. Xie S.P, and Hafner, J. 2013. La Niña forces unprecedented Leeuwin Current warming in 2011. Scientific Reports Scientific Reports 3: 1277

DOI::10.1038/srep01277.

Fletcher, D. 2008. Confidence intervals for the mean of the delta-lognormal distribution. Environmental and Ecological Statistics 15(2): 175-189. doi: 10.1007/s10651-007-0046-8

Fournier, D.A., Skaug, H.J., Ancheta, J., Ianelli, J., Magnusson, A., Maunder, M.N., Nielsen, A., Sibert, J. 2012. AD Model Builder: using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. Optimization Methods and Software. 27: 233-249.

Francesconi, K. and Clayton, D. 1996. Shark Bay: Management Paper for Fish Resources. Fisheries Management Paper No. 91. Department of Fisheries, Western Australia. 118pp.

Hanumara, R.C. and Hoenig, N.A. 1987. An empirical comparison of a fit of linear and non-linear models for seasonal growth in fish. Fisheries Research. 5 (4): 359-381.

Harris, D., Johnston, D., Sporer, E., Kangas, M., Felipe, N. and Caputi, N. 2014. Status of the Blue Swimmer Crab Fishery in Shark Bay, Western Australia. Fisheries Research Report No. 233. Department of Fisheries, Western Australia. 84p.

Hobday, A. and Pecl, G. 2013. Identification of global marine hotspots: sentinels for change and vanguards for adaptation action. Reviews in Fish Biology and Fisheries: 1-11.

Johnston, D., Harris, D., Caputi, N., de Lestang, S. and Thomson, A. 2011. Status of the Cockburn Sound Crab Fishery. Fisheries Research Report No. 219. Department of Fisheries, Western Australia. 104pp.

Johnston, D., Harris, D., Syers, C., and Lunow, C. 2012. Gascoyne Coast Blue Swimmer Crab Fishery Status Report. In: *Status Reports of the Fisheries and Aquatic Resources of Western Australia 2011/12: The State of the Fisheries* eds. W.J. Fletcher and K. Santoro, Department of Fisheries, Western Australia, pp. 161-166.

Kangas, M. I., Chandrapavan, A., Hetzel, Y.L., and Sporer, E.C. 2012. Minimising gear conflict and resource sharing issues in the Shark Bay trawl fisheries and promotion of scallop recruitment. Fisheries Research Report No 229. Department of Fisheries Western Australia. 136p.

Lai, J., Ng, P.K.L and Davie, P.J.F. 2010. A revision of the *Portunus pelagicus* species complex (Crustacea: Brachyura: Portunidae) with the recognition of four species. Raffles Bulletin of Zoology. 58 (2): 199–237.

Lloyd-Jones, L.R., Nguyen, H.D., McLachlan, G.J., Sumpton, W. and Wang Y. 2016. Mixture of time-dependent growth models with an application to blue swimmer crab length-frequency data. Biometrics: doi:10.1111/biom.12531

Melville-Smith, R., Bellchambers, L. M. and Kangas, M. 2001. The collection of fisheries data for the management of the blue swimmer crab fishery in central and lower coasts of Australia. Final FRDC Report 98/121.

Nahas, E.L. 2004. Physical processes controlling circulation and frontal zones in Shark Bay, Western Australia. Masters Thesis. University of Western Australia.

Pearce, A., R. Lenanton, G. Jackson, J. Moore, M. Feng, and D. Gaughan. 2011. The "marine heat wave" off Western Australia during the summer of 2010/11. Research Report 222, Department of Fisheries, Western Australia, 36 pp.

Pearce, A.F. and M.Feng. 2007. Observations of warming on the Western Australian continental shelf. Marine and Freshwater Research. 58: 914-920.

Pearce, A.F. and Feng, M. 2013. The rise and fall of the "marine heat wave" off Western Australia during summer of 2010/11. Journal of Marine Systems:139-156.

R Core Team (2014). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Reynolds, R. W., Smith, T. M., Liu, C., Chelton, D. B., Casey, K. S. and Schlax, M. G.2007. Daily high-resolution-blended analyses for sea surface temperature. Journal of Climate. 20: 5473-5496.

Ryan, K.L., Hall, N.G., Lai, E.K., Smallwood, C.B., Taylor, S.M., and Wise, B.S. 2015. State-wide survey of boat-based recreational fishing in Western Australia 2013/14. Fisheries Research Report No. 268, Department of Fisheries, Western Australia. 208pp.

Schaefer, M.B. 1954. Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. Bulletin, Inter-American Tropical Tuna Commission 1:25-26.

Smith, K.D., Hall, N.G., de Lestang, S. and Potter I.C. 2004. Potential bias in estimates of the size of maturity of crabs derived from trap samples. ICES Journal of Marine Science. 61: 906-912.

Somers, I.F. 1988. On a seasonally oscillating growth function. Fishbyte 6:8–11

Sumpton. W.D., Potter, M.A. and Smith G.S. 1994. The biology of the commercial sand crab *Portunus pelagicus* L. In a subtropical Australian embayment. Asian Fisheries Science. 7: 103 – 113.

Waddell, P.A., Thomas, P.W.E. and Findlater, P.A. 2012. A Report on the Gascoyne River Catchment Following the 2010/11 Flood Events. Department of Agriculture and Food: South Perth, Australia.

Walters, C. and Martell, S.J.D. 2002. Stock assessment needs for sustainable fisheries management. Bulletin of Marine Science 70: 629-638.