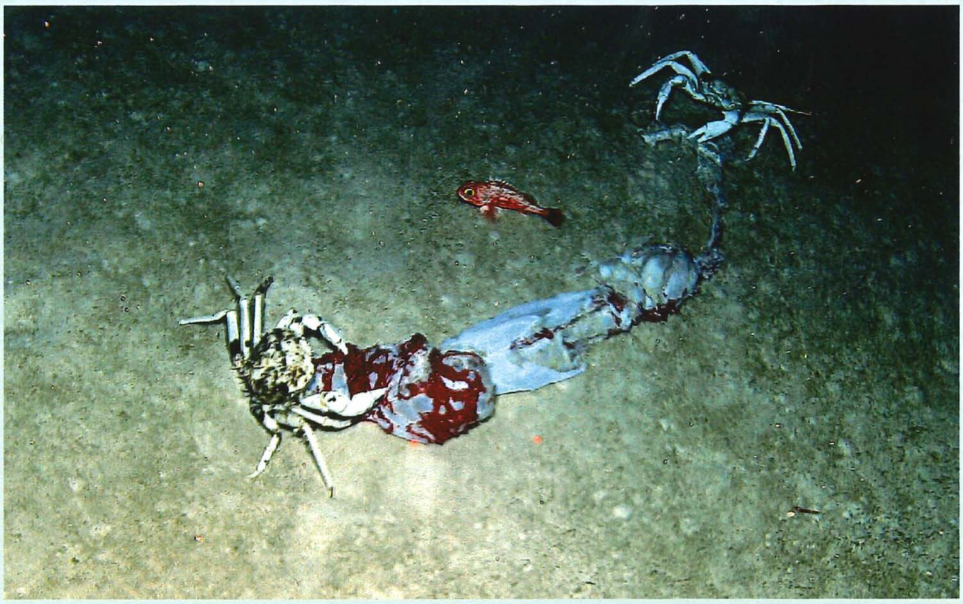
FISHERIES RESEARCH REPORT

No. 165, 2007

Biological and Fisheries Data for Managing Deep Sea Crabs in Western Australia

Final FRDC Report – Project 2001/055

R. Melville-Smith, S.M.G. Norton and A.W. Thomson



Department of Fisheries

Australian Government
Fisheries Research and Development Corporation

Fish for the future

Western Australian Fisheries and Marine Research Laboratories

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2001/055 Biological and Fisheries Data for Managing Deep Sea Crabs in Western Australia

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Non-technical summary

The crystal crab fishery on the west coast of Western Australia has only been commercially fished since the late 1990s. When this project was initiated in 2001, only compulsory monthly catch and effort data were being collected. This project has successfully set up the methods and means to collect and analyse more appropriate commercial catch and effort data for the fishery. Fishers now record detailed daily catch and effort data for legal as well as undersize and berried crabs and the Department of Fisheries, WA, has a regular monitoring programme to record population size structure information.

This project has also allowed for the collection, analysis and interpretation of biological data for the species. An extensive tagging programme has been undertaken over the five-year duration of this project. Tag recaptures have provided information on the growth rates and movement patterns of crystal crabs. These data have shown that crystal crabs grow slowly; best estimates are that legal size male crabs are 13 to 15 years old and that some large crabs in the population are around 30 years old. The size range of female crabs returned was insufficient to attempt an estimate of size at age for that sex.

Tag recaptures have also shown that neither sex, nor particular size class over the size range tagged, showed strong trends in their direction of movement after release. The majority moved less than 50 km, even after three and four years at large. Only 2% of recaptured crabs moved more than 100 km while at large.

The efficacy of escape gaps currently in use in the fishery has been examined. The gap is effective for females, but not for males. Pots fitted with two escape gaps lost approximately 16% of the legal size male catch.

In addition to researching the biology of the species, an assessment has also been made of the status of the stock. The fishery is largely focused on the coast between North West Cape and Fremantle and most of catch has been taken between 500-800 m. Fishing outside of those depths has contributed less than 5% and in some years less than 1% of the total landings.

Annual catches have hovered around 200 t since 2001 and peaked at 233 t in 2004. Effort has increased in each year except 2005. Catch rates declined from 2000, but soon stabilized and in recent years have shown an upward trend. Undersize crabs showed a continual decline in catch rates from 2000 to 2004, but in 2005 increased sharply. Berried crabs have shown a continuous increase in CPUE since 2001.

Catch length frequency monitoring has shown a decrease in mean size for both sexes, with the decline being more marked for males than females, presumably because of their larger maximum size. This decline is expected at the start of a fishery. Mean size frequencies appear to have stabilized for both sexes in recent years.

Although crystal crabs cover an extensive area they would not be expected to sustain intense fishing pressure. The reason for this is that at the depths at which they are found (~500-800 m), temperatures are low and food is probably limited. In addition, the species has been shown to be slow growing and long lived, a fact that has already been mentioned.

Given that there is uncertainty surrounding any TAC recommendation and that recent catches have been maintained at about 200 t, it has been decided that an adaptive management approach will be adopted. It is proposed that a TAC of 140 t will be set for the fishery in the future and that its performance will be monitored, primarily against cpue. It is clear that a fishery of 140 t is unlikely to support seven full time fishers, but under future management arrangements each licence holder will have an even share of quota, which will be transferable.

The success of this project is that it has established the systems, databases, sampling regimes and basic biological information that have enabled a stock assessment to be undertaken for the fishery. It has also established performance indicators to assess the status of the stock. This fishery is undergoing major changes, in moving from an interim to full management plan. The research from this project will be crucial in enabling future decisions in this fishery to be made on a scientifically defensible basis.

KEYWORDS: *Chaceon*, crab, deep-sea, movement, growth, escape gap, CPUE

Objectives:

1. Implement a voluntary logbook system in which fishers will record the number, size and location of captured crabs and establish the databases that are necessary to record and maintain logbook, size composition and tagging studies.
2. Collect and process biological research data on the size, weight, moult stage, shell state, sex ratio, gonadal weight and gonadal stage of crystal crabs caught by commercial fishers at regular intervals during the year.
3. Determine the relative abundance of crystal crabs in the various depths and regions in which this species is fished.
4. Determine the patterns of movement, growth and frequency of spawning of crystal crabs.
5. Determine the size of crystal crabs at first maturity.
6. Determine the size of the gaps that are required in the traps to allow undersize crabs to escape.
7. Undertake a depletion study to provide direct estimates of catchability and densities in different areas.
8. Produce an initial assessment of the status of the crystal crab stock on the west coast of WA.

Outcomes Achieved To Date

This project has set up the methods and means to collect and analyse commercial catch and effort data for the crystal crab fishery on the west coast of Western Australia. It has also allowed for the collection, analysis and interpretation of biological data for the species. This information has collectively been used to successfully establish the foundations for the future management of the fishery.

Acknowledgements

We would like to thank participants in the west coast deep sea crab fishery for their support of this research. Thanks goes to past and present licence holders Lance Hand, Dennis Gaunt (Pristine Fisheries Pty Ltd), Peter Kyros (H & P Kyros Pty Ltd), Ben Goh and Glen Bosman (Panorama Management Pty Ltd), Burt Boschetti (Latitude Fisheries Pty Ltd), Graham Pateman (Bouvard Fisheries), Neil and Hayes Dorrington (Yennett Pty Ltd and DA, JC, LM, NC, JG & HP Dorrington) for their input into developing the fishery for future management of the resource; and crab processors Mulataga Aquaculture, Southern Trading Co and Aussie Marine Exports (Harlequin Pty Ltd) for their assistance with catch data and tag recapture data. A special thanks goes to the past and present deep sea crab skippers David Hand, Steve “Macca” Davis, Hartley Smithwick, Vitalie-Sorin Rotaru, Terry Dixon, Drew Wassman and the late Terry Ralph, including their crews, for accommodating research staff on their vessels during ongoing research sampling trips and their assistance with the collection of logbook, biological monitoring and tag recapture data.

We acknowledge the assistance of Department of Fisheries Western Australia employed research assistants: Blair Hendriks, Tye Pope, Chad Burns, Graeme Baudains, Damon Wiggens, Kim Smith, Josh Bairstow and Roger Duggan who assisted with at-sea data collection.

Numerous Department of Fisheries, Western Australia, staff have assisted by providing policy information and/or reading and commenting on drafts of this final report. Our thanks go particularly to Drs Danielle Johnston, Simon de Lestang and Nick Caputi for reviews of the whole draft final report, and to Mr Ross Gould and Dr Lindsay Joll for useful comments and suggestions on early versions of some chapters that have been incorporated into this report.

We acknowledge our Murdoch University co-investigator research team of Dr Kim Smith and Professors Ian Potter and Norm Hall for their part in the biological and reproductive elements of the project. Their contribution to the project forms Appendix 6 of this report. Some of the raw data from their completed report have been incorporated in the Department of Fisheries database and have been used in this report.

We acknowledge the CSIRO for granting us permission to use their photographic images of crystal crabs *in situ*. These pictures were taken while mapping benthic ecosystems on the deep continental shelf and slope in Australia’s South West Region, to understand evolution and biogeography and support implementation of the SW Regional Marine Plan and Commonwealth Marine Protected Areas. That work was undertaken under CSIRO’s Wealth from Oceans Flagship Programme.

Finally, we thank the Fisheries Research and Development Corporation for financial support of this project.

1.0 General Introduction

1.1 Background

In Western Australia several large crab species occur in the offshore waters. However only three, the giant *Pseudocarcinus gigas*, champagne *Hypothalassia acerba* and crystal crab (formally commonly known as snow crab) *Chaceon albus*, are of commercial importance.

The biogeographical boundary separating the cool water of the south coast of the state from the warmer waters of the west coast has provided a logical boundary between crustacean fisheries in Western Australia (Figure 1.1). These fisheries are managed as the South Coast Crustacean Fishery (SCCF) and the West Coast Deep Sea Crab Interim Managed Fishery (WCDSCIMF). Permit holders in the WCDSCIMF are entitled to take champagne, giant and crystal crabs, but not rock lobsters. The WCDSCIMF operates along side Australia's largest rock lobster fishery, the West Coast Rock Lobster Managed Fishery (WCRLMF), where fishing generally occurs in 0-200 m. Although managed separately, licensees in the WCRLMF are permitted to retain 12 deep-sea crabs, per day per boat. Licensees in the South Coast Deep Sea Crab Fishery are entitled to take champagne, giant and crystal crabs and as a result of the licensing framework surrounding the development of this fishery, most fishers are also entitled to take southern rock lobster (*Jasus edwardsii*).

The Department of Fisheries have records of various fishers from the 1960's, 1970's and 1980's, expressing interest in establishing commercial fishing operations based on champagne, giant and 'deep sea crabs' on the west coast. Although most of these proposed ventures did not go any further, some small-scale exploratory fishing targeting champagne crabs by rock lobster fishers was undertaken between 1985 and 1990, with some rekindled interest in the 1990's. Champagne crab catches peaked between 30 and 45 tonnes for three years (1997 to 1999), before decreasing to negligible levels (< 100 kg) from 2001 onwards. The decrease in catches was in part due to a decline in champagne crab stocks, however low beach prices and increased interest in the more valuable crystal crab, which occur in deeper waters, also contributed. Therefore, on the west coast, management of giant and champagne crabs is primarily focused on ensuring biological sustainability and maintaining breeding stocks of the species rather than developing a viable commercial fishery.

Both giant and champagne crabs landings have been larger and more regular in the South Coast Crustacean Fishery than on the west coast. Since 1990 the combined giant and champagne crab catch has, in most years, been in excess of 30 tonnes, with occasional annual catches reaching 40 to 50 tonnes.

In recent times there has been a keen interest in fishing for crystal crabs on particularly the West Coast, but also on the South Coast. Crystal crabs, which occur deeper than Giant and Champagne crabs, belong to the genus *Chaceon*. The species, which is only known to occur off the Western Australian Coast, has recently been described as new to science (Davie *et al*. 2007). It has previously been incorrectly identified as *Chaceon bicolor*.

Interest in fishing for crystal crabs began on the South Coast in around 2001. Around 10 t was landed in 2002, before a moratorium was placed on targeting the species pending further research. An FRDC funded research project (Project 2003/077) has since been undertaken to determine the size frequency distribution and relative densities of crystal crab from the South Australian border to Cape Leeuwin, as well as to collect information on growth and movement of the crabs in that region. The moratorium on crystal crab fishing on the South Coast is no longer in place, but to date landings of the species have remained well below the levels achieved in 2002.

Significant catches of crystal crabs have been made on the West Coast since around 1998 and the fishery is now almost entirely dependent on the size and productivity of the crystal crab resource. The fishing has focussed on the area from North West Cape to Mandurah and has largely been confined to depths of 500-800 m. Landings over recent years have been around 200 t per annum.

The situation surrounding the crystal crab fishery on the West Coast at the start of this project, was one that besets managers of many new fisheries: on one hand being faced with a previously unfished resource that has a potentially long term yield, together with an industry geared up and keen to exploit it; while on the other hand having no catch history, biological information, or information on the spatial extent of the fishery. Given the current focus in Western Australia on the exploitation of crystal crab, this FRDC project was initiated to establish the mechanisms to (i) record appropriate catch and effort statistics and catch size structure information; (ii) obtain basic biological data on the stock, such as size at maturity, growth, movement patterns, frequency of spawning etc., and (iii) integrate this and related information to provide data suitable for assessing the state of the stock and its likely future fishing potential on the west coast.

1.2 Need

Since the crystal crab is presumably slow growing and long-lived and therefore vulnerable to overfishing, there is a pressing need for collecting baseline biological and fishery data that can be used to produce a preliminary stock assessment for assisting in the management and conservation of this species in Western Australia. Mechanisms for obtaining data on size compositions and catch statistics for the fishery in the early stages of its development need to be established so that the extent to which large animals are depleted as a result of fishing pressure can be determined.

In the early stages of the proposed work, it will be necessary to determine the catch and distribution of the commercial fishery and the size (carapace length), sex ratio and relative abundance by depth of the crabs that form the basis for the fishery. This will enable any future changes that occur in these characteristics as a result of fishing pressure to be detected.

Since crystal crabs are expected to have long intermoult periods, it will be necessary to tag crabs as soon as possible to provide, in the relatively near future, information on growth rates, movements, and estimates of yield and eggs (or spawning biomass) per recruit.

Accurate information is needed on the size at which crabs first reach maturity and how frequently spawning occurs within a year.

Information is required on the size of escape gaps in traps that would allow sub-legal sized crabs to escape and thereby prevent unnecessary mortality and displacement.

A basic stock assessment is required to meet Environment Australia's (now Department of Environment and Heritage) Schedule 4 exemption in the short term and Fisheries WA/ Environment Australia requirements which are to be initiated in December 2002.

1.3 Objectives

1. Implement a voluntary logbook system in which fishers will record the number, size and location of captured crabs and establish the databases that are necessary to record and maintain logbook, size composition and tagging studies.
2. Collect and process biological research data on the size, weight, moult stage, shell state, sex ratio, gonadal weight and gonadal stage of crystal crabs caught by commercial fishers at regular intervals during the year.
3. Determine the relative abundance of crystal crabs in the various depths and regions in which this species is fished.
4. Determine the patterns of movement, growth and frequency of spawning of crystal crabs.
5. Determine the size of crystal crabs at first maturity.
6. Determine the size of the gaps that are required in the traps to allow undersize crabs to escape.
7. Undertake a depletion study to provide direct estimates of catchability and densities in different areas.
8. Produce an initial assessment of the status of the crystal crab stock on the west coast of WA.

1.4 Management of the Fishery

As has already been noted, the Department of Fisheries has had interest from fishers in establishing commercial fishing operations on giant and champagne deep-sea crabs on the west coast from the 1960s, but significant catches have only been reported from the late 1980s onwards.

In 1991 it was recognised that with increasing interest in deep-sea crabs of all species, there was a need to move to more formal management. In January 1992, following a request for expressions of interest, the Minister for Fisheries made a press release announcing that by April 1 1992 a plan would be in place to develop the fishery. This resulted in more than 80 expressions of interest for endorsements to take deep-sea crabs outside the rock lobster fishery. In response, in June 1993, 53 endorsements were approved (49 on the south coast and four on the west coast). A one tonne catch per year minimum performance criteria was placed on each approved vessel. Following a review of these allocations, in May 1993 a further three endorsements were granted on the west coast.

Champagne crabs were intensively targeted for three years between 1997-1999, but the stock did not withstand the pressure and during those years one of the fishers that had been targeting that species (Lance Hand, Bellenden Nominees, Geraldton), began to look at other crab fishing possibilities in deeper water. His successes in finding good quantities of crystal crabs in waters deeper than 500 m led him to initiate this new fishery. As his landings increased, so too did interest in this fishery from other permit holders authorized to take deep-sea crabs.

Seven permit holders are authorized to take deep-sea crabs on the west coast. In 2000, to ensure the west coast fishery was not over exploited during its development period, the Department negotiated arrangements that allowed only three of the seven west coast endorsement holders to fish full time, while the other four could fish for a maximum of three months. The intention of this arrangement was to give all fishers the opportunity to fish for deep-sea crabs should they so wish, with the understanding that whether they fished or not, all seven permit holders would have equal access at the end of the developmental phase. These arrangements were subsequently formalized in the West Coast Deep Sea Crab Interim Managed Fishery (WCDSCIMF) which was introduced in January 2003. The plan divided the fishery on the west coast into five zones (Figure 1.1). These were defined under the Fish Resources Management Act 1994 – West Coast Deep Sea Crab Fishery (Interim) Management Plan 2003, as:

(a) Zone 1 – The waters of the Fishery that are between 129° east longitude (Western Australia/ Northern Territory border) and 21° 47.1' south latitude (North West Cape);

(b) Zone 2 – The waters of the Fishery that are between 21° 47.1' south latitude (North West Cape) and 24° 52.5' south latitude (Carnarvon);

(c) Zone 3 – The waters of the Fishery that are between 24° 52.5' south latitude (Carnarvon) and 28° 47.0' south latitude (Geraldton);

(d) Zone 4 – The waters of the Fishery that are between 28° 47.0' south latitude (Geraldton) and 32° 03.2' south latitude (Fremantle);

(e) Zone 5 – The waters of the Fishery that are between 32° 03.2' south latitude (Fremantle) and 34° 24.0' south latitude (Cape Leeuwin) up to 115° 08.0' east longitude.

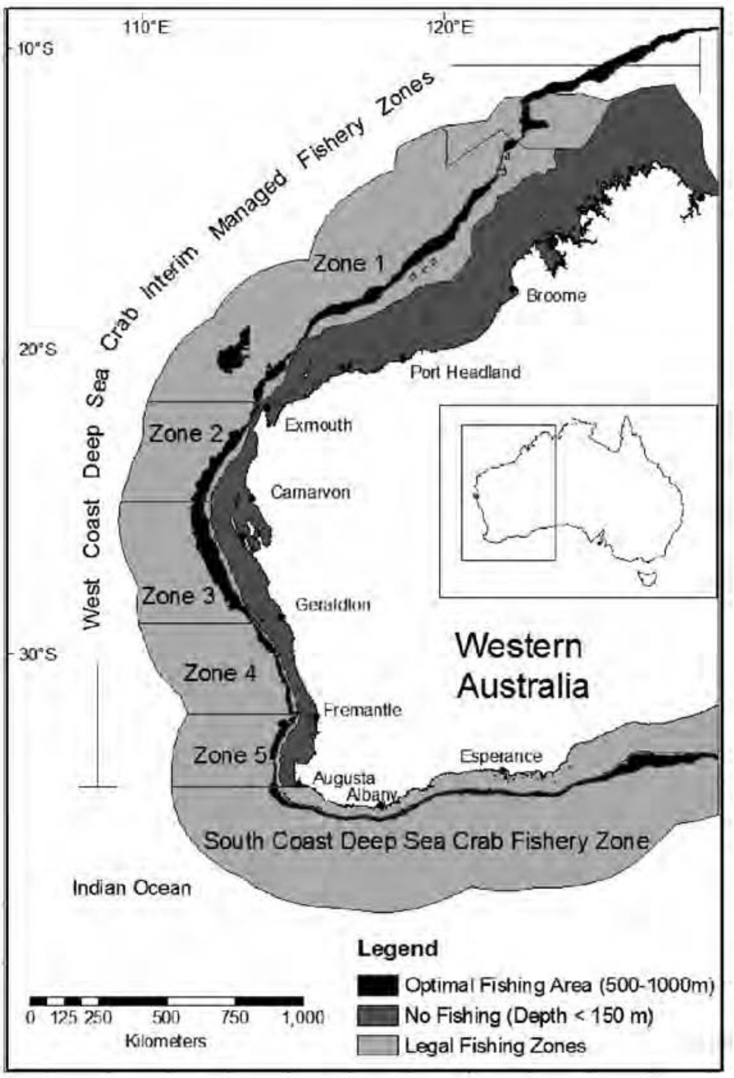

Figure 1.1 Map of the W.A. coastline showing the crystal crab management zones and depth contours between 500-1,000 m.

Under the Interim Management Plan the seven permits are issued as either full time, 'Class F', or part time, 'Class P', permits. The latter case prohibiting the holder from fishing more than three months in the year. The Interim Management Plan restricts operations in the fishery to permit holders, creates five zones in the fishery (Figure 1.1), restricts the number of permit holders in each zone (a maximum of one Class F and one Class P or two Class P), provides for annual permit fees and controls the type and number of the pots used. Fishers are only permitted to retain deep-sea crabs (*Chaceon albus, Pseudocarcinus gigas* and *Hypothalassia acerba*). There is very little by-catch in this fishery. The interim Management Plan has provision for the CEO to close all or part of the fishery for any period during the operation.

Under the interim plan the masters of authorised boats in the fishery are required to supply the Department with daily records detailing the number of traps used, location fished, catch details (numbers, weight, size and sex) and species caught (including by-catch). Fish processors are also required to provide records related to crab processing to the Department.

The intention was that the interim plan would expire on 31 December 2005, but due to delays in the drafting of a new plan, this date has been deferred to late 2007. Under the new plan, management arrangements will undergo considerable change. These are described in 8.2.

1.5 Fishing methods

Under the WCDSCIMF plan, fishers are restricted to a maximum of 700 traps in the water at any time. Fishers use moulded plastic rock lobster traps with a 5 to 10 kg flat piece of metal wired to the base of the trap to act as ballast providing stability to the pot. A side slat is removed to provide one escape gap of 301.9 mm in length by 56.5 mm height, for undersized crabs to escape. The traps are usually set on longlines of approximately 100 traps per line and are baited with fish. The traps are generally left soaking for three to seven days before retrieval and approximately 400-500 traps (four to five longlines) are pulled per day. Fishers are required to submit daily logbook catch and effort data for each line of traps fished.

Biological restrictions require that all crabs smaller than 120 mm carapace width (CW) (approx 700 g), as well as egg bearing females, must be returned to the sea. As most females are below the legal minimum size, the catch in the crystal crab fishery is male-dominated.

1.6 Extent of the Grounds

Where size frequency information exists for Geryonid crabs, populations are generally stratified by sex and size. Little of this sort of information exists for *Chaceon albus* off the Western Australian coastline, apart from Smith *et al*. (2004a; Appendix 6) which showed that the mean carapace length of the species is significantly greater on the fishing grounds south of 28°50'S (approximately Geraldton) than north of that latitude.

To date most commercial fishing for crystal crabs in Western Australia has been within the 500 to 1,000 m depth range. The area of the fishing grounds between these depth contours has been estimated in nautical miles^2 by GIS software for each of the management zones on the west coast (Figure 1.1). The results show that the amount of fishing ground in the different zones is very variable and that Zone 1, which has yet to yield commercial quantities of crabs, has approximately 1.5 times the combined potential fishing area of Zones 2 to 5 inclusive.

2.0 Spatial and temporal catch and effort trends

2.1 Methods

2.1.1 Data sources

There are three sources of catch and/or effort data for the crystal crab fishery:

1. Compulsory catch and effort statistics (CAES) is completed by each vessel in the fishery for each month of the year. These data consist of block numbers fished by one degree units (60 X 60 nautical mile grid blocks); total pots pulled per day and catch, including by-catch, in kg. The data are available since the inception of the fishery.
2. Logbook data, which are available to varying degrees of completeness prior to 2000, provide a more detailed account of fishing activities. The detailed logbooks provide daily catch records (on a longline-by-longline basis), transect numbers fished by 10 minute degrees of latitude (10 X 10 nautical mile grid), number of pots pulled per longline, estimated catch in baskets, numbers or kg per line of the target species and any by-catch species, as well as estimates (by number, not weight) of the discarded catch (i.e. ovigerous, small, soft and dead animals). Since 2003 all fishers have been providing their catch positions in the form of vessel GPS positions at the start and end of each longline.
3. Factory processing returns, which are supplied by all processors and which document the total amount (in kg) of crabs purchased from boats each fishing trip. Returns from this data source have become reliable from 2001 onwards for some processors and from 2004 onwards for all processors. These processor landings are used in conjunction with fisher logbook data to accurately estimate catches by pot-line fished.

The size (in km^2) of the crystal crab fishing grounds has been estimated using ARCMAP 9.1 to generate the chart for the fishery and calculate the areas between the 500 m and 1,000 m contour lines for each of the fishing zones. Depth contours on these charts are provided by the Department for Planning and Infrastructure (bathymetry shape files using the GCS_GDA_1994 geographical coordinate system). In deep water the depth contour intervals are large 100 m, 200 m, 500 m, 1,000 m, 2,000 m, etc. Virtually all commercial crab fishing is conducted between 500-1,000 m and we have therefore estimated the commercial fishing area within each zone as the depths between 500-1,000 m, but acknowledge that this is an overestimate given that directed fishing effort covers a narrower band of depths than 500-1,000 m, generally between 500-800 m.

2.1.2 Validation and choice of CAES and logbook information

Both CAES and detailed logbook data have been used to analyse catches over time.

Before undertaking any analysis, logbook data were plotted to reveal possible outlying catch rates. Using this method, potential anomalies in the data were identified and were rectified if necessary by examining the log sheets that had been submitted for data entry errors, as well as by consulting with the relevant fishers. The positions where the lines were recorded as being set were validated by comparing their latitudes and longitudes with the coordinates of the zone in which the vessel was licenced to fish. Where the two sets of coordinates disagreed, the validity of the catch positions were checked. Finally, the depths where the lines were recorded as being set were validated by isolating those that were < 300 m and > 1200 m and checking them for entry or interpretation error.

Crystal crab logbook data were also validated with the relevant CAES and processor return data, to eliminate discrepancies that may have occurred between different data sources. In some cases significant discrepancies occurred due to the wrong species being recorded in CAES, and these were corrected within that system. Some discrepancies were due to instances where detailed logbook records have been omitted due to missing data. This can occur because logbooks are completed by the skipper on board the fishing vessel and papers are occasionally misplaced in that sort of environment. CAES data by comparison, are generally completed by the permit holder at home. In recent years, it has been noticed that processor return data equates more closely to logbook data than CAES returns and therefore logbooks may now be a more accurate estimate of the total catch than CAES data. This may be because fishers have become more accustomed and, possibly more diligent, in completing logbooks than in the past.

The most serious shortcoming of CAES data, is that the very large 60 x 60 n. mile reporting blocks, result in catches reported by zone being less accurate than from logbook data. The borders of the zones straddle the CAES reporting grids and make it impossible to accurately attribute catches to the zones in which they were caught. Given these failings in the reporting of data, we have used CAES data when reporting catch and effort statistics prior to 2000, because logbooks were not routinely completed between 1998 when they were first introduced and 2000. Since 2000 we have only used logbook data for reporting catch and effort statistics.

2.1.3 Analysis of logbook and CAES data

Because (as discussed above) CAES has been a more reliable record of monthly and annual catch than logbooks prior to 2000, all crystal crab data presented for years before 2000 refers to catch reported in CAES. Unfortunately, CAES data are not useful for reporting effort, because there is no capacity to record day-to-day variations in the number of pots pulled in the CAES recording system. Effort values prior to 2000 have therefore been calculated by dividing catch (from CAES), by CPUE estimated from logbook data. Although logbook data in earlier years are not available for all fishing trips, there are sufficient data within each of the years to provide indicative CPUE values.

Based on the consistently low levels of effort and catch in Zone 5 over time and because most of the catch and fishing effort in Zone 5 was taken close to the border with Zone 4, we have combined these zones in most presentations of catch statistics data.

The different catch rates analyzed for crystal crabs were legal-sized non berried, sub-legal sized and ovigerous. All catch rates were analyzed in a similar way. Skewness in the distribution of catch rates was significantly reduced by the data being log-transformed prior to analysis. Where it has not been explicitly stated that the data have been log transformed, it can be assumed that raw catch rates have been used in the analysis.

Catch rates were analysed for each pot-line of the logbook data. Analysis used an effort-weighted (effort being the number of pots that were used in the line from which the observation was associated) ANOVA to determine which factors might have a significant effect on catch rates. An effort-weighted analysis was used to give greater importance to a catch rate that was obtained for a greater number of pot lifts. Factors considered in the model were:

- Y_i calendar year, $i \varepsilon \{2000, 2001, 2002, 2003, 2004, 2005\}$;
- D_k depth, $k \varepsilon \{1, 2, 3\}$, where the actual depth lies in the range < 600 if $k = 1$, 600-700m if $k = 2$ or > 700 if $k = 3$;

- S_p soak time, where p ε {1-3, > 3} days; and
- Z_j zone, j ε {2, 3, 4/5}.

All higher order interaction terms involving year, depth and zone were included in the ANOVAs. Soak time however, was only considered as an interaction factor with zone, because it was felt not to be logical that it would have valid significant interactions with other factors. It was considered possible that the interaction of soak time and zone might show significant interactions, because the same skippers and vessels tend to operate in particular zones. This means that fishing experience and practices (different soak times), are to some extent related to zone.

Significant main effects have been presented as least-squares means (LSM), so as to study the variation of the response variable being modelled after removing the influence of other significant factors. LSMs are equivalent to arithmetic means in a balanced design and were necessary to use because logbook data, by its very nature, is unbalanced. For this reason type III sum of squares were also presented in =the ANOVAs. Attention has not been given to significant interactions, because it is believed that these largely reflect the learning of fishers in their new fishery, rather than the biology of the animal.

There have been infrequent occasions when skippers have recorded the daily catch of legal sized crabs in their logbooks, but have not recorded information on undersize, ovigerous and soft-shelled crabs returned to the sea. Assumptions about the data were therefore made so as to exclude data from an analysis that reported zero crabs of a particular category because they were failed to be reported (as opposed to have really caught zero). For undersize and ovigerous crabs, it was assumed that a line of pots would always have caught at least one undersize crab. This assumption is not unreasonable given that the usual catch of undersize crabs is in the tens to even hundreds of crabs per line. Therefore, those lines for which no information on undersize crabs was recorded were removed prior to any further analysis relating to undersize crabs in the catch

In determining the depth categories it was initially trialled to use narrower depth categories to better understand the variation in catch rates over depth (i.e. < 500, 500 – 600, 600 – 700, 700 – 800, > 800 m). The much broader depth categories (< 600, 600 – 700, > 700 m) had to be used however to keep the experimental design complete (at least one observation per treatment) which is important in attaining stable results.

2.1.4 Establishing the extent of the grounds

The area of ground between the 500 and 1,000 m depth contours has been estimated in km^2 by GIS software for each of the management zones of the west cost deep sea crab fishery. The percentage of available ground has also been calculated by dividing the total area available in the west coast fishery by the area potentially available in each individual zone on the basis of depth. No attempt has been made to establish the proportion of available fishing ground for Zone 1, because there is a lack of evidence of the grounds in Zone 1 having commercial quantities of crystal crabs.

2.1.5 Establishing production by Zone

If it is assumed that the density of crabs is reasonably uniform over the grounds, then an indication of productivity of individual zones to date can be gauged from the landings made per nautical mile of fishing ground. Data used for this purpose were CAES reported catches prior to 2000 and reported logbook catches since that time. Extent of the fishing ground are those data estimated in section 2.1.4 (above).

2.2 Results

2.2.1 Catch data for legal sized crabs

Small amounts of crystal crab have been reported since 1993, but significant landings of this species only started being made in 1998, with catches escalating rapidly since that time before plateauing out between 2001 and 2005 (Table 2.1). The total catch peaked in 2004 at 233.1 t and has declined by 11% to 207.4 in 2005 (Table 2.1).

Table 2.1 Reported logbook and CAES data for catches targeting crystal crab on the West Coast. The CPUE data are for logbook catch and effort.

Year	Vessels Reporting	Logbook Catch (kg)	Logbook Effort (Pot Lifts)	Logbook Catch rate (kg/pot lift)	CAES Catch (kg)	CAES Effort (Pot Lifts)
1997	1	-	-	-	689	-
1998	2	1,144	500	2.29	7,077	3,093
1999	2	10,563	8,780	1.20	24,792	20,607
2000	3	146,497	51,227	2.86	143,337	50,122
2001	3	206,126	87,329	2.36	221,832	93,983
2002	3	196,747	98,179	2.00	205,423	102,508
2003	6	188,745	124,057	1.52	196,433	129,110
2004	4	233,085	135,446	1.72	225,794	131,209
2005	3	207,377	109,588	1.89	201,819	106,651

Catches and effort (in pot lifts) by zone, by year, are presented in Table 2.2. Zones 2, 3 and 4 have been consistently fished since 2000, but Zone 5 has been less frequently fished and in some years (2000 and 2005) virtually ignored. Because Zone 5 has always had less than 10% (and in most years less than 5%) of the catch and effort in the fishery, and because most of the limited catch and effort for Zone 5 has been near to Zone 4, these two zones have been combined in most subsequent analyses.

Table 2.2 Crystal crab catches (tonnes) and effort (in 1,000's of pot lifts) for each zone in the fishery between 1997 - 2005.

	Zone 2		Zone 3		Zone 4		Zone 5	
Year	Pot lifts	Catch	Pot lifts	Catch	Pot lifts	Catch	Pot lifts	Catch
1997	0	0	5.3	0.05	19.1	0.2	8.4	0.4
1998	0	0	42.2	5.0	20.9	2.1	0	0
1999	3.2	2.2	25.8	11.4	31.0	11.2	0	0
2000	8.4	26.1	31.0	95.4	11.8	25.1	0	0
2001	26.2	55.1	51.0	132.2	2.3	4.4	7.7	14.4
2002	28.1	46.2	35.1	101.0	30.8	42.8	4.2	6.8
2003	26.7	41.9	51.9	93.5	36.9	45.0	8.0	7.5
2004	46.8	99.0	39.2	67.0	34.2	47.0	13.0	17.2
2005	32.8	78.6	38.5	78.6	37.6	49.3	0.8	0.9

No data for Zone 1 are presented, because catches by exploratory fishing were minimal and it is assumed that there are no commercial quantities in that zone.

While the total catch for all zones has been relatively steady over recent years (Table 2.2 and Figure 2.1) the contribution made by individual zones has been quite variable. All three shown increases and plateau. The plateau occurs in 2004 in Zone 2, 2001 in Zone 3 and 2002 in Zone 4/5.

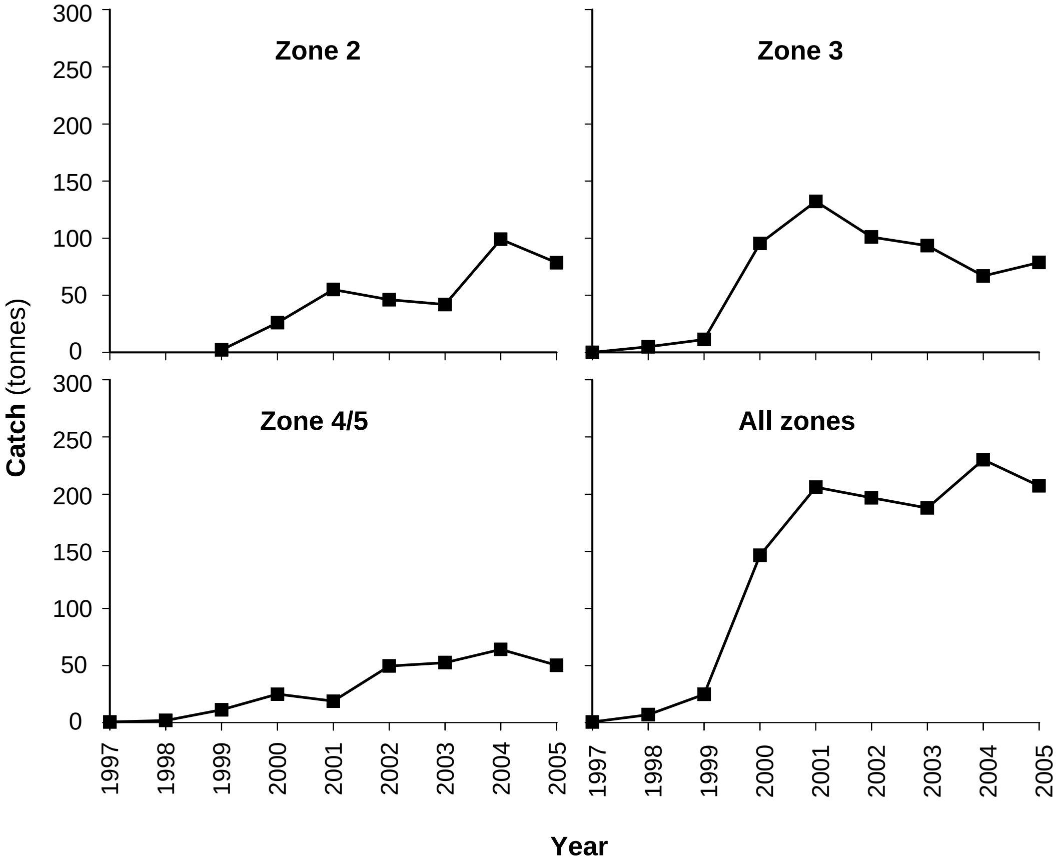

Figure 2.1 Total catch of crystal crabs (in tonnes) reported by zone from CAES data (1997 - 1999) and logbooks (2000 – 2005).

2.2.2 Effort data for legal sized crabs

Effort directed at crystal crab (expressed as number of pot lifts per day) is presented for the whole fishery in Figure 2.2 and Table 2.1 and for each of the management zones in Figure 2.2 and Table 2.2. Effort increased rapidly and maximum levels were reached in 2004. The 2005 calendar year was the first since pre-1997 to see a downturn in effort, in this case by 17.6% over the 2004 figure (Table 2.1, Figure 2.2). Effort decreased in 2005 in all fishing zones except Zone 4.

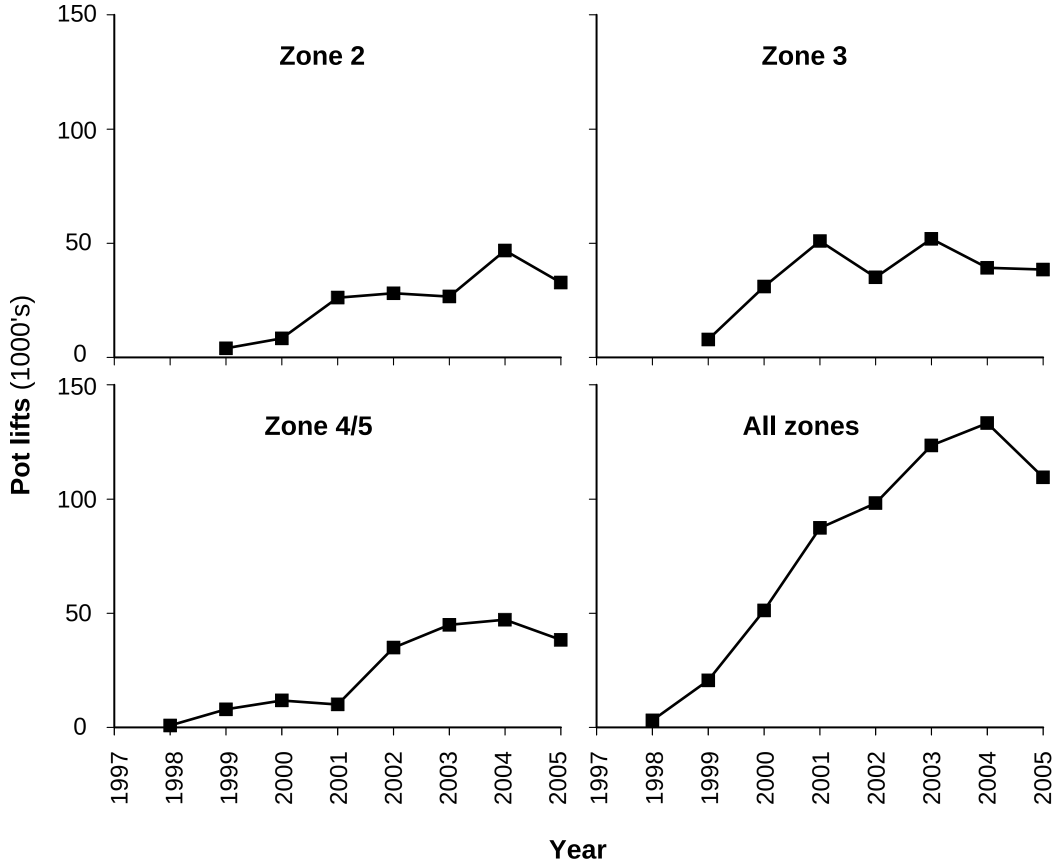

Figure 2.2 Total effort for crystal crab fishing in 1,000's of pot lifts, reported by zone from CAES data (- 1999) and logbooks (2000 – 2005).

It should be noted that effort has not been reported in Figure 2.2 for 1997, but that a catch was reported in that year (see Figure 2.1). The reason for this discrepancy is that there were no logbook data for 1997. Since effort in the earlier years has been calculated as CAES catch / logbook CPUE, that calculation has not been possible for 1997.

There was a particularly large increase in fishing effort in Zone 2 in 2004. This was due to one of the part-time fishers spending three months (the full part-time allocation period) in that Zone.

2.2.3 CPUE data for legal sized crabs

Catch per unit effort (expressed as kg/pot lift) for crystal crab fishing are presented for each of the zones in the West Coast Deep Sea Crab Fishery from 1998 onwards (Figure 2.3).

Catch rates were relatively low in some zones before 2000, probably as skippers learned the best fishing locations and how best to deploy the gear. Catch rates (unadjusted for efficiency increases) were very high in all zones in 2000 (Figure 2.3), possibly due to increased experience of the skippers, combined with the accumulated biomass of crabs in a previously unexploited fishery. As with most new fisheries, catch rates have declined for a few years as the accumulated biomass of legal sized individuals was reduced by fishing (Figure 2.3). Since 2003, CPUE has been relatively stable in all but Zone 2, where it has shown an increasing trend. The increase coincided with the introduction of the additional fishing effort of one of the part-time fishers who used different (but legal) selection criteria in selecting crabs for processing, to those of the full time licence holder in that Zone.

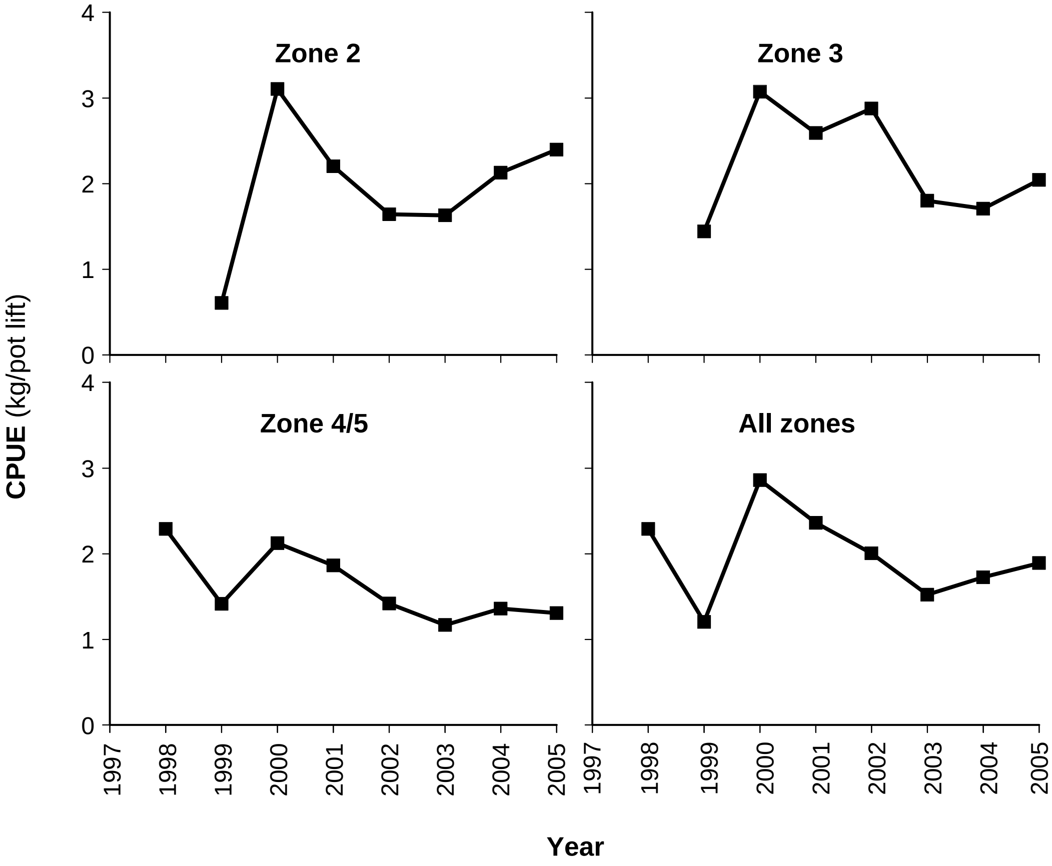

Figure 2.3 Catch rate of crystal crab (kg/pot lift) as determined from logbook data, 1998-2005.

2.2.4 Logbook analysis for legal size crabs

The total amount of catch targeting particular fishing depths in Zones 2 to 5 each year between 2000 – 2005 is presented in Table 2.3. It is clear that most fishing has taken place each year in the 500-800 m depth range. In 2000 around 14% of the catch was recorded as being taken deeper than 800 m. Such a high proportion of the catch being taken from that depth category appears doubtful given what has been the case in subsequent years, however there is no way of retrospectively validating these particular catch depth allocation figures. Since 2001, the amount of catch taken from outside of 500-800 m has varied from 0.03-4.2%, with the majority of this catch being taken in the < 500 m interval.

Table 2.3 Total annual catch (t) reported in different depth intervals, 2000-2005.

Year	Depth (m)				
	< 500	500-600	600-700	700-800	> 800
2000	270	26,136	61,745	36,831	20,040
2001	107	30,195	147,738	25,361	1,675
2002	0	16,511	154,811	23,209	60
2003	7,009	26,715	118,198	28,584	382
2004	7,676	42,001	131,320	35,785	524
2005	3,938	42,693	119,062	41,139	0

Logbook data have been used to derive CPUE indices for each boat, using accurate position (latitude/longitude), depth and catch information for each line set. Factors affecting catch rates have been examined using an effort-weighted ANOVA, taking into account calendar year, depth, soak time and zone. The result (Table 2.4) showed all factors to have a significant effect ($p< 0.01$).

Table 2.4 The weighted (in terms of pot lifts) ANOVA for the catch rate of crystal crabs as recorded by the logbook program. Type III sum of squares have been presented. Data has been restricted to years 2000 – 2005 ($R^2 = 0.13$).

Factor	df	SS	MS	F	P
Year	5	2,747.6	549.5	60.67	< 0.01
Zone	2	741.0	370.5	40.91	< 0.01
Depth	2	139.8	69.9	7.72	< 0.01
Soak time	1	944.2	944.2	104.25	< 0.01
Year*Zone	10	926.7	92.7	10.23	< 0.01
Year*Depth	10	253.6	25.4	2.80	< 0.01
Zone*Depth	4	330.7	82.7	9.13	< 0.01
Soak time*Zone	2	170.3	85.1	9.40	< 0.01
Year*Zone*Depth	18	898.9	49.9	5.51	< 0.01
Residuals	5,265	47,685.0	9.1		

Catch rates standardised for zone, month and fishing depth, have been developed for the fishery for each year from 2000-2005, (Figure 2.4). There was a sharp decline in CPUE from 2000 to 2003 which we believe was due to depleted densities of legal size animals on the grounds over this period as a result of fishing pressure. In the last couple of years there has been a small increase in CPUE which could be due to efficiency increases in the fishery, good cohorts of recruiting animals or changes in fishing patterns. These possibilities are considered in more detail in section 2.3.

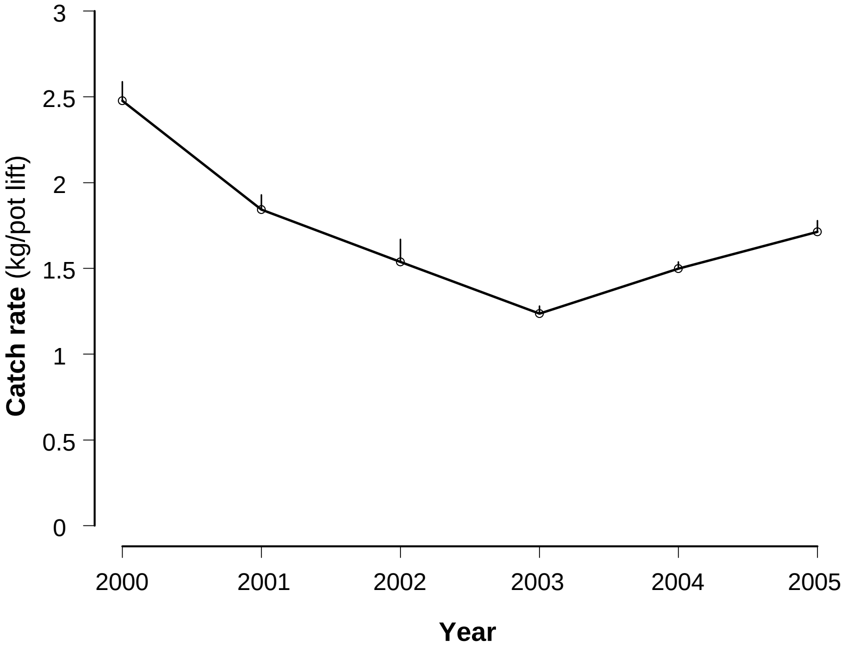

Figure 2.4 The LSM catch rate of legal crystal crabs (kg/pot lift) for 2000 - 2005. Standard errors have also been included.

It may be expected that there have been large efficiency gains in this new fishery and that they are likely to still be taking place at a rapid rate. A second set of CPUE figures have therefore been applied to the standardised CPUE data in Figure 2.4, by assuming that efficiency increases have taken place since 1998 at a rate of 5% per year. The CPUE for the fishery both with and without 5% efficiency gains taken into account, are presented in Figure 2.5. Under this scenario, it can be seen that the increase in catch rates noted in Figure 2.4 are not nearly as marked if efficiency increases are considered.

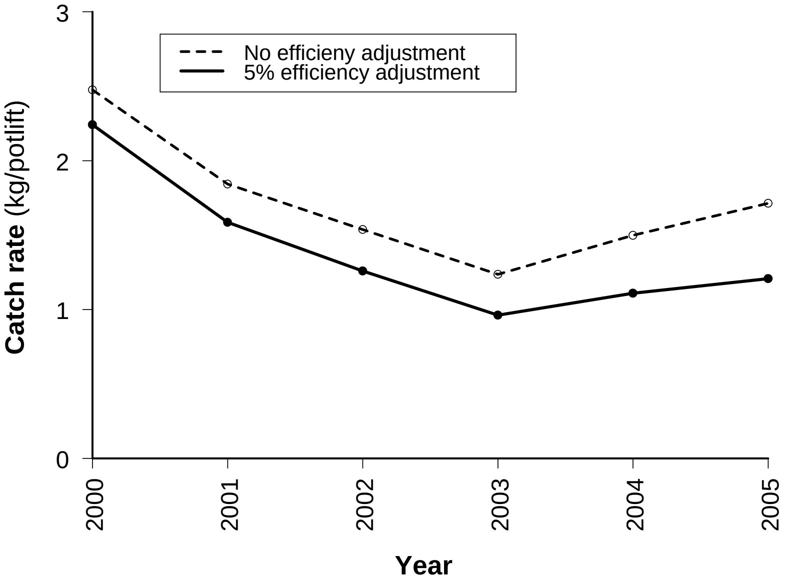

Figure 2.5 LSM catch rates of legal crystal crabs (kg/pot lift) for 2000 - 2005, under the assumption that fishery efficiency increases have been increasing at a rate of 5% per year since 1998.

The effect of each of the single factors shown to significantly influence legal size catch rates has been considered in Tables 2.5, 2.6 and 2.7. Only the main effects have been discussed, even though all of the interactions presented in Table 2.4 were significant. It is felt that the main effects give the general trend across the fishery, but it does need to be recognized that there are other influences on the result besides those single factors.

Catch rates in Zones 2 to 4 are shown in Table 2.5. Zone 3 has the highest catch rate, followed by Zone 2, and some way behind, Zone 4/5. It should be noted that this by-zone assessment of catch rates may be confounded by the fact that particular vessels and skippers have fished in discrete zones for long periods of time. Under these circumstances catch rates in the different zones can become more a reflection of a particular skipper/vessel than the density of legal-sized crabs in the zone.

Casting aside the possibility that the results might be biased in the way described above, this result might be explained by the fact that Zone 3 is the largest zone (excluding Zone 1), followed by Zone 2. Assuming that densities and fishing effort are similar on the zonal fishing grounds, then the larger the zone the higher one might expect the standardized catch rates, as the frequency of fishing in a given location would be less. If the higher catch rates in Zone 3 are a true reflection of the density of crabs across the fishery, then this would indicate that that zone is in the centre of the fishery in terms of crab abundance.

Table 2.5 The LSM catch rate of legal sized crystal crabs for each zone in the fishery.

Effect (Zone)	Value	s.e.
2	1.76	0.08
3	1.92	0.07
4/5	1.42	0.05

There has always been very little commercial fishing for crystal crabs in depths shallower than 500 m or deeper than 800 m (Table 2.3), presumably because catches outside of these depths are less optimal. Catch rates (Table 2.6) show the 600-700 m zone to provide the highest CPUE of legal sized crabs, marginally but not significantly higher than < 600 m.

Table 2.6 The LSM catch rate of legal sized crystal crabs for a range of depths.

Effect (Depth)	Value	s.e.
< 600 m	1.76	0.06
600-700 m	1.78	0.03
> 700 m	1.54	0.07

Fishers operate differently in the period that they leave their crab pots soaking between hauls. These differences are related to amongst other things, the number of pots that they are working, their location of operation and the requirements of the processors to whom they are selling their crabs. Table 2.7 shows that catch rates can be increased by leaving pots for more than three days before retrieval.

Table 2.7 The LSM catch rate of legal sized crystal crabs for two soak time categories.

Effect (Soak time)	Value	s.e.
1 – 3 days	1.55	0.04
> 3 days	1.84	0.03

2.2.5 Logbook analysis for sub-legal size crabs

An effort weighted ANOVA of catch rates for the fishery is shown in Table 2.8. As with a similar analysis for legal sized crabs, the main factors tested (year, zone, depth and soak time) were all significant. In contrast with the analysis for legal size crabs, the analysis for sub-legal crabs produced very strong year*zone interaction effects.

Table 2.8 Weighted (in terms of pot lifts) ANOVA for the log transformed catch rate of sub-legal sized crystal crabs as recorded by the logbook program. Type III sum of squares have been presented. (R^2 =0.14).

Factor	df	SS	MS	F	P
Year	5	1,805.2	361.0	23.35	< 0.01
Zone	2	155.9	78.0	5.04	0.01
Depth	2	505.1	252.5	16.33	< 0.01
Soak time	1	407.7	407.7	26.36	< 0.01
Year*Zone	10	5,687.9	568.8	36.78	< 0.01
Year*Depth	10	795.7	79.6	5.15	< 0.01
Zone*Depth	4	516.1	129.0	8.34	< 0.01
Soak time*Zone	2	84.3	42.2	2.73	0.07
Year*Zone*Depth	18	2,250.7	125.0	8.09	< 0.01
Residuals	4,953	76,590.9	15.5		

An analysis of the catch rates of undersize crabs separately by year, zone, depth and soak time and taking into account the significant and marginally significant factors affecting catch rate (above) are presented in Figure 2.7 and Tables 2.9, 2.10 and 2.11.

Catch rates have been plotted both separately for Zones 2, 3 and 4/5, and combined in Fig. 2.7. Trends within individual zones are difficult to interpret because unlike for legal sized animals, there is a much greater degree of error possible in the estimation and reporting of undersize crabs in the logbooks. Also, this error can vary depending on how dedicated the skipper is in accurately completing the log book.

In Zone 2 (Figure 2.7), there was a high catch rate of undersize crabs in 2000, but this was based on a relatively small amount of fishing effort (see Figure 2.2). The low catch rates in that Zone in 2004 was based on the highest amount of effort that has been recorded to date in that Zone and may have been influenced by differences in undersize catch rate reporting by the additional vessel that fished in that Zone in that year. There has been little change in catch rates in that Zone in the other years.

in Zone 3 (Figure 2.7), there was a particularly low catch rate recorded in 2002, once again possibly due to differences in skippers reporting undersize catch. This Zone has had a particularly high turnover of skippers compared to the other Zones. With 2002 excluded, there does not seem to be a particularly strong trend in undersize catch rates in this Zone.

Zones 4/5 (Figure 2.7) have shown a sharp decrease in undersize catch rates from the first few years of fishing to the years from 2003 onwards. There does not seem to be any obvious explanation for this change.

Combining all the undersize catch rate data for all Zones (Figure 2.7), shows there to have been a continuous decline in the catch rate of undersize crabs, which apart from the 2004 result was concomitant with the decline seen in legal sized crabs (Figure 2.4). There has been a substantial upturn in the catch rates of undersize crabs in the 2005 season which is similar to the upturn in catch rates for legal size crabs in Figure 2.4.

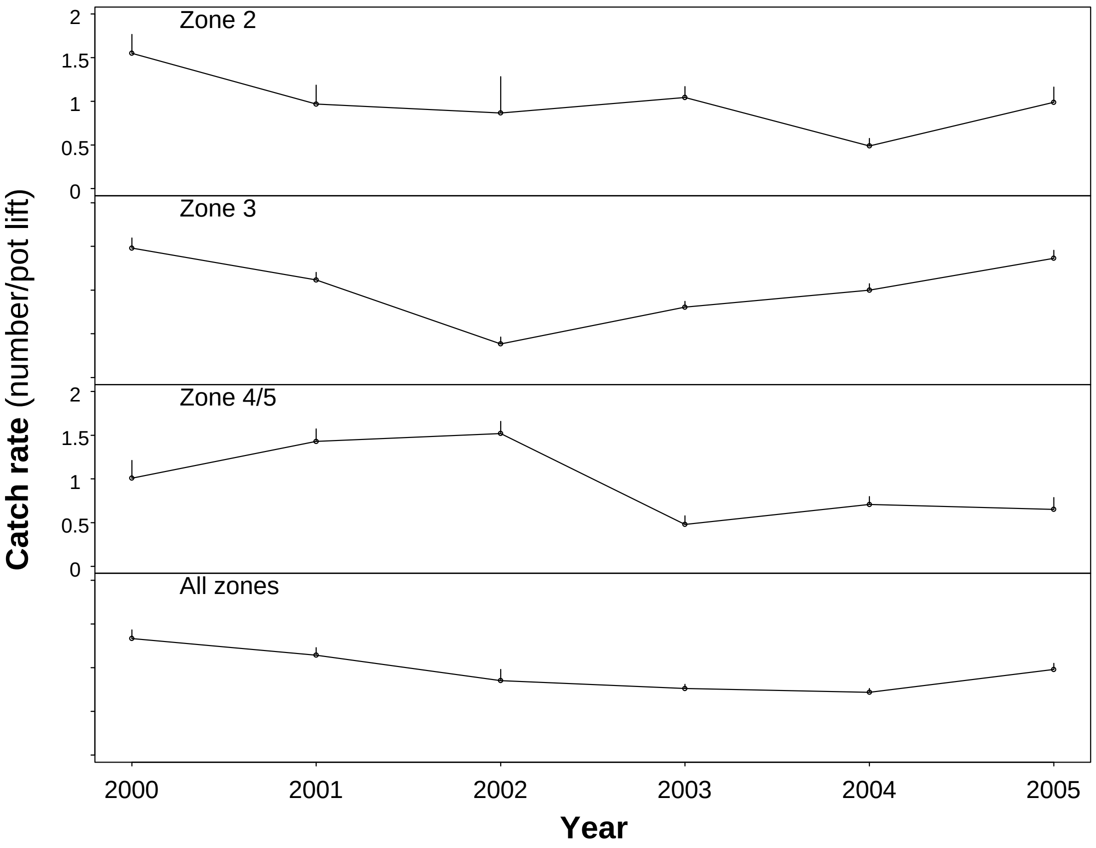

Figure 2.7 The LSM catch rate of undersize crystal crabs (number/pot lift) for each zone by year. Standard errors have also been included.

The effect of each of the single factors shown to significantly influence undersize catch rates has been considered in Tables 2.9, 2.10 and 2.11. Only the main effects have been discussed, even though all but the soak time*zone interaction in Table 2.8 were significant. It is felt that the main effects give the general trend across the fishery, but it does need to be recognized that there are other influences on the result besides those single factors.

Catch rates for undersize crabs across three zones are shown in Table 2.9. Zone 2 has the lowest catch rates of undersize crabs, but overall the range of difference in catch rates between the three zones was small, with only about 20% variation between the highest and lowest zonal CPUEs.

Table 2.9 The LSM catch rate of undersize crystal crabs for each zone in the fishery.

Effect (Zone)	Value	s.e.
2	0.83	0.07
3	1.03	0.03
4/5	1.01	0.06

Catch rates of undersize crabs for three depth zones is shown in Table 2.10. Highest numbers corresponded with the 600-700 m zone, which is the same zone that recorded the largest catch rates of legal size crabs (Table 2.6). If catch rates are a reasonable proxy for abundance, then it would seem that undersize and legal size crabs are occupying similar depth zones.

Table 2.10 The LSM catch rate of undersize crystal crabs for a range of depths.

Effect (depth)	Value	s.e.
< 600 m	0.79	0.05
600-700 m	1.14	0.03
> 700 m	0.95	0.07

As with legal sized crabs, better catch rates of undersize crabs were experienced for long pot soaking times (> 3 days) compared to short (1-3 days) Table 2.11.

Table 2.11 The LSM catch rate of undersize crystal crabs for two soak time categories.

Effect (soak time)	Value	s.e.
1 – 3 days	0.88	0.04
> 3 days	1.03	0.03

2.2.6 Logbook analysis for ovigerous crabs

Catch rates for ovigerous crabs from an effort weighted ANOVA using logbook data are shown in Table 2.12. As with similar analyses for legal and undersize crabs, year and zone were shown to be highly significant factors influencing ovigerous crab catch rates. However, in contrast to the analysis for legal and undersize crabs, depth was not significant (though at P=0.08 the significance value was marginal) and soak time was not significant at all (P=0.73). In contrast with the analysis for legal sized crabs and more in keeping with the analysis for sub-legal crabs, the analysis (Table 2.12) produced strong year*zone interaction effects.

After removing the single highly non-significant factor, soak time, LSMs for the remaining significant factors have been estimated in Figure 2.8 and Tables 2.13 and 2.14.

Table 2.12 Weighted (in terms of pot lifts) ANOVA for the catch rate of ovigerous crystal crabs as recorded by the logbook program. Type III sum of squares have been presented. ($R^2 = 0.10$).

Factor	df	SS	MS	F	p
Year	5	284.6	56.9	18.62	< 0.01
Zone	2	251.2	125.6	41.09	< 0.01
Depth	2	15.8	7.9	2.59	0.08
Soak time	1	0.4	0.4	0.12	0.73
Year*Zone	10	678.8	67.9	22.20	< 0.01
Year*Depth	10	83.0	8.3	2.72	< 0.01
Zone*Depth	4	35.8	9.0	2.93	0.02
Soak time*Zone	2	10.4	5.2	1.70	0.18
Year*Zone*Depth	18	178.7	9.9	3.25	< 0.01
Residuals	4,645	14,202.0	3.1		

Because of the strong year*zone interaction effects indicating that the trends in all zones were not the same, catch rates have been plotted both separately for Zones 2, 3 and 4/5, and in combination in Fig. 2.7. As with the under-size catch (Figure 2.7), trends within individual zones are difficult to interpret because of the potential for errors to occur in the estimation and reporting of ovigerous crabs in the catch. Also, this error is likely to vary from skipper to skipper depending on individual diligence in accurately completing the log books.

In Zones 3 and 4/5, the catch rate of crabs has remained consistently low (Figure 2.8). Zone 2 however, has produced an interesting trend over time. Catch rates of ovigerous crabs were initially very low (2002-2002), but since then they have shown a rapid increase, to maximum values in 2005 of on average, an ovigerous crab in every second pot.

Combining all the undersize catch rate data for all Zones (Figure 2.8), shows a similar but less exaggerated trend to that for Zone 2, as a result of the influence of the ovigerous catch rates in that Zone on the overall trend. The combined Zone catch rates of ovigerous crabs have increased from approximately one individual every twentieth pot, to one every fifth pot.

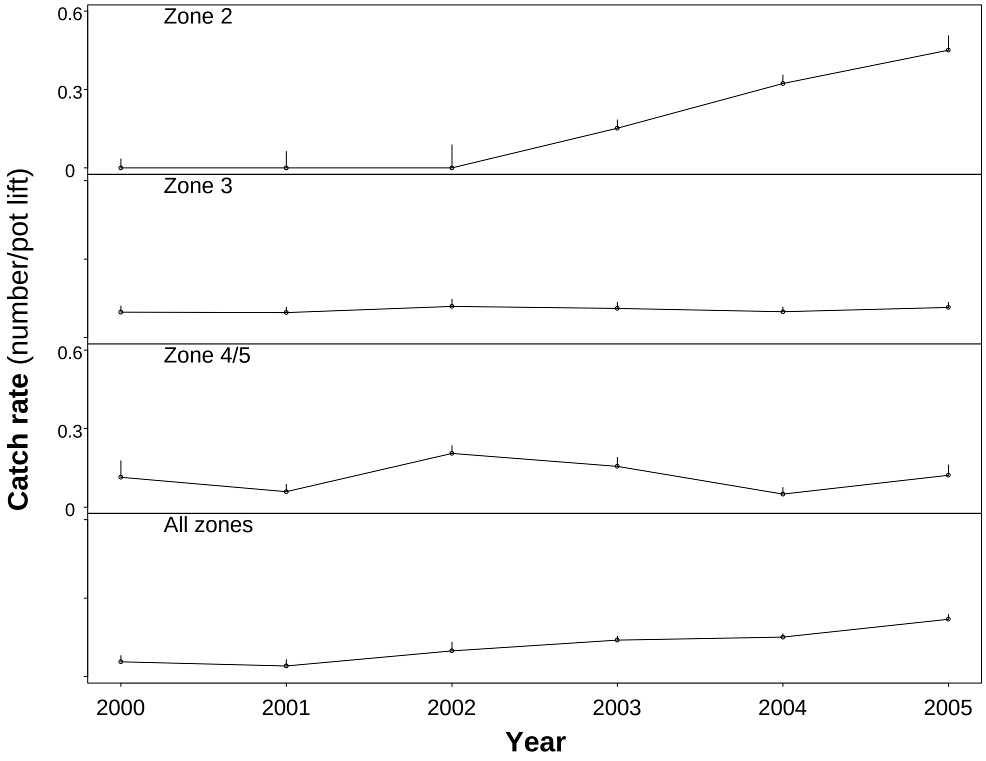

Figure 2.8 The LSM catch rate of ovigerous crystal crabs (number/pot lift) for each year. Standard errors have also been included.

The effect of each of the single factors shown to significantly influence ovigerous catch rates has been considered in Tables 2.13, 2.14. Only the main effects have been discussed, even though all but the soak time*zone interaction in Table 2.12 were significant. It is felt that the main effects give the general trend across the fishery, but it does need to be recognized that there are other influences on the result besides those single factors.

Catch rates for ovigerous crabs across the three zones is shown in Table 2.13. The data show sharp differences in the numbers of ovigerous females in different parts of the ground, with fewest ovigerous animals recorded in the central zone (Zone 3, Table 2.13). Once again it needs to be emphasized that quantities of ovigerous animals in the catch are relatively small. Based on the figures in Table 2.13, only one ovigerous female is caught on average every 20 pots in Zone 3. Compared to Zone 3, Zone 4 catches of berried females are approximately twice as common (one in every 11 pots) and four times as common in Zone 2 (one in every five pots).

Table 2.13 The LSM catch rate of ovigerous crystal crabs for each zone in the fishery.

Effect (Zone)	Value	s.e.
2	0.22	0.02
3	0.05	0.005
4/5	0.09	0.02

Catch rates for ovigerous crabs were higher in the central 600-700 m depth zones than shallower and deeper depths (Table 2.14). Given that the central depth zone is also that depth in which highest catch rates were obtained for both legal and undersize crabs, it would appear that ovigerous crabs remain in similar depths to the rest of the population and show no tendency to move to different depths when they are ovigerous.

Table 2.14 The LSM catch rate of ovigerous crystal crabs for a range of depths.

Effect (Depth)	Value	s.e.
< 600 m	0.10	0.02
600-700 m	0.14	0.005
> 700 m	0.11	0.02

2.2.7 Extent of the grounds by Zone

To date (January 2006) most commercial fishing for crystal crabs in Western Australia has been within the 500 to 1,000 m depth range (Table 2.3). In most years, well over 95% of the catch has been made between 500-800 m.

The amount of fishing ground in all of the zones is variable (Table 2.15). Of the total area of Zones 2-5, Zone 3 contains about half the area of the fishery (i.e. ground between 500-1,000 m).

Table 2.15 Estimated areas (in thousands of km^2) covering the 500-1,000 m depth zones in Zones 1 to 5 of the deep sea crab fishery, and the proportion of fishing ground in Zones 2 to 5. Area calculations for Zone 1 exclude rises in the 500-1,000 m zone offshore from the shelf break.

Zone	Area (1,000s of km^2)	% of available ground
1	65	-
2	13	26.5
3	24	49.0
4	6	12.2
5	6	12.2
Total	114	

2.2.8 Production of crystal crabs per Zone

If it is assumed that the density of crabs is reasonably uniform over the grounds, then an indication of productivity of individual zones to date can be gauged from the landings made per nautical mile of fishing ground. The amount of ground between 500-1,000 m has been calculated in Table 2.15. While all of the ground within this depth range may not be optimal fishing ground for crystal crabs, such an assessment does provide an indication (index) of the available fishing ground in the five zones.

Table 2.16 A summary of production of crystal crabs by area of the grounds from 1997 to the end of 2005.

Zone	Area of grounds (1,000s of km^2)	Total production to date (t)	Production (kg/km^2)
1	65	0	N/A
2	13	349.1	26.8
3	24	572.8	23.9
4	6	237.6	39.6
5	6	48.1	8.0
Total		1,207.6	

Substantial quantities of crabs have been harvested in Zones 2 to 4 (237-573 t). Although Zones 2 and 3 have produced considerably larger tonnages of crystal crabs than Zone 4, the latter zone has produced long term yields per km^2 of 1.5 and 1.7 times those of the two more northerly grounds. Zones 1 and to a lesser extent Zone 5 have produced comparatively little catch to date. Because Zone 5 is relatively small in terms of fishing area compared to other zones, its landed catch has translated into reasonable production over time.

2.3 Discussion

The interpretation of catch statistics data in this fishery is not straightforward. The fishery is unusual, in that the three main zones (Zones 2, 3, and 4) have largely been fished by three different boats, each belonging to a different owner. These zones have also all, to a greater or lesser degree, been fished by other ‘part time’ fishing boats in one or more years.

The fact that the full-time fishers have enjoyed long periods of uncompetitive fishing has allowed them to develop their own set of fishing rules. This has been the case in all zones, but particularly that in Zone 2, where the company fishing that zone has at various times over the years had a self imposed size limit that was well above the 120 mm CW legal size limit. That company and one other, has at times during their fishing histories also banned the taking of female crabs by their boats. In both cases these self-imposed catch restrictions have been made by the respective companies on marketing and/or perceived conservation grounds.

With the realisation that when the fishery moves to become fully managed all zones will become open to any fisher with a Deep Sea Crab licence, there has been less incentive to maintain self imposed size limits above the legal minimum size or a ban on retaining females. Accordingly these measures have been retracted in recent years. This has opened up exploitation on a previously unfished component of the fishery and has had an effect on catch, CPUE, size frequency distribution and sex ratio composition of crabs above the legal size limit.

One example of how this change in fishing behaviour has confounded interpretation of the data, is the observation in Figure 2.4 that catch rates of legal sized crabs decreased between 1998 and 2003, before showing an upswing in 2004 and 2005. There is more than one possible explanation for this increase in catch rate. One possibility might be that there could have been good recruitment into the fishery in the last two years. This seems unlikely because the species is long-lived and slow growing. Such species do not tend to show large fluctuations in recruitment to the fishery. A more likely explanation in our view, is that the staged withdrawal of self imposed catch (legal size and female) restrictions, has opened up a previously unfished portion of the stock, leading to increased catch rates. This, combined with efficiency increases resulting from fishers becoming more adapt at positioning their lines where they know they get the best catch rates, could explain the trend in Figure 2.4. The same reasons could also account for the increase in catch in Zone 2 in the last couple of years (Figure 2.1).

One effect of the fishers gradually removing their self imposed legal size and female catch restrictions, would have been an expectation of seeing a decrease in the catch rates of undersize crabs. This would have been expected to come about as more of what were previously being considered as undersize and being returned to the sea only to be recaught, were being permanently removed from the fishery as the self imposed size limit decreased. Although there has been an overall decrease in the catch rates of the under-size component of the fishery (Figure 2.7), it is clear from the variation in catch rate from Zone to Zone, that any explanation in these changes is likely to be more complex than the trend for the overall fishery suggests.

Catch rates of the legal size component of a fishery is one of the universal indicators of the state of an exploited resource. We have used two indices of CPUE for legal sized crabs in this fishery, one which assumes that there have been no efficiency increases over time and a second which assumes that efficiency has been increasing at 5% per year since 1998 when the fishery first began in earnest (Figure 2.5).

There is no doubt that efficiency in this fishery has increased. One area where this has been particularly obvious is in the ability of fishers to regularly be able to locate and haul their gear. To give but one example, in the early years there were many trips when some, or even all of the lines were inaccessible, due to the floats being dragged down by strong currents. Technology improvements have to a large extent solved this and probably many other problems that have confronted the pioneers in this industry. Whether efficiency increases have led to as much or as little as a 5% efficiency gain each year in the fishery is unknown and will need further consideration in the future. What does remain undeniable is that efficiency gains persist. A good example of this is the western rock lobster fishery, where despite input controls limiting obvious areas of technology change such as pot dimensions, the fishery is still showing efficiency increments due to technology improvements of 1-1.5% in shallow water (0-40 m) and 2-3% per year in deep water (> 40 m) (Caputi *et al.* 2000), even after 50 years of fishing.

Catch rates have been compared for pot soaking times of 1 - 3 and < 3 days. The reason that a wider range of soaking times was not examined is that the majority of pot settings in this fishery fall into a narrow range of soaking times. A wider range of soaking times would have negatively affected the balance of the design. The two soaking time periods that were considered showed that longer (> 3 day) soaking times produce significantly better catches for both legal and undersize crabs. The ability of pots to increase their catch after three days indicates that the bait fishes for relatively long periods of time. This is in contrast to crystal crab pot settings on the South Coast of Western Australia, where fishers experienced problems with their bait being predated by sea lice after very short periods (FRDC Project 2003/077), in some cases resulting in the bait being consumed before any crystal crabs got a chance to enter.

Most fishing in all zones of this study have targeted depths from 500-800 m (Table 2.3). This depth range is similar to the depths targeted by many other *Chaceon* sp. Fisheries elsewhere in the world e.g. South Africa, 400-900 m (Melville-Smith 1988); southern New England 450-720 (Holmsen and McAllister 1974); Palau, Western Caroline Islands 400-800m (Saunders and Hastie 1992).

Although these depths were the most targeted by the fishery, the species has been reported as occurring on the Western Australian coast over a far wider depth range, from 450 to 1220 m (Lance Hand, Bellenden Nominees, Geraldton, Australia and Western Australian Museum records).

It was not surprising that best catch rates of legal sizes crabs (Table 2.6) were between 600-700 m, in the middle of the depth range most frequently fished. This suggests that the bulk of the crystal crab population is confined to a relatively small area sandwiched between the 500-800 m contours. Those depths might be regarded as a hot spot in the fishery and there may be movements over time on and off these hot spot depths.

It is not possible with existing data to determine what favourable characteristics encourage the high densities of crystal crabs in the 500-800 m depth range over other depths. Temperature is relatively stable at these depths (Appendix 4) and it is possible that the crabs accumulate because they are sensitive to a narrow and well-defined temperature range. Alternatively, this depth range is on the outside margin of the Leeuwin Current core flow and it could be that this leads to high levels of particulate matter accumulating on the seabed in this depth range. High levels of particulate matter would lead to an associated increase in benthic filter feeders and detritivores, which in turn would provide food for higher order predators such as crystal crabs.

An investigation into the cause of the well-defined depth boundaries of *Chaceon maritae* off the Namibian coast was unsuccessful in isolating a single hydrological, sedimentological or biological factor responsible for causing the inshore and offshore depth distribution of that species. However, temperature and dissolved oxygen appeared to be important in limiting the shallow distribution, while particle size proved to be a possible factor limiting the offshore distribution (Melville-Smith and Bailey 1989).

It is notable that unlike most other species of *Chaceon* crabs elsewhere in the world that show a well defined gradient in size and sex ratio with depth, this species either does not appear to follow that pattern, or if it does, does not do it so markedly. The highest catch rates of undersize crabs were found in the mid-fishing depths (600-700 m, Table 2.10), indicating that it is at these depths that undersize crabs are most abundant. There was little difference in catch rates of undersize crabs either deeper or shallower of this optimal depth indicating that there is no obvious trend for higher abundances on either side of the optimal depth. Establishing definitive correlations between crab size and depth are hindered by these data because the pots are so selective for large (near legal) sized crabs.

Logbook data shows that ovigerous crabs are widespread over the grounds and unlike recorded distributions for *Chaceon* species elsewhere in the world which show a tendancy to occur more frequently in shallow depths (eg. *C. affinis*, Lóbez Abellán; *Geryon quinquedens* (since renamed *Chaceon quinquedens*) Haefner 1977), this species shows no such indication. This is surprising given that, as pointed out by Haefner (1977), there are obvious ecological benefits for ovigerous females to move into shallow, warmer water, to enhance egg development. The considerable differences in temperature between shallow and deep water on the crystal crab grounds are shown in Appendix 4.

Unlike the legal and undersize component of the catch, ovigerous crystal crabs showed no difference in catch rates when pots were set for short or long soaking times. The reason for this is unclear, but may be because ovigerous crabs are less mobile than other crabs. It may be that they only climb into pots set close to where they are sheltering and once having entered, are possibly reluctant to leave the pot. There are studies for other decapods (Branford 1978; Waddington *et al*. 2005), showing that ovigerous females, particularly those with well developed eggs, are less mobile than other animals in the population.

One of the unexpected outcomes from the logbook data was the very large increase in catch rates of ovigerous crabs in Zone 2. There is no obvious explanation for this increase.

3.0 Monitoring the commercial catch composition

3.1 Methods

Commercial crystal crab catch monitoring data have been collected by two different research organizations (Department of Fisheries WA and Murdoch University Centre for Fish and Fisheries Research) using similar methods. Methods used by the Murdoch University are outlined in Appendix 6. An outline of the methods used by the Department of Fisheries is provided below.

Department of Fisheries research staff have attempted to accompany all commercial crystal crab fishing vessels in the fleet on at least one fishing trip in each six month period over the course of this study.

In general, the catch from half the pots in a longline was measured, sexed and assessed for shell state, limb loss and maturity features (Appendix 5a Catch monitoring datasheet). The other half of the pots in the longline were used to select suitable animals (generally undersize) for tagging. In cases, where the pots have been hauled too quickly, or the catch rates in the pots have been too high for all the crabs to be measured, sampling has been limited to alternate pots.

The legal minimum size for crystal crabs is measured across the widest region of the carapace, between the two lateral spines, and is 120 mm Carapace Width (CW). These points on the carapace can wear down by small amounts during the intermoult period and become a less reliable measurement than a measurement taken lengthwise along the carapace, particularly on small animals. All measurements used for research purposes have therefore been taken as Carapace Length (CL), from the indentation between the base of the two anterior medial horns to the posterior margin of the carapace.

Relationships to enable carapace size to be converted between either length or width have been established for both sexes during the course of onboard sampling in mm to one decimal place. Some of these same crabs have been used to establish a length-live weight relationship for the species. These animals were kept live and were remeasured (to the nearest mm). After inverting the crab to allow the majority of the internal water to drip out and drying of the shell with paper towel, the crabs were accurately weighed ashore to the nearest gram. The crabs used for developing the length-width and length weight relationships were collected in an *ad hoc* way, from depths ranging between 500-800 m, from Northwest Cape (21° 47'S) to west of Fremantle (32° 03'S) and ranged in size from 75.3 – 164.8 mm CL for males and 70.0 - 128.5 mm CL for females.

Maturity in the case of males, was determined by pigmented scars on the merus of the first and second pereiopods as described by Melville-Smith 1987a. The limitation of this method is that the absence of mating scars does not necessarily indicate immaturity; it can simply indicate that the male has not mated since its last moult (Melville-Smith 1987a). Maturity in females has been determined by the state of the gonopores. This method of establishing female maturity is much more reliable than the method used for the males (Melville-Smith 1987a, Smith *et al.* 2004a).

Because so little fishing has been undertaken in Zone 1, there has been no opportunity for the catch to be sampled in that zone. Where possible, those commercial catch monitoring samples which were collected by Murdoch University in a similar way to that described for this study, and which have been reported elsewhere (Appendix 6; Smith *et al.* 2004a) have been combined with our data.

The length frequency distribution per 5 mm CL size class has been presented for crabs of both sexes for 2000-2005, by Zone. Because some of the sample sizes are small, it was considered more informative to present the distribution in each size class by numbers of animals, rather than percentage proportion.

Length frequency data have been analysed by ANOVA separately for the sexes, to examine whether carapace length was influenced by years, depth of fishing, zone of fishing and soaking time of the pots. The length frequency data standardised for these factors, has then been plotted to show trends over time.

3.2 Results

3.2.1 Carapace length-width and live weight relationships

Carapace measurements have been taken lengthwise during the course of commercial catch monitoring, but the legal minimum size is measured across the carapace (widthwise). There are therefore occasional circumstances which require carapace measurements taken one way, to be converted to the other.

To develop this ability, carapace length of animal *z* has been modelled as:

$$\text{Length}_z = a + b{*}\text{Width}_z + c{*}\text{Sex}_z + \varepsilon_z$$

where length and width of carapace are measured in mm, sex is a binary variable that identifies the animal as male (1) or female (0), a, b and c are parameters that need to be estimated and ε_z is normally distributed with mean 0. The model has been fitted and is presented in Table 3.1.

Table 3.1 Least square coefficients of a linear model describing crystal crab carapace length versus carapace width (b) and sex (c), and including the intercept (a). The significance of these coefficients to 0 is also included ($R^2 = 0.98$).

Coefficients	Value	s.e.	t-value	P
a	-5.84	0.72	-8.15	< 0.01
b	0.91	0.0057	159.51	< 0.01
c	-0.22	0.23	-0.96	0.34

There was no significant difference between the carapace length and width of males and females (P=0.34, Table 1) and the model was therefore refitted with the sexes combined.

The following relationship between carapace length and width for animal *z* was obtained:

$$\text{Length} = -5.66 \text{ (s.e.} = 0.69) + 0.90 \text{ (s.e.} = 0.0051){*} \text{ width} \qquad \text{(equation 3.1)}$$

This equation has been used throughout this study where there has been a need to express measurements as either length or width.

Sizes of crabs during monitoring of the commercial catch have been recorded as carapace length measurements. There has been an occasional need to turn this measurement into weights; for example when calculating yields per pot from catch monitoring data. To develop this ability weight has been modelled as:

$$\text{Log}_e(\text{Weight}_z) = (a + a_1{*}\text{Sex}_z) + (b + b_1{*}\text{Sex}_z){*}\log_e(\text{Length}_z) + \varepsilon_z \qquad \text{(equation 3.2)}$$

where weight is measured in grams, length of carapace in mm, sex is a binary variable that identifies the animal as male (1) or female (0), a, a_1, b and b_1 are parameters that need to be estimated and ε_z is normally distributed with mean 0. The model has been fitted and is presented in Table 3.2.

Table 3.2 Least square coefficients of a linear model describing crystal crab carapace length versus carapace width (b) and sex (c). An intercept has also been included (a). The significance of these coefficients to 0 is also included.

Coefficients	Value	s.e.	t-value	P
a	-7.62	0.12	-65.11	< 0.01
a_1	-0.85	0.13	-6.47	< 0.01
b	3.01	0.03	118.25	< 0.01
b_1	0.20	0.03	7.07	< 0.01

In contrast with the length-width relationship (Table 3.1) which showed no significant difference for the sexes, males and females of similar carapace size had significantly different weights (P< 0.01; Table 3.2). Based on these results, a legal sized male or female crystal crab (i.e. 120 mm CW) would have an estimated carapace length of 102.3 mm (equation 3.1) and would weigh 593.2 and 550.0 g for a male and female respectively (equation 3.2).

3.2.2 Catch monitoring

Sample sizes of all animals measured by the Department of Fisheries, Western Australia and Murdoch University length monitoring programs over the course of the project, are presented in Table 3.3. Altogether a total of 29,258 crabs were measured. Because licence holders are restricted to particular zones in the fishery, there has been good dispersion of sampling each year over the grounds (Table 3.3).

Table 3.3 Numbers of crystal crabs measured in each zone of the fishery for each year (2001-2005).

Month		J	F	M	A	M	J	J	A	S	O	N	D	Tot
Zone	Year													
2	2001											368		368
	2002				570			957						1,527
	2003					3459	324	593						4,376
	2004						376				1114			1,490
	2005				570			506						1,076
3	2001										359	240		599
	2002		520							1121				1,641
	2003		982						365		1417	129		2,893
	2004						214			387				601
	2005			179		453			592					1,224
4	2001						225						582	807
	2002				800	6	374	614	604			668	974	4,040
	2003			1322	115	3		795	42	11		143		2,431
	2004			267		351			198					816
	2005				106		96							202
5	2001						331	853	1347				800	3,331
	2002							290	511			290	218	1,309
	2003					15					458			473
	2004													
	2005						54							54
													Tot	29,258

3.2.3 Male crab length-frequency monitoring

The length frequency distribution per 5 mm CL size class for male crabs for 2000-5005 is presented in Figure 3.1.

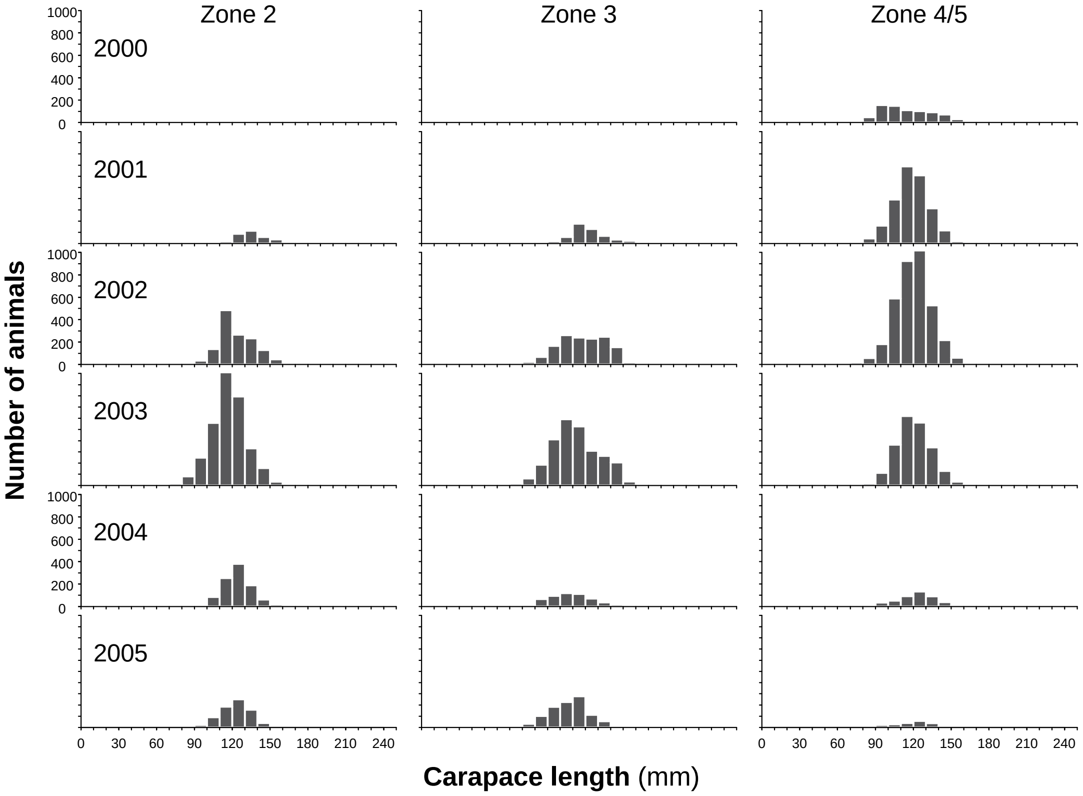

Figure 3.1 Carapace length distribution of male crystal crabs by year and zone for the length monitoring program.

The mean carapace length of male and female crabs in a line of pots, has been analysed using a main effects model which has considered year, depth, zone and soak time (as defined in section 2.1.3, but with year taking values 2001 – 2005) using length frequency data. It was not possible to consider interactions because of the 90 possible treatment combinations, 64 had no observations and 15 had only one. With a lack of multiple observations for many treatment combinations, any estimate of interaction terms would have been severely biased and therefore unreliable.

ANOVA for the mean size of male crabs are shown in Table 3.4. LSM of mean carapace length are given for years (Figure 3.2), zones (Table 3.5), depths (Table 3.6) and soak times (Table 3.7) which are all significant ($P < 0.05$) or marginally significant ($P < 0.10$) factors. Year was by far the most important factor to have influence on the mean size of male crystal crabs (Table 3.4).

Table 3.4 Weighted (in terms of catch per line of pots) ANOVA for the mean size of male crystal crabs for each year, depth, zone and soak time treatment, using length monitoring data. Type III sum of squares have been presented. Data has been restricted to years 2001 – 2005 (R^2= 0.23).

Factor	df	SS	MS	F	P
Year	4	101408.2	25352.0	6.21	< 0.01
Depth	2	35059.8	17529.9	4.29	0.02
Zone	2	43280.5	21640.3	5.30	0.01
Soak time	1	14136.0	14136.0	3.46	0.06
Residual	158	645102.9	4082.9		

The mean carapace length of male crabs standardised for depth, zone and soak time, from 2001 to 2005, is shown in Figure 3.2. The average carapace length of male crabs in the commercial catch in 2001 was 128 mm, which translates into a carapace width of 148.5 mm, 28.5 mm above the legal minimum size. In 2005 the size of males dropped to ~121 mm (CL), which translates into a carapace width of ~141.7 mm or 21.7 mm above the legal minimum size. Over the five year period a 7 mm decrease in mean carapace length has been observed (Figure 3.2). There was a sharp drop in mean size in the first couple of years, but this decline appears to have either stabilised since 2003 or at least decreased its rate of decline.

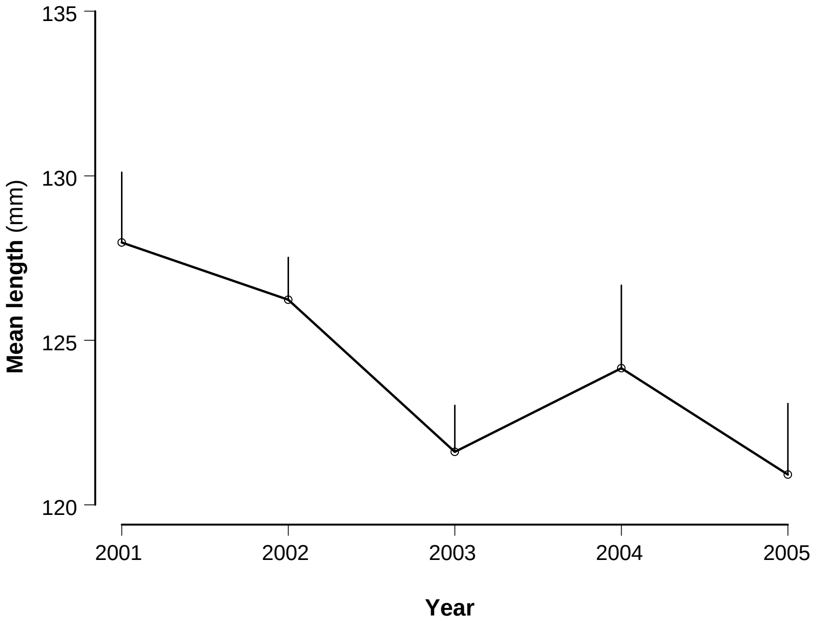

Figure 3.2 Mean length (mm) of male crystal crabs by year with standard error bars.

The mean carapace length for each zone standardised for year, depth and soak time is shown in Table 3.5. Sizes are quite similar across zones, with the sizes being largest in Zone 3 and smallest in Zone 4/5.

Table 3.5 The LSM of mean carapace length of male crystal crabs for each zone of the fishery.

Zone	Carapace length (mm)	s.e.
2	124.4	1.43
3	126.6	1.27
4/5	121.5	1.48

Standardised male carapace lengths are shown for three depth categories in Table 3.6. The largest males were in the shallowest depth zone (< 600 m). There was little difference in the mean size of male crabs in the 600-700 m and > 700 m depth categories.

Table 3.6 The LSM of mean carapace length of male crystal crabs for each depth range of the fishery.

Depth range	Carapace length (mm)	s.e.
< 600m	127.1	1.7
600-700m	123.2	1.2
> 700m	122.2	1.4

The mean carapace length of male crabs in pots soaking for 1-3 compared to > 3 days is shown in Table 3.7. There was little difference in mean carapace length of the catch taken from the two sampling periods.

Table 3.7 The LSM of mean carapace length of male crystal crabs for two soak time categories.

Soak time (days)	Carapace length (mm)	s.e.
1 – 3	125.7	1.5
> 3	122.7	0.9

3.2.4 Female crab length-frequency monitoring

The length frequency distribution per 5 mm CL size class for female crabs for 2000-5005 is presented in Figure 3.3.

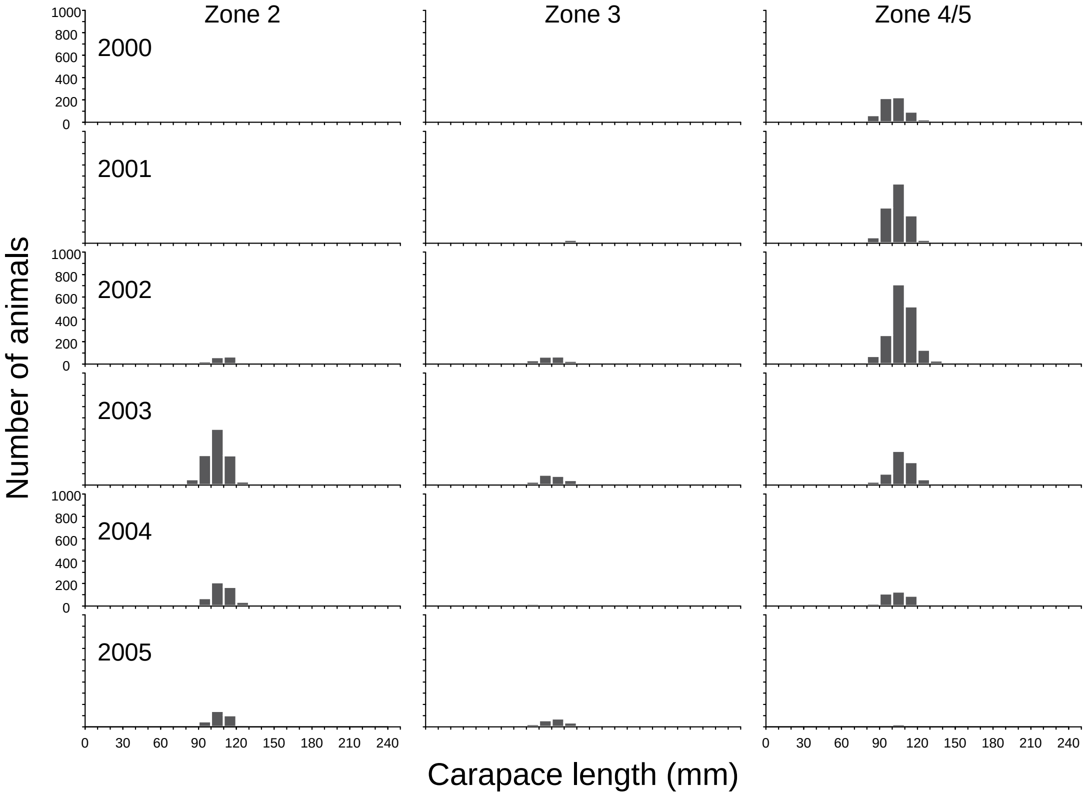

Figure 3.3 Carapace length distribution of female crystal crabs by year and zone for the length monitoring program.

ANOVA for the mean size of female crabs is shown in Table 3.8. While year was the most important influencing factor for males (Table 3.4), zone was found to be the most important influencing factor for females (Table 3.8). The LSM of mean carapace length for all factors that are found to be significant ($P < 0.05$) in the female length-frequency data are given: year (Figure 3.4) and zone (Table 3.9). Soak time was shown to have marginal significance and is also presented (Table 3.7).

Table 3.8. The weighted (in terms of catch per line of pots) ANOVA for each year, depth, zone and soak time treatment, using length monitoring data. Type III sum of squares have been presented. Data has been restricted to years 2001 – 2005 and to Zones 2 – 5 (R^2= 0.22).

Factor	df	SS	MS	F	p
Year	4	7014.2	1753.6	3.10	0.02
Depth	2	564.6	282.3	0.50	0.61
Zone	2	15427.1	7713.5	13.63	< 0.01
Soak time	1	1564.1	1564.1	2.76	0.10
Residual	152	86005.4	565.8		

The mean size of female crabs has shown a decline since 2001 (Figure 3.4). The average carapace length of female crabs in the commercial catch in 2001 was 108.5 mm, which translates into a carapace width of ~127 mm, seven mm above the legal minimum size. In 2005 the size of females dropped to ~106 mm, which translates into a carapace width of ~124 mm or just four mm above the legal minimum size. Over the five year period a three mm decrease in mean carapace width has been observed (Figure 3.4). However it is not yet clear from the short time series whether the mean size of females has stabilised since 2003, or whether the mean size in 2003 was simply unusually low and that the size of females has been steadily decreasing over time.

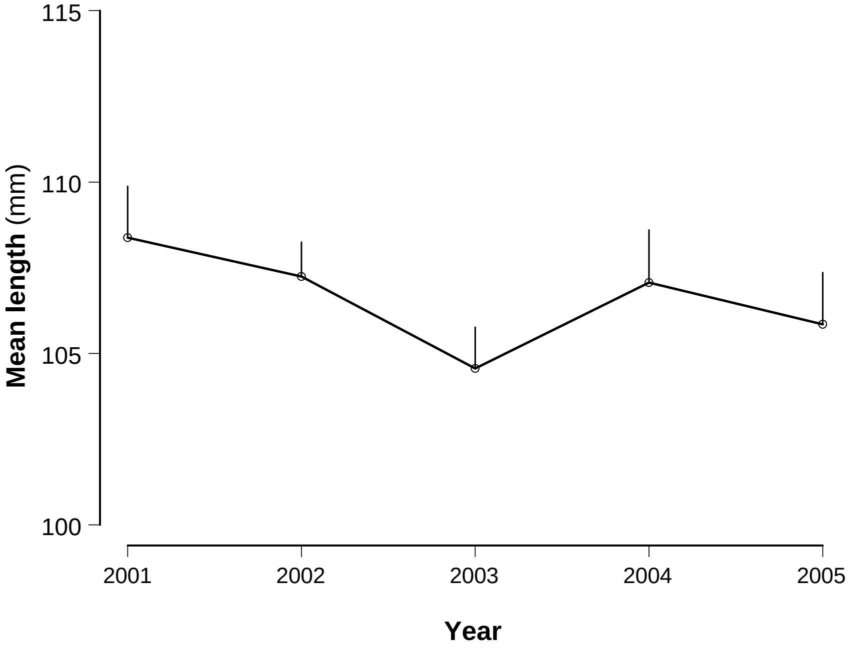

Figure 3.4 Mean length (mm) of female crystal crabs by year with standard error.

The mean size of female crabs, standardised for year, depth and soak time, is shown in Table 3.9. The largest mean size of female crabs were sampled in Zone 2 and the smallest in Zone 3.

Table 3.9 The LSM of mean carapace length of female crystal crabs for each zone of the fishery.

Zone	Carapace length (mm)	s.e.
2	109.3	1.0
3	103.6	1.2
4/5	107.0	1.1

The mean size of female crabs increased for two different soaking times, as shown in Table 3.10, although this was not significant. As for male crabs, soaking periods of less than three days yielded catches of female crabs that had a larger mean size than catches for longer than three days.

Table 3.10 The LSM of mean carapace length of female crystal crabs for two soak time categories.

Soak time (days)	Carapace length (mm)	s.e.
1 – 3	107.5	1.1
> 3	105.8	0.6

3.3 Discussion

The size frequency distributions for both sexes have, in most samples (Figures 3.1 and 3.3) followed a normal distribution.

A decrease in the mean size of both sexes on the crab grounds (Figures 3.2 and 3.4) is to be expected. This length-frequency monitoring program started within a few years of the current level of fishing pressure, and a change in the mean size of the catch is a logical expectation of the increase in harvest rate that has been experienced since that time. The decrease in mean size of both sexes appears to be stabilizing, but a longer time series at current exploitation rates will be necessary to confirm this trend.

Because females do not grow as large as males (Figures 3.1 and 3.3; Smith *et al.* 2004a) relatively few are above the legal minimum size. Those that are above the legal minimum size tend not to be far over the legal size limit. Females would therefore not be expected to show as big a change in mean size as a result of fishing. There are however two factors that would have influenced the magnitude of the decrease in female mean size. On one hand the decrease in mean size would have been stalled by a policy which has been voluntarily adopted at various times by at least two of the licence holders, whereby they have returned all females in the catch to the sea, or at least restricted their harvest of females to only those well above the legal minimum size. The fishers that had these self-imposed restrictions on female catch, operated in Zones 2 and 4/5 and it is significant that these zones have a substantially larger mean size of females than Zone 3 (Table 3.9).

On the other hand a decrease in mean size would have been artificially accelerated by a likely difference between the sexes in moulting patterns. In this regard Melville-Smith (1987a) has shown that female *Chaceon maritae*, a species closely related to crystal crabs, have very long intermoult intervals after reaching maturity and that it is unlikely that they moult more than twice after maturity. Size at maturity (SAM50) has been estimated by Smith *et al.* (2004a) as 90.5 mm CL. If this is the case for crystal crabs, a disproportionately long intermoult interval for mature female crabs would result in a bigger decrease in mean carapace length as a result of fishing pressure than for males.

Zone 3 had the largest mean size of males of all the zones (Table 3.5), closely followed by Zone 2 which has had self-imposed restrictions on the minimum size of males harvested. In Zone 4/5 the mean size of males was substantially smaller than the other two zones. The reason for this is most likely because of the long history of fishing in Zone 4 and the high production rate in relation to the size of grounds in that zone (Table 2.16). It would seem that the more intense fishing pressure in Zone 4 has depleted the larger male animals more markedly than in the other zones.

Females did not show any tendency to segregate by size into any particular depth category (Table 3.8). This result is in keeping with the finding in Chapter 2, that ovigerous females appeared to show no tendency to be prevalent in any particular depth. This result is unexpected, because in most parts of the world where *Chaceon* crabs have been studied they have shown a tendency for the sexes and different size classes to partially segregate by depth (eg. Wigley *et al.* 1975; Beyers and Wilke 1980; Lockhart *et al.* 1990; López Abellán *et al.* 2002).

Males showed a highly significant difference in mean size at different depths (Table 3.4) which is more in keeping with what is known for the species elsewhere. However, from Table 3.6 it can be seen that the main reason for this difference was that the mean size of males < 600 m was substantially larger than males in deeper depths and that there was little difference in the mean size of males in 600-700 m and > 700 m. The segregation of size by depth in this sex is therefore not nearly as marked as what one might have expected if was an inherent biological feature of this species.

The mean size of both sexes was larger when pots were set for short periods of 1-3 days than when they were set for longer than three days (Table 3.7 and 3.10). This result was surprising in that it would have been expected that with escape gaps in the pots to release undersize crabs, that after three days small crabs would have fed and escaped, leading to a result that was opposite to that which was found. One possible explanation is that large crabs find it easier to escape from the pots than small crabs above the escape gap size.

4.0 Effect of escape gaps

4.1 Introduction

One of the objectives of the project was to 'determine the size of the gaps that are required in the traps to allow undersize crabs to escape'. That objective was proposed at a time when the fishery was using plastic recreational-style rock lobster pots without escape gaps. However, between the time the proposal was written and the beginning of the project, fishers began removing one of the slats on one or both sides of the pots to act as escape gaps. The industry believe that this works very effectively in releasing undersize crabs and they supported this type of escape gap being introduced as a permit condition in the West Coast Deep Sea Crab Fishery (Interim) Management Plan. Given these developments, together with the fact that even if a more effective escape gap size were to be developed that it would be difficult to insert it into the plastic moulded pots that are used in this fishery, it was agreed that it would be somewhat pointless to be undertaking the original objective as it was described. The revised objective, which was accepted as a project variation, was to 'determine the effectiveness of the escape gaps currently in use in the fishery in reducing the catch of sub-legal sized crystal crabs'.

In terms of fishery regulations (Item 5 of Part 2 of Schedule 13 of the Fish Resources Management Regulations 1995 referred to in Part 4 of the West Coast Deep Sea Crab Fishery (Interim) Management Plan 2003), the plastic fish trap (i.e. crab pot) used in this fishery, is required to have an escape gap. Escape gaps in the moulded pots in use in the fishery are achieved by the removal of two horizontal bars and a vertical bar, leaving a pot with gap dimensions of approximately 56.5 mm high by 301.9 mm wide.

4.2 Methods and sampling regime

In order to quantify the effectiveness of escape gaps in allowing undersize crystal crabs to escape from pots, an experiment was carried out using a pot-line with alternating pots, fitted with either two, or no escape gaps. The catch from each pair of pot treatments was compared and analysed on the basis of catch per unit effort of animals above and below the legal size limit.

The experiment was carried out with the assistance of a licence holder (Mulataga Pty Ltd) in Zone 2 (Figure 1.1) of the WCDSCIMF. From October to December 2004 the experimental line was fished on four occasions. A technical officer measured crabs on the first two occasions the line was pulled. On two subsequent occasions the experimental line was sampled by the skipper of the commercial vessel. On these occasions the skipper was provided with electronic data recording vernier calipers (Figure 4.1) and trained in their use by Department of Fisheries staff.

Figure 4.1 Electronic vernier calipers including data logger box with four data type options.

4.2.1 Equipment

The experimental line contained a total of 82 pots: 40 new experimental pots, half with none and half with two escape gaps, provided by the Department of Fisheries, Western Australia, and 42 standard pots provided by the licence holder. The 42 additional pots were used to alternate with the experimental pots, and thereby extend the length over which the pot line fished, but were not used in this experiment. The arrangement of the experimental and non-experimental pots on the long line are diagrammatically presented in Figure 4.2.

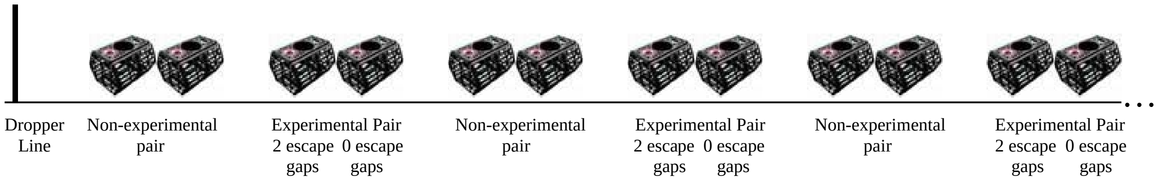

Figure 4.2 The arrangement of pots on long lines used to test the effects of escape gaps on crystal crab catch size composition. Three of the 20 pairs of experimental pots are shown.

Results from previous experiments where data loggers have been attached to pot longlines (Appendix 4), have shown that lighter pots (5 kg ballast) move around more in times of high seas, winds and strong tides. To reduce pot movement on the seafloor in this experiment, and to maintain consistency within pot design, each of the pots on the longline was fitted with a 10 kg weight for ballast. The pots were conditioned prior to their use in this experiment by fishing the longline twice before the start of this experiment.

Escape gaps on the experimental pots were 301.9 mm wide by 56.5 mm high and located on each side of the pots and conformed with escape gap dimensions in use in the commercial fishery. Legislation requires that only one escape gap is required on a pot. However, we fitted two escape gaps for two reasons – some fishers were known to use an escape gap on each side of the pot, and secondly we wanted to optimize the opportunities for crabs in the pot to be able to escape if they were capable of passing through an escape gap.

The experimental pots were ordered into 20 pairs of each treatment, with and without escape gaps (Figure 4.2). The two non-experimental pots between the pairs of experimental pots were used to ensure enough time was provided for the technical officer to accurately sample all crabs caught in each pair of experimental pots, without slowing down the winch and exposing the crabs to prolonged periods in the warm surface waters. The additional spacer pots also ensured that a wide depth range was sampled. To minimize the possibility of high seas or strong currents moving the pots closest to the dropper line and biasing the catch, a pair of unsampled pots were positioned at each end of the line.

4.2.2 Sampling

Parameters sampled for the experimental line varied depending on the sampling regime. On the first two occasions, the experimental lines were sampled by Department of Fisheries staff. In addition to recording the number of escape gaps in each experimental pot, the carapace length, sex, maturity state, moult (shell condition) state, egg development stage and loss of appendages of each crab was also recorded.

Sampling on two subsequent occasions was carried out with the assistance of the skipper of the vessel using SciElect electronic data storage vernier calipers (Figure 4.1). The lengths measured by the electronic calipers were assigned one of four values: males from pots with zero escape gaps; females from pots with zero escape gaps; males from pots with two escape gaps; and females from pots with two escape gaps. For these trips, only the number of escape gaps, sex and crab carapace length were recorded.

4.2.3 Data analysis

Size frequency measurements, which were collected as carapace length, have been converted to carapace width prior to analysis, using the carapace length-width relationship described by equation 3.1. It was felt that this was necessary because the results were mostly pertinent to the legal minimum size, which is legislated as a carapace width measurement.

Raw data have been presented, showing the total number of crabs (both sexes combined) that were caught in 5 mm size classes using pots with and without escape gaps. The sexes have then been separated and plotted as bar charts, comparing numbers of legal size males, legal size females, undersize males and undersize females caught in pots with and without escape gaps. Selectivity curves were constructed for the sexes, by plotting numbers of animals in pots with escape gaps in one and five mm size classes, as a percentage of those caught in pots without escape gaps.

A power curve has been fitted to the cumulative size frequency distribution data for crabs below legal size (120 mm CW), from pots with and without escape gaps. Differences in the slope of the curves have been used to establish the effects of the escape gaps on the size distribution of the catch. Paired differences in numbers of crabs below the legal size limit caught by pots with and without escape gaps have been used to establish, by way of a one-tailed T-test, whether catches by pots with and without the treatment were significantly different.

4.2 Results

The size composition (in carapace width) of the catch made by pots with and without escape gaps is shown in Figure 4.3. It can clearly be seen from the figure that pots with escape gaps caught fewer crabs in most size categories up to about 130 mm CW, including those smaller than the 120 mm CW size range. Compared to the catch from pots with no escape gaps, pots with two escape gaps caught 16% fewer legal size males, but 8% more legal size females (Figure 4.4). This impact on the male crab commercial catch is offset by the reduced effect on sub legal size animals. Compared to the catch from pots with no escape gaps, pots with two escape gaps caught 91% fewer undersize males and 48% fewer undersize females (Figure 4.4).

Selectivity curves for the percentage of animals retained in pots with escape gaps compared with those without escape gaps did not produce useful results, due to sample sizes being too small. The plotted data have not been presented.

A comparison of the cumulative catch size frequency distribution for male and female crabs caught in pots with 0 or 2 escape gaps is shown in Figure 4.5 and Figure 4.6 respectively.

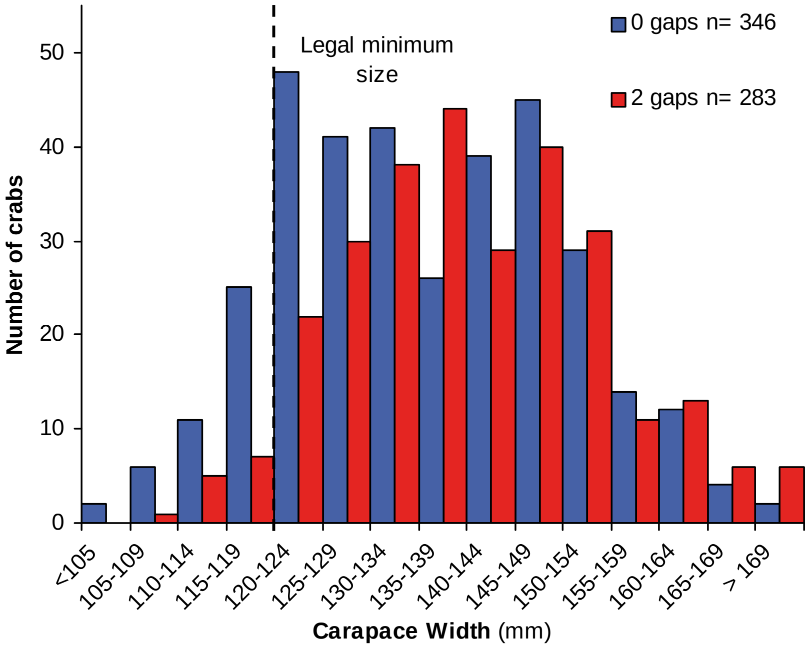

Figure 4.3 Length frequency histogram showing the number of crystal crabs caught using pots with 0 or 2 escape gaps. The dotted line indicates the legal minimum size.

5.0 Movement of tagged crystal crabs

5.1 Introduction

This project undertook to tag 8,000 crabs over its duration, in order to obtain basic biological information on movement patterns and growth rates. The tagging was to be done from commercial vessels and it was always realized that animals to which we would have access to for this work would mostly be those that were not wanted for processing (i.e. sub-legal size or ovigerous), although a small amount of funding was set aside for purchasing legal sized animals.

Relatively few tagging studies have been undertaken on *Chaceo*n species. Lux *et al*. (1982) used vinyl tags that were lost at moult, to tag *Chaceon quinqueden*s crabs off southern New England, USA. They showed that the majority of crabs were recaptured within 20 km or less of their release position, but that some moved as far as 90 km from where they were tagged. Perhaps more significant, was the up and down slope movement recorded, with some showing depth changes between release and recapture of up to 500 m.

Large numbers of *Chaceon maritae* crabs have been tagged on the Namibian coast off West Africa, since the late 1970s (Melville-Smith 1987b). These studies have used spaghetti-type tags inserted through the epimeral suture with the toggle lodged in the branchial cavity, a method which allows the tag to be retained when the exoskeleton splits along the suture line at moulting (Melville-Smith 1987b). Tag recaptures from these studies have allowed movement patterns to be determined (Melville-Smith 1987b; le Roux 1997, 2001). Their results showed that for *Chaceon maritae* there was no significant difference shown in the distances moved by male and immature females, with most of their movement being less than 25 km, but some in excess of 100 km. However, mature females tended to move further than other crabs, with distances in excess of 100 km and even 200 km being relatively common. These longer movements recorded by mature females were considered to possibly be migration patterns associated with breeding (Melville-Smith 1987b).

There are two components to the tagging for movement that have been undertaken in this study. The first has been an experiment to address a concern that was raised by several reviewers of our funding proposal. We had undertaken to release tagged crabs at the surface. There were those that doubted this strategy, pointing out that because the crabs would need to sink up to 800 m after release, that this could significantly impact on their survival (i.e. recapture rates) due to being exposed to midwater predators and secondly, because of the potential to drift in midwater currents, that movement data obtained by this method might be unreliable. Having examined that concern, the second component has used tag recapture returns to examine movement and migration patterns of crystal crabs of different sizes of both sexes.

5.2 Methods

All crabs tagged in this study were captured during commercial fishing operations and were tagged through the epimeral suture by trained research staff using Hallprint double T-Bar anchor tags. The animals were held out of water for minimal periods (< 5 minutes) before release. Data recorded at tagging included latitude and longitude and depth at release, sex, CL, and maturity markings. No animals with lost or damaged appendages were tagged.

To test whether the movements and survival of tagged crabs released at the surface is affected by sinking to the bottom unassisted, we trialled two different tagging release methods; one a control, where crabs were simply tagged and released, and the other where crabs were tagged, before being individually weighted with a paper bag filled with approximately 250 g of gravel and fastened to the tagged animal with an elastic band (Figure 5.1).

Figure 5.1 A tagged crystal crab with a weighted bag attached.

It was considered that because these weighted animals would sink faster, that they might record comparatively less movement and better survival rates than unweighted individuals.

We ensured that the paper bag filled with gravel would not inhibit the movements of the crabs once they reached the sea bed, by tying the bag to the crab with two elastic bands. One elastic band was attached to each crab around the base of the fifth pereiopods and the other band was tied to the paper bag. The two elastic bands were linked together by a “lifesaver” lolly (Figure 5.1**)** A prior experiment showed that lifesavers take ~30 minutes to dissolve in sea water at 7^{o}C. Therefore, if the waterlogged gravel-filled paper bag did not disintegrate within 30 minutes, the lolly would dissolve and release the bag. Elastic bands were established as having a life expectancy in seawater of around two weeks before perishing, so their attachment to the fifth legs was not considered to be a long-term hindrance to the crab.

Movement by all recaptured tagged crabs has been calculated as the straight-line distance between release and the first recapture. Where tagged crabs have been recaptured more than once as a result of being returned to the sea after capture and then been recaptured a second time, only the first recapture information has been used. This applies to both crabs tagged in the weighted versus unweighted experiment, as well as subsequent to that when all crabs were released without weights.

For a variety of reasons, certain tag recapture information has not been utilized. For example, it was found that duplicate tag numbers were used by the two organisations working on this project. Some of those animals with duplicate tag numbers were of the opposite sex and where this was the case, the Fisheries Department tagged information was retained. All other information from crabs with duplicate tag numbers was discarded. In other instances a few skippers were found to be unreliable in their reporting of recapture information and their data were disregarded.

Tag release and recapture data have been presented by three zone-based locations (Zones 2, 3 and Zones 4 and 5 combined). These zone groups effectively separate interpretation of movement patterns of crystal crabs into the southern (Zones 4 and 5), central (Zone 3) and northern (Zone 2) parts of the fishery.

3.3 Results

In the experiment to test whether the movements of crabs that were weighted, so as to sink quickly and as directly as possible to the bottom, was compared to unweighted crabs, 646 crabs were released in two localities (Table 5.1). Differences in the proportions of weighted to unweighted crabs that were tagged and recaptured were not significantly different for either Fremantle (p=0.97) or Carnarvon (p=0.90).

Table 5.1 Release and recapture numbers and proportions at two different tagging localities, for weighted and unweighted crystal crabs.

Release	Released non weighted			Released weighted		
location	Recaptured (n)	Released (n)	% recaptured	Recaptured (n)	Released (n)	% recaptured
Fremantle	7	263	2.7	6	184	3.3
Carnarvon	13	102	12.7	12	97	12.4

A Mann-Whitney test used to establish whether release method (weighted or non-weighted) affected the angular direction moved by recaptured crabs showed no significant difference for those released at either Fremantle (p=0.20), or Geraldton (p> 0.20) (Table 5.2). The non-significant result allowed for data from the two locations to be combined; this also showed the angular direction of weighted compared to unweighted crabs to not be significantly different (p> 0.20) (Table 5.2).

Table 5.2 Mann-Whitney statistic (U) for the effects of crab release method and location, on the angular direction of displacement of tagged crystal crabs.

Effect	n_1	n_2	U	p
Release method (for Fremantle)	6	7	29	0.20
Release method (for Carnarvon)	12	13	75	> 0.20
Location	13	25	157	> 0.20

Having established that there was no significant difference in the movement patterns of weighted compared to unweighted crabs, a further 5,157 crabs were tagged between Fremantle (close to the border between Zones 4 and 5) and North West Cape (at the top of Zone 2) between December 2001 and August 2005 (Figure 1.1). The numbers of each sex tagged and the proportions recaptured in Zones 2, 3 and 4/5 are shown in Table 5.3.

Most crabs were tagged in Zone 2 (Table 5.3) and this zone also provided the highest percentage of recaptures. Females had substantially lower recapture rates than males in all zones, but especially in Zone 2 where their recapture rate was only half of that of the males. Although Zone 3 is the biggest and most centrally situated commercially fished zone in the fishery, it accounted for only 22% of the total number of tagged crabs that were released. Recapture rates from this zone were disappointingly low at slightly over 1% of numbers tagged (Table 5.3).

Table 5.3 Numbers of male and female crystal crabs tagged and percentages recaptured between December 2001 and April 2006.

Zone	Male		Female	
	Number tagged	% recaptured	Number tagged	% recaptured
2	1604	24.4	1466	12.7
3	680	1.6	452	1.3
4 and 5	406	11.1	549	8.2

The proportion of male and female crabs recaptured in 5 mm CL size classes is shown in Figures 5.2 and 5.3. Large crabs of both sexes had a higher probability of being recaptured than small individuals. The same figures show that male and females were recaptured in similar proportions to the numbers tagged in most corresponding size classes.

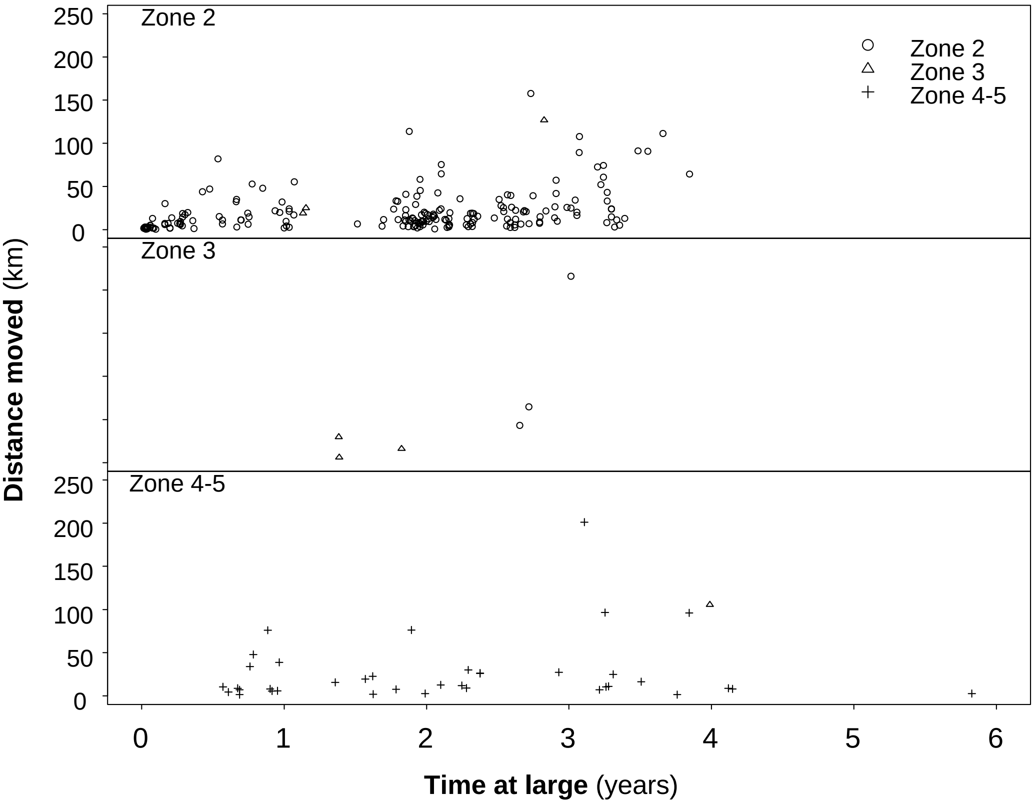

Figure 5.2 Proportion of male crystal crabs tagged and recaptured (based on their size at tagging) for Zones 2, 3 and 4/5.

Figure 5.3 Proportion of female crystal crabs tagged and recaptured (based on their size at tagging) for Zones 2, 3 and 4/5.

The distances moved by male and female recaptured tagged crabs in 5 mm CL size classes is shown in Figures 5.4 and 5.5 and summarised in Table 5.2. There is a trend in the data to suggest that both sexes move further with increased time at large. This trend was tested by modelling log (distance travelled + 0.1) in terms of time at large and was found to be significant for both males and females (both $p < 0.01$).

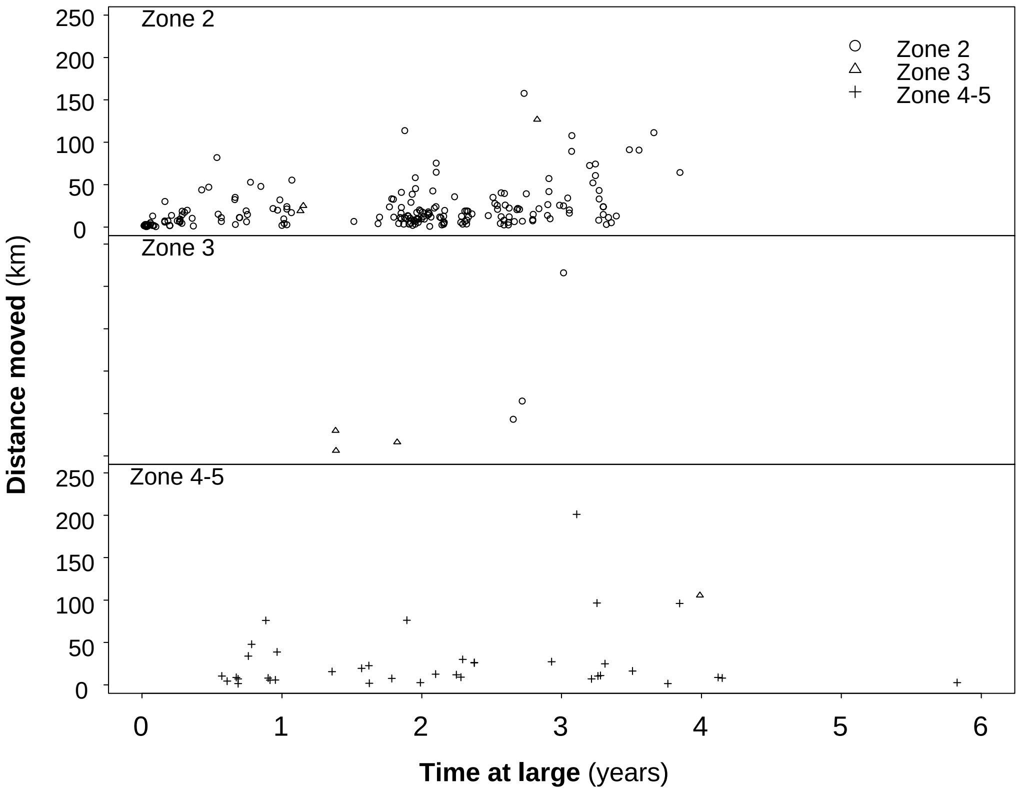

Figure 5.4 Distances moved (km) plotted against time at large (yr) for male crystal crabs tagged in Zones 2, 3 and 4/5. The legend refers to zone of recapture.

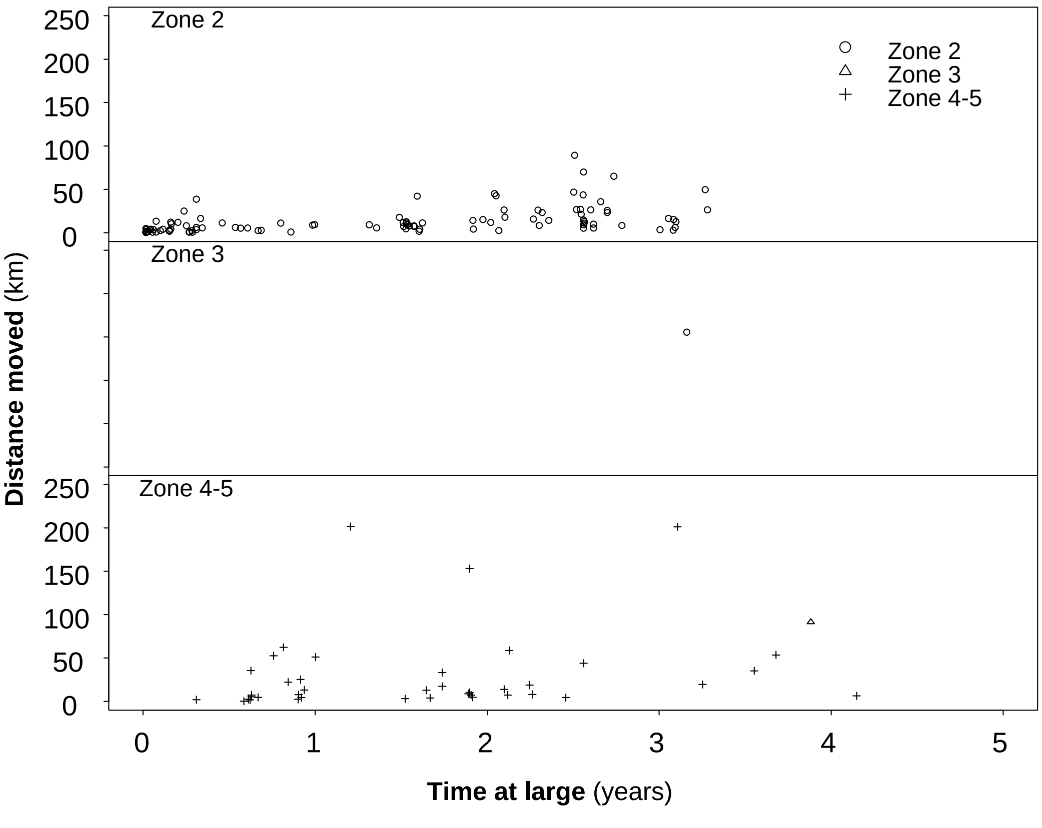

Figure 5.5 Distances moved (km) plotted against time at large (yr) for female crystal crabs tagged in Zones 2, 3 and 4/5. The legend refers to zone or recapture.

Distances moved for different sized crabs are plotted for males in Figure 5.6 and females in Figure 5.7. There was no trend for either sex, to suggest that the size of the animal at tagging influenced the distance that it moved before recapture.

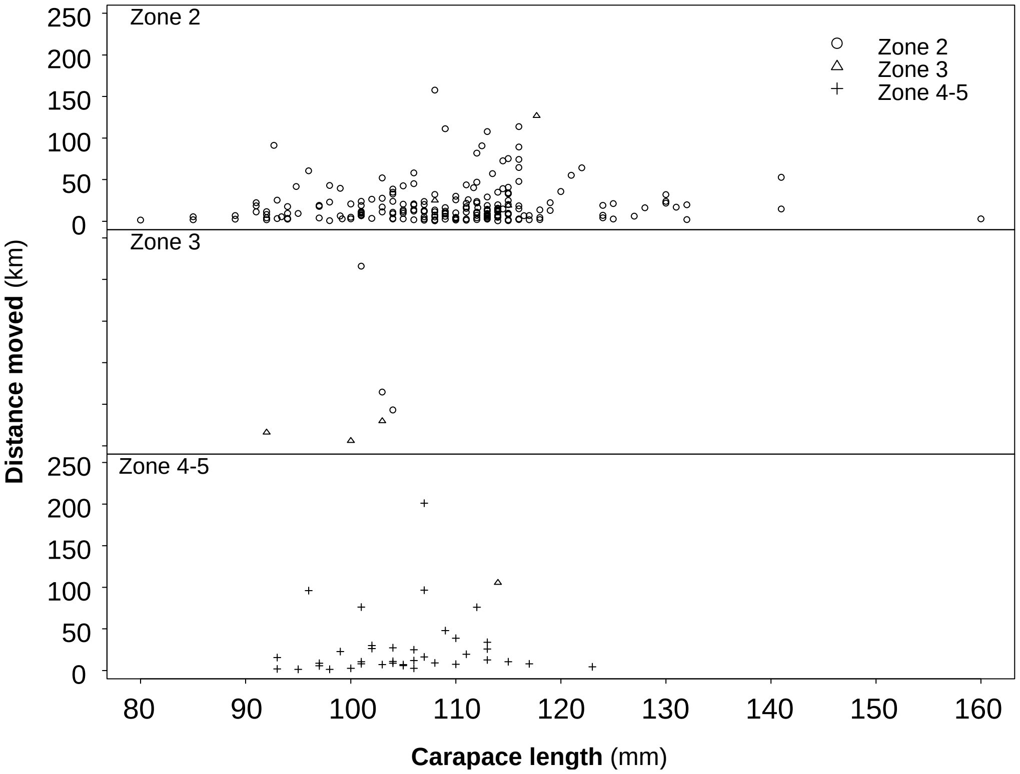

Figure 5.6 Distances moved (km) plotted against carapace length for male crystal crabs tagged in Zones 2, 3 and 4/5. The legend refers to zone of recapture.

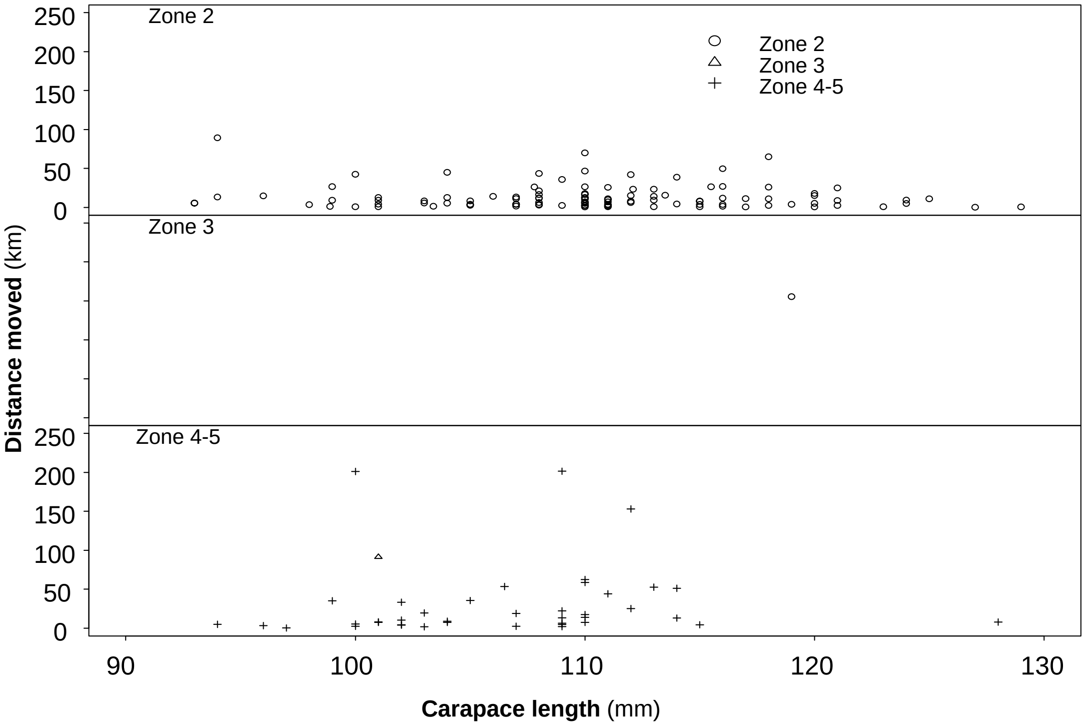

Figure 5.7 Distances moved (km) plotted against carapace length for female crystal crabs tagged in Zones 2, 3 and 4/5. The legend refers to zone of recapture.

An attempt was made in Table 5.4, to compare directional movements of tagged crabs. The Western Australian coastline has a north-south orientation over the commercially fished distributional range of the west coast deep sea crab fishery, with a relatively narrow east-west segment in those depth ranges (500-800 m, see Chapter 2) in which the crabs mostly occur. These limitations to a large extent constrain the possible direction of movement of the tagged crabs and allow the direction of movement to be expressed in terms of a north or southward direction.

Neither sex showed a strong directional orientation (Table 5.4). In the northern region the majority of males tended to move southwards, while the opposite was true of the females. The central area had too few tag recaptures to provide a reliable directional trend of movement. In the southern region the majority of both sexes tended to move northwards (Table 5.4).

Table 5.4 Ratios of tagged crystal crabs recovered north to those recovered south of their release position.

Zone	Males			Females		
	Southwards n	Northwards n	Ratio	Southwards n	Northwards n	Ratio
2	223	168	0.75	85	101	1.19
3	3	8	2.67	1	5	5
4/5	20	35	1.75	15	36	2.4

Movements of tagged crabs across depth contours has been examined in Table 5.5. Both sexes tagged in the mid-depth (600-700 m) tended to stay within the depth range in which they had been tagged, but in both the deeper and shallower tagging depths there was a general movement of both sexes towards the mid-depth.

Table 5.5 Depth movement of crabs. Numbers of male and female crystal crabs which were recovered either deeper, shallower, or at the same depth as at tagging.

Tagging depth (m)	Males			Females		
	Deeper *n*	Shallower *n*	Same *n*	Deeper *n*	Shallower *n*	Same *n*
500-600	35	0	26	16	0	4
600-700	5	61	183	2	22	129
700-800	0	7	0	0	4	16

5.3 Discussion

The majority of crabs of both sexes moved less than 50 km between release and recapture, even after three and four years at large. Only ~2% of the crabs that were recaptured moved more than 100 km. Because of the amount of movement relative to the size of the fishing zones, there were few crabs that were recorded as being tagged in one zone and moving to another.

There was also not a strong trend in the direction of movement in either sex, either in a north-south direction, or outside of the mid-depth (600-700 m) range. These results suggest that crystal crabs move up, down and along the continental slope, crossing a fairly limited range of depths in what is suggestive of random movement.

Male crabs had a higher tag recapture rate compared to females (Table 5.3), but this was not unexpected given that proportionally more small females were tagged than males. Because of escape gaps in the pots, small crabs are less likely to be retained than large. This can clearly be seen in Figures 5.2 and 5.3 which show the proportions of crabs that were recaptured in different size classes. Those figures confirm that for size classes > 102 mm CL (which equates to the legal minimum size of 120 mm CW) there is a sharp change in the slope of the graphs indicating that large individuals have a distinctly higher probability of being recaptured.

As is commonly the case in tagging studies, recapture information in this analysis has been reliant on commercial fishing operations. This does introduce a potential bias in the interpretation of tag recapture information, in that the greatest possibility of tag recaptures is in the areas and depths most frequently fished. Depths outside of 500-800 m and areas south of Fremantle and north of North West Cape receive relatively limited fishing effort and it is therefore possible that tag recaptures might be under-represented in the returns recorded. However, given that recaptured crabs recovered from the fished areas showed predictable movement patters, it would seem unlikely that different patterns would have occurred for crabs that moved outside of the regularly fished areas.

Another potential cause for bias in inferring movement patterns from tag recapture data is that the quality of the data is dependent on cooperation of commercial fishers. We believe that the relatively high rate of tag recapture reporting in Zones 2 and 4 is a reflection of the cooperation and support that has been received from fishers in those zones. There is good evidence that the low recapture rate in Zone 3 is due to a lack of cooperation by at least one of the skippers who fished in this zone. The low recapture rate in Zones 4 and 5 is due to many of the tags that have been longest in the water since release (and therefore having had the greatest chance of being recaptured), having been rejected from this analysis due to uncertainty surrounding their origin. This was a result of the two organisations working on the project coincidently using tags with the same numbering system and it therefore not being possible to with certainty, be able to distinguish the origin of tagged animals with duplicate tag numbers.

There had been concern that the release of tagged crabs from the surface might bias the interpretation of recapture rates and movement patterns. The lack of a significant difference between the recapture rates of weighted compared to unweighted crabs, suggests that mid-water predation of the tagged crabs after release is unrelated to whether they are sinking quickly (weighted) or slowly (unweighted). A lack of any significant difference between the angular direction of movement of weighted compared to control (unweighted) crabs, suggests that crabs released at the surface without any form of ballast do not move any differently than those that are weighted. We consider, in line with this result, that the tag release methods used in this study have not led to the movement patterns of the crabs being biased.

Herrnkind (1980) has described the possible movement patterns of spiny lobsters in terms of one of three categories: homing, migration or nomadism. While it is possible that crystal crabs might exhibit some degree of homing behaviour, whereby the animal shows some degree of residency by occupying the same shelter continuously over an extended period of time, this was not apparent from the recapture data. There was also no evidence of long directed movements of the type considered to be typical of migrational behaviour. Mostly the movement patterns observed were multidirectional and of varying distance, typical of nomadic movement.

It has been shown in spiny lobster tagging studies that displacing them from their point of capture can affect subsequent movement patterns, (Chittleborough 1974, Melville-Smith and Cheng 2002) and may lead to nomadism (Herrnkind *et al.* 1975). Care was taken to release all tagged crabs straight after tagging so as to minimize their displacement after capture. It has been shown that crabs weighted so as to sink faster, did not move significantly differently to unweighted individuals. However given that the catching vessels can drift quite far in the process of hauling their longlines to the surface, it is quite possible that by the time crabs have been taken from the pots, measured and tagged, that they may have been considerably displaced from their point of capture.

These results on the movement patterns of crystal crabs are particularly relevant to future management of the fishery. In the past, effort has been spread across the fishery due to management zones forcing licence holders to fish in their particular allocated zone. Zones as a management tool will be discontinued when the fishery moves to output controls in the near future. Given that these results show that the species does not undertake extensive movements, there is the possibility that large amounts of effort by participants in the fishery moving across the grounds in a systematic way, could lead to serial depletion if not checked. This possibility will need to be borne in mind in the way that catch statistics are interpreted under the proposed management plan.

6.0 Growth of tagged crystal crabs

6.1 Introduction

Tag recaptures are a valuable source of data on movement patterns, growth rates, mortality rates and population size estimates. Most of the information on growth rates discussed in this Chapter, result from an analysis of tag recaptures and much of the background to the tagging of crystal crabs in this fishery has already been covered in Chapter 5.

Very few growth studies have been undertaken on *Chaceon* crabs. Lux *et al.* (1982) tagged *Chaceon quinquedens* off the north east coast of the United States with vinyl tags that were lost at moulting. The fact that the tag was lost at moulting made it useless for estimating growth increments, but tagged crab recaptures for several years after the tagging event showed that species to be very slow growing. Tagging of *Chaceon maritae* crabs off the Namibian coast off West Africa was done using spaghetti-type tags that allowed the tag to be retained after a moult. Data from those studies have been used to show that *C. maritae* are slow growing, without an annual moulting cycle (Melville-Smith 1989). Studies by Melville-Smith (1989) and le Roux (1997) have both shown that this species recruits to the commercial fishery at 6 to 9 years of age. They also showed males to have 16 to 17 instars which they predicted were reached at 33 years (Melville-Smith 1989) and 21 years (le Roux 1997), and that females had a very extended intermoult period after reaching maturity.

The aims of this chapter are to use available tagging data to estimate growth increments and intermoult periods separately for the sexes, and then to combine this information to construct size at age curves for the sexes.

6.2 Methods

All crystal crabs tagged during the course of this project were tagged from commercial fishing operations (as described in chapter 5). As noted, most of the tagged crabs were not required by the commercial fishers, either because they were undersize or below the self-imposed size limits of those fishers that operated under that system. Another category of crabs that was tagged were those that were recent moults, as identified by a soft carapace and by the unworn tips of their dactyls. Because of their recent moult, the flesh of these crabs tends to be watery and their survival is poor, so most operators return them to the water. No crabs with lost limbs were tagged, as it is well known that crustaceans with lost limbs show low growth due to energy being diverted from their overall growth increment (Davis 1981; Brouwer *et al.* 2006).

In the first couple of years of tagging, skippers were asked to measure any recaptured crabs and release the animals. The obvious advantage of this procedure was that there was the possibility of getting information on multiple recaptures of the same tagged animal. This strategy was later changed because it was felt that asking fishers to accurately measure crabs during their busy fishing operations was too onerous and that this could lead to the accuracy of the data being compromised. Fishers now record the date, position and depth of any recaptured crabs and consign the tagged animals with their catch to the factory where they are later measured by the Department of Fisheries WA staff. Tag numbers are used to marry up the measurement of the tagged animal in the factory with the information on the catch position of the animal supplied by the skipper.

6.3 Data analysis

Growth rates in crustaceans have two components: growth increment – the increase in size or weight of the animal each moult, and intermoult period – the time period between moults.

The number of moults undergone by crystal crabs while at large, were determined by plotting the growth increment of all recaptured crabs against their pre-moult carapace length. A hierarchical cluster analysis, using Euclidean distance (Venables & Ripley, 1999), was then used to determine growth increment groupings that corresponded to 0, 1 and 2 moult intervals.

Percentage carapace increments or growth factors have been calculated by plotting percentage CL increments separately for the sexes, against premoult CL. Only those animals that moulted once between release and recapture were used. Hiatt growth curves (Hiatt 1948) were produced for both sexes, to determine whether it was possible to use these data as a way of determining size at maturity in crystal crabs, by Somerton's (1980) method.

Intermoult periods were established separately for the sexes, by regressing the mean number of days at large for crabs that moulted only once, against their premoult CL. The assumption was been made that the intermoult duration for a single moulted crab might be expected on average, to reflect the intermoult period of that crabs premoult carapace length. The equation describing this relationship was developed using a least median square regression analysis (Venables & Ripley, 1999).

Percentage increments and intermoult periods for different sized crabs have been used to estimate the age and weight at size of crystal crabs over their lifetime. No tagged crabs smaller than 85 mm CL were recaptured after moulting. It has therefore been necessary to extrapolate percentage increments and intermoult periods for small size classes using relationships developed for the sizes for which there were data available.

The size at which crystal crabs metamorphose into juvenile crabs is unknown, but is probably close to that documented for *Chaceon quinquedens*. Van Heukelem *et al.* (1983), cultured *C. quinquedens* juvenile post megalopae (4 mm CW or ~3 mm CL) for several moults at 6, 9, 12 and 16 degrees centigrade. We have used those estimations of size at age as an indicator of the likely growth rate of juvenile crystal crabs and have extrapolated those growth data to meet with our growth data for animals > 85 mm CL.

6.4 Results

Growth increments, showing the number of moults for each recaptured crab as estimated by hierarchical cluster analysis, has been plotted against premoult carapace length for males in Figure 6.1 and females in Figure 6.2. Negative growth increments in both Figures are believed to be the result of measurement errors for crabs that had not moulted between tagging and recapture.

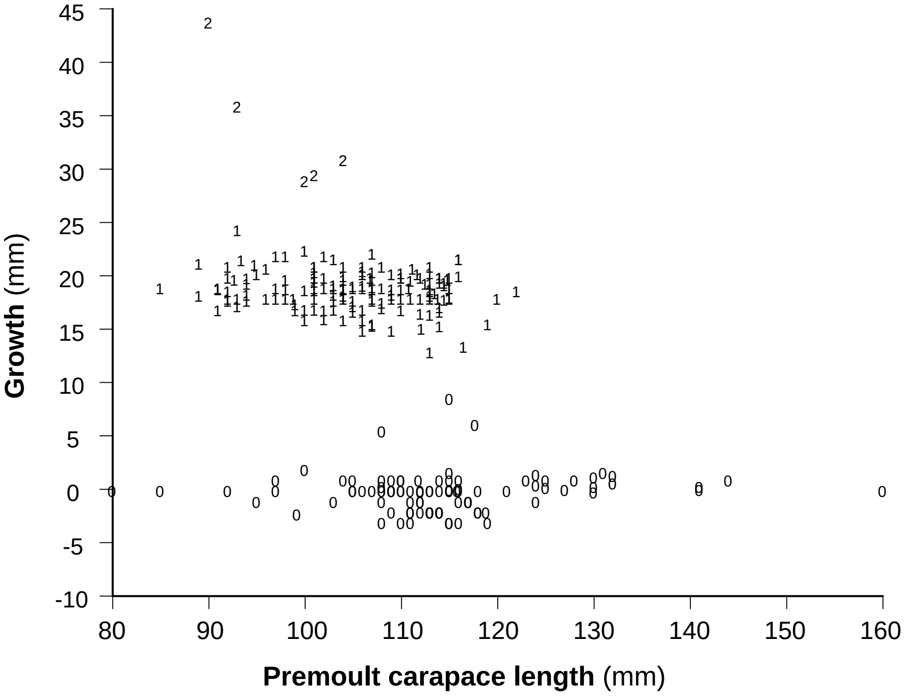

Figure 6.1 Growth increments of recaptured male crystal crabs plotted against carapace length when tagged. Each data point is labelled with the estimated number of moults that the animal had whilst at large, as determined by a cluster analysis.

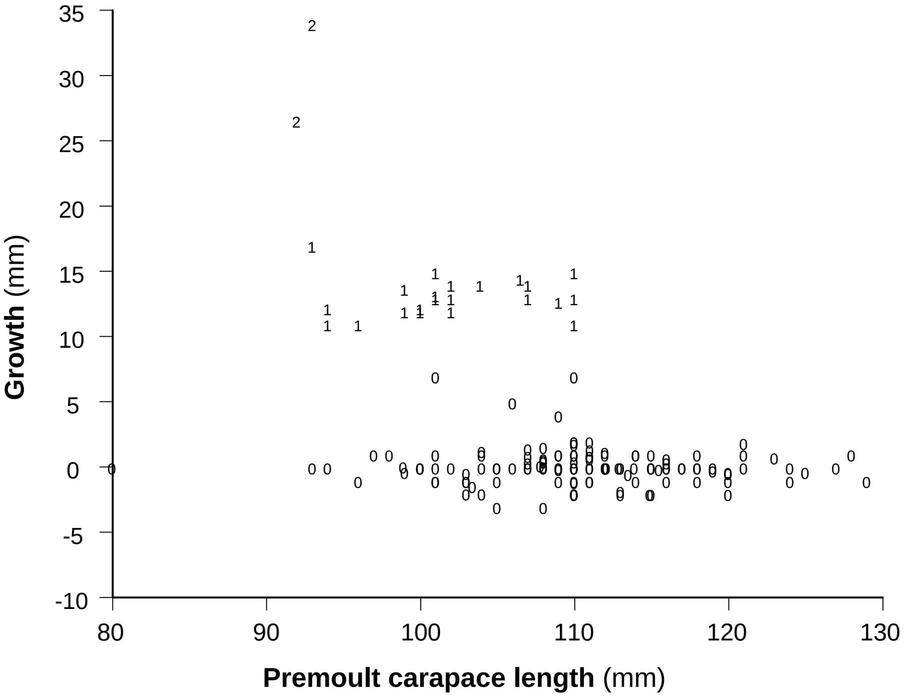

Figure 6.2 Growth increments of recaptured female crystal crabs plotted against carapace length when tagged. Each data point is labelled with the estimated number of moults that the animal had whilst at large, as determined by a cluster analysis.

To date (April 2006), a total of 411 crabs have been recaptured with growth information suitable for this analysis. Indications from these recaptures (Figure 6.1 and 6.2) are that 155 males and

22 females have moulted once and that 5 males and 2 females have moulted twice while at large. The relatively small numbers of females that moulted did not provide sufficient data to allow growth rates to be reliably estimated. However, the available data for females have been presented and are discussed.

The percentage growth increment for male crabs that have moulted once are presented in Figure 6.3. The data indicate that the proportional increase in male crab carapace length with moulting declines linearly with increasing carapace length. The equation describing that relationship is:

$$y = -0.2160 \text{ (s.e. = 0.02, } p < 0.01) x + 40.74 \text{ (s.e. = 1.87, } p < 0.01) (R^2 = 0.49).$$

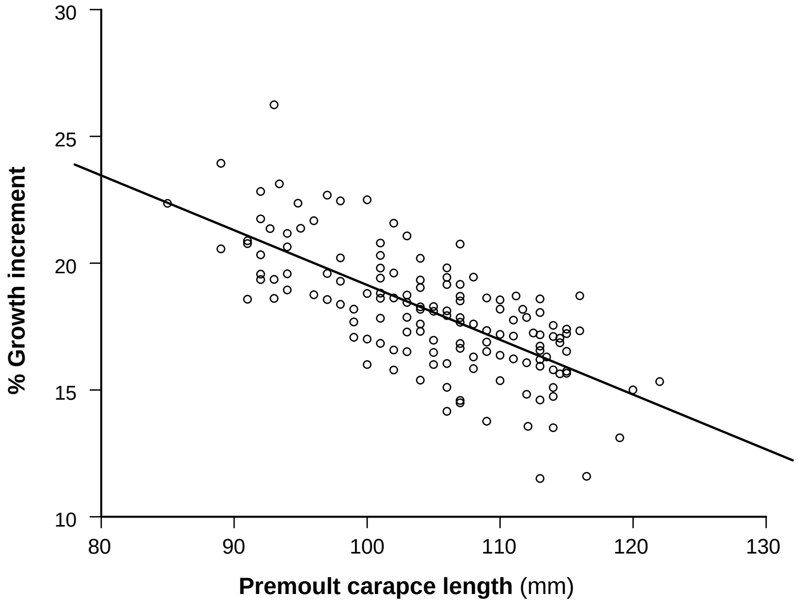

Figure 6.3 Plot of percentage growth increment for recaptured tagged male crystal crabs versus pre-moult carapace length. Only animals identified to have undergone a single moult while at large have been included.

The relationship between premoult and postmoult carapace length (Hiatt growth diagram) for male crabs is shown in Figure 6.4. The equation describing that relationship is given by:

$$y = 0.9597 \text{ (s.e. = 0.0186, } p < 0.01) x + 23.06 \text{ (s.e. = 1.96, } p < 0.01) (R^2 = 0.95).$$

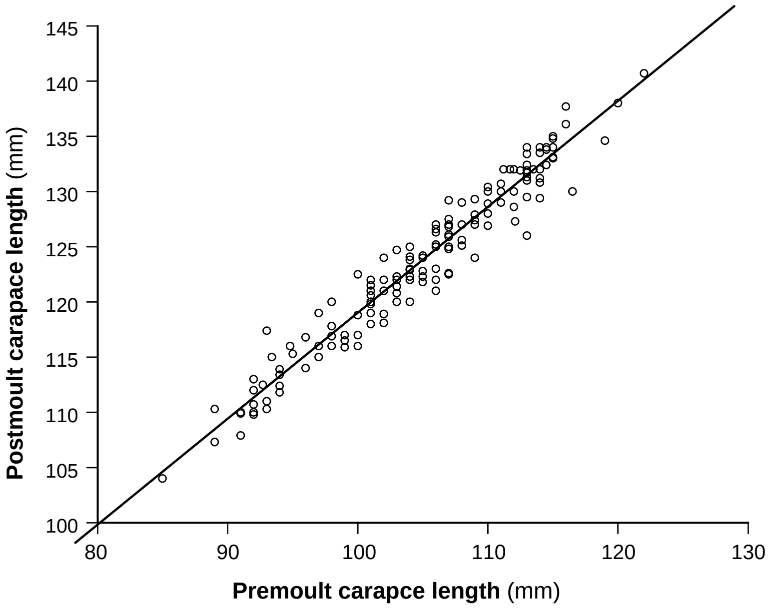

Figure 6.4 Hiatt growth diagram for recaptured tagged male crystal crabs. Only animals identified to have undergone a single moult while at large have been included.

As has already been noted, data for female tag recaptures were less plentiful than for males. However, for completeness, the percentage growth increment and Hiatt diagram for female crabs that have moulted once are presented in Figure 6.5 and Figure 6.6. As with males, the percentage growth increment data (Figure 6.5) indicate that the proportional increase in carapace length with moulting declines linearly with increasing carapace length.

The equation describing that relationship is:

$$y = -0.1074 \text{ (s.e.} = 0.06, p = 0.11) x + 23.84 \text{ (s.e.} = 3.67, p < 0.01) (R^2 = 0.12).$$

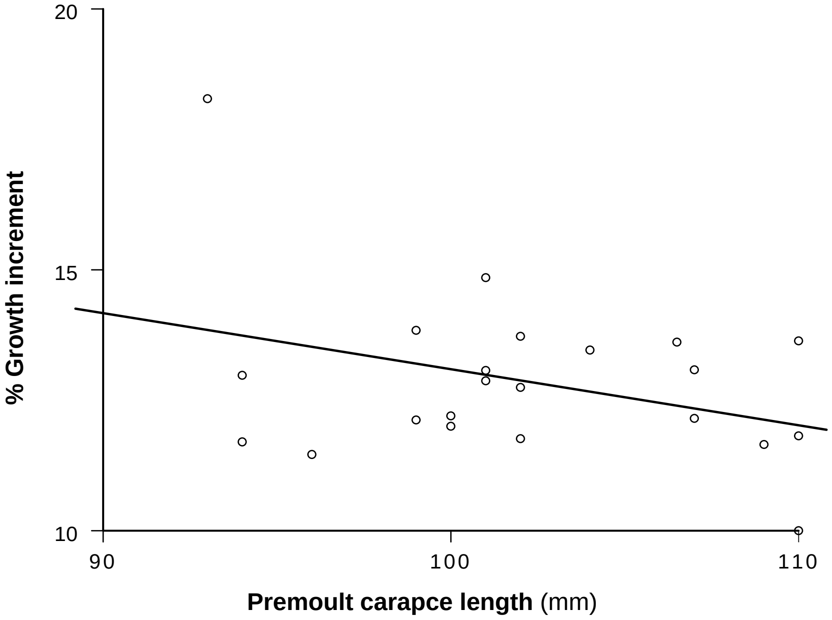

Figure 6.5 Percentage growth increment for recaptured tagged female crystal crabs versus pre-moult carapace length. Only animals identified to have undergone a single moult while at large have been included.

The relationship between premoult and postmoult carapace length (Hiatt growth diagram) for female crabs is shown in Figure 6.6. The equation describing that relationship is given by:

$$y = 1.02 \text{ (s.e.} = 0.06, p < 0.01) x + 11.04 \text{ (s.e.} = 6.37, p = 0.10) (R^2 = 0.93).$$

One of the benefits of Hiatt diagrams is that they can often be used as an indirect way of estimating size at maturity in crustaceans by following the technique described by Somerton (1980). It has not been possible to use that method in this instance because of a lack of data for small animals of both sexes.

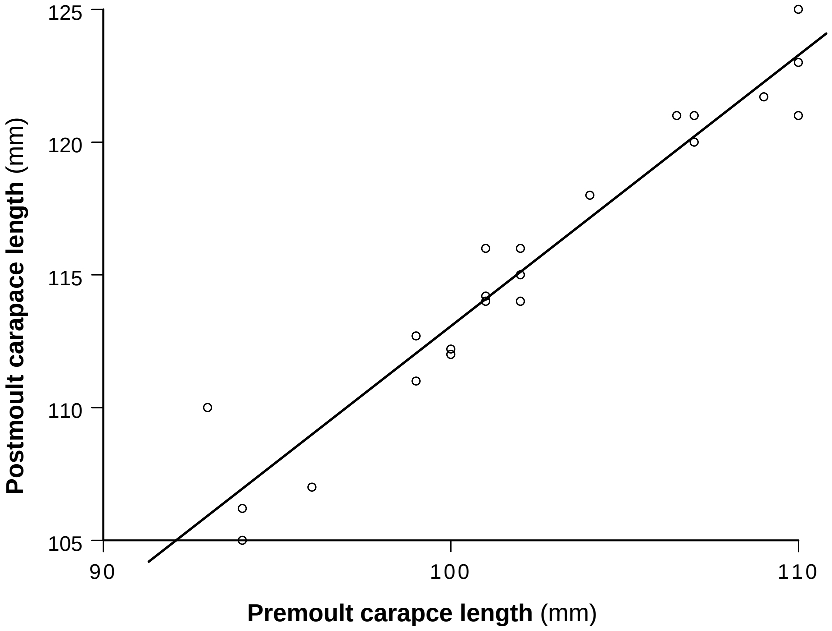

Figure 6.6 Hiatt growth diagram for recaptured tagged female crystal crabs. Only animals identified to have undergone a single moult while at large have been included.

The average number of days at large for male crystal crabs that had moulted once was regressed against premoult carapace length to determine the relationship between size and intermoult period (Figure 6.7). The equation describing that relationship is given by:

$$y = 1.1678 \text{ (s.e.} = 0.0168, p < 0.01) + 0.0096x \text{ (s.e.} = 0.0012, p < 0.01) (R^2 = 0.04).$$

Given the limited data available for the average number of days at large for female crystal crabs that had only moulted once (Figure 6.8), no attempt has been made to establish a relationship between size and time at large for that sex.

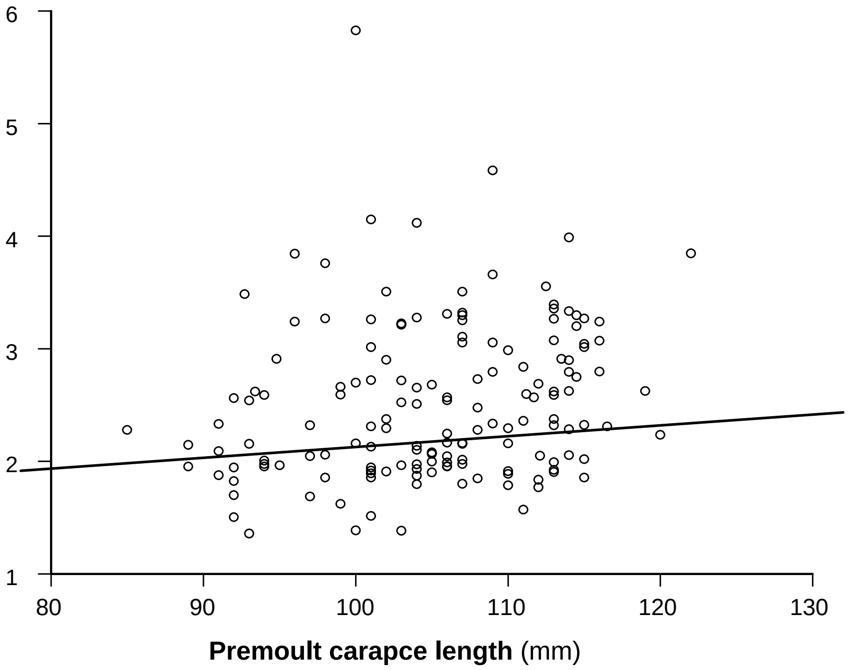

Figure 6.7 Time at large versus pre-moult carapace length for male crystal crabs assumed to have undergone a single moult during their time at large. The best fitting regression line based on least-median squares (less affected by outliers than least-square means) has also been included.

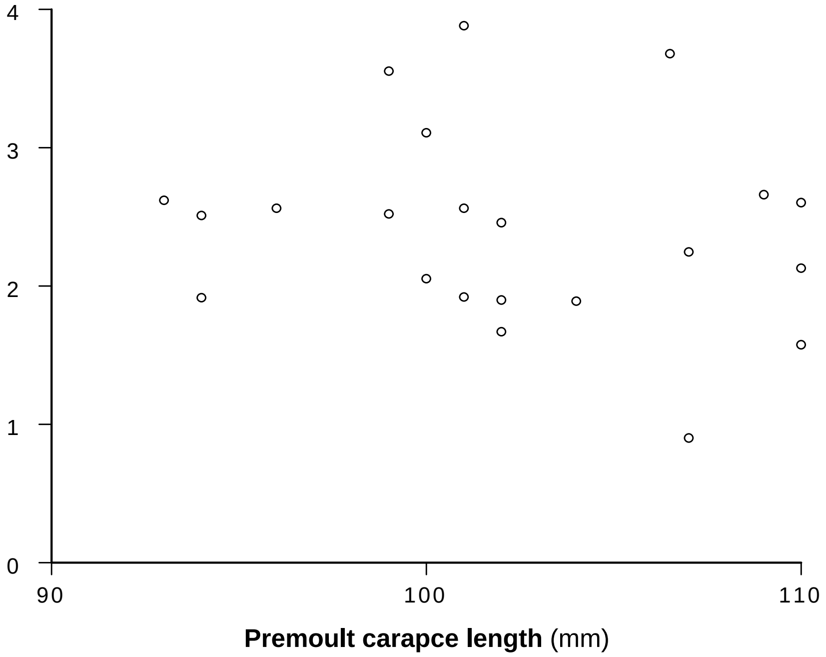

Figure 6.8 Time at large versus pre-moult carapace length for female crystal crabs assumed to have undergone a single moult during their time at large.

It is clear from Figures 6.7 and 6.8, that crystal crabs do not have an annual moulting cycle. It is also clear from Figure 6.7, that there is a general trend for larger males to show longer intermoult periods. However this trend is not apparent for females in Figure 6.8. Percentage increments (Figure 6.3) and intermoult periods (Figure 6.7) for male crabs have been used to estimate the relationship between size and age in male crystal crabs (Figure 6.9). The data presented graphically in Figure 6.9, assuming a mid-range (12 °C) for juvenile growth, has been used in Table 6.1 to estimate the number of instars that it would take for a crystal crab to grow from size at settlement to the maximum size seen in the fishery. The estimated age and weight corresponding to male crabs at each size have also been provided.

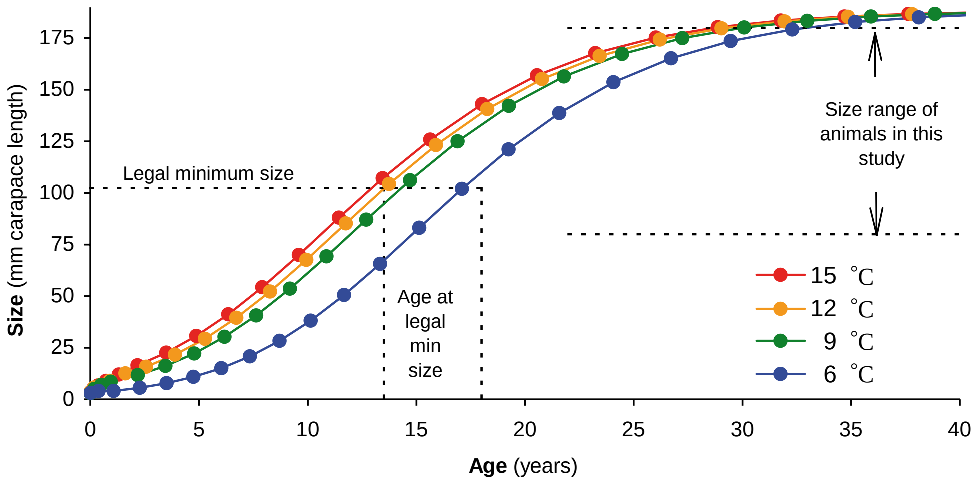

Figure 6.9 Size at age growth curves using four different ambient temperatures at the juvenile growth stage. The size of animals and the legal minimum size were converted from carapace width to length using the width to length equation in chapter 3.

Table 6.1 A growth model estimating the number of instars for male crystal crabs throughout their lifetime based on the 12 °C growth curve (Figure 6.9). Estimates of the size (CL) and weight at each instar are also provided.

Instar Number	Age (yrs)	Size (mm carapace length)	Weight (g)
1	0.01	3.60	0.013
2	0.19	5.68	0.055
3	0.47	7.06	0.111
4	0.90	8.93	0.236
5	1.61	12.51	0.698
6	2.58	15.72	1.453
7	3.99	21.59	4.024
8	5.46	29.38	10.817
9	6.99	39.49	27.938
10	8.62	52.21	68.462
11	10.35	67.59	156.834
12	12.23	85.26	330.511
13	14.25	104.29	631.104
14	16.45	123.29	1,079.836
15	18.81	140.68	1,649.566
16	21.32	155.25	2,263.098
17	23.97	166.43	2,829.549
18	26.71	174.41	3,288.106
19	29.52	179.76	3,623.052
20	32.38	183.20	3,850.186

6.5 Discussion

Growth increments

The percentage growth increments of crystal crabs in this study were smaller for females than males of a similar size. Furthermore, at least in males, percentage increments decreased steadily with size. These trends have been noted by Hartnoll (1982) as being typical of many decapod species and have been shown for *C. maritate*, a species closely related to crystal crabs by Melville-Smith (1989) and le Roux (1997). The percentage decrease in moult increments with increasing size effectively sets a limit to growth in crystal crabs and other decapods. It was of interest that actual moult increments remained relatively constant for females (10-15 mm over sizes 90-110 mm CL) and males (15-20 mm CL over sizes 90-120 mm CL) over the size ranges for which the tag recaptures were collected.

Extrapolating the relationship between percentage growth increment and size calculated in this study, a crystal crab of 3 mm CL would be expected to increase in size by 40% at moulting. An increment of this size is slightly above the expected levels for small (larval) decapods reviewed by Rice (1968). Obviously if the moult increments have been overestimated by our relationship, then the modelled growth (Figure 6.9) will have been faster than what is occurring in the field.

Instead of using the percentage growth increment to calculate moult increases for each instar, it is possible to use the pre to post moult (Hiatt) carapace length relationship. Hartnoll (1982) has cautioned against the use of that method, pointing out that the autocorrelation in that relationship makes it mathematically unsatisfactory to use for this purpose.

Size at maturity

Marked changes in growth increment after puberty are well recorded in many crustaceans. In *C. maritae* this change in increment has been used as a morphometric method of establishing size at maturity in both sexes (Melville-Smith 1989). Our data in this study did not prove to be suitable for this purpose, because the size range of animals tagged and which have therefore been used to provide moult increment information, was biased towards large, and therefore mostly mature animals. It is relevant to note that Smith *et al.* (2004a) showed that length of gonadal maturity in females is 90.5 mm and Hall *et al.* (2006) showed that length of gonadal maturity in males is 94.3 mm.

A single sample, which was the smallest female crab in Figure 6.5, suggests that this individual might have shown a particularly large increment because of being immature, however more data for small females will be necessary to confirm this possibility and the potential use of this technique for estimating size at maturity in crystal crabs.

Intermoult period

It is well known that in general, intermoult period in crustaceans lengthens with increased size. Various linear and log linear relationships between intermoult duration and size or weight have been reviewed by Hartnoll (1982). No single relationship consistently provided the best fit. We have used a simple linear regression between intermoult duration and size proposed by Mauchline (1977) for shrimp, crabs and lobsters.

The regression has assumed that a sample of crabs of similar size and sex recaptured after one moult, would on average reflect the time between moults corresponding to that size range. This method has implicitly assumed that crabs of similar sex and size range were randomly selected. However, it has already been noted that fishers made available for tagging any crabs not required for production and that in this category there were crabs that had recently moulted. We believe that this biased selection of crabs made available for tagging, may have contributed to the large amount of variation in the data relating time at large to carapace size (Figure 6.7).

As a way of addressing this bias, the equation describing the relationship between time at large and size in this study, has been described using a least median square regression analysis (Venables & Ripley, 1999). This regression analysis method is unaffected by outliers (assuming they comprise < 50% of the data), whereas the use of the least squares method can be drastically affected by as few as one outlying observation (Venables & Ripley, 1999).

No intermoult period estimates were made for female crystal crabs because their relationship between time at large and premoult carapace length was unclear. In part this was due to the limited data for large females of 92-110 mm CL. Size at maturity for females is 90.5 mm CL (Smith *et al.* 2004a), which means that most, if not all of the recaptured animals, were likely to have been mature. Mature females in *Chaceon maritae* have been shown by Melville-Smith (1989) to have very extended intermoult periods. If female crystal crabs share this characteristic, the intermoult data for these mature crabs would not be expected to conform with the linear relationship that has been established for male crabs.

Size at age relationship

The main aim of this research into crystal crab growth, was to develop a size at age model for this species. Unfortunately all tagging and tag recapture data in this study have been reliant on commercial catches and there is therefore no information on growth increment or intermoult periods for small crabs < 85 mm CL. Accordingly, estimations of growth parameters for small animals have had to be made by extrapolating data for large individuals.

Data for small individuals has borrowed on size at age estimations produced by Van Heukelem *et al.* (1983) for *Chaceon quinquedens*. That species is closely related, both being members of the *Chaceon* genus. Both species also grow to a similar maximum size and live at a similar depth and temperature. It would seem likely that they would show similar growth characteristics.

Estimations of size at age for *Chaceon quinquedens* were similar for juveniles cultured at 9, 12 and 16^{o}C, but juveniles kept at 6^{o}C grew much slower Van Heukelem *et al.* (1983). There is very little information on the depth of occurrence of juvenile *Chaceon* crabs and none at all on crystal crabs. We would expect, based on the exceptionally slow growth rates at 6^{o}C, that juveniles would be most likely to colonise depths corresponding with temperatures upwards of 9^{o}C. We have therefore placed a greater likelihood of juvenile crystal crabs growing at similar rates to *Chaceon quinquedens* juveniles cultured at the three higher temperatures.

The age at growth for male crystal crabs estimated from this study shows them to reach size at maturity at around 12 years, legal size at 14 years and the maximum size seen in the field at 25 to 30 years old. Maximum size corresponds to around 18-20 post larval instars, which is typical of numerous decapod species (e.g. *Porcellio scaber, Homarus americanus* (Hartnoll 1982); and *Chaceon maritae* (le Roux 1997)). Growth of crystal crabs would appear to be similar, or perhaps slightly slower than the only other *Chaceon* species for which size at age estimates have been produced – *Chaceon maritae* has been estimated to reach size at maturity at about 9 years and maximum size at over 25 years old (Melville-Smith 1989). Size at age information is not available for *Chaceon quinquedens*, but both sexes have been recorded with intermoult periods of up to 7 years (Lux *et al.* 1982).

It needs to be emphasised that the growth estimates that have been produced in this study for crystal crabs are preliminary. In order to produce an estimate of size at age for this species it has been necessary to make many assumptions that have inevitably introduced uncertainty into the model estimates. Particular components of the crystal crab growth model that will need further research, are estimates of intermoult for animals of all sizes and both sexes. More information on moult increments in crabs smaller than what were tagged in this study would also improve the model estimates, although their ability to change the outcome would be small compared to estimates of the relationship between size and intermoult increment.

7.0 Depletion experiments

7.1 Introduction

Depletion experiments are a potentially valuable method of estimating absolute stock size where more direct techniques are not possible. The technique, often described as Leslie-DeLury experiments (Leslie 1952; DeLury 1947), involves deliberately depleting a population by fishing and then using the relationship between the cumulative catch and the observed decline in catch rates, to estimate the initial exploitable stock size.

An estimate of the initial stock size of a population using depletion methods is dependent on CPUE being proportional to stock size. The best possibility of this being achieved is by undertaking the experiment over a short time period and in this way limiting emigration, immigration and natural mortality.

One of the objectives of this project was to undertake depletion studies in two zones of the crystal crab fishing grounds (Figure 1.1). The first of these studies commenced in mid 2002 in Zone 4, out of Fremantle. Unfortunately the gear used in the depletion study was lost on the second trip. At the request of the fisher that had agreed to undertake the survey, it was decided to temporally postpone the experiment for a few months until the gear could be repaired.

A second offer by a different crystal crab licensed operator was made to undertake the experiment from Zone 2, out of Carnarvon. The skipper selected an area in the southern region of Zone 2 to be the study site, as it was considered a typical area of “good ground”. Good ground is characterised as being consistently productive and having few snags that could cause pot lines to be lost. The survey commenced in this area on May 2, 2003.

2.2 Methods

The proposed sampling strategy was to set and haul four pot lines of 50 pots with the lines set as close as possible to each other, over five successive occasions with the pots soaking in the water for seven days. The parameters recorded in the study followed the standard monitoring protocol (see Chapter 3) of sampling every crab in every experimental pot. This included measuring and sexing each crab and assessing their shell state, limb loss and maturity features (see detailed description in Chapter 3 section 3.1).

The depletion survey employed four long lines with dropper ropes at either end buoyed by floats. Each long line had 50 plastic moulded pots, each with 10 kg of ballast and with two escape gaps 56.5 mm high by 301.9 mm wide. The experimental design in the project proposal described each line as being positioned in parallel, 0.5 km distance apart, with pots spaced 20 fathoms (36.4 m) apart. The intended study area was to be approximately 2.0 km (1.8 km + 10% error margin for placement on the bottom) by 2.2 km, or 4.4 km^2. In practice however, the four longlines were set approximately 1.5-2 km apart at the insistence of the skipper, so as to avoid risk of entanglement of the lines.

The position at the start of each pot line was estimated by the mean of the GPS position when the first pot was set and the ship’s position when it was retrieved. Similarly, the end position of each line was estimated by the mean of the ships position when the last pot was released during the setting of the line and its position when the last pot on the line was hauled.

Determining the position when the last pot was lifted off the bottom was difficult to estimate. The procedure followed was to record the position of the boat when 32 pots were on board, effectively leaving 18 pots hanging in the water column. Since each pot was spaced 36 m from the next, it was considered that at that stage of hauling the line the ship would be approximately over the last pot.

The set and pot-line locations should have in theory been similar, however both positions had inherent errors. The release location assumed that the pots would settle on the seabed directly below the position at which they were released. In practice, once the pots are released from the vessel they often drift as the pot line sinks to the bottom. The retrieval position is also biased, as it assumes that the vessel is located directly over the pot being hauled. In practice prevailing winds and currents generally prevent this from being the case. Combining the line positions was considered to be the best estimate of the position of the longline at these fishing depths.

It had been planned to do five successive hauls of the four depletion longlines at weekly intervals, reflecting the interval (at the time of the experiment) that commercial operators tended to leave their pots to soak. However, at the end of five weeks it was still unclear as to whether the grounds were showing depletion effects. Rather than end the study after the five weeks as had been planned the FRDC agreed the experiment continuing for a further five weeks in place of a second depletion experiment in another zone, as the original project funding plan had stipulated.

Unfortunately, the additional sampling period was not conducive to fishing. Although the fishing boat went to sea each of those weeks, most of the gear, including that of the depletion experiment, was submerged and not retrievable due to strong currents and high seas. Only on trip nine was it possible to recover some of the depletion study gear. At this late stage it was felt that sufficient time had probably elapsed to allow crabs to have moved into and out of the study areas. This would have disrupted any depletion effects that might have occurred due to the experimental fishing. On this basis it was decided to terminate the study at that point. The work presented in the results of this study include data collected using the four 50 pot lines hauled weekly from 02/05/2003 to 30/05/03, as well as the final two lines retrieved on 25/06/03.

To monitor temperature and pressure (depth) changes over the duration of the experiment a Lotek LTD 1100 archival data logger was attached to each end of the first and last lines making up the corners of the depletion experiment. One logger produced erroneous depth data throughout the sampling period and was sent back to the manufacturer at the end of the experiment. The fault was determined to be sensor failure and depth data from this logger have therefore not been used.

The temperature sensors are rated to an accuracy of +/-0.3 °C and a resolution of 0.2 °C. The pressure sensors have an accuracy of +/-10m and a resolution of 3.9 m at the depth at which they were sampling.

2.3 Results

7.3.1 Study site

The precise position of the each pot line in the experiment varied from week-to-week, due to changing currents and winds causing difficulties in getting the longline to land on a particular position after a 600 m decent through the water column. The location of the four depletion lines set over the first five weeks of the experiment are shown in Figure 7.1. The overall study area, which has been estimated from the most outer bounds of the lines set over the five-week survey period, formed a rectangle 5.9 km long and 2.4 km wide, or 14.0 km^2.

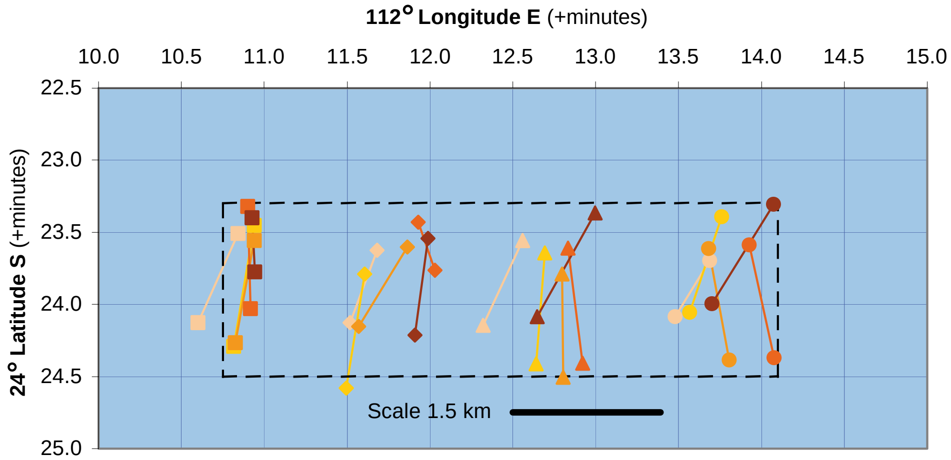

Figure 7.1 The estimated position of the four pot-lines set weekly over the five week crystal crab depletion experiment (label codes: beige – week 1, light Orange – week 2,, Orange – week 3,, dark orange – week 4,, brown – week 5.

7.3.2 Temperature and depth data

There was a delay in the deployment of the four data loggers, and they were only set after week two. The loggers recorded from when they were deployed to the end of the experiment. However, the temperature and depth data presented here has been limited to weeks three to five as in terms of this study, this is the period of interest.

Weekly spot temperatures were required to characterize the sampling site from the time series data. The occasional periods where there were small spikes of variation in the temperature and depth recorded by the data loggers was presumed to be fluctuations due to the effects of the pots lifting from the bottom. The pots were attached to dropper lines and a series of floatation buoys which appeared to be jerked and lifted off the bottom in periods of rough seas and stormy weather. To eliminate these variations, we used the median temperature and depth for each fishing period.

Temperature data from the loggers ranged from 6.31 °C to 7.16 °C, and depths from 595 m to 634 m (Table 7.1). Table 7.1 shows that there was little variation in temperature over weeks three to five of the study at each of the logger positions. Given the logger accuracy of $^{+/-}$0.3 °C and a resolution of 0.2 °C, it would seem likely that temperature remained constant from week one to week five and that temperature was not an influencing factor in the catch results.

Table 7.1 Median temperature and depth data sampled by the four data loggers at each of the four ‘corners’ of the crystal crab depletion experiment study site.

		Logger	1		2		3		4*	
Period		Position	North/West		South/West		North/East		South/East	
From	To	Week	Temp (°C)	Depth (m)	Temp (°C)	Depth (m)	Temp (°C)	Depth (m)	Temp (°C)	Depth (m)
08/05/03	15/05/03	3	6.51	625	6.51	614	7.00	604	6.97	na
15/05/03	22/05/03	4	6.51	634	6.31	617	6.81	612	6.78	na
22/05/03	30/05/03	5	6.51	625	6.51	628	6.81	612	6.78	na

* Logger 4 pressure sensor error, data unavailable.

7.3.3 Catch data

Attempts at depleting the study site by repeatedly setting traps over the survey area failed to produce any real perceptible change in catch rate (Figure 7.2 and 7.3), or size composition of the catch (Figure 7.4) and the data have therefore not been used to attempt a depletion analysis.

CPUE was highest for legal sized animals of both sexes in the first survey, but dropped off and remained relatively constant for the next four trips. Catch rates were much lower in the last (ninth) week, but that was because the pots had been left for an extended period without being hauled and escapement had presumably occurred.

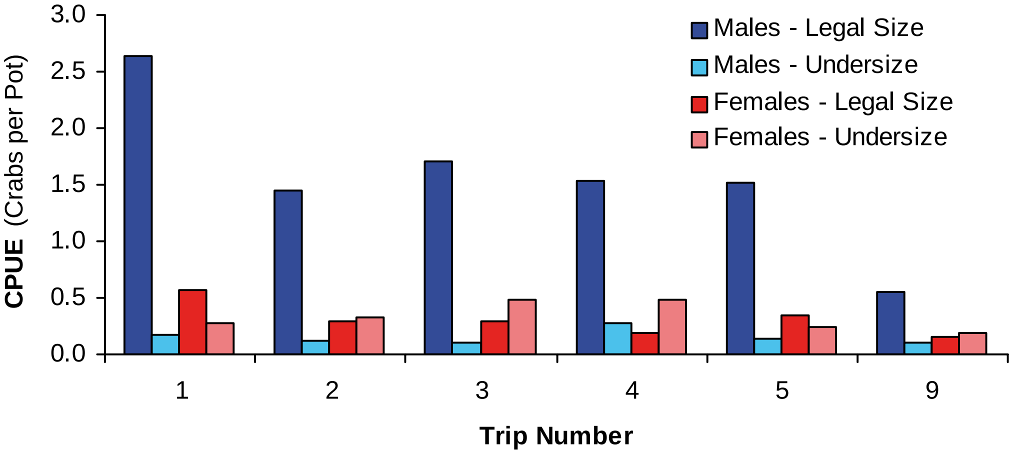

Figure 7.2 CPUE of male and female crystal crabs above and below legal minimum size for trips 1 to 5 and 9 of the depletion study.

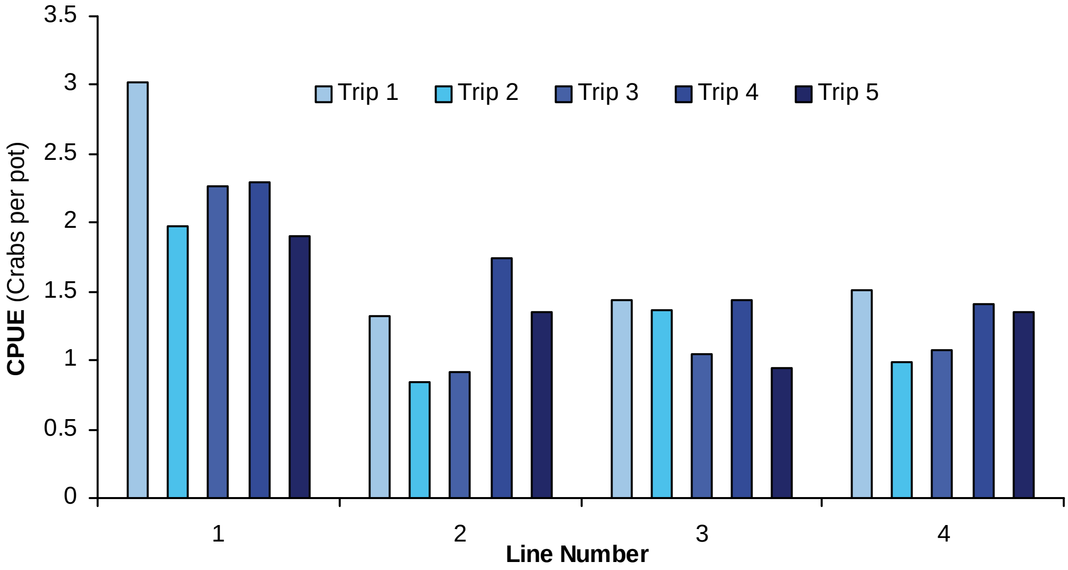

Figure 7.3 CPUE of crystal crabs (all sizes and both sexes) on lines 1 to 4 of the depletion study. Trip 9 has been excluded.

Crab length frequency data indicated that there was a slight decrease in mean size over the first four weeks of the study (Figure 7.4). The average male crab decreased in size from 124.8 mm carapace length in week 1 to 120.2 mm in week 4. Females decreased in size from 109.3 mm carapace length mm in week 1 to 102.8 mm in week 4. Week five showed a small increase in the size of animals; with little change for males to 120.5 mm, and some increase for females to 105.7 mm. Data collected from week 9 has been included only for completeness. It has not been considered because only two of the four lines were located and sampled on week 9 and furthermore it had been unbaited for an excessively long period of time (one month) and would have lost much of its catch.

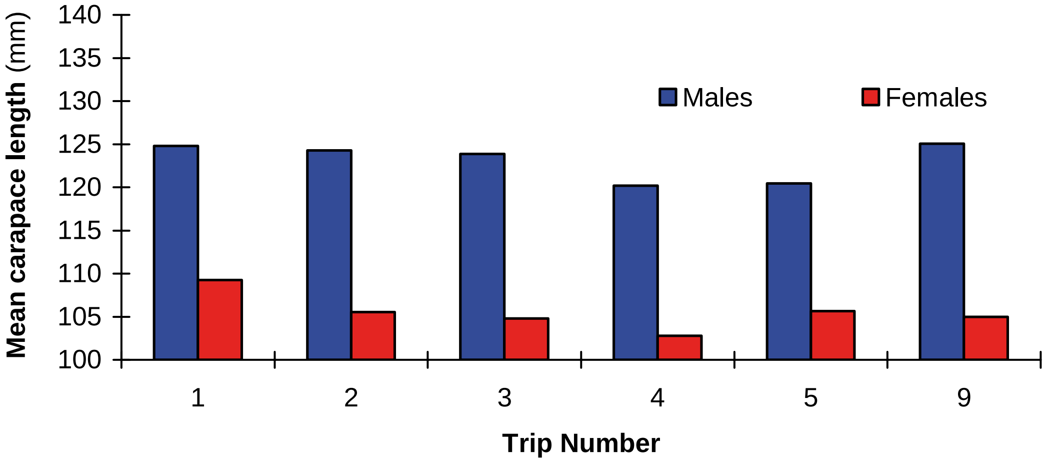

Figure 7.4 Mean size of male and female crystal crabs for trips 1 to 5 and 9 of the depletion study.

7.4 Discussion

It has already been noted in the results, that the catch data did not show any obvious changes in catch rate to indicate depletion and that therefore the experiment does not hold any value for the purpose for which it was designed. It is useful therefore to examine why the experimental design proved inadequate.

The biases inherent in using depletion studies to estimate crustacean stock sizes are well known (Miller 1990; Miller and Mohn 1993; Wright *et al.* 2006).

One potential bias is that they assume no migration into or out of the depletion area. As can be seen from Chapter 5, crystal crabs are very mobile and would easily be capable of immigration or emigration into or out of the depletion area. The same chapter also showed that the longer the crabs are at large, the further they move. To have been an effective depletion experiment this might have meant setting and hauling the pots in the study area more frequently than weekly. This information had not been available at the time that the depletion study was considered.

A second potential bias to depletion study results is that all crabs on the grounds are catchable. It is well known that decapods have periods of different catchability related to environmental conditions such as temperature, moon phase and swell (Sumpton and Smith 1990; Aagaard *et al.* 1995; Srisurichan *et al.* 2005), as well as biological reasons such as moulting (Williams and Hill 1982; Aagard *et al.* 1995) and whilst ovigerous (Howard 1982; Skinner and Hill 1987; Waddington *et al.* 2005).

In the case of crystal crabs, there were no obvious environmental factors in their deep sea environment that were considered might cause synchronized, short to medium term fluctuations in catchability. Temperature loggers showed that temperature was constant over the survey period. Swell and lunar phase were not considered likely to be detected by animals at depth. In terms of their biology, there does not appear to be a well-defined breeding season (Smith *et al.* 2004b) or moulting pattern (this report). It is likely therefore that at any one time there will be a small subset of the population that is less catchable, but that this should be constant through the year. In summary therefore, there is no obvious reason to assume that catchability would not have been constant over the duration of the experiment.

Thirdly, it is possible that if trap catches are saturated, in other words that the catches are that good that there is no opportunity for more animals to enter into the pots, that this would mask any depletion effects. Catches over the duration of this experiment were good, but not exceptional. On trip 1, line 1, the mean CPUE was ~3 kg pot^{-1} (Figure 7.3), whereas on lines 2, 3 and 4 catches did not reach 2 kg pot^{-1} at any stage. This indicates that the pots were not saturated and that this therefore could not explain the lack of response in catch rate to depletion fishing.

The reason that the depletion experiment failed is probably two-fold. Firstly, the long lines were spaced further apart than had initially been intended. This resulted in the area of ground being depleted (14.0 km^2) being too large to show changes in CPUE and therefore by implication, any change in stock size. Secondly, it appears that the crabs are quite mobile and do not remain within specific home ranges (Chapter 5 – tagging movement results). Movement of crabs into the study area from surrounding grounds probably masked the effects of fishing on the rate of depletion of crabs in the study area.

8.0 Assessment of the stock

8.1 Introduction

The final objective of this project was to produce an assessment of the status of the crystal crab stock on the west coast of Western Australia. This objective has been very much a work in progress throughout the five-year duration of this project, with assessments being made each year using data as they have become available. What is outlined here is an up to date summary of the key findings. Much of the information used in assessing the status of the stock has been produced in earlier chapters. As far as possible those figures and results have been referred to without being duplicated in this chapter.

There has been much deliberation as to future management of this fishery once it moves to a new interim management plan on 31 December 2006. A brief review will be provided as to the likely management measures that will be adopted under this plan. Special emphasis has been placed on how the research that has been supported by this project has been used to provide the scientific basis for proposed management measures.

8.2 Stock status

Spatial and temporal changes in size frequency structure since 2001 have been presented and discussed in full in Chapter 3. It was noted that there was an initial downturn in mean size in the first couple of years of fishing, but there are indications that this may now have stabilised. A longer time series will be important to confirm this trend.

Spatial and temporal changes in catch effort and CPUE are discussed in full in Chapter 2. It has been noted that total catch in the fishery has stabilised over the last five years at around 200 t per annum, but that with the exception of 2005, there has been a continuous increase in fishing effort. Overall, this has translated into a decrease in CPUE, which has stabilised in recent years and has even shown signs of increasing in 2004 and 2005. A caveat to this apparent increase in catch rates in recent years, is that it is unknown to what extent these improvements might have been driven by fishers better understanding their gear and the way it should be deployed to optimise their catches. Additionally, there is an unknown contribution to the catch of small, but legal, crabs of both sexes that were not previously kept by some operators.

While these catch, effort and size frequency indicators have been positive in recent years, they do not necessarily indicate that the current harvest size is sustainable.

It has been noted in Chapters 2 and 3 that the fishery has been managed to date by zones and that these have influenced fishing patterns and therefore catch, effort and size frequency statistics. Zone 4 is the second smallest zone and probably for this reason has been fished far harder than the other zones in terms of its production per km^2 since the start of the fishery. It is considered that when this fishery moves to its fully managed status, that management by zones will cease and at that stage it is likely that catch statistics will be affected by a spatial and temporal change in effort distribution.

The current large legal minimum size (120 mm CW or 102.3 mm CL) makes this a highly male-dominated fishery. With size at maturity for both sexes being below the legal minimum size [size at maturity for females is 90.5 mm CL (Smith *et al.* 2004a) and for males 94.3 mm CL (Hall 2006)], the brood stock would seem to be reasonably well protected whilst the current minimum size is maintained.

8.3 What is a sustainable catch?

The time series of catch and effort data in this fishery is limited. In the first few years fishing was sporadic and fishers were developing techniques for setting their pots and keeping their floats from being dragged under by strong currents. The increase in catch rates in around 2000 would indicate that fishing techniques had been reasonably well developed at that point and were being bolstered by the accumulated biomass of a previously unexploited fishery.

Estimates produced in 2003 (Melville-Smith *et al.* 2006), used a depletion technique to calculate the unexploited biomass (B_0) of animals > 120 mm CW in the fishery. Those estimates of B_0=1,200 t, with a likely MSY in the range of 30-90 t p.a., appear conservative, given that since 2000 the fishery has landed around 200 t p.a. Catch rates appear to have stabilized, but this is a long lived species and there is a need to establish a reasonable time series before the harvest potential of a fishery can be properly understood.

8.4 Deciding on a future TAC

The current interim management plan is expected to become a full management plan in late 2007. Extensive consultations regarding future management strategies in this fishery have been undertaken and managers and fishers have agreed that it should be managed by output controls. The fishery is particularly suited to quota management, because from a compliance point of view it would be difficult and expensive to monitor pot numbers in a deep water long line fishery, but relatively simple to monitor landings by the small numbers of boats in the fishery.

As has been noted throughout this report, whilst crystal crabs cover an extensive area they would not be expected to sustain intense fishing pressure. The reason for this is that at the depths at which the crabs are found (~500-800 m), temperatures range between 5 to 8 °C (Appendix 4) and in this cold and probably food limited environment, productivity is believed to be low. We know from tagging data (Chapter 6), that the species is slow growing and long-lived. In addition, the Industry backed minimum size (120 mm CW or ~103 mm CL) is large, which means that productivity is not being optimised. However, there is no proposal to change the minimum size as the market demand is for large sized crabs and as well, the minimum size in place is doing an excellent job of protecting the brood stock.

Given that there is uncertainty surrounding any TAC recommendation and that recent catches have been maintained at about 200 t, it has been decided that an adaptive management approach will be adopted. A TAC of 140 t will be set for the fishery and its performance will be monitored, primarily against cpue. It is clear that a fishery of 140 t is unlikely to support seven full time fishers, but under future management arrangements each licence holder will have an even share of quota, which will be transferable.

8.5 Future stock assessment considerations

It has been noted that the current large legal minimum size makes this a highly male-dominated fishery and that because of the size at maturity being below the legal minimum size, that the brood stock would seem to be reasonably well protected. However there is a need to monitor this situation as evident by the ever growing quantity of scientific literature pointing to the vulnerability of egg production in crustacean fisheries resulting from male dominated fishing practices (Kendall *et al.* 2001; MacDiarmid and Butler 1999; Sato and Goshima 2006). Size at maturity in some crustacean populations has also changed, possibly as a result of populations evolving to maximise their rate of increase in response to fishing (Sainte-Marie 1993; Landers *et al.* 2001; Melville-Smith and de Lestang 2006) and it will therefore be important to monitor for these sorts of changes in the future.

A particular area of research for which there is very little information in deep water crab populations is spawning frequency. It is clear for many of these long-lived slow-growing deep water crab species, that once mature they have long intermoult periods and some species (crystal crabs included), would appear to have only one or two moults after attaining maturity. What has proved very difficult to establish is their reproductive output in terms of egg production after maturity. Indications are that they may only produce a few broods in their lifetime, in which case even relatively low levels of exploitation might have serious implications for a long-lived species. Furthermore, since all indications are that crystal crabs take in excess of 12 years to reach maturity, any changes to recruitment caused by overfishing the brood stock would take many years before becoming apparent in the catches.

Now that there is a longer time series of catch and effort data, future stock assessments might start to make use of biomass dynamics model. In this and any other modelling context, it will be very necessary to obtain some indication of improvements in fishing efficiency. In any new fishery, efficiency can be expected to undergo rapid change. This fishery is unlikely to be an exception to this rule.

There is a need to better understand the juvenile, unfished component of this fishery. At present there is no information on the depths to which they recruit. Obviously knowledge of this could be important in managing offshore activities in the mining and other fishing industries. Information on the juvenile component might also contribute to growth information, which at present is reliant on extrapolating backwards from commercially caught animals.

A particularly important area for future research consideration is that of attempting to establish both natural and fishing mortality rates. Now that there is information on movement patterns and growth rates, some future tagging targeting well-defined areas and depths, may be able to establish these parameters.

9.0 Benefits and adoption

At the time that funds were granted for this project there was no understanding of the size or biological characteristics of the crystal crab fishery. Since that time an interim management plan has been established for deep sea crab fishing on the west coast of Western Australia and by the end of 2007 this will become a fully managed fishery.

The outcomes of this research project has directly benefited the commercial fishers in the West Coast Deep Sea Crab Interim Managed Fishery, by providing the scientific backing to support many of the decisions that have been taken as to the way that this fishery will be managed when it moves to its full management status.

The baseline data that has been collected during the course of this project will continue to be built on in the future and will continue to be important in future management decision making. Critical information gaps have been identified by the project and they will form the basis of future research on this important fishery.

Aside from the benefits of the project in allowing more informed decisions to be made in terms of the management of their fishery than would have been possible without this information, it has also provided the data used in the ESD report prepared for the Department of Environment and Heritage's assessment of the fishery under guidelines for Schedule 303DB of the Environment Protection and Biodiversity Conservation Act.

10.0 Further Development

Further development of the results of this research will be through:

- Continuation of the data collection regime that has been established.
- Addressing research needs to deal with critical information gaps that have been identified by the project (see 8.5 Future Stock Assessment Considerations)
- The development of a more efficient escape gap (if this is what licence holders wish to see). This project has shown that a significant number of legal sized crabs are being lost through the use of an escape gap that is larger than necessary. While this does have positive benefits in terms of stock protection, it is not an efficient means of fishing.

The results of this project have been disseminated to license holders at meetings that have been held irregularly throughout the life of the project. This will continue in the future.

Some results have been disseminated to the scientific community at Deep Sea 2003, a conference on the governance and management of deep-sea fisheries organised by the FAO (Melville-Smith *et al.* 2006). Further research publications dealing with components of this final report are anticipated in the future. Preliminary results aimed at commercial fishers and the general public have been published in a popular magazine (Anon. 2003). More such articles are anticipated now that the project has concluded.

11.0 Planned outcomes

The planned outcomes as identified in the funding application, was for this project to develop the research foundations upon which future management decisions in the fishery would be based. There is no question that it has achieved this goal. The project has established:

- A fully functioning logbook program for fishers to record their catch and effort data for legal and undersize components of the catch. Also databases enabling this information to be captured for analysis.
- A fully functioning monitoring program in which research staff visit the commercial vessels on multiple occasions through the year to collect size frequency and biological information on the catch. Also databases enabling this information to be captured for analysis.
- Knowledge of the relative abundance of crystal crabs in the various regions and depths across which the species is commercially fished.
- Biological information on reproductive characteristics, as well as growth and movement patterns of crystal crabs.
- Information on the effectiveness of the escape gaps in use in the fishery.
- An annual assessment being produced on the state of the stock.
- Sufficient knowledge about the fishery to have enabled the fishery to have had export approval for its products under the Department of Environment and Heritage's Environmentally Sustainable Development accreditation program.

12.0 Conclusion

This project has been undertaken by two different organizations: Murdoch University and the Department of Fisheries, Western Australia. Murdoch University has submitted their component of the final report (Appendix 6) and the conclusions from the work for which they were responsible has been dealt with in that report and will not be repeated here.

All objectives for which the Fisheries Department was responsible have been completed. The major findings and contributions to the future management of the crystal crab fishery were that:

- A logbook system has been established for fishers to record catch positions and depths and catch details of the legal, undersize and berried components of their catch (Appendix 5).
- A voluntary system whereby fishers would record the sex and carapace lengths of all crabs in the first few pots of each line was trialed for over a year before being rejected.
- A system has been established whereby Departmental research staff on multiple occasions per year, go out on commercial crab boats to measure and record the sex and size structure and collect other biological information as necessary from the commercial catch (Appendix 5). Research staff have tagged crabs in all zones of the fishery from 2001. This work is continuing.
- Databases have been established to capture commercial catch statistics logbook data, commercial catch monitoring data, tag release and recapture data (Appendix 3).
- Most of the commercial catch of crystal crabs since the inception of the fishery has been between 500-800 m. Fishing outside of those depths has contributed less than 5% and in some years less than 1% of the total landings.
- The fishery is largely focused on the coast between North West Cape and Fremantle.
- Annual catches have hovered around 200 t since 2001 and peaked at 233 t in 2004. Effort has increased in each year bar 2005. Catch rates declined drastically from 2000, but soon stabilized and in recent years have shown an upward trend.
- Undersize crabs showed a continual decline in catch rates from 2000 to 2004, but in 2005 the have shown a remarkable increase. Ovigerous crabs have shown a continuous increase in CPUE since 2001. These patterns for undersize and ovigerous crab catch rates have been hard to explain.
- Catch length frequency monitoring has shown a decrease in mean size for both sexes, with the decline been more marked for males than females, presumably because of their larger maximum size. Mean size frequencies appear to have stabilized for both sexes.
- The escape gap currently in use in the fishery is effective for females but not for males. Pots fitted with two escape gaps reduced the catch rate of legal size male crabs by 16%.
- Tagged crabs weighted prior to release so as to sink quickly to the bottom, showed no significant difference in distance, direction or recapture rates. As a consequence of this finding, no special precautions have been taken when releasing tagged crabs in this study.
- Tagging studies have shown crystal crabs to be very slow growing. Best estimates would suggest that legal size male crabs are 13 to 15 years old and that some large crabs in the population are around 30 years old. Females are more difficult to age because of long intermoult periods after maturity, but there is no reason to consider that their age at maturity would be different to that for males.

- Neither sex, nor particular size classes over the size range tagged, showed strong trends in terms of their direction of movement after release. The majority moved less than 50 km, even after three and four years at large. Only 2% of recaptured crabs moved more than 100 km while at large.
- An assessment of the stock shows that catch rates and size frequency distributions have apparently stabilized. Best estimates of the long term sustainable yield from this fishery is 30-90 t, which is substantially less than the 200 t landings of the last five years, or the 140 t TAC proposed for the fishery in the future. Research ideas have been proposed to improve the quality of future stock assessment advice in this fishery.
- The impact of a TAC on the performance of the fishery will be monitored by annual reviews of cpue and changes in length frequency distribution.

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14.0 Appendices

Appendix 1

Intellectual Property

The value of the intellectual property will be 57.38% based on PART C of the FRDC project proposal.

Appendix 2

Staff

Dr Roy Melville-Smith

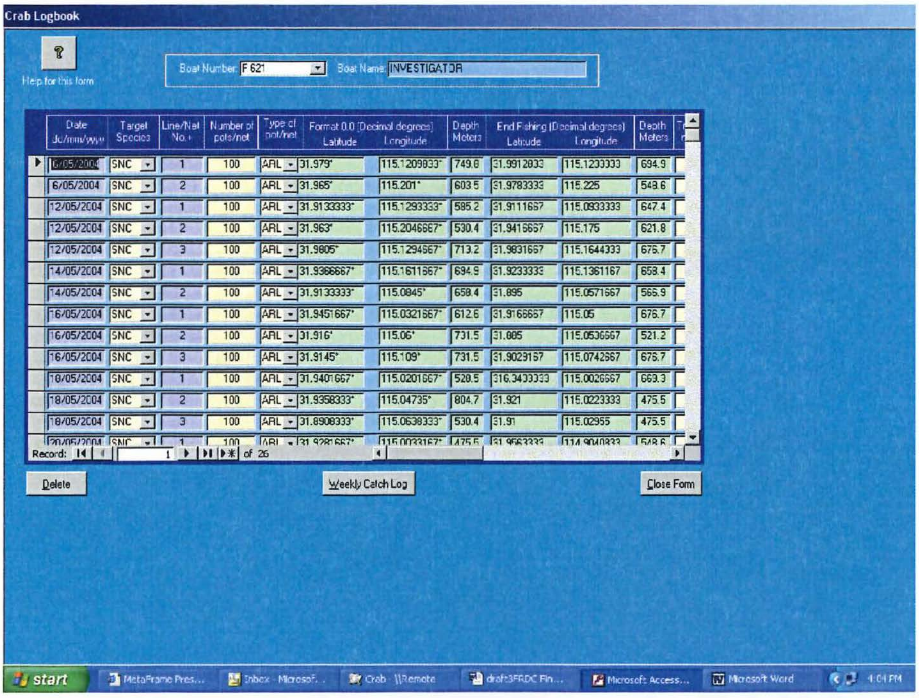
Mr Adrian Thomson

Mr Sam Norton

Mr Ross Gould

Appendix 3 Databases

A number of Microsoft Access databases were established in order to meet the objectives of this project. The logbook database system stores the voluntary logbook information. The data entry interface (Figure 1) allows for the entry and editing of catch and effort. The reporting option offers the option of generating a number of standard self-explanatory reports (Figure 2).



Boat Number: F 621 Boat Name: INVESTIGATOR

Date dd/mm/yyyy	Target Species	Line/Net No.+	Number of pots/net	Type of pot/net	Format 0.0 (Decimal degrees) Latitude	Longitude	Depth Meters	End Fishing (Decimal degrees) Latitude	Longitude	Depth Meters
6/05/2004	SNC	1	100	ARL	31.979°	115.1209833°	749.8	31.9912833	115.1233333	694.9
6/05/2004	SNC	2	100	ARL	31.965°	115.201°	603.5	31.9783333	115.225	548.6
12/05/2004	SNC	1	100	ARL	31.9133333°	115.1293333°	585.2	31.9111667	115.0933333	647.4
12/05/2004	SNC	2	100	ARL	31.963°	115.2046667°	530.4	31.9416667	115.175	621.8
12/05/2004	SNC	3	100	ARL	31.9805°	115.1294667°	713.2	31.9831667	115.1644333	676.7
14/05/2004	SNC	1	100	ARL	31.9366667°	115.1611667°	694.9	31.9233333	115.1361167	658.4
14/05/2004	SNC	2	100	ARL	31.9133333°	115.0845°	658.4	31.895	115.0571667	566.9
16/05/2004	SNC	1	100	ARL	31.9451667°	115.0321667°	612.6	31.9166667	115.05	676.7
16/05/2004	SNC	2	100	ARL	31.916°	115.06°	731.5	31.885	115.0536667	521.2
16/05/2004	SNC	3	100	ARL	31.9145°	115.109°	731.5	31.9029167	115.0742667	676.7
18/05/2004	SNC	1	100	ARL	31.9401667°	115.0201667°	528.5	316.3433333	115.0026667	669.3
18/05/2004	SNC	2	100	ARL	31.9358333°	115.04735°	804.7	31.921	115.0223333	475.5
18/05/2004	SNC	3	100	ARL	31.8908333°	115.0638333°	530.4	31.91	115.02955	475.5
20/05/2004	SNC	1	100	ARL	31.9281667°	115.0033167°	475.5	31.9563333	114.9040833	548.6

Figure 1 Data entry interface of the compulsory catch and effort database.

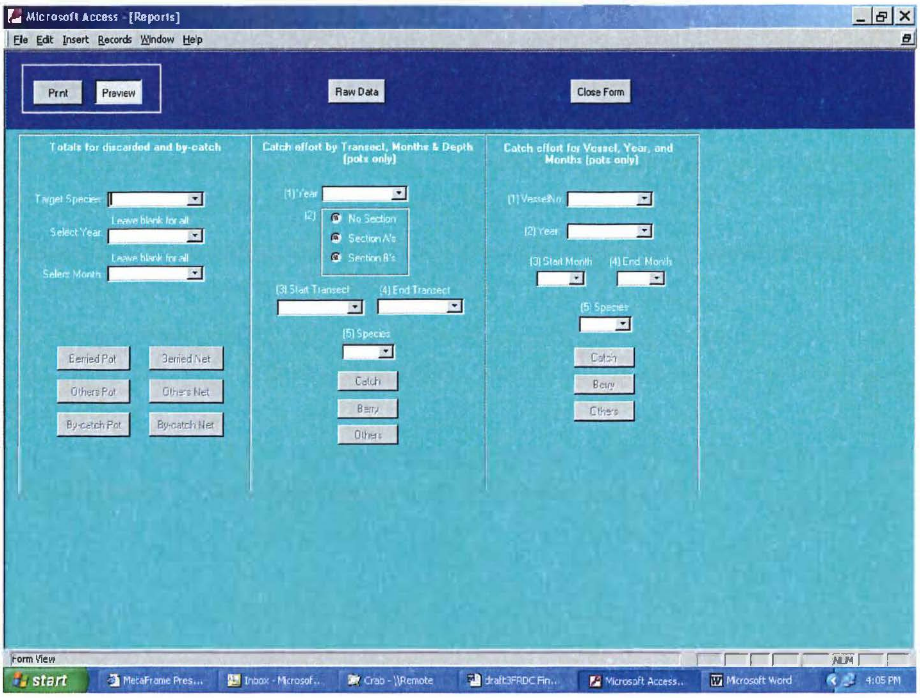
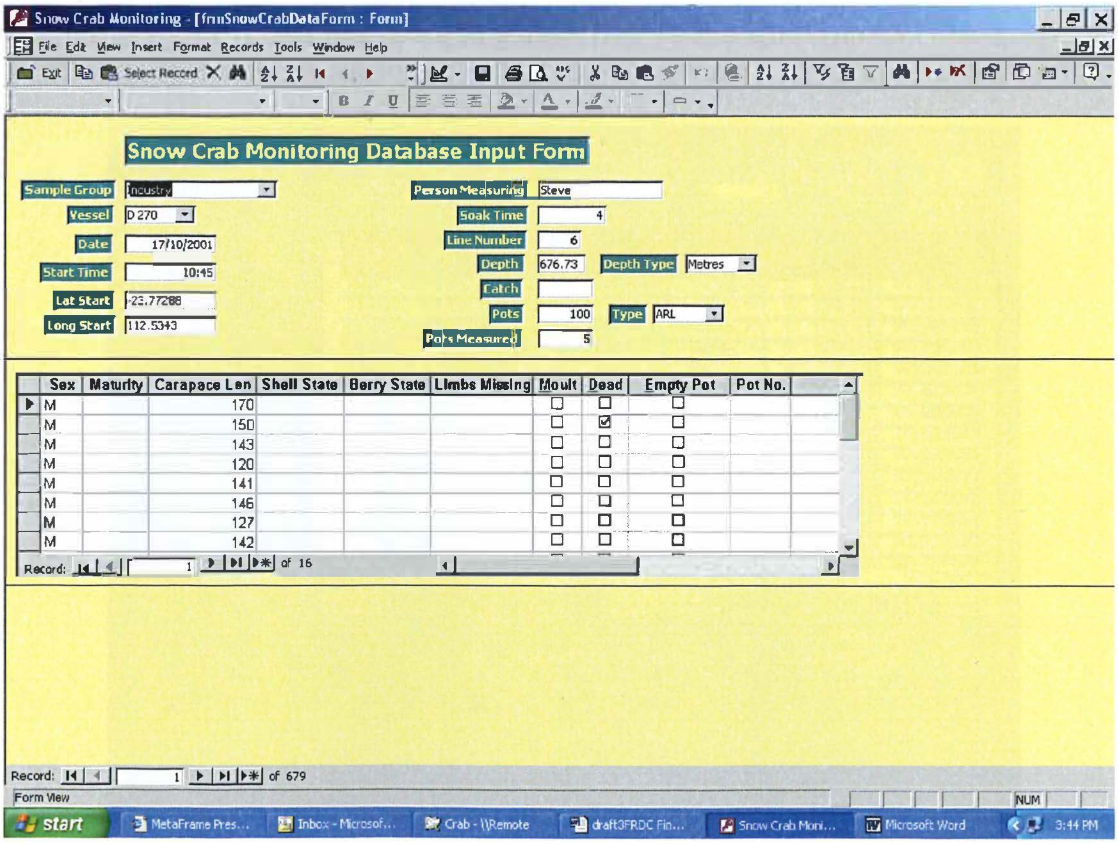


Figure 2 Report option for the compulsory catch and effort database.

A database has been established for recording biological data. This has the capacity for recording length-frequency monitoring information (Figure 3) and tag and release recapture data (Figure 4 and 5).



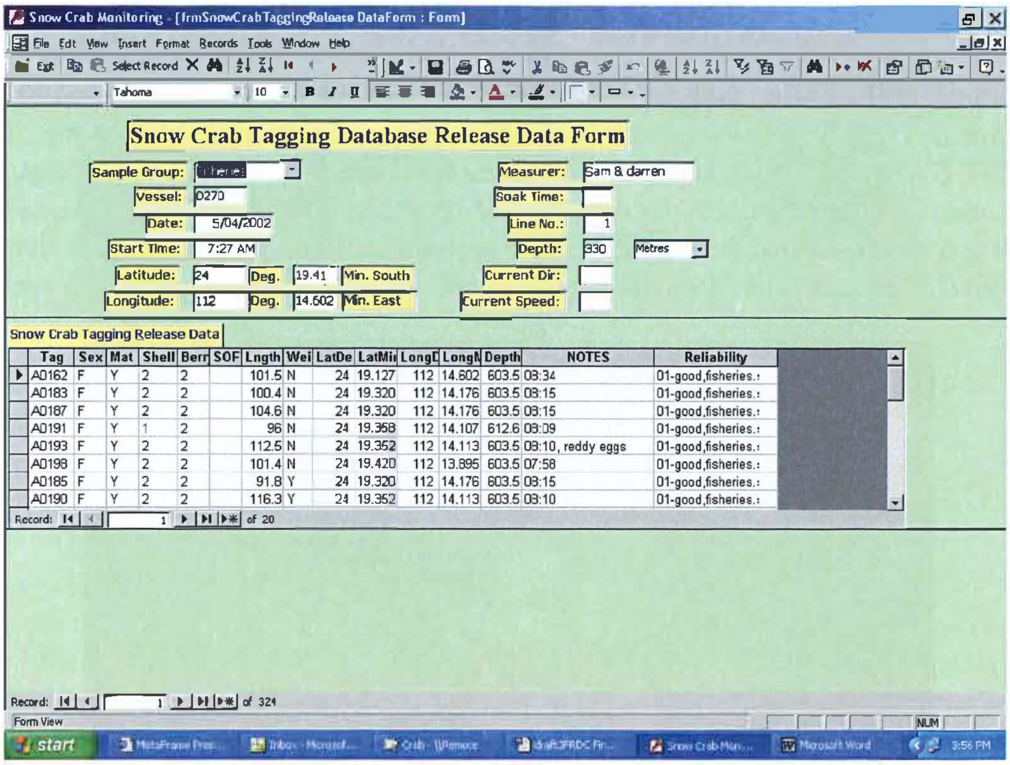
Sample Group: Industry
Vessel: D 270
Date: 17/10/2001
Start Time: 10:45
Lat Start: -23.77288
Long Start: 112.5343
Person Measuring: Steve
Soak Time: 4
Line Number: 6
Depth: 676.73
Depth Type: Metres
Catch:
Pots: 100
Type: ARL
Pots Measured: 5

Sex	Maturity	Carapace Len	Shell State	Berry State	Limbs Missing	Moult	Dead	Empty Pot	Pot No.
M		170				☐	☐	☐	
M		150				☐	☑	☐	
M		143				☐	☐	☐	
M		120				☐	☐	☐	
M		141				☐	☐	☐	
M		146				☐	☐	☐	
M		127				☐	☐	☐	
M		142				☐	☐	☐	

Record: 1 of 16

Record: 1 of 679

Figure 3 Data entry interface of the length-frequency monitoring database.



Snow Crab Tagging Database Release Data Form

Sample Group: Fisheries
Vessel: D270
Date: 5/04/2002
Start Time: 7:27 AM
Latitude: 24 Deg. 19.41 Min. South
Longitude: 112 Deg. 14.602 Min. East
Measurer: Sam & darren
Soak Time:
Line No.: 1
Depth: 330 Metres
Current Dir:
Current Speed:

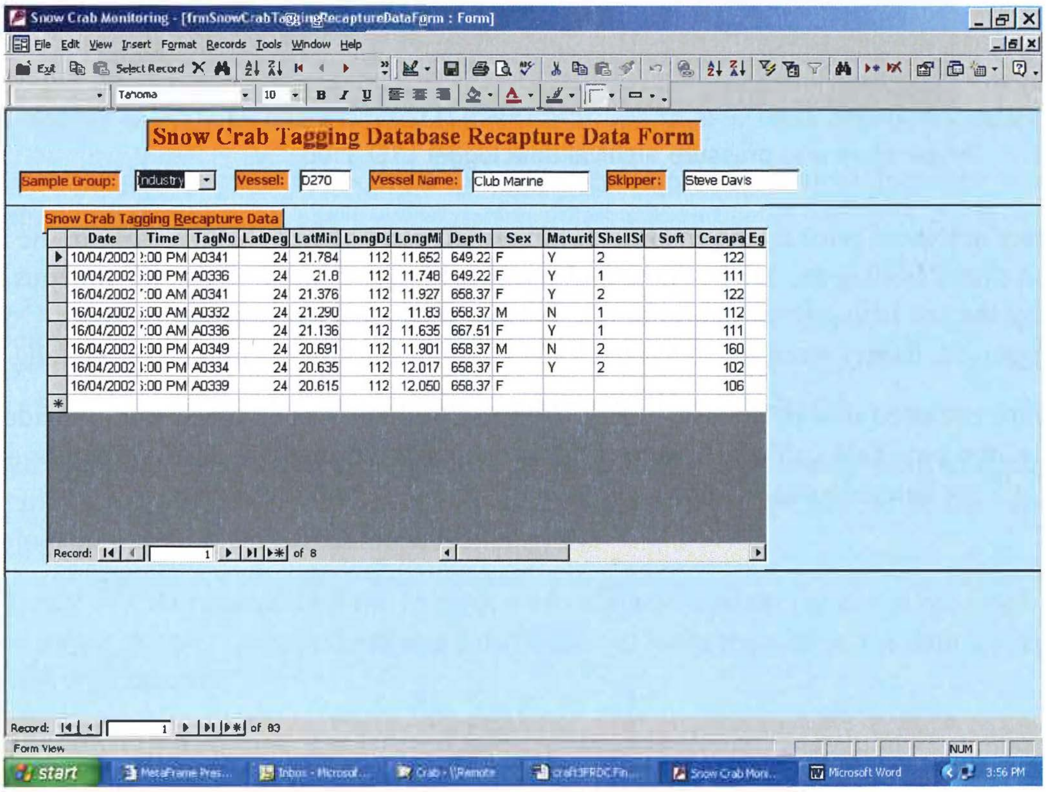
Snow Crab Tagging Release Data

Tag	Sex	Mat	Shell	Berr	SOF	Lngth	Wei	LatDe	LatMi	LongD	LongM	Depth	NOTES	Reliability
A0162	F	Y	2	2		101.5	N	24	19.127	112	14.602	603.5	08:34	01-good,fisheries.:
A0183	F	Y	2	2		100.4	N	24	19.320	112	14.176	603.5	08:15	01-good,fisheries.:
A0187	F	Y	2	2		104.6	N	24	19.320	112	14.176	603.5	08:15	01-good,fisheries.:
A0191	F	Y	1	2		96	N	24	19.358	112	14.107	612.6	08:09	01-good,fisheries.:
A0193	F	Y	2	2		112.5	N	24	19.352	112	14.113	603.5	08:10, reddy eggs	01-good,fisheries.:
A0198	F	Y	2	2		101.4	N	24	19.420	112	13.895	603.5	07:58	01-good,fisheries.:
A0185	F	Y	2	2		91.8	Y	24	19.320	112	14.176	603.5	08:15	01-good,fisheries.:
A0190	F	Y	2	2		116.3	Y	24	19.352	112	14.113	603.5	08:10	01-good,fisheries.:

Record: 1 of 20

Record: 1 of 324

Figure 4 Data entry interface of the tag-release database.



Snow Crab Tagging Database Recapture Data Form

Sample Group: Industry
Vessel: D270
Vessel Name: Club Marine
Skipper: Steve Davis

Snow Crab Tagging Recapture Data

Date	Time	TagNo	LatDeg	LatMin	LongDe	LongMi	Depth	Sex	Maturit	ShellSt	Soft	Carapa	Eg
10/04/2002	:00 PM	A0341	24	21.784	112	11.652	649.22	F	Y	2		122	
10/04/2002	:00 PM	A0336	24	21.8	112	11.748	649.22	F	Y	1		111	
16/04/2002	:00 AM	A0341	24	21.376	112	11.927	658.37	F	Y	2		122	
16/04/2002	:00 AM	A0332	24	21.290	112	11.83	658.37	M	N	1		112	
16/04/2002	:00 AM	A0336	24	21.136	112	11.635	667.51	F	Y	1		111	
16/04/2002	:00 PM	A0349	24	20.691	112	11.901	658.37	M	N	2		160	
16/04/2002	:00 PM	A0334	24	20.635	112	12.017	658.37	F	Y	2		102	
16/04/2002	:00 PM	A0339	24	20.615	112	12.050	658.37	F				106	

Record: 1 of 8

Record: 1 of 83

Figure 5 Data entry interface of the tag-recapture database.

Appendix 4 Monitoring bottom temperature on the crystal crab grounds

Temperatures on the crystal crab fishing grounds were investigated using LTD 1100 archival data storage tags (DST) manufactured by Lotek Wireless Fish & Wildlife Monitoring. The LTD 11000 DST (Figure 1), which is capable of operating down to 1,000 m, records temperature, pressure and real-time 256 times per hour (at 14 sec intervals) until the 32KB memory is full (i.e. after 2.6 days). At that time an extension recording (TER) program begins overwriting every second record, effectively extending the sampling period to months, or even years.

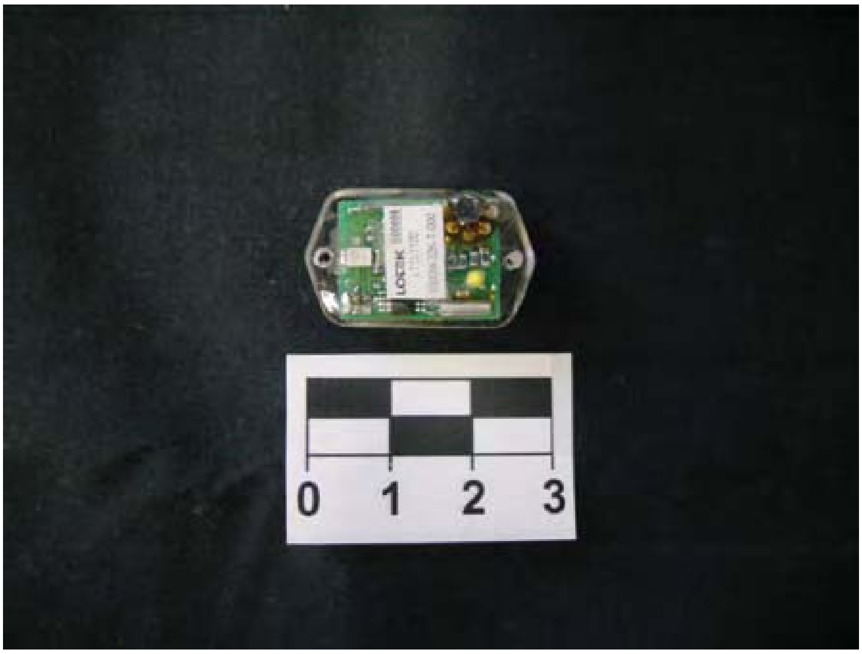


Figure 1 Temperature and pressure archival data logger LTD 1100.

DSTs were activated prior to shipment to commercial crab fishers. Results early in the project indicated that attaching the DSTs to the end pot in a longline could produce erroneous results caused by the pot lifting from the bottom in periods of high seas or strong currents. Once this was recognised, fishers were asked to attach the DSTs to a pot in the middle of the long line.

DSTs were enclosed in a protective casing (Figure 2) which was attached to the inside upper surface of the pot. Two cable-ties were used to anchor the protective case to the pot so as to prevent it from being damaged during deployment and retrieval of the gear.

Figure 2 The casing used to protect and attach data logger to crab pot.

On each occasion that a line containing a DST was set, the fisher was asked to record the date and time set, line number, pot number, latitude, longitude and depth (Appendix 5). The DSTs were deployed for the soak time of the line, generally three to seven days, and remained attached to the pot for four to five trips before being returned to the Fisheries Department Research Division.

The LTD 11000 archival data loggers can record temperature from –5°C to 35°C, to an accuracy of < 0.3°C and to a resolution of 0.20°C. The pressure sensor has a depth auto-scaling function of 250 m, 500 m and 1,000 m to improve accuracy and resolution. The resolution of the sensor is scale dependant and equal to current scale /256 (i.e. 0.98 m, 1.95 m and 3.91 m). The pressure sensor accuracy is ± 1% of current scale (i.e. ± 2.5 m, ± 5 m or ± 10 m depending on the scale.

To calculate depth measurements from pressure readings the units of the data were first transformed to KPa by:

$$1 \text{ PSI} / 0.1450376 = 1 \text{ Kpa}$$

Depth below water was calculated from KPa using:

$$\text{Kpa (at depth)} - \text{Kpa (at surface}^{1}) / 10 = \text{depth (m)}$$

Where surface[1] Kpa - was taken as an average of 10 readings immediately prior to deployment to account for atmospheric pressure. This was considered a good estimate of the prevailing meteorological pressure whilst the tag was deployed.

The accuracy of data recorded by the loggers was validated against the depth recorded for the same line by the skipper. Where there was a difference of more than 20 m, the data logger result was treated with caution.

The loggers produced a detailed time series of temperature and pressure at depth, however fluctuations in the data were observed. A combination of factors (including the error margin, “ADC jitter” where the digital device oscillates between readings at its finest scale, and real changes in environmental conditions) produced spikes in the data (Figure 3). This prevented a mean temperature being taken for each depth sampled on a trip. Instead, representative estimates of temperature and pressure (depth) were obtained by taking the modal temperature and depth for each trip.

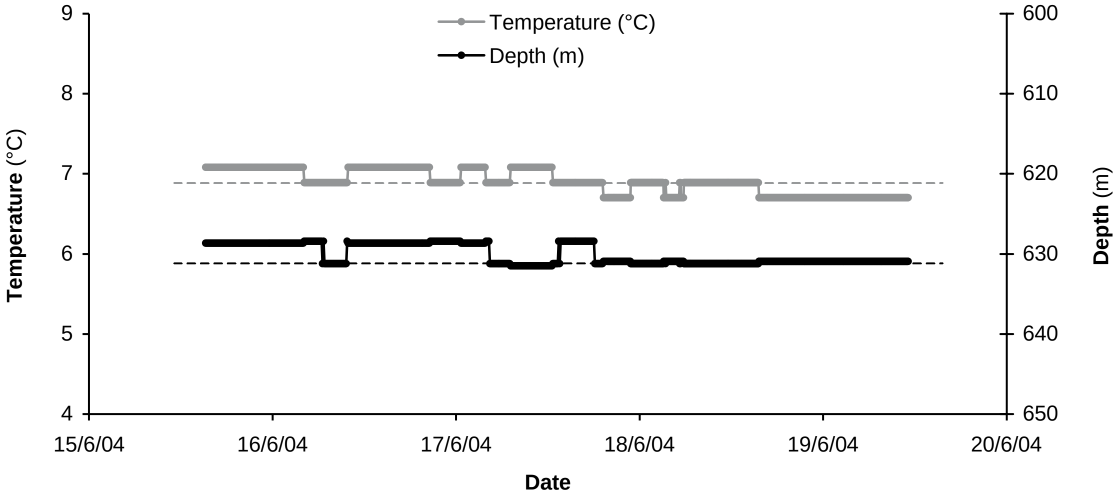


Figure 3. Showing a temperature and depth data series with periods of fluctuation and stability. The dotted lines represent the mode for the two parameters.

Temperature depth relationships for the crystal crab grounds using data collected over the period that DSTs were deployed are shown in Figure 4. The error in the DST readings were considered to nullify the value of standardising the data for time of year and locality and this has not therefore been attempted. The relationship between temperature and depth can be described by:

$$y = -0.0138x + 15.43$$

where y=temperature (°C) and x=depth (m)

The crystal crab commercial fishery on the west coast of Western Australia is largely confined to the 500-800 m depth range. The results from all of the monitoring of temperature at different depths that have been undertaken by this study, shows that temperatures in these depths is in the range 5-9 °C.

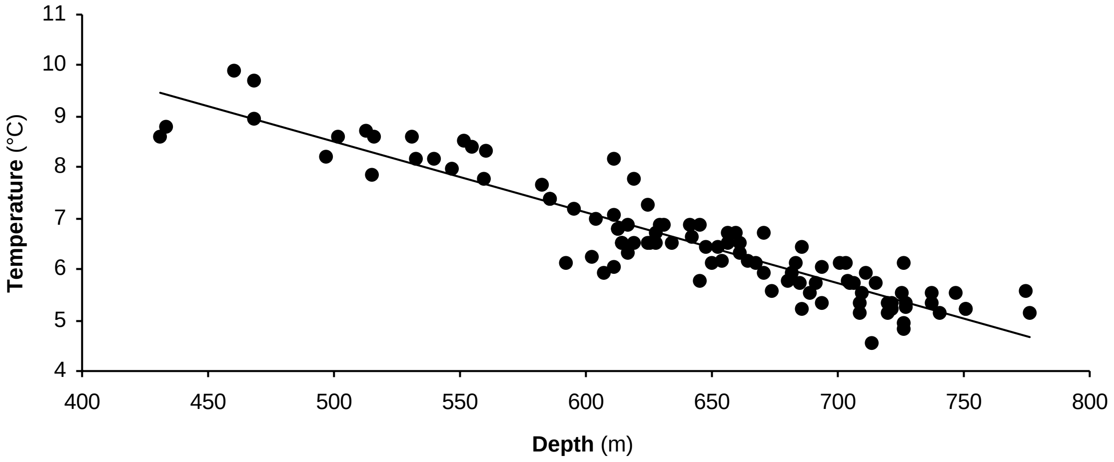


Figure 4 Temperature and depth relationship for all data collected by DSTs attached to commercial crystal crab pots deployed between 8/05/2003 and 28/09/

Appendix 5 Datasheets

(a) Catch monitoring datasheet

DEPARTMENT OF FISHERIES
DEEPSEA CRAB CATCH MONITORING DATASHEET

VESSEL LFB Number		**MEASURER**		**CRAB SP.**	
DATE		**SOAK TIME (Days)**		SAMPLING GROUP (CIRCLE)	FISHERIES INDUSTRY
START **TIME**		**LINE NUMBER**			
START **LATITUDE (Deg/Min)**		**POTS MEASURED**			
START **LONGITUDE (Deg/Min)**		**CRABS MEASURED**		**CPUE**	
START **DEPTH (fm) or (m)**		**EMPTY POTS**		**PAGE 1** OF	

	SEX (M / F)	**MAT MARKS** (Y / N)	**CRPC LNGTH** (mm)	**SHELL STATE** (1 - 3)	**BERRIED STATE** (1 - 4)	**LIMBS MISSING** (R1-5, L1-5)	**SOFT MOULT** (Y)	**DEAD** (Y)	**EMPTY POT** (Y)	**POT NO.**	**COMMENTS**
1											
2											
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5											
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33											

Return to: Deep sea crab research, Western Australian Fisheries and Marine Research Laboratories, P.O. Box 20 North Beach, WA 6920. Ph (08) 9203 0111

(b) Length, width, height and weight datasheet

DEPARTMENT OF FISHERIES
DEEPSEA CRAB LENGTH WIDTH HEIGHT WEIGHT DATASHEET

LFB Number		**MEASURER**			**CRAB SP.**	
DATE		**SOAK TIME (DAYS)**			SAMPLING GROUP (CIRCLE)	FISHERIES INDUSTRY
START **TIME**		**LINE NUMBER**				
START **LATITUDE (DEG/MIN)**		**CRABS MEASURED**				
START **LONGITUDE (DEG/MIN)**						
START **DEPTH (FM) or (M)**			**PAGE**		**OF**	

	SEX (M / F)	**MAT MARKS** (Y / N)	**CRPC LNGTH** (mm)	**CRPC WDTH (mm)**	**CRPC HGHT (mm)**	**CRAB WGHT** (g)	**SHELL STATE** (1 - 3)	**BERRIED STATE** (1 - 4)	**LIMBS MISSING** (R1-5, L1-5)	**SOFT MOULT** (Y)	**DEAD** (Y)	**COMMENTS**
1												
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4												
5												
6												
7												
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32												
35												

Please return this sheet to: Deepsea Crab Research, Western Australian Marine Research Laboratories, P.O. Box 20 North Beach, WA 6920. Ph (08) 9246 8444

(c) Tagging datasheet

DEPARTMENT OF FISHERIES
DEEPSEA CRAB TAGGING DATASHEET

VESSEL LFB Number		**CRAB SP.**		**SAMPLING GROUP (CIRCLE)**
DATE		**SOAK TIME (DAYS)**		
START TIME		**LINE NUMBER**		
START LATITUDE DEG/MIN		**NUMBER OF CRABS TAGGED**		**FISHERIES**
START LONGITUDE DEG/MIN		**PAGE 1 OF**		
START DEPTH (FM)		**MEASURER**		**INDUSTRY**

	TAG NO.	**SEX** (M/F)	**MAT MARKS** (Y / N)	**SHELL STATE** (1 - 3)	**BERRIED STAGE** (Y/ 1 - 4)	**SOFT** (Y)	**CRPC LNGTH** (mm)	**RELEASE LOCATION**				**DEPTH** (fm)	**COMMENTS**
								DEG	**LATITUDE** MIN	DEG	**LONGITUDE** MIN		
1													
2													
3													
4													
5													
6													
7													
8													
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Return to: Deep sea crab research, Western Australian Fisheries and Marine Research Laboratories, P.O. Box 20 North Beach, WA 6920. Ph (08) 9203 0111

(d) Tag recapture datasheet

DEPARTMENT OF FISHERIES
DEEPSEA CRAB TAG RECAPTURE DATASHEET

SAMPLING GROUP (CIRCLE)
FISHERIES INDUSTRY

LFB
BOAT NAME
SKIPPER
CRAB SP

	DATE	TAG NO.	RECAPTURE LOCATION		DEPTH (fm)	SEX (M or F)	MAT MARK (Y or N)	SHELL STATE (1 - 3)	TAG PUNCTURE HOLE (OLD/NEW)	CRPC LNGTH (mm)	EGG STAGE (Y, 1 - 4)	LIMBS MISSING (R1-5,L1-5)	SOFT (Y)	DISPOSAL (K-Kept, R-released)	RELEASE LOCATION		DEPTH (fm)	COMMENT
			LATITUDE	LONGITUDE											LATITUDE	LONGITUDE		
1																		
2																		
3																		
4																		
5																		
6																		
7																		
8																		
9																		
10																		

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(e) Data storage tag datsheets

DEPARTMENT OF FISHERIES

DATA STORAGE TAG (DST) DATASHEET

LFB No. ____ **VESSEL NAME** ____ SKIPPER ____

#	DATE	TIME	LINE No.	# POTS ON LINE	ATTACHED TO POT #	WEIGHT OF BALLAST (KG)	DEPTH (fm)	LATITUDE	LONGITUDE	COMMENTS
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										

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Deep Sea Crustacean Log Sheet

BOAT NO.	BOAT NAME	SKIPPER	POT TYPE eg. Amateur rock lobster, Steel Beehive, Fathoms plus	BAIT USED	TARGET SPECIES CODES				
					CRYSTAL (SNOW) CRAB (SnC)	CHAMPAGNE (SPINY) CRAB (SpC)	GIANT (KING) CRAB (GC)	SOUTHERN ROCK LOBSTER (SRL)	WESTERN ROCK LOBSTER (WRL)

DATE (DAY GEAR IS RETRIEVED)	LINE NUMBER	TARGET SPECIES	No. POTS (IN LINE)	FISHING LOCATION Please record the START and END details – for each pot line fished, or the START details only – for each group of individual pots used in the same depth.						SOAK TIME (Days)	CATCH 1					CATCH 2**			REMARKS
											(Species Name)					(Species Name)			
				START			END				CATCH	DISCARDED (numbers)				CATCH	DISCARDED (numbers)		
				LATITUDE	LONGITUDE	DEPTH Specify Metres or Fathoms	LATITUDE	LONGITUDE	DEPTH Specify Metres or Fathoms		*Specify* Kilograms Baskets* Numbers*	Berried	Small	Soft	Dead	*Specify* Kilograms Baskets* Numbers*	Berried	Small	

NOTE: * IF CATCH IS GIVEN IN BASKETS OR NUMBERS PLEASE PROVIDE AN ESTIMATE OF THE AVERAGE WEIGHT PER BASKET OR ANIMAL; ** CATCH 2 CAN BE USED TO RECORD A SECOND COMMERCIAL SPECIES.

Bycatch Type and approximate number of all non-commercial animals caught in pots; note any interactions (death/entanglement) of fishing gear with marine mammals, turtles or birds for the period recorded above.

NOTE: TEAR OUT AND RETURN THE ORIGINAL COPY (THE WHITE SHEET) AND KEEP THE DUPLICATE (THE YELLOW SHEET) IN THE BOOK FOR YOUR PERSONAL USE.

Appendix 6 Final report for project 1999/154 and 2001/055, Murdoch University component

Note that this report deals with a component of 2001/055 that was undertaken by researchers at Murdoch University. This part of the project was published separately under its own ISBN number and is included as an appendix of this report for completeness.

Biological and fisheries data for managing the deep-sea crabs *Hypothalassia acerba* and *Chaceon bicolor* in Western Australia

Smith, K.D., Potter, I.C. and Hall, N.G.

Projects No. 1999/154 and 2001/055

Fisheries Research and Development Corporation Report

FRDC projects 1999/154 and 2001/055

Fisheries Research and Development Corporation Report

FRDC projects 1999/154 and 2001/055

FINAL REPORT

Biological and fisheries data for managing the deep-sea crabs *Hypothalassia acerba* and *Chaceon bicolor* in Western Australia

Smith, K. D.
Potter, I. C.
Hall, N. G.

September 2004

ISBN: 0-86905-883-5

Centre for Fish and Fisheries Research
Murdoch University
Murdoch, Western Australia 6150

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2001/055 Biological and fisheries data for managing deep sea crabs in Western Australia

PRINCIPAL INVESTIGATOR: Professor I. C. Potter

ADDRESS:
Centre for Fish and Fisheries Research
Division of Science and Engineering
Murdoch University
South Street, Murdoch WA 6150
Ph: 08 9360 2524 Fax: 08 9360 6303

OBJECTIVES:

The champagne crab Hypothalassia acerba (FRDC 1999/154)

1. Determine the composition by sex, size (carapace length (CL), to the nearest 1 mm), and weight (to the nearest 1 g) of champagne crabs in commercial crab pots from different depths in the two regions in which the champagne crab is fished , *i.e.* Geraldton to Fremantle and Augusta to Albany.
2. Use traps with a small mesh size to determine the full range in size (CL) and weight of crabs in different depths in the two sampling regions.
3. Produce preliminary estimates of growth of female and male crabs, based on growth increments and inter-moult periods.
4. Obtain indications of the movements of crabs and their relationships to body size and reproductive status.
5. Determine the carapace lengths at which 5 and 50% of female and male crabs reach maturity.
6. Determine the duration and location (area and water depth) of spawning and the fecundity and its relationship to body size.
7. Determine the diets of crabs and how they vary with body size and shell state. N.B. This study, which will also provide information on the type of habitat occupied by champagne crabs, will be carried out by a student at no cost to the project.
8. Establish the distribution patterns, size composition and prevalence of ovigerous females, and analyse data for other biological variables that were observed by fishers and recorded in log books.
9. The yield and egg (or mature biomass) per recruit relationships.
10. Assess the management implications of the biological data, and provide the results to managers in a form that can be used to help manage and conserve the fishery for the champagne crab.

The crystal crab Chaceon bicolor (FRDC 2001/055)

1. Implement a voluntary log book system in which fishers will record the number, size and location of capture of crabs and establish the data bases that are necessary to record and maintain logbook, size composition and tagging data.
2. Collect and process biological data on the size, weight, moult stage, shell state, sex ratio, gonadal weight and gonadal stage of crystal crabs caught by commercial fishers at regular intervals throughout the year.

3. Determine the relative abundance of crystal crabs in the various depths and regions in which this species is fished.
4. Determine the pattern of movement, growth and frequency of spawning of crystal crabs.
5. Estimate the carapace lengths at which 5 and 50% of female and male crabs reach maturity.
6. Determine the duration and location (area and water depth) of spawning and the fecundity and its relationship to body size.
7. Determine the size of the gaps that are required in the traps to allow undersize crabs to escape.
8. Determine the distribution patterns, size composition and the prevalence of ovigerous females, and other biological variables, observed by fishers and recorded in log books.
9. Undertake a depletion study to provide direct estimates of catchability and densities in different area.
10. Provide an initial assessment of the status of the crystal crab stock on the west coast of Western Australia.

Note that 1,4,7,8,9 and 10 will be undertaken by the Department of Fisheries Western Australia as its contribution to FRDC Project No. 2001/055 and the results of those components will be provided in a separate final report produced by the Department when the project finishes on 30 June 2005.

NON-TECHNICAL SUMMARY:

OUTCOMES ACHIEVED TO DATE

Biological data for the champagne crab *Hypothalassia acerba* and crystal crab *Chaceon bicolor* have been collected to enable managers to develop appropriate plans for conserving the stocks of these two commercial species of deep sea crabs. Emphasis was placed on outlining the catch statistics for the early years of the fisheries and on determining the depth distributions, size compositions, sizes at maturity, spawning periods, sex ratios and fecundity of these species. The use of samples of female champagne and crystal crabs collected by traps (their only method of capture) almost certainly leads to the size at gonadal maturity of those crabs to be underestimated. This needs to be taken into account if size at maturity is to be used for setting minimum legal lengths. Since the patterns of growth of the claws of male champagne and crystal crabs do not change at the pubertal moult, they could not be used in the traditional manner to determine maturity. The implications of these and our other results have been discussed with Dr Roy Melville Smith (WA Fisheries), who is continuing research into the biology of the crystal crab.

During recent years, commercial trap fisheries have developed for the champagne and crystal crabs in deep waters off the lower west and south coasts of Western Australia. Thus, data on crucial aspects of the biology of these species were required to enable plans to be developed for conserving their stocks. No such biological data were previously available.

Commercial catches of champagne crabs in south-western Australia rose from negligible levels in 1990 to peak at ~73 000 kg in 1998 and then declined progressively to ~17 300 kg in 2003, due mainly to fishers on the west coast shifting their effort towards crystal crabs. The catches of champagne crabs underwent a progressive seasonal change, particularly on the south coast where they reflected a decline in fishing effort during the inclement late autumn to middle spring months. Commercial catches of crystal crabs in south-western Australia, which came almost entirely from the lower coast, rose from very low levels in 1997 to reach ~222 000 kg in 2001 and then remained close to this level in 2002 and 2003. Catches and catch per unit effort of crystal crabs remained similar throughout the year. For the fisheries for both champagne and crystal crabs, the mean carapace lengths and catch rates were greater for males than females. Enclosure of traps in fine mesh did not lead to the capture of a relatively greater number of small crabs.

On the west and south coasts, the abundance of champagne crabs peaked at depths of 200 and 145 m, respectively, but at similar temperatures of 16.1-17.1°C. On the former coast, the crystal crab lives in depths of 450 to 1 220 m, where temperatures are only 4 to 6.5°C. The percentage of males in catches of champagne crabs was less on the west (69%) than south coast (84%). The carapace length of champagne crabs declined significantly by 4 mm with each 100 m increase in depth. As with commercial catches, the maximum and mean carapace lengths for males were greater than for females on both the west and south coasts. From the above, it follows that, in the case of champagne crabs, (1) distribution is related to water depth and temperature, (2) body size is inversely related to water depth and (3) males grow larger and are caught in greater numbers than females. There was also evidence that the distribution of champagne crabs changed slightly with season and that champagne crabs and other large deep water invertebrate predators tended to live in different water depths and thus avoid major competition for resources.

The trends exhibited by reproductive variables demonstrate that champagne crabs reproduce seasonally on the lower west coast, with females maturing progressively between July and December and becoming berried (egg bearing) between January and March. The reproductive characteristics of champagne crabs on the south coast differed markedly, in the following ways, from those on the lower west coast. (i) No berried females and only two females with egg remnants were caught. (ii) The development of large mature eggs was delayed until females reached a larger size. (iii) Investment of food resources in gonadal development was less. These results strongly indicate that (i) conditions on the south coast are not as conducive for ovarian development and reproduction and (ii) females migrate from the south to lower west coast for spawning. In contrast to champagne crabs, crystal crabs reproduce throughout all or most of the year on the lower west coast, presumably reflecting their occupancy of far deeper waters where environmental conditions vary less during the year. Although the mean weights of berried females of champagne and crystal crabs were not significantly different ($P > 0.05$), the mean fecundity of the former species (356 210) was significantly greater ($P < 0.001$) than that of the latter species (192 070). The high fecundity of the champagne crab may reflect adaptations by this seasonal spawner to optimise egg production during its relatively short breeding season.

The size at onset of sexual maturity (SOM) of female crustaceans is typically estimated by analysing the proportions of mature females in sequential size classes. The validity of this approach depends on the composition of the samples reflecting accurately that present in the environment. However, catches obtained by traps, a passive fishing method, typically contain a disproportionately greater numbers of large crabs, whereas those obtained using active fishing methods, such as seine netting and otter trawling, represent far better the size composition of the population. From data collected during a previous study, the samples of female blue swimmer crabs, *Portunus pelagicus*, caught by trapping were predominantly mature, whereas those collected by seining and trawling contained numerous immature as well as mature females. Thus, the samples of females collected by trap are biased towards mature crabs, which results in an underestimate of the SOM. From the results for the blue swimmer crab, the mature females of the champagne and crystal crab would also be likely to particularly susceptible to capture by traps, their only current method of capture. The respective sizes at which, on average, the females of these two species reach maturity, based on trap samples, namely carapace lengths of 69.7 and 90.5 mm, are thus likely to be lower than would be the case with truly representative samples.

The fact that the claws of male crabs are frequently assumed to undergo a change in relative size at the pubertal moult has been used as the basis for determining the size of male crabs at maturity. Initial plots of claw length versus carapace width (CW) or length (CL) of the males of blue swimmer, champagne and crystal crabs revealed no conspicuous change in the relative sizes of the claws. However, detailed statistical analysis revealed that the claws of blue swimmer crabs do undergo a change in the pattern of growth at 80 mm CW, namely at 8 mm less than their width at gonadal maturity. In contrast, no such evidence was found that the claws of either champagne or crystal crabs undergo similar changes. Maturity could not therefore be determined for these two species from the relative lengths of their claws. The lengths at gonadal maturity of trap-caught males of champagne and crystal crabs were 68.1 and 94.3 mm CL, respectively.

It follows that the establishment of minimum legal sizes for the males and females of both champagne and crystal crabs has to be based on the lengths at which gonadal maturity is attained, but recognising that, in the case of females, these values are likely to underestimate slightly the true average size at maturity. Size-frequency data indicate that, by the time champagne and crystal crabs are caught in traps, they are approaching their maximum sizes. Thus, if fishing effort increases, yield per recruit will increase and spawning biomass per recruit will decrease. Consequently, exploitation should be controlled to ensure that, in the future, catch per unit of effort is maintained above a specified minimum acceptable level.

KEYWORDS: crabs, deep sea, distribution, depth, temperature, size, reproduction, maturity

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1.0 GENERAL INTRODUCTION

1.1 THE CHAMPAGNE CRAB HYPOTHALASSIA ACERBA

Hypothalassia acerba Koh and Ng (**Figure 1.1a**), which used to be referred to as the spiny crab but is now termed the champagne crab, belongs to the Family Eriphiidae. This species lives in deep water off the south-western Australian coast and has recently been recognised as distinct from the only other member and type species of the genus *Hypothalassia*, namely *Hypothalassia armata*, which is restricted to the Pacific (Koh and Ng, 2000). Commercial catches indicate that, in Western Australia, the distribution of *H. acerba* extends from at least as far north as Kalbarri at ~114°E 27°S on the west coast, southwards and eastwards to at least Eucla at ~129° E, 32° S on the south coast.

Until 1989, the champagne crab was only exploited on the west coast of Australia by western rock lobster fishers working in deep water during December and January. However, since 1989, a small number of fishers have focused on catching *H. acerba* on this coast under a deep-sea crab endorsement license. On the south coast, champagne crabs have formed, since 1990, a component of a multi-species fishery, which also includes the king crab *Pseudocarcinus gigas* and the southern rock lobster *Jasus edwardsii.* A live export fishery for *H. acerba* commenced in 1989 and the Western Australian Fisheries Department Catch and Effort Statistics (CAES) show that, during the next decade, catches (total live weight) rose progressively to reach a peak of over 75 000 kg in 1998.

1.2 THE CRYSTAL CRAB CHACEON BICOLOR

Chaceon bicolor Manning and Holthuis (**Figure 1.1a**), which used to be referred to as the snow crab but is now termed the crystal crab, belongs to the family Geryonidae. This species is found in deep waters off large regions of the Australian and New Zealand coastlines (Jones

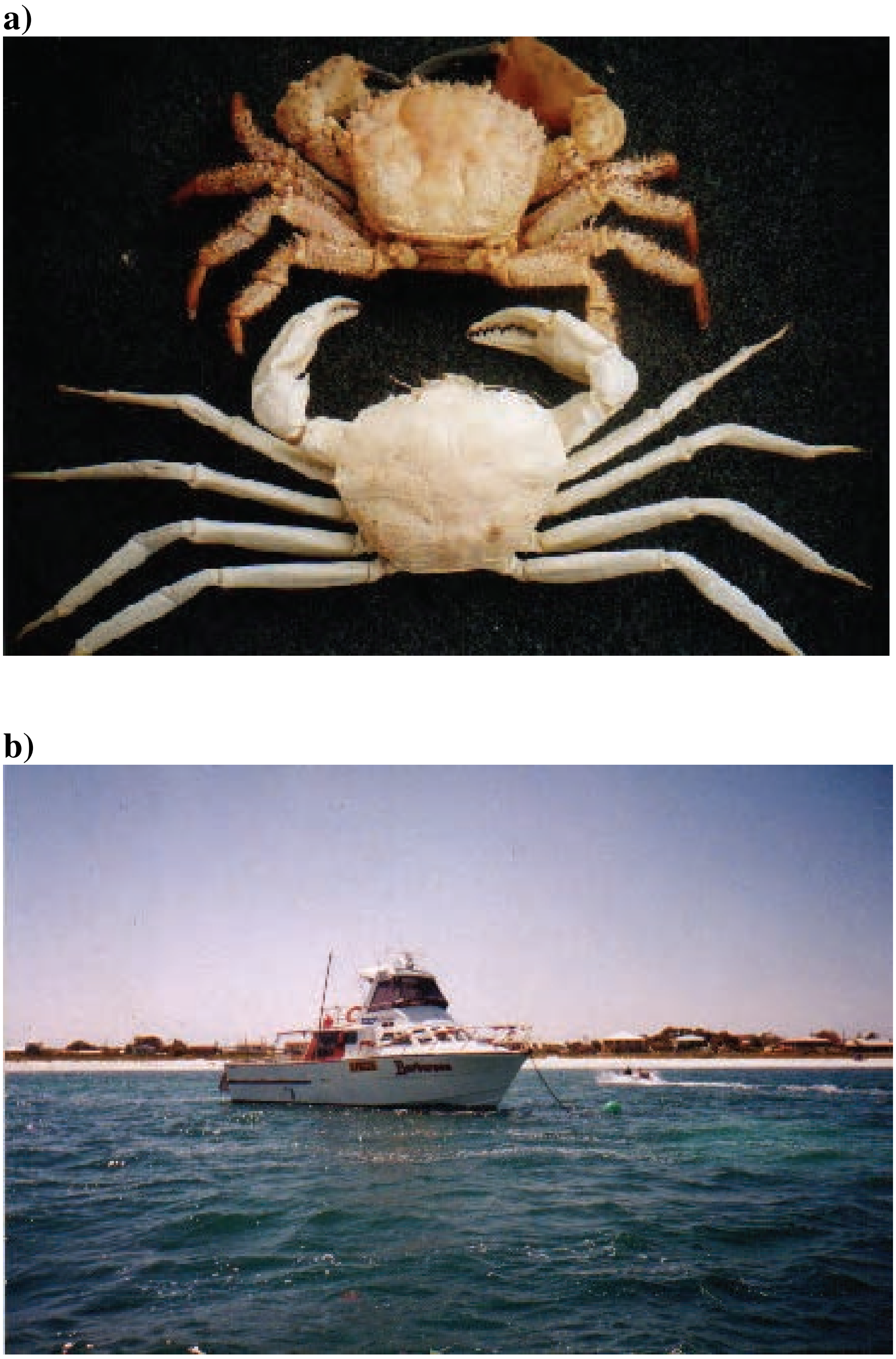


Figure 1.1 (a) Male *Hypothalassia acerba* (above) and male *Chaceon bicolor* (below) and (b) the fishing vessel *Barbarossa* which was used on the lower west coast for the depth-stratified sampling regime (see Chapter 2).

and Morgan 1996). A live export fishery for *C. bicolor* from Western Australia commenced in 2000 and catches increased to 143 000 kg during 2000 (Western Australian Department of Fisheries CAES).

A comprehensive account of the fisheries for both *H. acerba* and *C. bicolor* in Western Australia is provided in Chapter 3.

1.3 PREVIOUS BIOLOGICAL STUDIES ON DEEP-SEA CRABS

Prior to the present study, no biological data of the type required for fisheries management had been collected for either *H. acerba* or *C. bicolor*. However, the biology of *Pseudocarcinus gigas,* which is the most valuable of Australia's deep-water crabs and belongs to the same family (Eriphiidae) as *H. acerba*, have been studied (Gardner, 1996; Levings *et al.,* 1996; Gardner, 1997; Gardner and Northam, 1997; Gardner, 1998a,b; Levings *et al.,* 2001; Gardner and Williams, 2002; McGarvey *et al*., 2002). Thus, there are now data on the following aspects of *P. gigas*, namely geographical distribution, growth, reproductive biology, egg production and size at sexual maturity and on fisheries aspects, such as catches and catch per unit effort, the water depths at which king crabs are caught, and the size structure of the catches. Furthermore, the larvae of *P. gigas* have been reared in the laboratory to the megalopae stage (Gardner, 1996; Gardner and Northam, 1997).

Established deep-sea crab fisheries exist for the geryonid species, *Chaceon maritae*, off south west Africa (Melville Smith, 1988) and *Chaceon quinquedens* off the southern coast of New England (Wigley *et al.,* 1975). Smaller scale exploratory fisheries have also existed over the years for *Chaceon affinis* off Portugal (Pinho *et al.,* 2001), the Canary islands (López Abellán *et al.,* 2002) and in the Gulf of Mexico (Haefner, 1978) and for *C. quinquedens* in the Gulf of Mexico (Haefner, 1978). Several species of deep-sea crab are exploited off Alaska, including the lithodid *Paralithodes camtschaticus* (Zhou and Shirley, 1997), and the majids *Chionoecetes tanneri*, *C. bairdii* and *C. opilio* (Claxton and Govind, 1993). *Chionoecetes* *opilio* is also fished off the Atlantic coast of Canada (Sainte Marie *et al.,* 1997). *Chionoecetes opilio, C. japonicus* and *C. bairdii* are fished off Japan (Kon, 1996).

1.4 NEED

The successful management of a fishery for any species is dependent on fisheries managers having reliable data on certain key aspects of the biology of that species. The growth rate, fecundity and frequency of spawning are of particular importance as they are essential for calculating yield and egg (or mature biomass) per recruit relationships, which may be used to establish an optimal legal minimum size at first harvesting or for assessment of the status of the stock. The sizes at which 5 and 50% of crabs reach maturity provide a convenient description of the logistic relationship between the proportion of crabs that are mature and body size, when this relationship is used for setting an appropriate minimum legal size at capture. The pattern of movements and the way in which they are related to size and reproductive condition are important for interpreting catch and effort data. No data are available for any of the above aspects of the biology of either the champagne crab *Hypothalassia acerba* or the crystal crab *Chaceon bicolor.*

The champagne crab and crystal crab are assumed to be slow growing and long-lived and therefore vulnerable to overfishing. For that reason, the massive increase that occurred in the catches of these species since they started to be fished commercially provided an urgent need for appropriate management arrangements to be set in place to protect the stocks of these brachyurans. The biological information required for developing management plans for these species include growth rates, size composition, size at first maturity, spawning period, frequency of spawning, fecundity and yield and egg (or mature biomass) per recruit relationships. Furthermore, there was an urgent need to collect data on the catch statistics, size compositions, sex ratios and relative abundances by depths of *H. acerba* and *C. bicolor* in the early stages of the development of the fisheries for these two species, so that any changes in these important variables in the future could be detected.

Thus, there was a pressing need to collect baseline biological and fishery data, as listed under objectives, which could be used to produce a preliminary stock assessment for assisting in the management and conservation of these species in Western Australia. Such a stock assessment was required to meet Environment Australia's Schedule 4 exemption in the short term, and Fisheries WA/Environment Australia's requirements which were to be initiated in December 2002.

2.0 GENERAL MATERIALS AND METHODS

2.1 SAMPLING OF HYPOTHALASSIA ACERBA

The biological data reported for champagne crabs in Chapters 4 to 7 were obtained from three sampling regimes. The first sampling regime was designed specifically to obtain monthly data on the relative abundance, reproductive biology and size composition of *H. acerba* in different water depths off the lower west and south coasts of Western Australia (Chapter 4). It is subsequently referred to as the depth-stratified sampling regime to distinguish it from the second sampling regime which involved obtaining data for *H. acerba* by examining crabs while onboard commercial fishing vessels during their normal fishing activities. The third sampling regime involved collecting or purchasing samples of commercial catches from fish markets.

2.1.1 Depth-stratified sampling regime

For the depth-stratified sampling regime, *Hypothalassia acerba* was sampled off the lower west coast of Western Australia at a latitude of ~30°45′S and a longitude of ~114°50′E and off its southern coast at a latitude of ~35°15′S and a longitude of ~118°30′E (**Figure 2.1**). Seven sites (water depths) were sampled on each sampling occasion on both coasts. The sites were selected so that they were located in areas where the mean water depths were 35, 90, 145, 200, 255, 310 and 365 m, respectively, *i.e.* sites were equally spaced at depth intervals of 55 m. They were located at distances from the shore of 21.6, 28.5, 34.1, 40.1, 40.8, 40.9 and 41.1 km off the lower west coast and of 0.5, 28.2, 31.8, 32.1, 32.5, 32.7 and 33.1 km from the shore off the south coast.

The seven sites on the lower west coast and seven sites on the south coast were sampled in nine and four months, respectively, between January 2000 and April 2002 with each coast

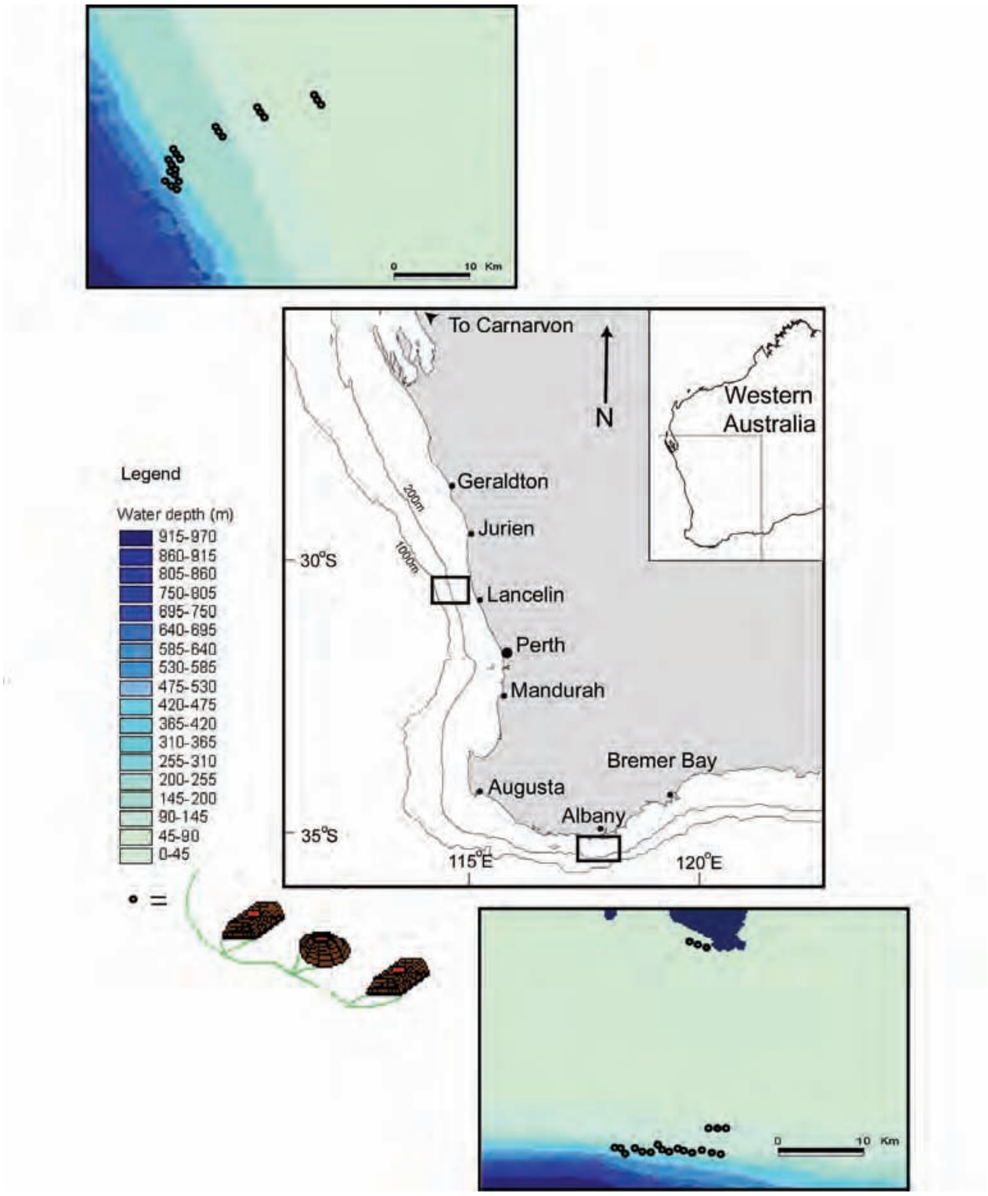


Figure 2.1. Map showing the region of south-western Australia where *Hypothalassia acerba* and *Chaceon bicolor* were caught. Boxes show location of the depth-related sampling regime on the west and south coasts. Circles designate the location where the samples at the different depths were collected. Each sampling unit contained one rectangular trap at each end and a central circular trap (see bottom left hand corner).

being sampled at least once in each calendar season (**Table 2.1**). Samples were collected from each site (water depth) on each sampling occasion using three lines of traps, with each line of 11 mm propylene rope having a rectangular trap at each end and a circular trap in the middle (see **Figure 2.2a**). The rectangular traps had a steel base and timber frame that was 960 mm long x 800 mm wide x 460 mm high and contained an entrance 270 mm in diameter x 170 mm in depth at the top. The trap bases consisted of parallel steel rods, 5 mm in diameter, situated 80 mm apart. The sides, top and ends of the traps were enclosed with wooden battens approximately 70 mm apart. The round traps were 880 mm in diameter x 450 mm in height and contained an entrance of 280 mm diameter x 200 mm deep at the top. Both of the trap types described above, which are typically employed to catch the western rock lobster *Panulirus cygnus* (George, 1962), are the same as those used by commercial fishers to catch champagne crabs.

In each water depth, the length of rope between the trap and the water surface was always approximately twice the water depth. A distance of 72 m separated the traps in each line (**Figure 2.2b**). Each line was set ~500 m apart. Escape gaps, a legal requirement of these commercial western rock lobster traps, were covered. Traps were baited with fish heads, such as those of the orange roughy *Hoplostethus atlanticus* Collett or the New Zealand hoki *Macryronus novaezelandiae* (Hector) which are commonly used to catch these crabs, and also with cattle hide or foreleg, which is more resistant to lice (isopods and amphipods) than the fish heads and thus last longer. A single inflatable fender and up to 5 cast alloy buoys were used to keep the surface rigs afloat (**Figure 2.3a**). Traps were typically set for five days.

In an attempt to catch greater numbers of small crabs off the lower west coast during May (autumn) and November (spring) 2001, the rectangular traps at each end of an additional equal number of lines were enclosed with welded galvanised aviary mesh with meshes of 12.7 × 25.4 mm (**Figure 2.3b**). The mesh, which was attached to the traps using cable ties, nails

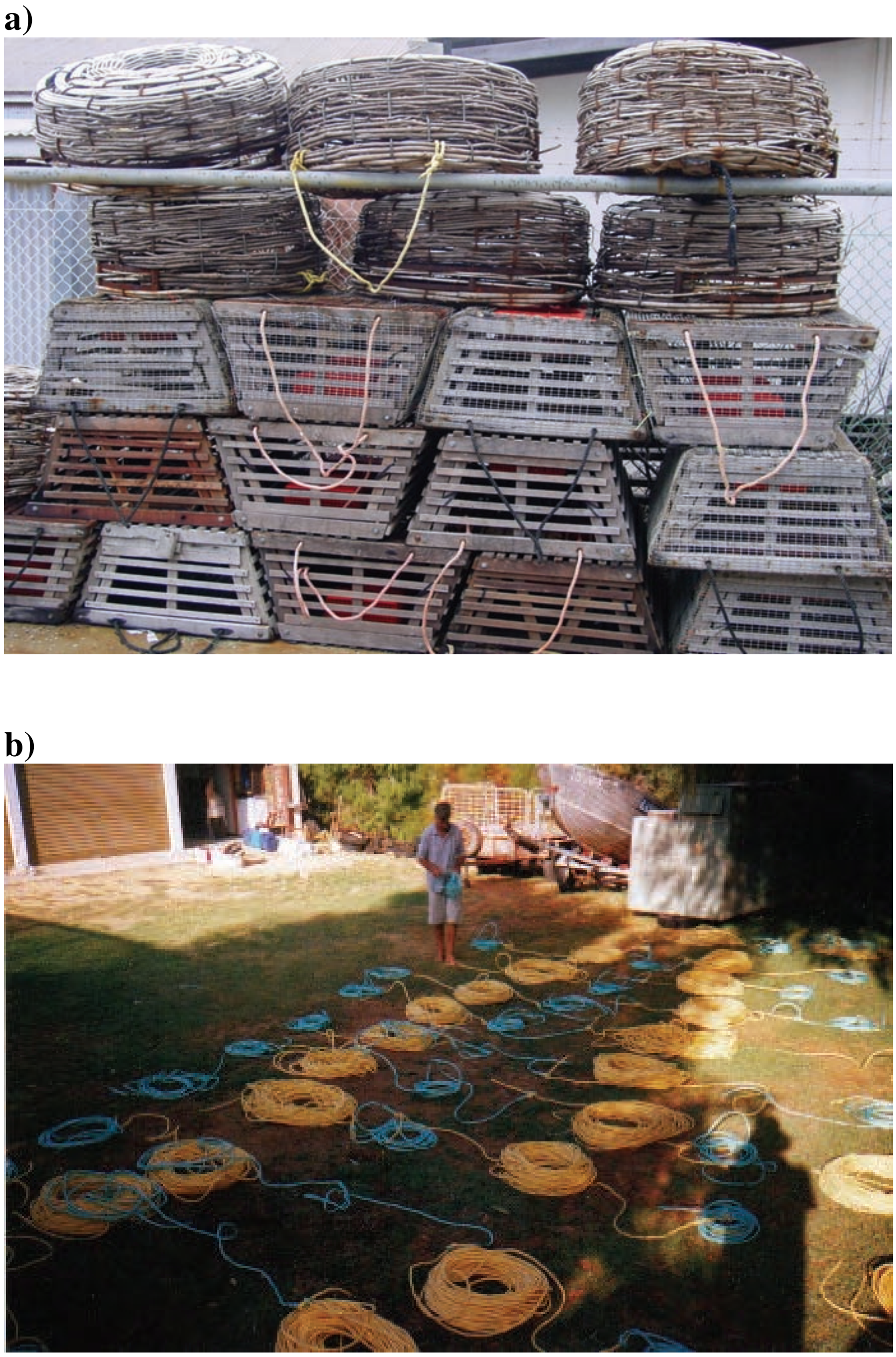


Figure 2.2. (a) Round cane stick traps (above) and rectangular jarrah slat traps (below) used for the depth - stratified sampling regime and (b) warning ropes (blue) to which the traps were attached. The traps were separated by 72 m of ground rope (yellow).

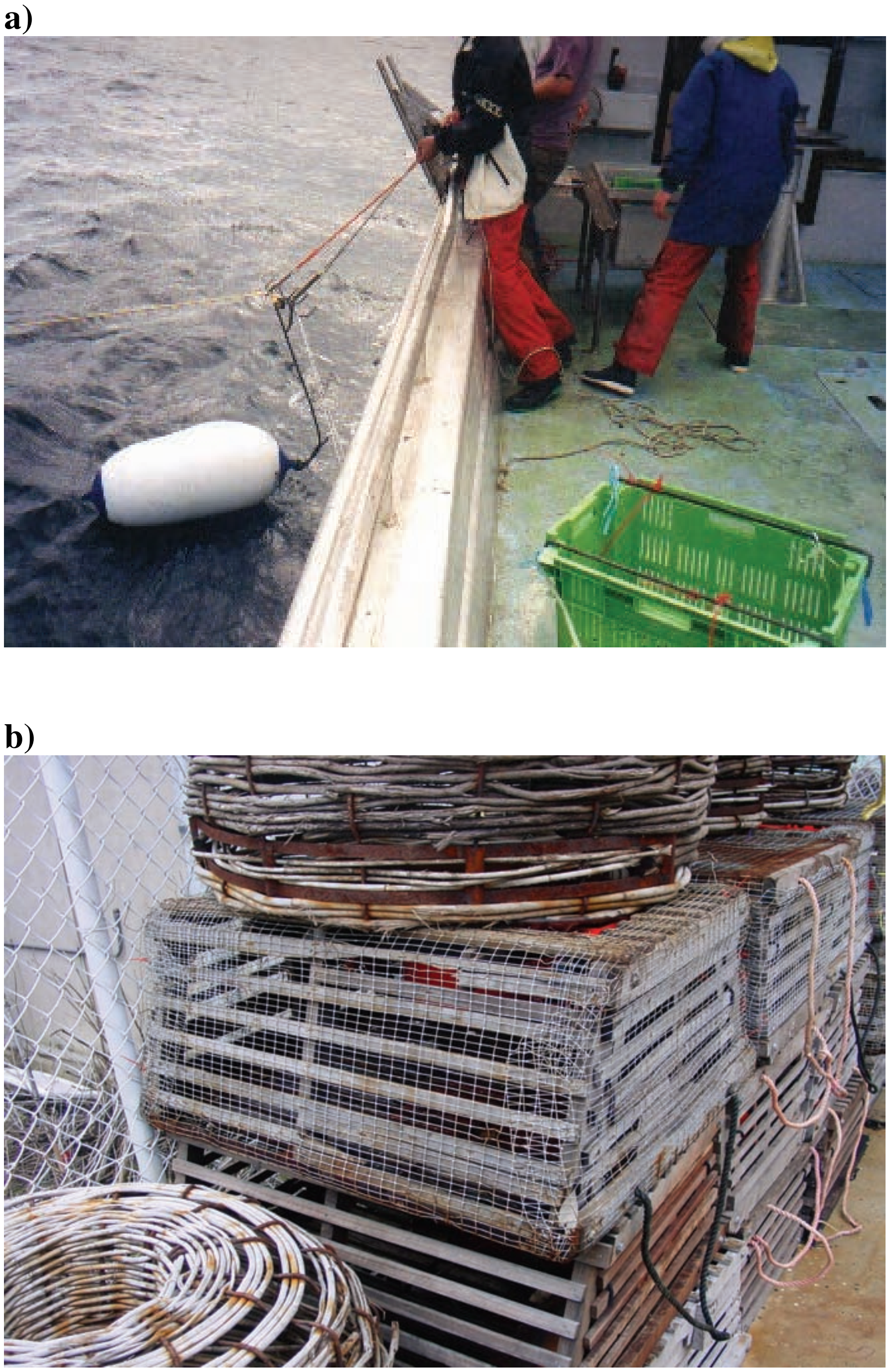


Figure 2.3. (a) Inflatable buoy, one of which was attached to each line of traps and (b) rectangular jarrah trap enclosed with wire mesh.

and staples, enclosed the whole of the traps, except for their entrance. Since the spaces between the canes used in the central circular trap were small, it was not considered necessary also to enclose these traps in aviary mesh. The additional lines of small mesh traps were used to fish the same water depths, but ~2 km further south, effectively replicating the experiment in those two months. In all of the sampling conducted off the lower west coast after November 2001, the rectangular traps were enclosed with aviary mesh (see **Table 2.1**).

Table 2.1 Dates and seasons when traps were used to catch *Hypothalassia acerba* off the lower west and south coasts of Western Australia. n.c., not covered with aviary mesh; c, covered with aviary mesh.

Date	Season
West coast	
17.02.00	Summer, n.c.
23.8.00	Winter, n.c.
3.3.01	Autumn, n.c.
18.9.00	Spring, n.c.
12.5.01	Autumn , n.c. & c
6.11.01	Spring, n.c. & c
18.12.01	Summer, c
20.1.02	Summer, c
25.4.02	Autumn, c
South coast	
19.3.00	Autumn, n.c.
17.6.00	Winter, n.c.
25.11.00	Spring, n.c.
22.2.02	Summer, n.c.

2.1.2 Onboard sampling of commercial catches of **Hypothalassia acerba**

Samples of *Hypothalassia acerba* were obtained onboard from the trap catches of commercial fishers operating off the lower west and south coasts of Western Australia between ~30° 10'S, 114° 30'E (~ west of Jurien) and 32° 30'S, 114° 60'E (west of Mandurah) and between ~34° 40'S, 115° 40'E (south of Augusta) and 34° 45'S, 119° 30'E (south of Bremer Bay), respectively (**Figure 2.1**). Off the lower west and south coasts, the water depths fished by commercial fishers during these monitoring cruises, ranged from 180 to 280 m and 70 to 240 m respectively. These trips were undertaken at regular intervals off the lower west coast between July 1999 and December 2000 and off the south coast between July 1999 and February 2002, respectively.

2.1.3 *Structure of traps used in the commercial fishery to catch* **Hypothalassia acerba**

The single commercial fisher, who targeted champagne crabs on the west coast, consistently used rectangular jarrah rock lobster traps of the type employed in the depth-stratified sampling regime described in Section 2.1.1. Note that other fishers, who were targeting western rock lobster on the west coast, were not allowed to retain for sale any incidental catches of champagne crabs.

Since there is no legislation specifying that a particular type of trap should be used by commercial fishers for catching champagne crabs, the trap types used on the south coast varied. Note that, on the south coast as opposed to the west coast, some fishers possessed licenses that enabled them to sell any catches of *H. acerba* that were obtained incidentally when they were fishing for other species such as the southern rock lobster *Jasus edwardsii* and the king crab *Pseudocarcinus gigas.*

The three main types of trap used on the south coast included the circular cane stick traps of the type used in the depth-stratified sampling regime (Section 2.1.1). The first of the other two trap types was round-sided with flat tops (1400 mm base diameter, 350 mm high, 272 mm neck diameter), while the second was conical and beehive shaped (860 mm base diameter, 407 mm high, 272 mm neck diameter). Both of these latter traps were enclosed with either diamond-shaped stainless steel chicken wire or resilient synthetic netting. All three traps were weighted with ~ 40 kg of steel ballast.

For commercial fishing off both coasts, between two and twelve traps were strung together in lines, with varying distances of rope between the traps. Furthermore, soak time ranged from four days to several weeks, mainly due to variations in weather conditions. Traps were usually baited with fresh or salted heads of fish species such as the orange roughy *Hoplostethus atlanticus* Collett or the New Zealand hoki *Coryphaenoides novaezelandiae* Hector. Cattle hide or foreleg was employed until its use was banned in January 2002.

2.1.4 *Tagging of* **Hypothalassia acerba**

Crabs were tagged using Hallprint TBA-1 t-bar tags. The tags were inserted using a Paxar tagging gun on the right hand side medial epimeral suture line of the carapace, between the fourth and fifth coxa, with the t-bar lodged in the branchial cavity (**Figure 2.4a**). After tagging, crabs were returned immediately to the water in order to minimise their displacement due to drift. Crabs with missing appendages were not tagged.

2.1.5 *Sampling of* **Chaceon bicolor**

Sampling for *C. bicolor* aboard commercial fishing vessels was undertaken on four occasions during 2000 and, wherever possible, bimonthly between June 2001 and December 2003.

a)

b)

Figure 2.4. (a) Female *Hypothalassia acerba* showing the t-bar anchor tag inserted within the epimeral suture line of the carapace and (b) commercial fishing trap used to catch *Chaceon bicolor.* (Photo courtesy of S. Norton).

2.1.6 *Structure of traps used in the commercial fishery to catch* **Chaceon bicolor**

Chaceon bicolor is fished commercially using lines containing up to 100 plastic recreational western rock lobster traps, which are 675 mm long, 350 mm wide and 475 mm high and possess, at their top, an entrance of 170 mm diameter and 200 mm depth (**Figure 2.4b**). The traps are made of light-weight plastic to prevent them sinking into the soft substrate and are baited with heads of the New Zealand hoki or whole Australian salmon, *Arripis truttaceus* (Cuvier).

2.2 MEASUREMENTS

2.2.1 *Water temperatures*

On each occasion that the depth-stratified sampling for *H. acerba* was implemented, the bottom water temperature at each site was recorded using StowAway TidbiT HTI-537 digital temperature loggers that were enclosed in protective wire mesh and attached to the inside top of one of the traps. As a logger very occasionally malfunctioned, the temperature in that depth was not recorded on that sampling occasion. Bottom water temperature was recorded using the same devices, which were attached to commercial traps deployed to catch *C. bicolor*. The temperature was recorded to 0.1°C at 5 min intervals and the resultant values downloaded from these loggers to a computer and subsequently averaged for each sampling occasion at each sampling site.

2.2.2 *Data recorded for crabs*

In the field, the contents of each individual trap were recorded separately and a note made of the location, date and depth (m) at which all crabs were caught. The following characteristics of each crab were recorded. (1) The carapace length (*CL*) of each *H. acerba* and *C. bicolor, i.e.* the distance from the midpoint between the bases of the two anterior medial horns and the posterior margin of the carapace, was measured to the nearest 1 mm. This is the typical way of measuring body size in deep-water crabs (Levings *et al.,* 1996; Gardner, 1997; Goshima and Kanazawa, 2000). It is preferable to using carapace width, *i.e.* the distance between the two lateral spines of the carapace, as those structures are particularly prone to wear. (2) In the case of females, pleopod condition was recorded as either clean with no sign of egg attachment, or as having either eggs (berried) or egg remnants attached. (3) For each female, a record was kept of the relative size and shape of the gonopores and whether mating abrasions were present around their gonopores. Most females of *C. bicolor* with a CL < 100 mm possessed elliptical/closed gonopores (**Figure 2.5a**) indicating that they had not mated, a conclusion consistent with the absence of mating scars in the region of their gonopores (**Figure 2.5b**) (see also Melville Smith, 1987a; Haefner, 1977). Although the gonopores of female *H. acerba* did not exhibit such a conspicuous dichotomy in shape as those of *C. bicolor*, the individuals of this species with a CL < ~70 mm had relatively very small gonopores and, unlike many larger individuals, never bore mating scars in the region of their gonopores (**Figure 2.6**). The first and small group of *H. acerba* was thus considered not to have mated, which is consistent with the ovaries of all such individuals being at stage I (see **Table 5.1**, Chapter 5 for description of the characteristics of the different stages in ovarian development).

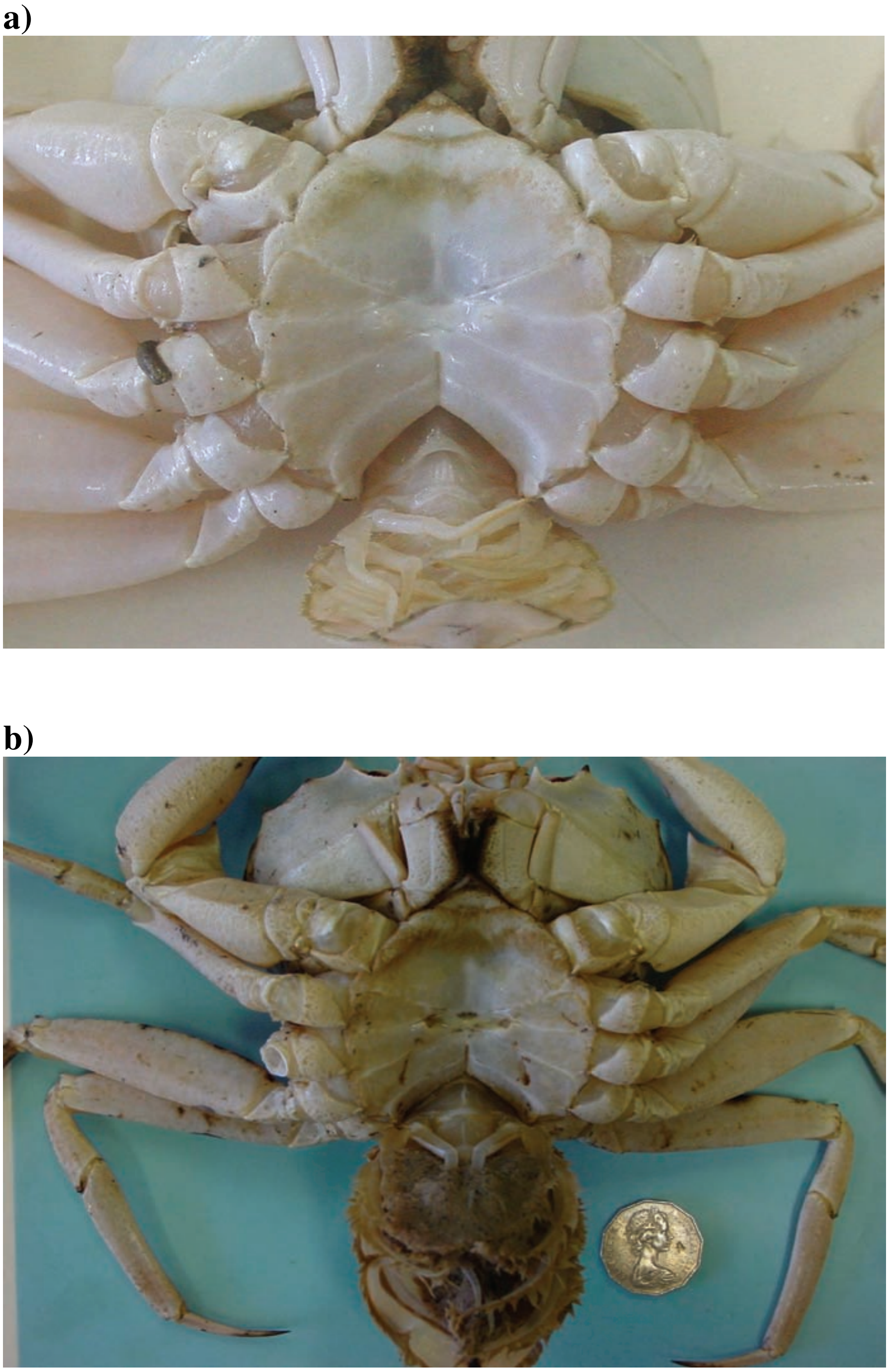


Figure 2.5. (a) Abdomen of an immature female *Chaceon bicolor* showing elliptical/closed gonopores and (b) abdomen of a mature female *Chaceon bicolor* showing open and circular gonopores and mating abrasions.

Figure 2.6. Abdomen of a mature female *Hypothalassia acerba* showing open and circular gonopores.

3.0 THE FISHERIES FOR *HYPOTHALASSIA ACERBA* AND *CHACEON BICOLOR*

3.1 INTRODUCTION

The fishery for the champagne crab *Hypothalassia acerba* is concentrated on the lower west coast of Australia between Jurien in the north at 30° 08'S, 114° 30'E and Mandurah in the south at 32° 29'S and 115° 40'E, and on its south coast between Augusta in the west at 34° 20'S, 115° 10'E and Bremer Bay in the east at 34° 40'S, 119° 30'E (Chapter 1). Under deep-sea crab endorsements to fishers by the Western Australian Department of Fisheries, *H. acerba* was only fished commercially on the lower west coast between 1989 and 2000. Although that endorsement extended beyond 2000, the holders of this endorsement switched to targeting the crystal crab C*haceon bicolor* in that year. The catches of *H. acerba* by fishers with deep-sea crab endorsements have been supplemented to a small degree by those of commercial rock lobster fishers. However, since 2000, the latter fishers have been permitted to retain only six *H. acerba* per vessel per day on the west coast during the western rock lobster season (Anon., 2004). In contrast to the situation on the west coast, the champagne crab has been fished commercially since 1991 on the south coast, where this species contributes to a multi-species fishery that also includes the king crab *Pseudocarcinus gigas* and the southern rock lobster *Jasus edwardsii* (Anon., 2004).

Chaceon bicolor occurs in water depths of 450 to 1220 m, which is far greater than the depths of 90 to 310 m in which *H. acerba* is typically caught (Melville Smith *et al.,* in press; Chapter 4). The fisheries for *C. bicolor* off the lower west coast and south coast commenced in 1999 and 2002 respectively. Although *C. bicolor* is distributed around Australia and New Zealand, it is only commercially fished in Western Australian waters. However, several other species belonging to the Geryonidae are fished elsewhere in the world (*e.g.* Wigley *et al.,* 1975; Wenner *et al.,* 1987; Erdman and Blake, 1988; Melville Smith, 1988; Defeo *et al.,* 1991;

López Abellán *et al.,* 2002). Although a deep-water crab endorsement entitles fishers to harvest *C. bicolor* as well as *H. acerba*, the former species requires refrigerated water for it to be kept alive and therefore tends to be fished independently of *H. acerba* by fishers who have specialised tanks for holding *C. bicolor*.

The first aim of this chapter is to describe quantitatively the trends exhibited by catch (landed live weight), fishing effort (number of pot lifts) and catch per unit effort (CPUE) for *H. acerba* and *C. bicolor* on the lower west and south coasts since the commencement of the fisheries for these species, and to determine whether these three variables change throughout the year. The second aim was to determine whether the relative abundance and size of both the females and males of *H. acerba* and *C. bicolor* differed among the regions in which they were being fished. The third aim was to tag and release individuals of *H. acerba* in an attempt to obtain data on the movement and growth of this species.

3.2 MATERIALS AND METHODS

3.2.1 Data on commercial catches

The monthly landed catches of each species by commercial fishers on both the lower west and south coasts between 1989 and 2003, together with the number of pot lifts, were extracted by M. Cliff and L. Bellchambers from the Catch and Effort Statistics (CAES) of the Department of Fisheries Western Australia.

3.2.2 Onboard collection of data

Hypothalassia acerba

Data for *H. acerba* were collected onboard the boat of a commercial fisher operating in five Department of Fisheries 1° x 1° fishing blocks along the lower west coast and those of three commercial fishers working in five such fishing blocks on the south coast. The first two digits identifying these fishing blocks represent the location of the north-west corner of the block in degrees latitude and the second two numbers represent the last two of the three numbers of the location of the north-west corner of the block in degrees longitude, *e.g.* longitude 114° is given as 14. Fishing blocks 3014, 3114 and 3115 were grouped to represent the northern region and blocks 3214 and 3215 the southern region of the lower west coast, while fishing blocks 3415, 3515 and 3516 were grouped to represent the western region and blocks 3517 and 3419 the eastern region of the south coast. The onboard trips were conducted at two to four month intervals between July 1999 and December 2000 on the lower west coast and less frequently between July 1999 and February 2002 on the south coast (see Chapter 2 for further details). Note that sampling on the south coast occurred less frequently because fishing on this coast was more sporadic and the time spent by fishers at sea was far greater. Whenever possible, a record was kept of the carapace length of each male and female *H. acerba* caught (see Chapter 2) and the latitude and longitude where each line of traps was laid.

Chaceon bicolor

The onboard collection of the same data for *C. bicolor*, as those recorded for *H. acerba* (see above), was restricted to the west coast as this species was not fished on the south coast during the present study. Catches of *C. bicolor* were grouped into two regions, *i.e.* to the north and south of 28° 50'S (approximately Geraldton), which lies in the middle of the range of latitudes where sampling was undertaken. Onboard recording of *C. bicolor* was undertaken bimonthly between June 2001 and December 2003, with an additional four trips being undertaken in 2000.

Mesh selectivity of **Chaceon bicolor**

During onboard sampling, three recreational rock lobster traps, enclosed with plastic mesh of 20 mm × 20 mm, were randomly placed in each of two lines of ~ 100 non-meshed traps of the same type as those used by the commercial fishers who target *C. bicolor* (see Chapter 2.1.6). On each sampling occasion, the carapace lengths of crabs caught in non-meshed and meshed traps were recorded. When the senior author was not present, commercial fishers were asked to record, whenever feasible, the sex and carapace length of crabs in both meshed traps and in an equal number of non-meshed traps. The data recorded by the fishers were later forwarded to Murdoch University for inclusion in our analyses.

Note that the experiments carried out to explore the mesh selectivity of *H. acerba* are reported in Chapter 4 as the data derived from those experiments contributed to the total data set used to determine the depth distribution of this species.

3.2.3 Data Analysis

Hypothalassia acerba

Plots of $\log_{10}$ of the standard deviation against $\log_{10}$ of the mean for both the CPUE (catch per pot lift) and the carapace lengths of *H. acerba* recorded on commercial vessels in each of the two regions on each coast showed that neither variable required transformation prior to subjection to analysis of variance (ANOVA) (see Clarke and Gorley (2001) for rationale for this approach).

The catches were subjected to ANOVA, with the number of crabs per pot lift as the dependent variable and sex and region as fixed factors. The carapace lengths were also subjected to ANOVA, with carapace length as the dependent variable, and sex and region as fixed factors. No attempt has been made to separate the data by season because it was not possible to obtain samples from each region in every season. Scheffé's *a posteriori* test was used to compare the CPUE and mean carapace lengths for each of the four regions.

Chaceon bicolor

The catch and carapace length data for *C. bicolor* were analysed in the same way as for *H. acerba.* Note however that in this case the catch rates required log transformation.

3.3 RESULTS

3.3.1 Commercial catch and effort data for **Hypothalassia acerba**

The total landed catch of *H. acerba* in Western Australia rose from less than 1 500 kg in 1989 and 1990 to between 13,050 and 10,850 kg in 1991 to 1996 and then sharply to a peak of 72,975 kg in 1998, before declining progressively to 17,295 kg in 2003 (**Figure 3.1a**). The annual catches peaked on the west coast at 30,900 to 45,630 kg in 1997 to 1999 and on the south coast at 26,070 and 27,345 kg in 1997 and 1998, respectively (**Figure 3.1b**). However, catches on the west coast declined precipitously to essentially zero after 2000, whereas on the south coast they remained at between 10,790 and 21,560 kg between 2000 and 2003 (**Figure 3.1b**).

The total number of pot lifts per annum on both coasts collectively rose progressively from ~5,500 in 1989 and 1990 to 114,850 in 1994 and then declined to 48,220 in 1996, before rising again to reach a maximum in 1998 (**Figure 3.2a**). It subsequently remained at between 44,000 and 61,000 pot lifts in 1999 to 2003. The number of pot lifts per annum on the west and south coasts followed different trends. Thus, on the west coast, they peaked sharply at 73,000 and 94,000 in 1997 and 1998, respectively, and had declined to very low levels by 2001, whereas, on the south coast, they peaked at 90,510 in 1994 and were relatively high in 2001 to 2003 (**Figure 3.2b**).

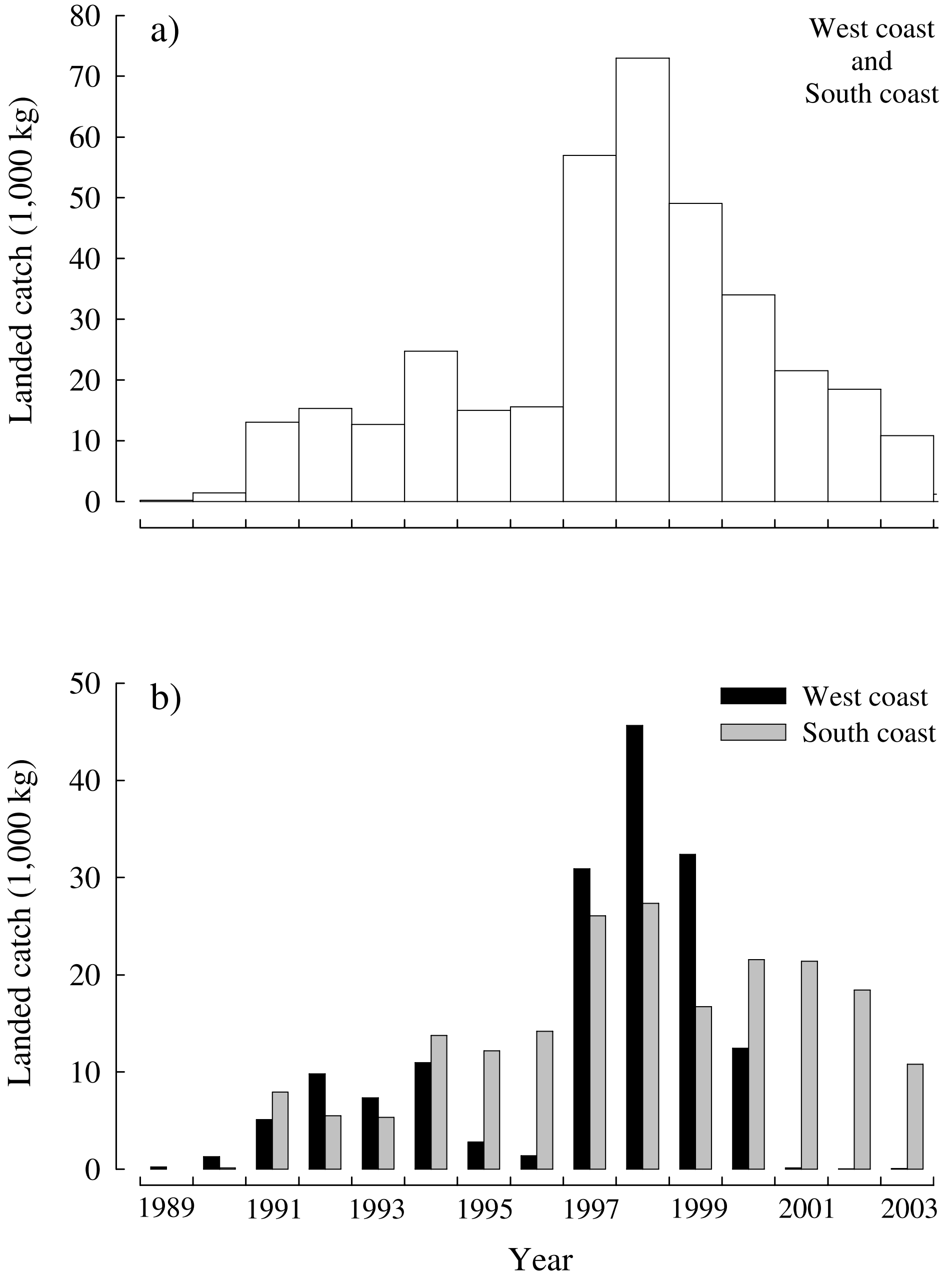


Figure 3.1. (a) Total landed catch of *Hypothalassia acerba* in south-western Australia and (b) landed catch of this species on the lower west and south coasts of Western Australia separately. Data were extracted from the catch and effort statistics of the Department of Fisheries Western Australia and encompass the years between 1989 and 2003.

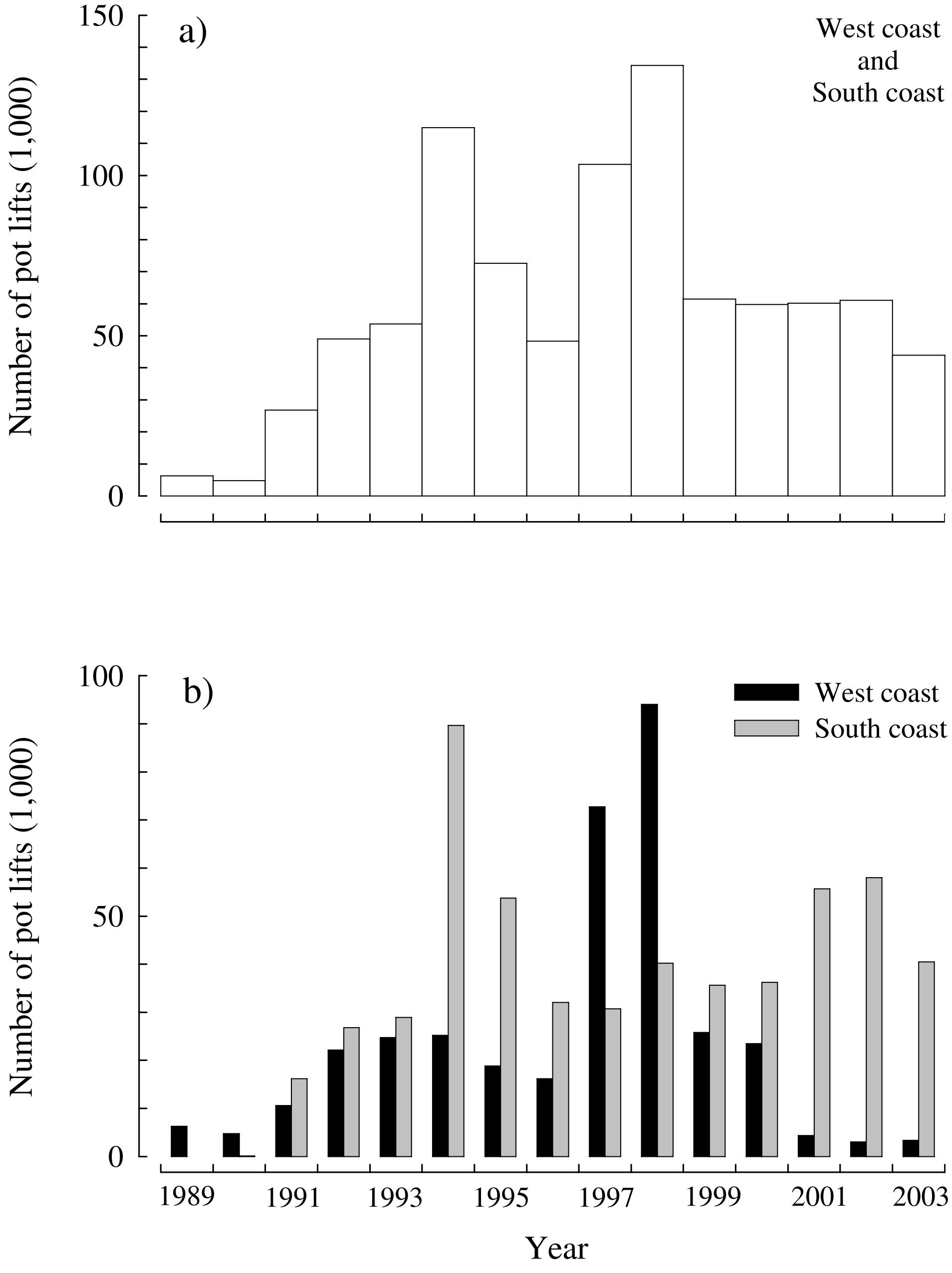


Figure 3.2. (a) Total number of pot lifts for *Hypothalassia acerba* in south-western Australia and (b) number of pot lifts for this species on the lower west and south coasts of Western Australia separately. Data were extracted from the catch and effort statistics of the Department of Fisheries Western Australia and encompass the years between 1989 and 2003.

The annual catch per unit effort (CPUE) for the whole fishery for *H. acerba,* as expressed by catch (kg) per pot lift, peaked in 1999 at 0.80, after which it declined progressively to 0.25 in 2003 (**Figure 3.3a**). Prior to 1991, the effort on both coasts was either low or zero (**Figure 3.2b**) and thus attention is not focused on the CPUEs for those years. On the west coast, the CPUEs remained at between 0.30 and 0.53 in all years between 1991 and 2000, except in 1995 and 1996 when they were 0.15 and 0.09, respectively, and in 1999 when they rose to a sharp peak at 1.25. The catch rates, and also the effort, on the west coast in 2001 to 2003 were negligible and thus are unlikely to provide reliable measures of relative abundance. The annual CPUE on the south coast rose to a maximum of 0.85 in 1997 and then declined to 0.27 in 2003 (**Figure 3.3b**).

Between 1992 and 1999, when the annual catches of *H. acerba* on the west coast of Australia were greatest, the mean monthly catches on that coast appeared to follow an annual cycle, increasing from low levels of 620 to 1,240 kg in March to June to maximum levels of 1,790 to 3,000 kg in August to January (**Figure 3.4a**). The mean monthly catches on the south coast for the years 1992 to 2003, when catches were substantial on that coast, followed a distinct annual cycle, declining from 2,390 kg in January to a minimum of 410 kg in August, and then rising steeply to 2,260 kg in December (**Figure 3.4b**).

The mean monthly number of pot lifts on the west coast followed a less seasonal cycle than that of total landed catch and only exceeded 4,000 in January and December (**Figures 3.4a, 3.5a**). The mean monthly number of pot lifts on the south coast followed similar trends to those exhibited by the mean monthly catches, declining from 8,085 in January to between 960 and 2,245 in May to October and then rising to 6,445 in December (**Figure 3.5b**).

The mean monthly CPUEs for *H. acerba* on the west coast rose progressively from low levels of < 0.65 kg per pot lift in January to April to reach a maximum of 2.47 kg per pot lift in November, and then declined precipitously to 0.20 kg per pot lift in December (**Figure 3.6a**).

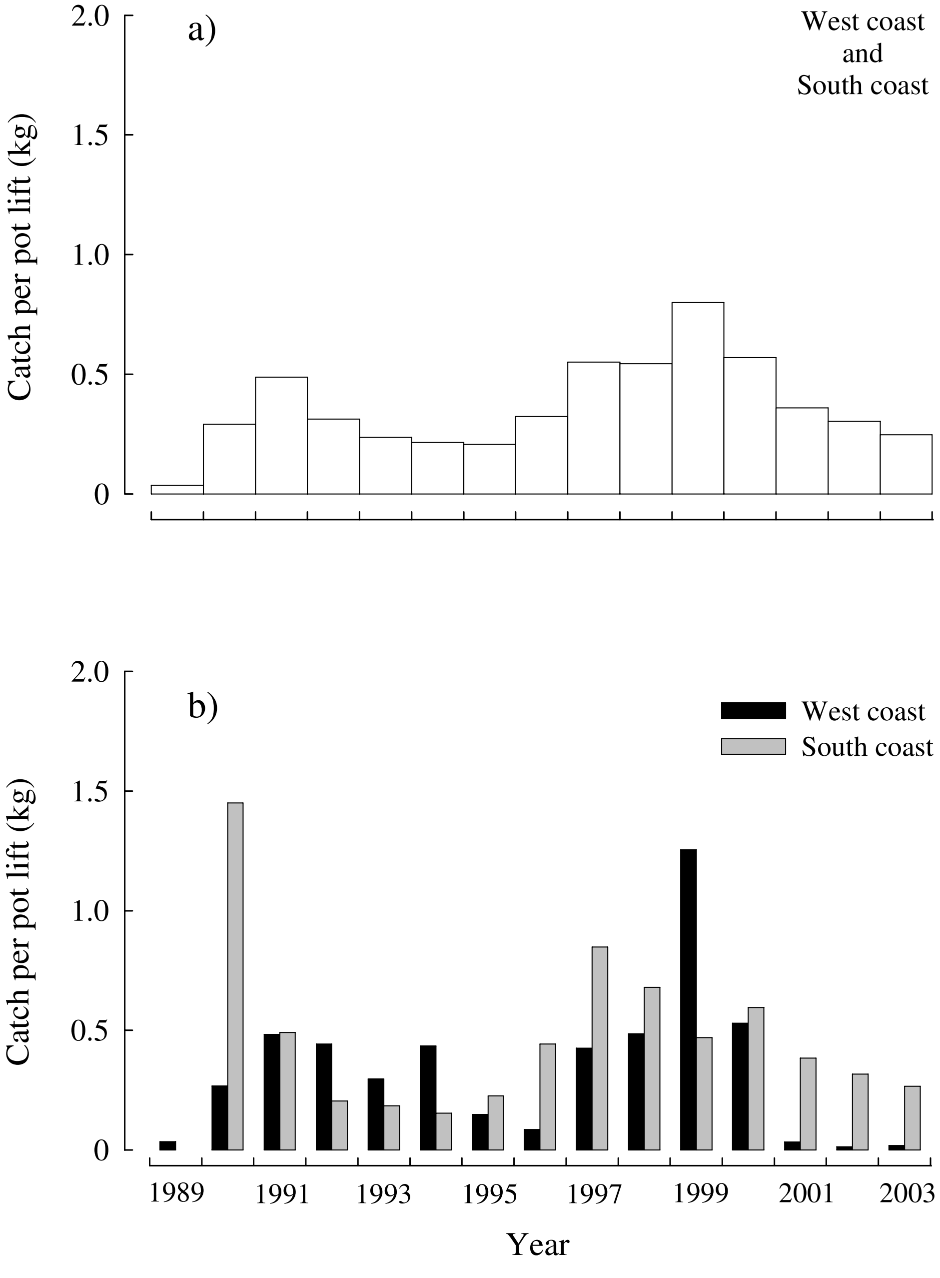


Figure 3.3. (a) Total catch per pot lift of *Hypothalassia acerba* in south-western Australia and (b) total catch per pot lift of this species on the lower west and south coasts of Western Australia separately. Data were extracted from the catch and effort statistics of the Department of Fisheries Western Australia and encompass the years between 1989 and 2003.

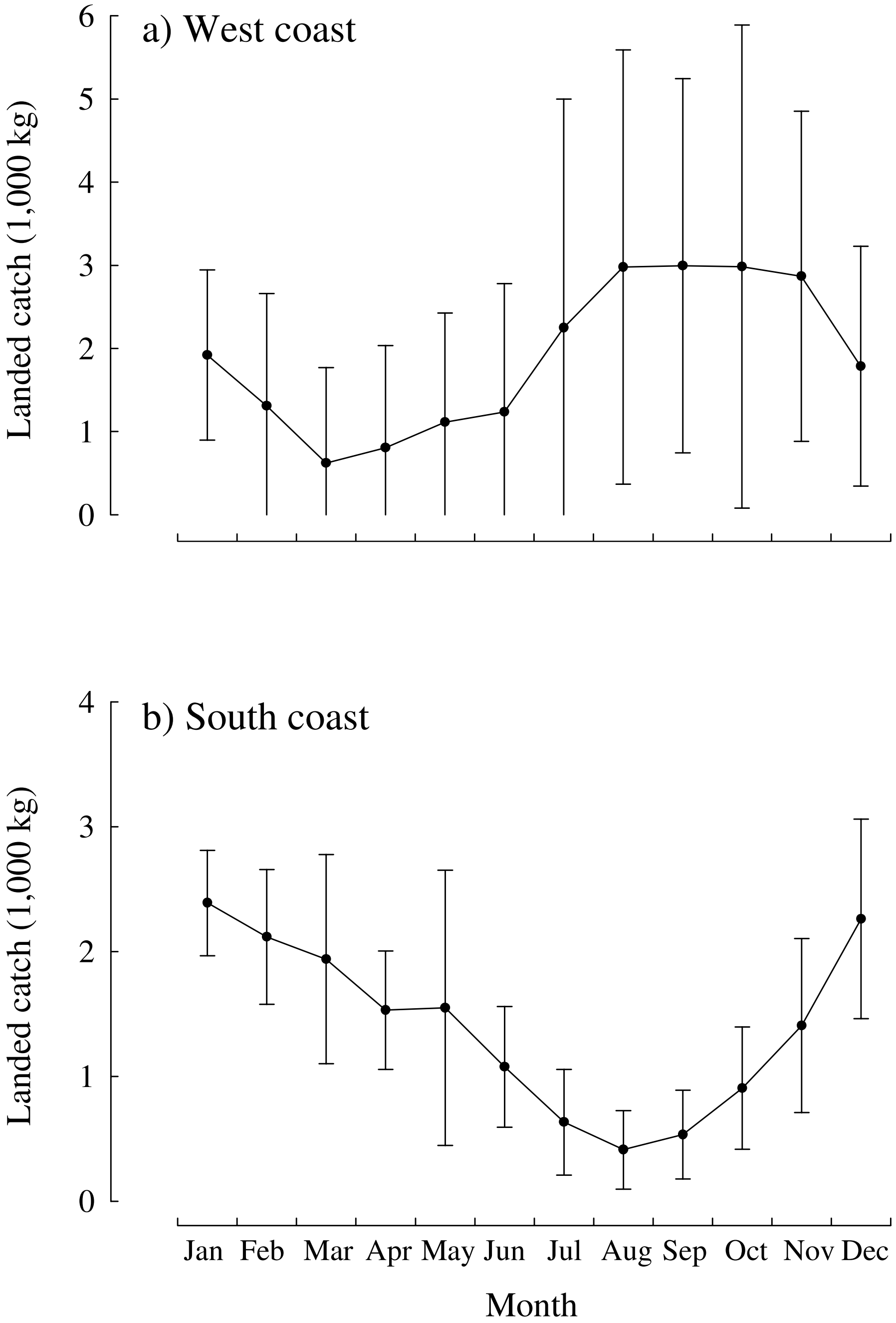


Figure 3.4. Mean monthly landed weight of *Hypothalassia acerba* ± 95 % CIs on (a) the lower west coast in the years 1992 - 1999 and (b) the south coast in the years 1992 - 2003.

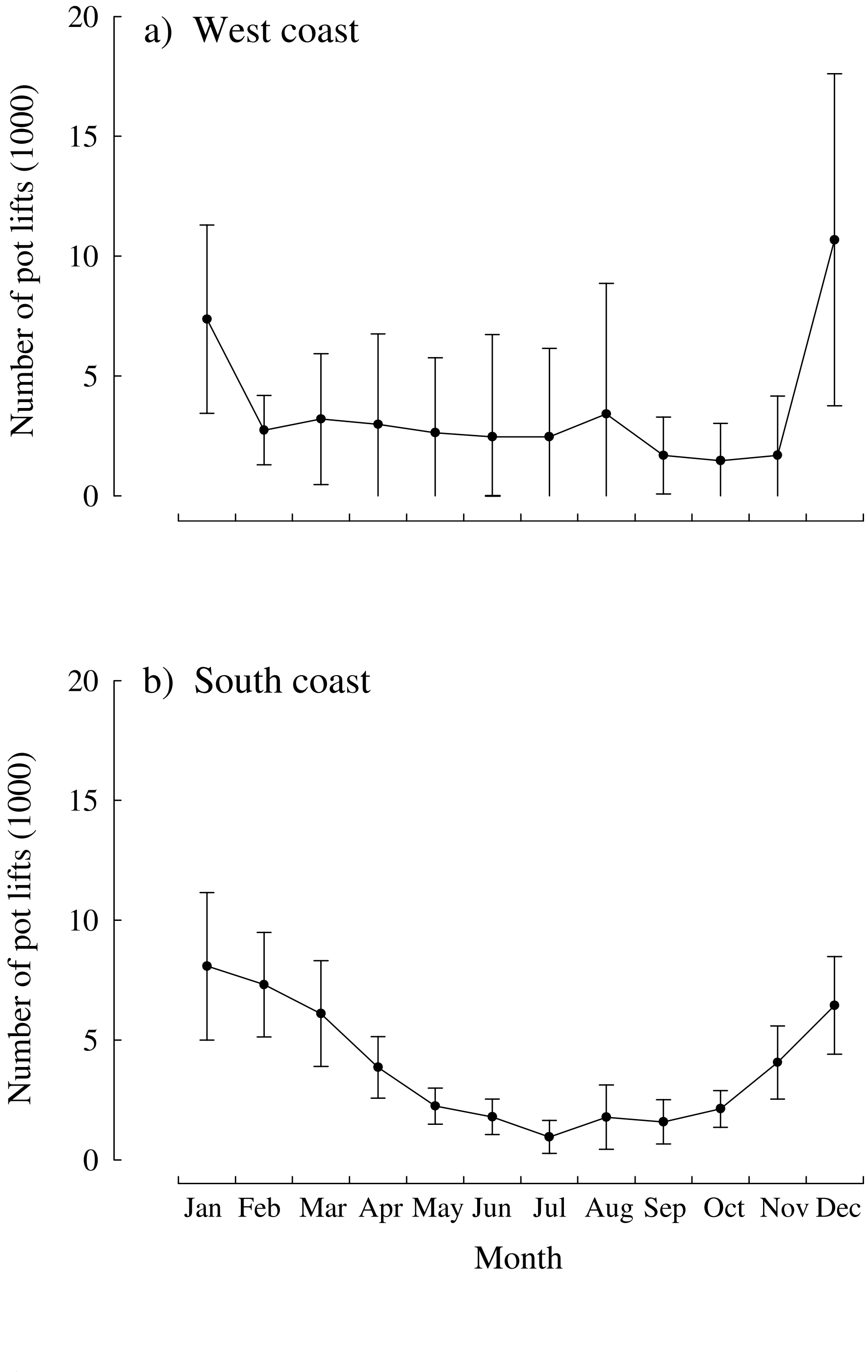


Figure 3.5. Mean monthly number of pot lifts for *Hypothalassia acerba* ± 95 % CIs on (a) the lower west coast in the years 1992 - 1999 and (b) the south coast in the years 1992 - 2003.

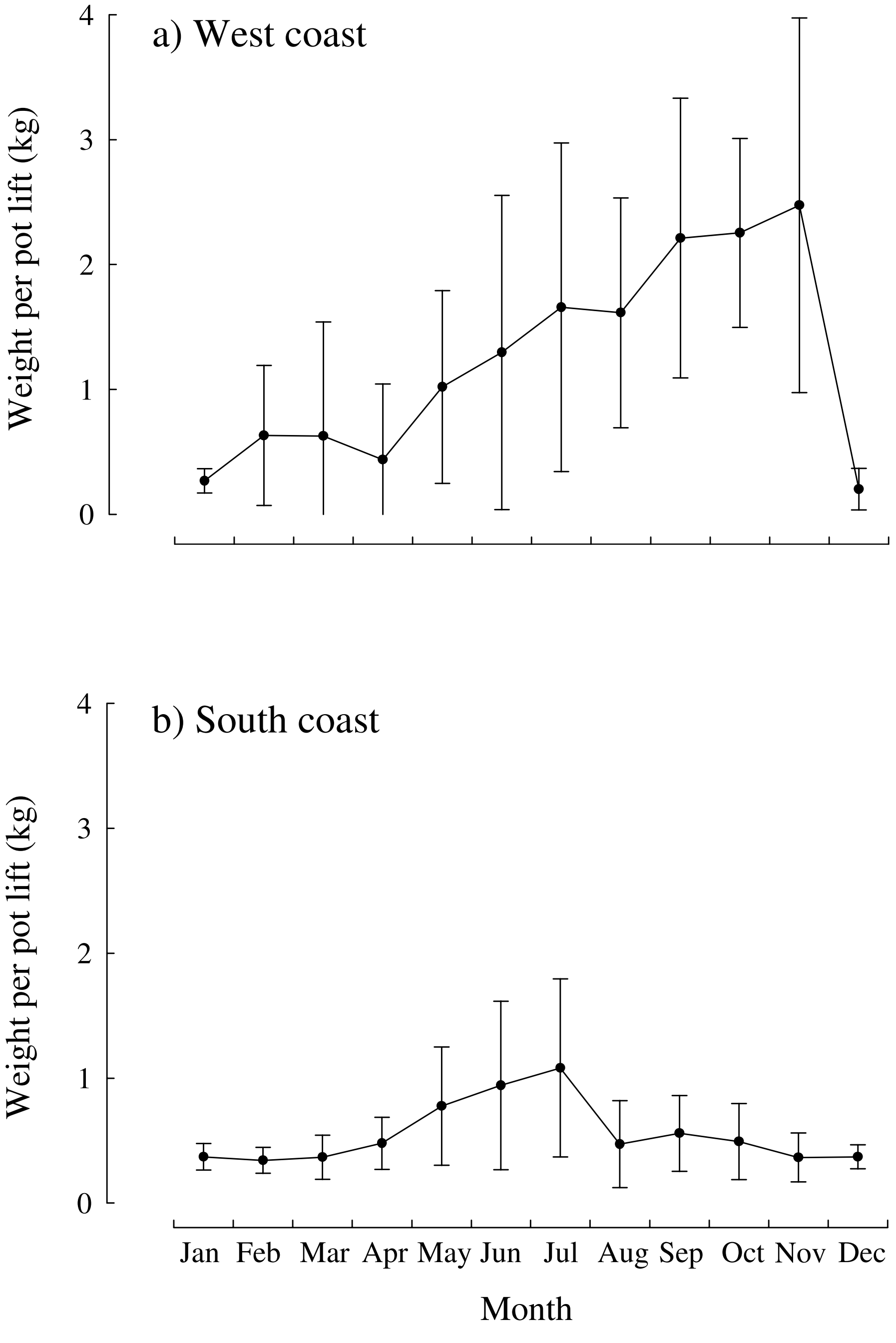


Figure 3.6. Mean monthly CPUEs of *Hypothalassia acerba* ± 95 % CIs on (a) the lower west coast between 1992 and 1999 and (b) the south coast between 1992 and 2003.

The mean monthly CPUEs for *H. acerba* on the south coast rose from ~ 0.37 kg per pot lift in January to March to attain a peak of 1.08 kg per pot lift in July (**Figure 3.6b**).

3.3.2 Commercial catch and effort data for **Chaceon bicolor**

The total annual catch of *C. bicolor* in Western Australia rose progressively from a negligible level in 1997 to reach a maximum of 222,520 kg in 2001 and remained at above 193,280 kg in 2002 and 2003 (**Figure 3.7a**). The vast majority of the catch in each year came from the west coast (**Figure 3.7b**).

The annual number of pot lifts for *C. bicolor* followed a similar trend to that of landed catch, except that they peaked one year earlier, *i.e.* in 2000 rather than 2001 (**Figure 3.8a**). The maximum number of pot lifts per year on the west coast was 245,000.

The CPUE for *C. bicolor* in south western Australia rose progressively from 0.11 kg per pot in 1998 to 1.16 kg per pot in 2002 and 2003 (**Figure 3.9a**). Since the effort was very low on the south coast (**Figure 3.8b**), emphasis was not placed on the catch per unit effort for this coast (**Figure 3.9b**).

The mean monthly catches of *C. bicolor* show no conspicuous seasonal trends, with values ranging from minima of 12,775 to 14,485 kg in April, June and November to maxima of 8,895 to 20,240 kg in January, August, September and October (**Figure 3.10a**). The trends exhibited by the mean monthly number of pot lifts and, to a large extent, the mean monthly CPUE, essentially parallel those of the mean monthly catches (cf **Figures 3.10a,b,c**).

3.3.3 Analysis of catches and sizes of crabs derived from onboard sampling

Hypothalassia acerba

ANOVA demonstrated that the CPUEs of *H. acerba* differed significantly between sexes and among regions, with the mean square being far higher for sex than region (**Table 3.1**). The sex × region interaction was not significant (**Table 3.1**). The

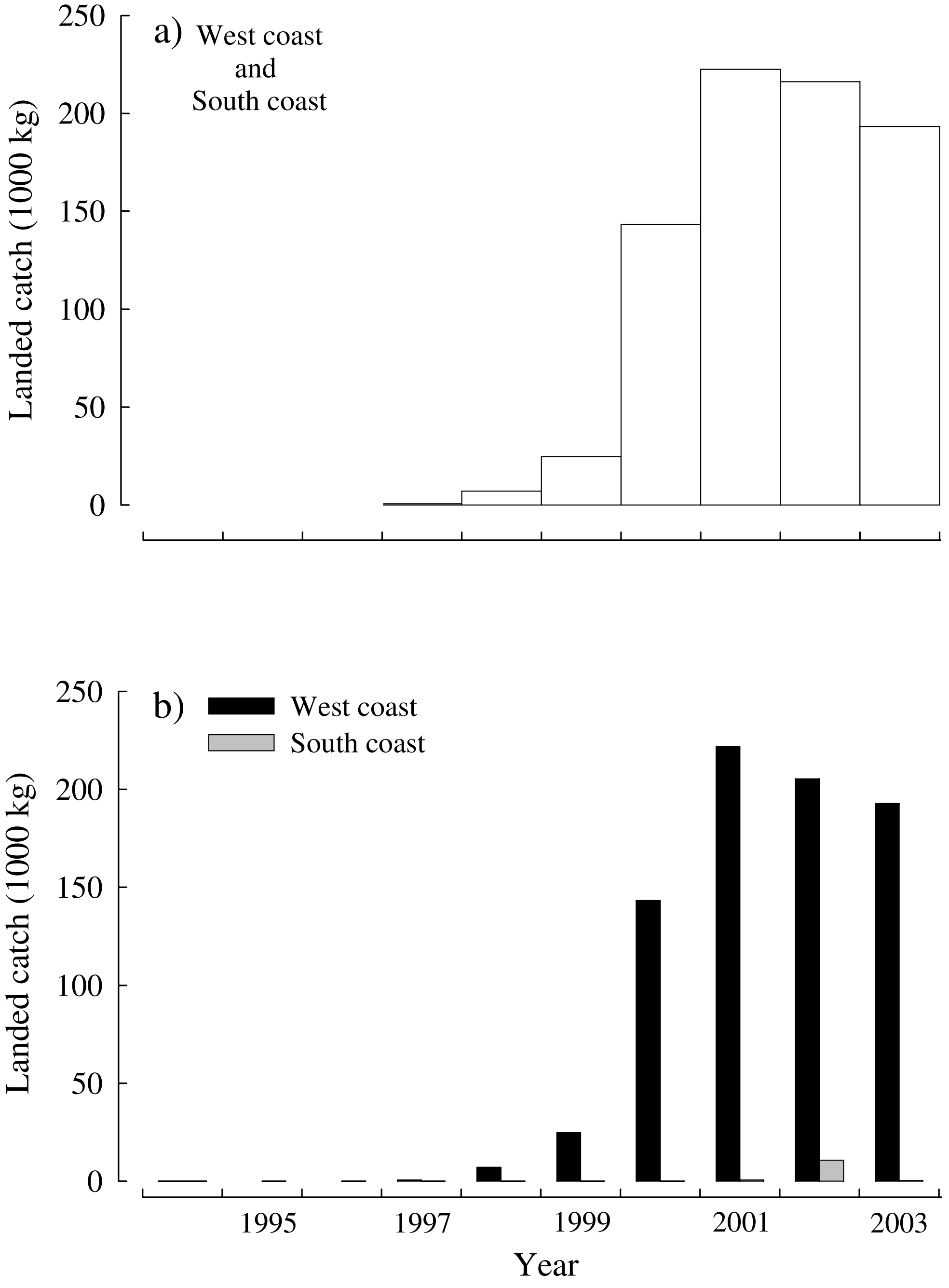


Figure 3.7. (a) Total landed catch of *Chaceon bicolor* in south-western Australia and (b) landed catch of this species on the lower west and south coasts of Western Australia separately. Data extracted from the catch and effort statistics of the Department of Fisheries Western Australia for the years between 1999 and 2003.

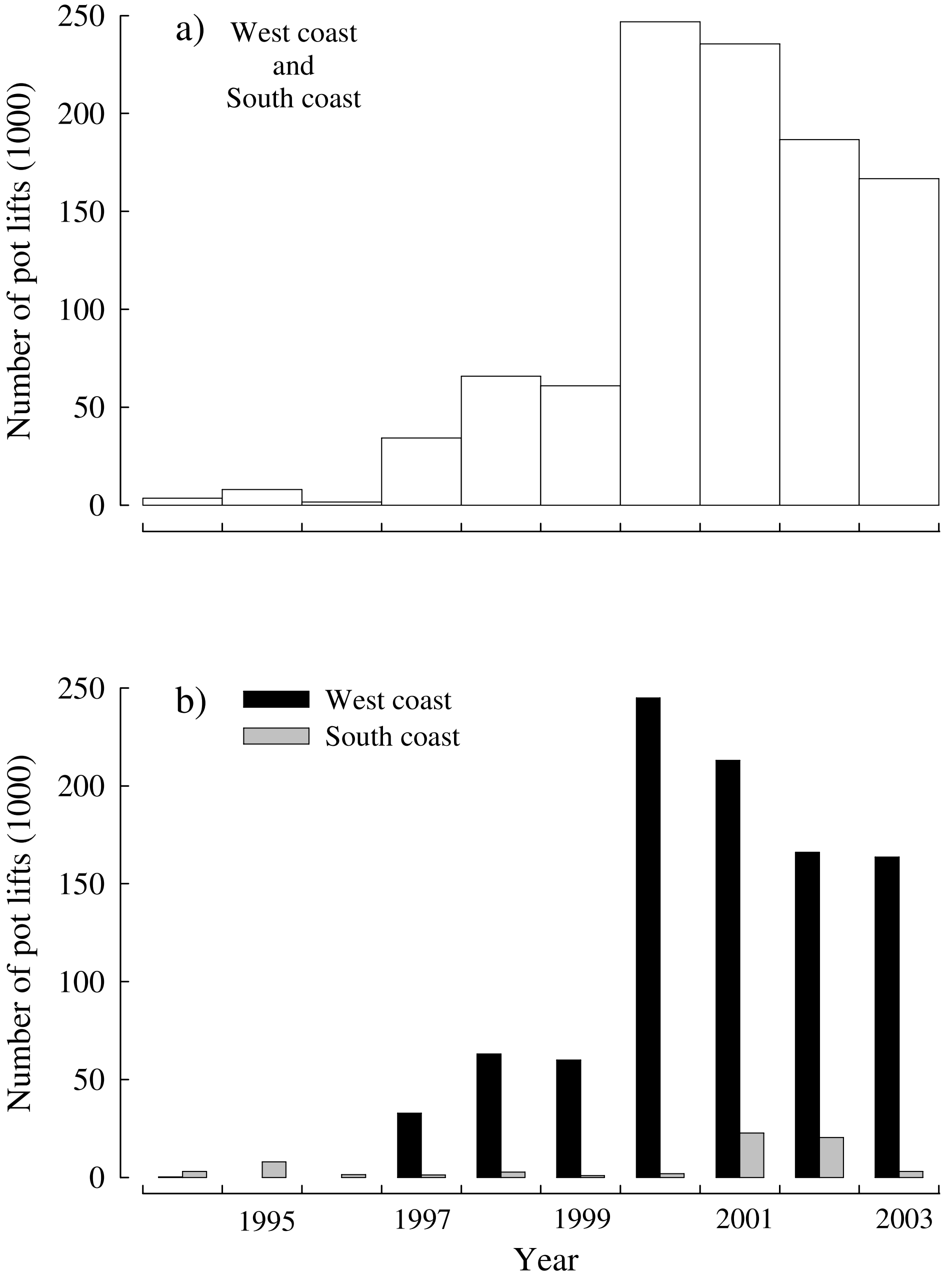


Figure 3.8. (a) Total number of pot lifts for *Chaceon bicolor* in south-western Australia and (b) number of pot lifts for this species on the lower west and south coasts of Western Australia separately between 1994 and 2003. Data extracted from the catch and effort statistics of the Department of Fisheries Western Australia

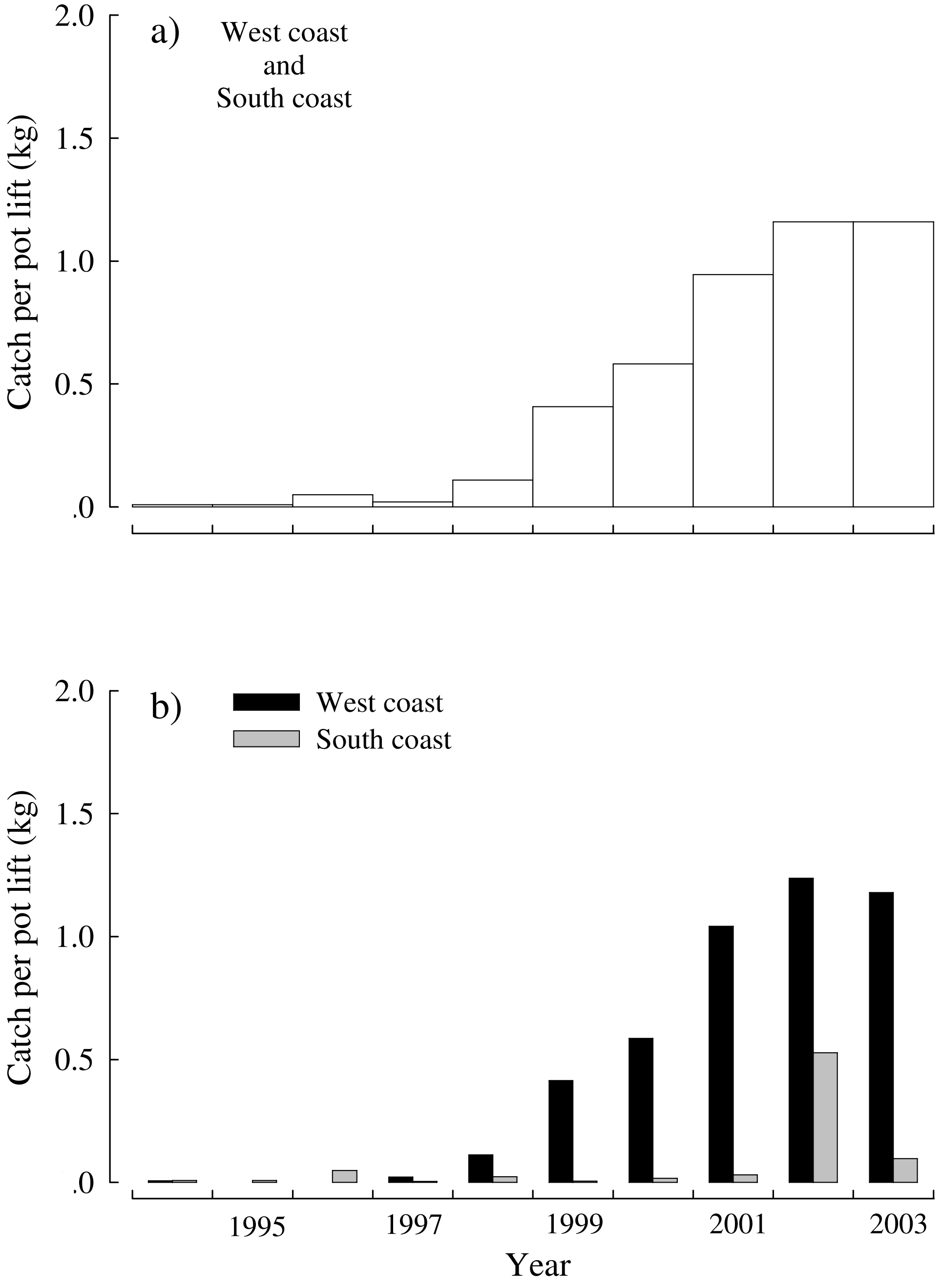


Figure 3.9. Total catch per pot lift of *Chaceon bicolor* in south-western Australia and (b) total catch per pot lift of this species on the lower west and south coasts separately for the years between 1994 and 2003. Data extracted from the catch and effort statistics of the Department of Fisheries Western Australia.

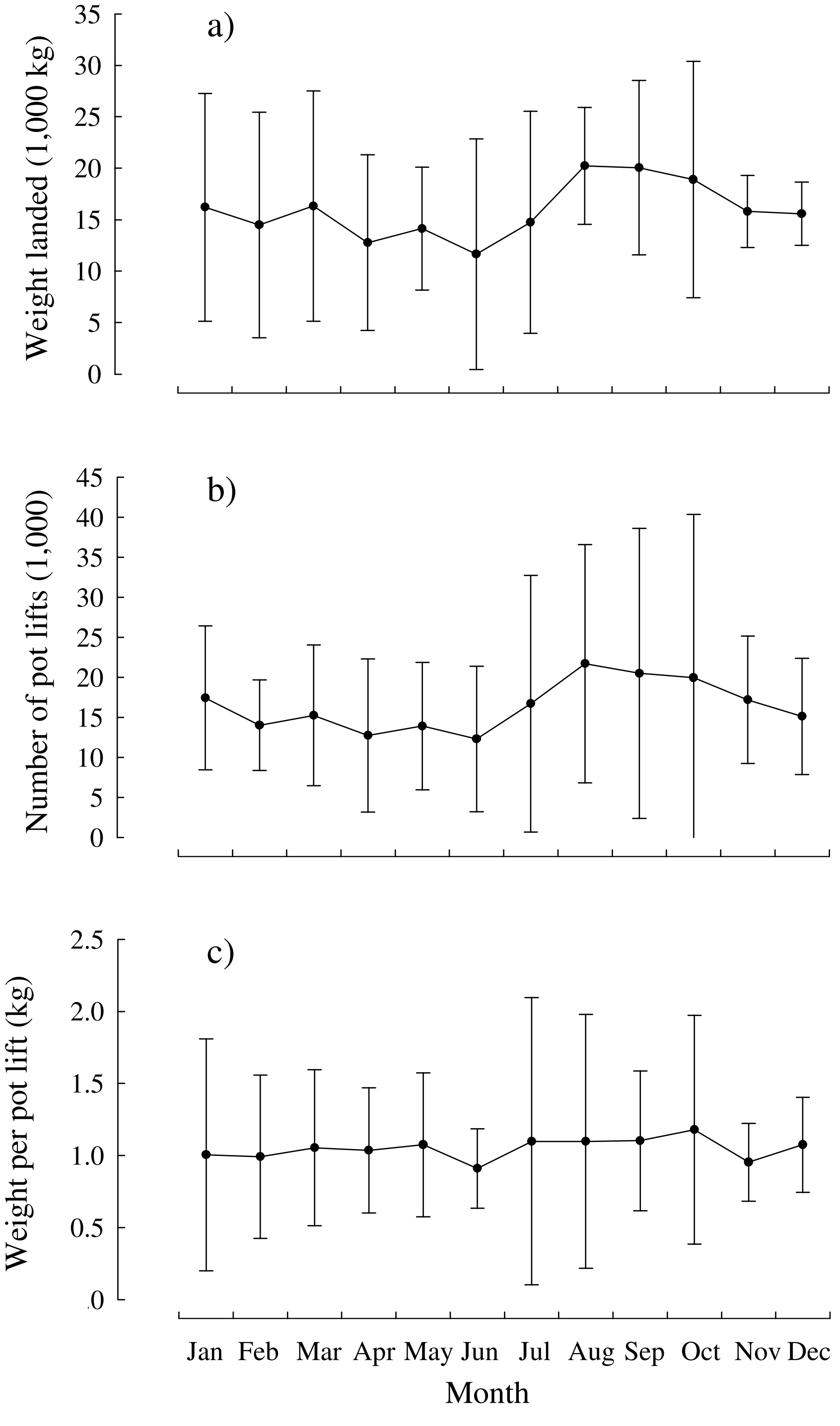


Figure 3.10. (a) Mean monthy landed weight of *Chaceon bicolor* ± 95 % CIs on the lower west coast and (b) mean monthy number of pot lifts ± 95 % CIs on the lower west coast and (c) mean monthy landed weight per pot lift ± 95 % CIs on the lower west coast. Data were for the years between 2000 and 2003.

mean CPUE of males, *i.e.* ~2.5 per pot, was far greater than that of females, *i.e* ~0.9 (**Figure 3.11a**).

Table 3.1 Mean squares and significance levels for ANOVA of catch per pot lift (CPUE) of male and female *Hypothalassia acerba* in northern and southern regions off the lower west coast and western and eastern regions off the south coast of Western Australia. Data were recorded onboard commercial vessels between 1999 and 2003. ***P*<0.01, ****P*<0.001; d.f., degrees of freedom.

	Mean Square	d.f.
Sex (S)	286.4***	1
Region (R)	13.7**	3
S x R	5.4	3
Residual	2.8	990

The mean number of crabs per pot in the four regions ranged from 2.1 in the southern region of the west coast to 1.4 in the western region of the south coast (**Figure 3.11b**). Scheffé's *a posteriori* test showed that the mean CPUE in the southern region of the lower west coast was significantly greater ($P < 0.05$) than in its northern region.

Chaceon bicolor

ANOVA demonstrated that the CPUE for C. bicolor differed significantly between sexes ($P < 0.001$) and between regions ($P < 0.01$), with the mean square being greater for sex than for region (**Table 3.2**). The sex × region interaction was not significant ($P > 0.05$) (**Table 3.2**). The mean CPUE was greater for males than females, *i.e.* 1.4 vs 1.2 per pot (**Figure 3.12a**) and was greater in the northern region than southern region, *i.e.* 1.4 vs 1.3 per pot (**Figure 3.12b**).

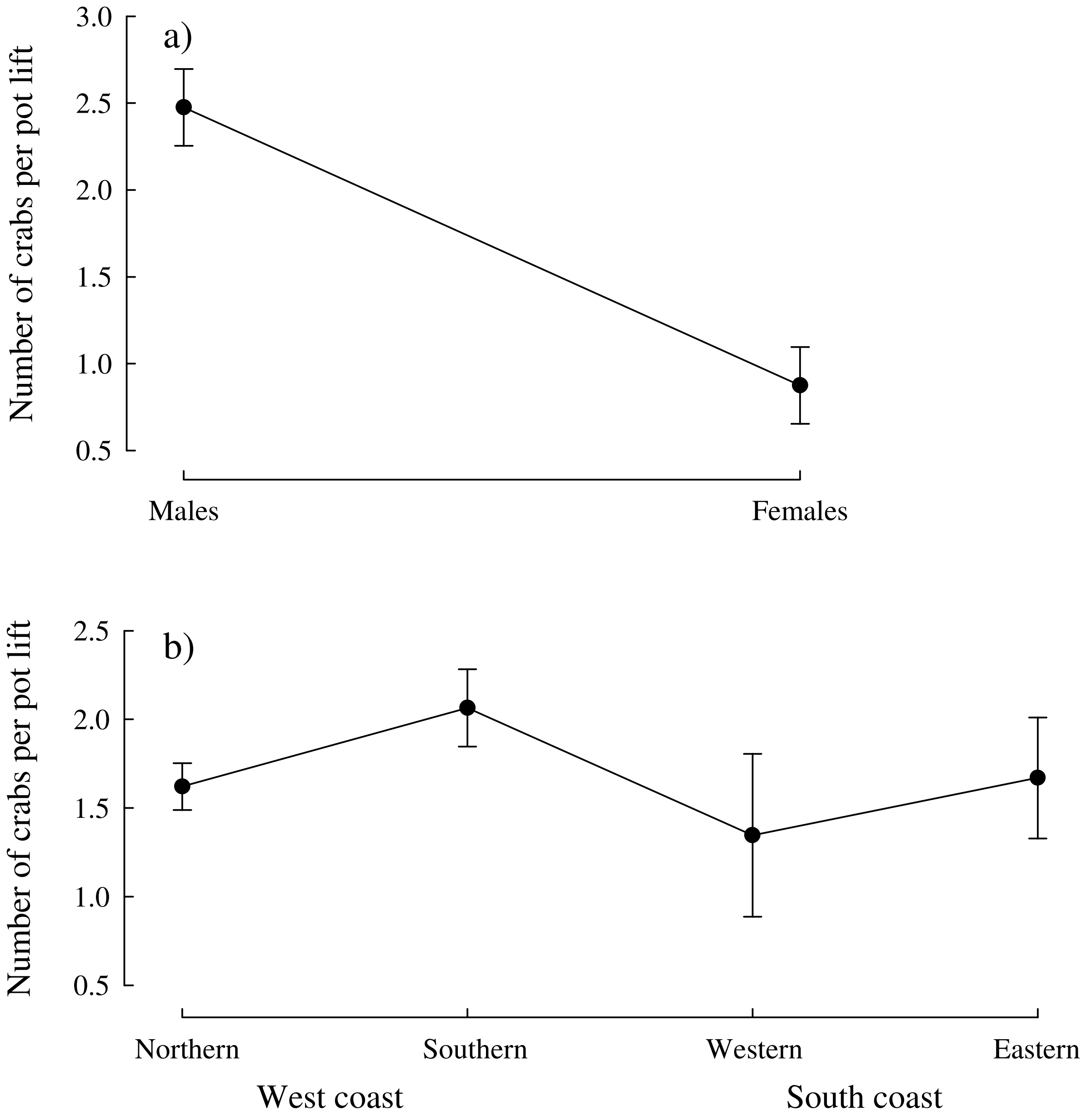


Figure 3.11. (a) Mean numbers of male and female *Hypothalassia acerba* per pot lift ± 95% CIs and (b) mean numbers of *Hypothalassia acerba* per pot lift ± 95% CIs in each region.

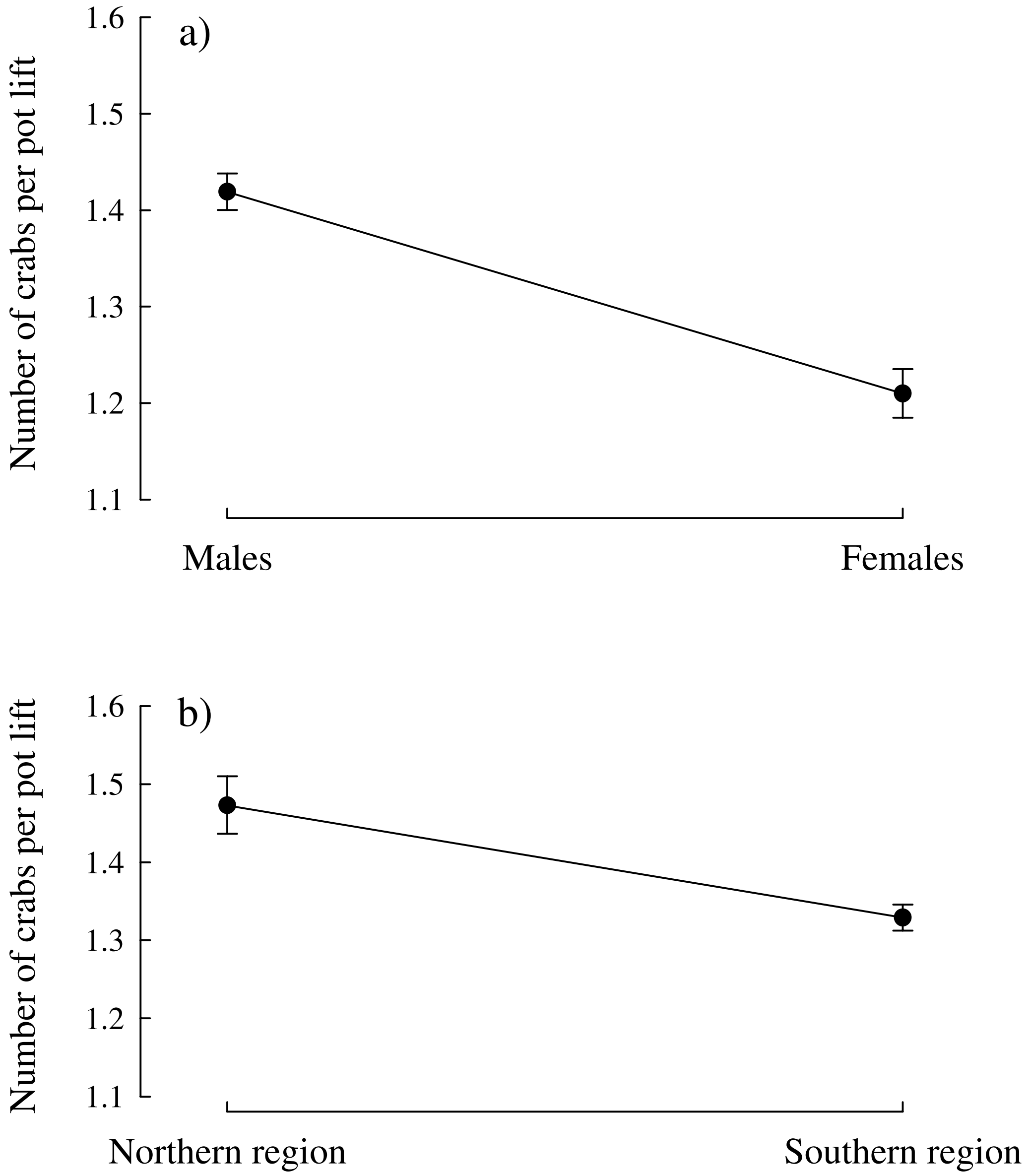


Figure 3.12. Mean numbers of *Chaceon bicolor* per pot lift ± 95% CIs for (a) males and females and (b) the northern and southern regions of the west coast.

Table 3.2 Mean squares and significance levels for ANOVA of catch per pot (CPUE) of male and female *Chaceon bicolor* in northern and southern regions off the lower west coast. Data were recorded onboard commercial vessels between 1999 and 2003. $^{**}P<0.01$, $^{***}P<0.001$; d.f., degrees of freedom.

	Mean Square	d.f.
Sex (S)	13.0***	1
Region (R)	2.2**	1
S x R	0.3	1
Residual	0.2	5671

3.3.4 Carapace Lengths

Hypothalassia acerba

ANOVA demonstrated that the carapace length of *H. acerba* was influenced significantly by both sex and region ($P < 0.001$), with the mean square for sex being slightly greater than that for region (**Table 3.3**). The region × sex interaction was not significant.

Table 3.3. Mean squares and significance levels for ANOVA of carapace lengths of male and female *Hypothalassia acerba* in northern and southern regions off the lower west coast and western and eastern regions off the south coast of Western Australia. Data were recorded onboard commercial vessels between 1999 and 2003. $^{***}P<0.001$; d.f., degrees of freedom.

	Mean Square	d.f.
Sex (S)	2954.2***	1
Region(R)	2559.7***	3
S x R	104.8	3
Residual	146.2	1713

The mean carapace length of males (100.7 mm) was greater than that of females (95.2 mm) (**Figure 3.13a,b**). The mean carapace length of *H. acerba* ranged from 91 mm in the eastern region of the south coast to 103 mm in the western region of the south coast (**Figure 3.13c**). Scheffé's *a posteriori* test showed that the mean carapace lengths of *H. acerba* differed

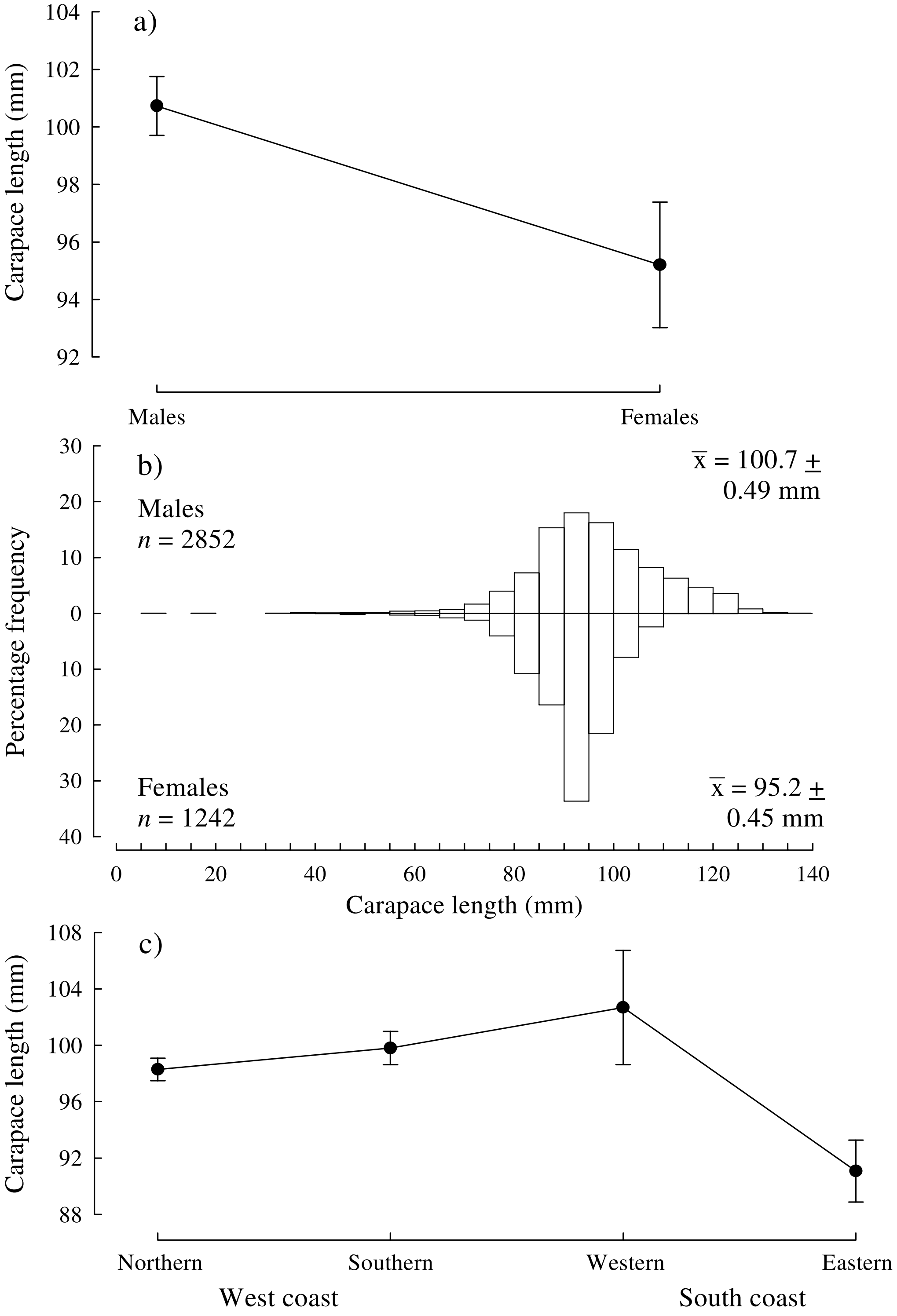


Figure 3.13. (a) Mean carapace lengths of male and female *Hypothalassia acerba* ± 95% CIs and (b) Carapace length - frequency distributions and mean carapace lengths for male and female *Hypothalassia acerba* caught by commercial fishers off the lower west and south coasts of Western Australia and c) mean carapace lengths of *Hypothalassia acerba* ± 95% CIs in each region.

significantly ($P < 0.05$) between each pair of regions, except for between the southern region of the west coast and the western region of the south coast.

Although the maximum length of males (139 mm) was greater than that of females (120 mm) in the samples examined onboard commercial vessels on the lower west and south coasts, the modal carapace length classes of males and females were both 90-94 mm (**Figure 3.13b**).

Chaceon bicolor

The carapace lengths of *C. bicolor* differed significantly between the sexes and between the two regions (**Table 3.4**). The mean square was far greater for sex than for region, and the region × sex interaction was not significant (**Table 3.4**).

Table 3.4 Mean squares and significance levels for ANOVA of carapace lengths of male and female *Chaceon bicolor* in northern and southern regions off the lower west coast of Western Australia. Data were recorded onboard commercial vessels between 1999 and 2003. ***$P<0.001$; d.f., degrees of freedom.

	Mean Square	d.f.
Sex (S)	72513.2***	1
Region(R)	6298.8***	1
S x R	28.1	1
Residual	323.7	13326

The mean carapace length of the males of *C. bicolor* (119.0 mm) was greater than that of its females (106.3 mm CL) (**Figure 3.14a,b**). Furthermore, males reach a larger maximum size (169 mm) than females (148 mm CL) (**Figure 3.14b**). In contrast to *H. acerba*, however, the modal size class of male *C. bicolor* (115–119 mm) was substantially greater than that of females (100–104 mm) (**Figure 3.14b**). Few crabs were caught with carapace lengths

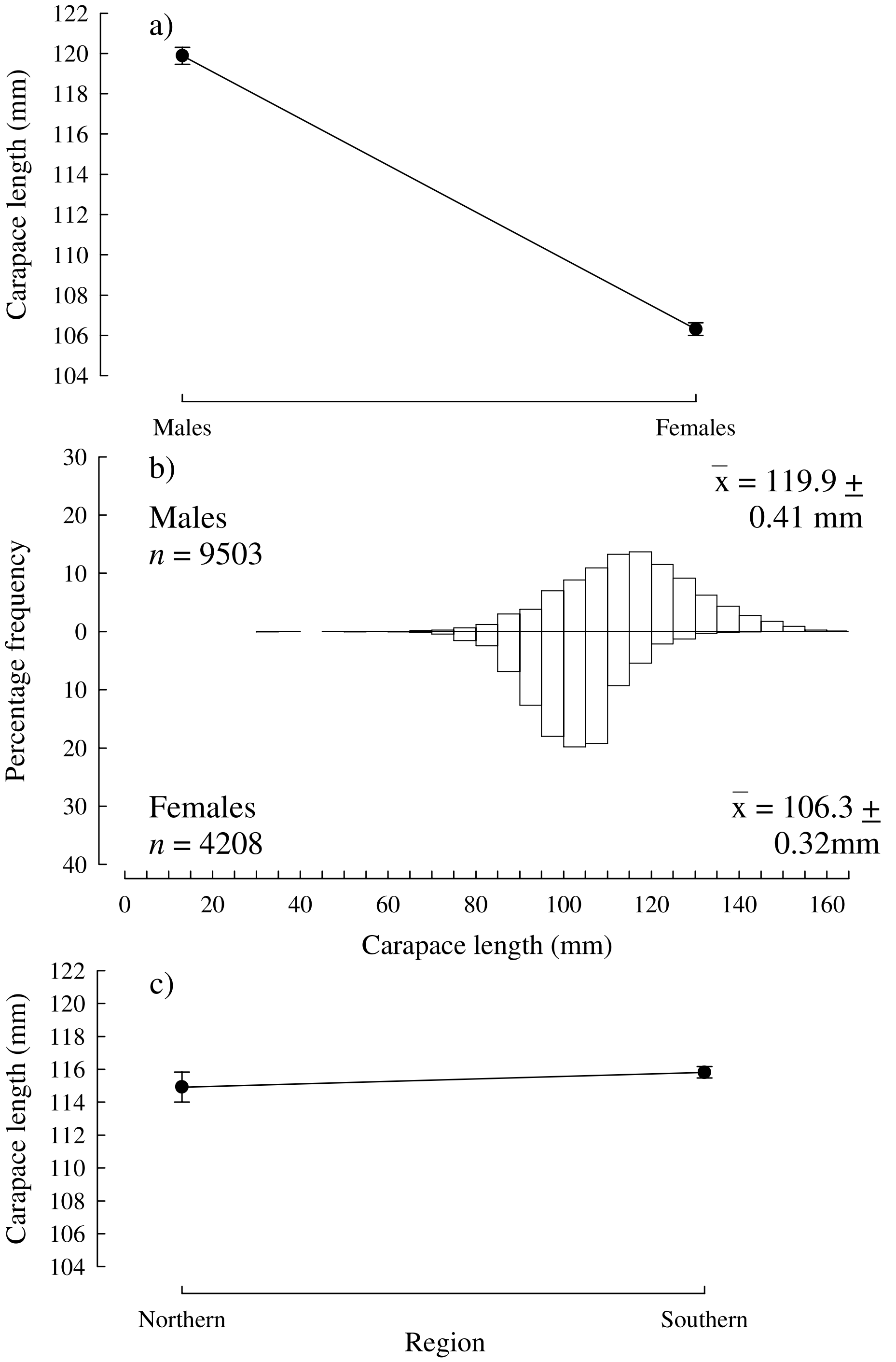


Figure 3.14. (a) Mean carapace lengths of male and female *Chaceon bicolor* ± 95% CIs, (b) Carapace length - frequency distributions and mean carapace lengths for male and female *Chaceon bicolor* caught by commercial fishers off the lower west coast of Western Australia and (c) mean carapace lengths of *Chaceon bicolor* ± 95% CIs for each region.

< 80 mm. The mean carapace length of *C. bicolor* was greater in the southern than northern region, *i.e.* 113 *vs.* 110 mm (**Figure 3.14c**).

3.3.5 Carapace lengths of **Chaceon bicolor** *in non-meshed and meshed traps*

In the case of the males of *C. bicolor*, the mean carapace lengths were greater in the catches obtained in meshed than non-meshed traps in each of the three seasons in which substantial numbers were caught in the non-meshed traps (**Table 3.5**). However in none of these seasons was the difference in size significant. The mean carapace length of females was significantly greater in the catches obtained in the non-meshed than meshed traps in summer ($P < 0.05$), the only season in which the catches of females in non-meshed traps was substantial (**Table 3.5**). However, even in this latter case, the difference between the carapace lengths in the two trap types was < 8 mm. It is thus concluded that the enclosure of traps in relatively fine mesh did not lead to a conspicuous increase in the capture of small crabs. This point is highlighted by the fact that the percentage of the crabs caught <80 mm CL in the meshed traps were only slightly greater than in the non-meshed traps, *i.e.* 3 vs 1%.

Table 3.5 Mean carapace lengths ± 95 % CIs of male and female *Chaceon bicolor* caught in non-meshed vs meshed traps in four seasons between 2001 and 2003. *n*, sample size; NS = not significant at $P > 0.05$; * = $P < 0.05$.

		Males	*n*	*P*	Size range (mm)
Summer	Non-mesh	119.6 ± 0.7 mm	2115	NS	34 - 169
	Mesh	115.8 ± 5.3 mm	63		38 - 155
Winter	Non-mesh	117.9 ± 1.1 mm	601	NS	59 - 160
	Mesh	112.6 ± 8.8 mm	20		82 - 140
Spring	Non-mesh	116.2 ± 1.0 mm	785	NS	72 - 153
	Mesh	114.8 ± 4.1 mm	45		88 - 143
		Females			
Summer	Non-mesh	106.5 ± 0.7 mm	782	*	57 - 141
	Mesh	98.8 ± 6.6 mm	47		35 - 128

3.3.6 Results from release of tagged **Hypothalassia acerba**

Twenty eight of the 1622 champagne crabs tagged and released off the lower west coast were recaptured. All of the nine tagged females and nineteen tagged males that were released and recaptured were mature. However, none of the females was ovigerous when it was either tagged, released or recaptured. All but four of the tagged females that were subsequently caught were recaptured within 50 km of their point of release. Two of the recaptured tagged crabs had moved ~ 200 km in a north-westerly direction and a further two had moved over 200 km in a south-westerly direction (**Figure 3.15**). These crabs had thus moved along the contour of the upper shelf break, which runs approximately parallel to the lower west Australian coastline.

None of the 28 recaptured crabs moulted, and this included even one female that had been released back into the environment for over 12 months.

3.4 DISCUSSION

3.4.1 Annual trends in catch statistics

Hypothalassia acerba

The data shown in **Figure 3.1** demonstrate very clearly how the overall catches of *Hypothalassia acerba* in Western Australia rose from very low levels in 1989 and 1990 to peak at over 70 000 kg in 1998 and then declined sequentially in subsequent years to under 20 000 kg in 2002 and 2003. Those data also show that the fishery for *H. acerba* on the west coast became essentially non-existent in 2001 to 2003, due to the deep-sea crab fishers on this coast shifting their effort almost exclusively to catching *Chaceon bicolor.*

The trends exhibited by the annual number of pot lifts for *H. acerba* in Western Australia demonstrate that the fishing effort in this state peaked in 1998, when the number of pot lifts was ~ 135 000, and has subsequently remained relatively constant at about half this level from 1999 to 2003. A decline in effort on the west coast in the last five years has been

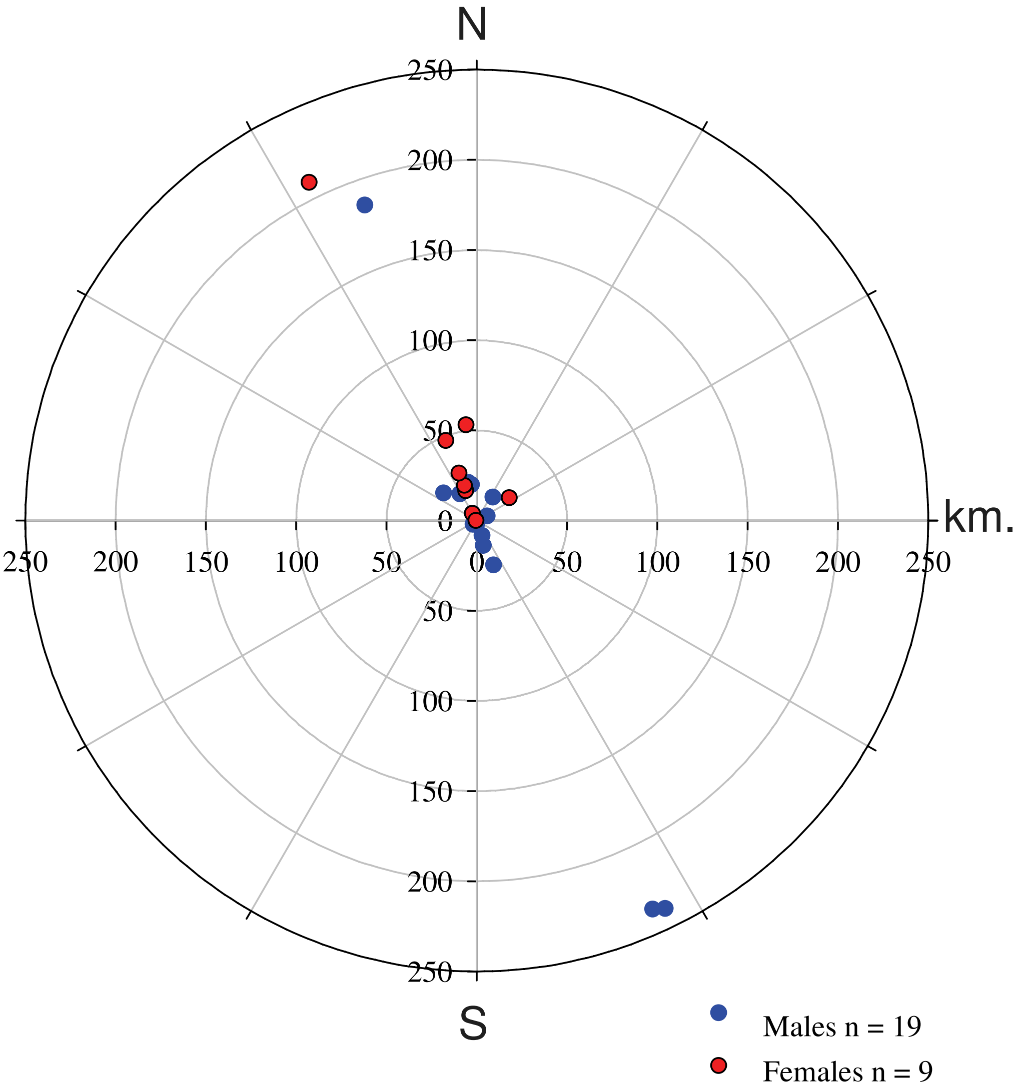


Figure 3.15. Distances in km of the location of recaptured tagged *Hypothalassia acerba* from the point of their release.

compensated for by an increase in effort on the south coast. The decline undergone each year since 1999 by the overall CPUE for Western Australia, as reflected in the trends exhibited by the annual catches per pot lift for the state, indicate that the relative abundance of *H. acerba* has declined during recent years. This suggests that fishing pressure has had an effect on the density of this species.

Chaceon bicolor

The data in **Figure 3.7** emphasise that the commercial fishery for *C. bicolor* in Western Australia commenced later than that of *H. acerba*, but that catches rose sharply from negligible values in 1997 and 1998 to peak at 225 000 kg in 2001 and remained close to that level in 2001 to 2003. The rapid increase in the fishery was due to the development of a sudden and focused interest on *C. bicolor*, which led to the construction of vessels that were purpose-built for targeting this species (D. Hand, pers. comm.). The fisheries data also emphasize that the fishery has been based almost exclusively on the west coast. Although the progressive rise in CPUE between 1998 and 2002/3 suggest that the relative abundance of *C. bicolor* increased during this period, that upward trend is almost certainly attributable to a rapid increase in the knowledge by fishers of the best locations and best fishing methods for catching this species.

3.4.2 Monthly trends in catch statistics

Hypothalassia acerba

The monthly trends exhibited by the fishing effort for *H. acerba* on the south coast closely paralleled those of catch, with values being least in early winter to mid spring. The relatively low fishing effort in the above period reflects, in part the adverse weather conditions at this time and, also in the case of the months between July and October, the closure of the fisheries for one of the other two species that comprise the multi-species fishery for large crustaceans on the south coast, *i.e.* the southern rock lobster *Jasus edwardsii*. The similarity in the trends exhibited by both catch and effort accounts for the fact that the catch per unit effort did not change markedly throughout the year.

In contrast to the situation with *H. acerba* on the south coast, the monthly trends displayed by effort for this species on the west coast did not parallel those of catch. Indeed, effort was least in September, October and November on this coast, which explains why the catch per unit effort was greatest in these months. Although caution must be exercised in drawing conclusions from these catch statistics for this new fishery, the consistency of the progressive rise in CPUE between summer and the following spring does suggest that the relative abundance, or more likely the catchability of *H. acerba*, is greatest in the spring months.

Chaceon bicolor

The lack of a conspicuous seasonality in either the catch or fishing effort for *C. bicolor* on the west coast accounts for the CPUE for this species on this coast remaining remarkably constant throughout the year. This, in turn, implies that the relative abundance and catchability of *C. bicolor* on the west coast vary little during the year.

3.4.3 Catches and carapace lengths of **Hypothalassia acerba** *and* **Chaceon bicolor**

The fact that the catches of females were significantly less than those of males in the case of both *H. acerba* and *C. bicolor* parallels the results recorded for the trap catches of other species of deep-sea, crabs such as *Chaceon affinis*, *Chaceon maritae* and *Chaceon notialis, Pseudocarcinus gigas*, *Chionoecetes bairdii, Chionoecetes tanneri* (Melville Smith, 1988; Defeo *et al.,* 1991; Levings *et al.,* 2001; López Abellán, *et al.,* 2002; Workman and Phillips, 2002; Rosenkranz, 2002). The dominance of males in trap catches has been attributed to such features as male aggression (Bovjberg, 1956) and trap avoidance by ovigerous females (Melville Smith, 1987). Although there were some regional differences in the CPUEs for both *H. acerba* and *C. bicolor*, the differences were not pronounced and the basis for these differences was not clear.

The mean carapace lengths of the males of both *H. acerba* and *C. bicolor* were significantly greater than those of their females, as is the case with several other species of deep-sea crab (Melville Smith, 1988; Levings *et al.,* 1996; López Abellán, *et al.,* 2002). However, the modal carapace length class of males and females of *H. acerba* are the same, *i.e.* 90–94 mm, whereas that of the males of *C. bicolor, i.e.* 115-119 mm, is considerably greater than that of the females, *i.e.* 100–104 mm. The differences between the sizes of the two sexes is thus greater in *C. bicolor* than *H. acerba*.

4.0 RELATIVE ABUNDANCES AND SIZE COMPOSITIONS OF *HYPOTHALASSIA ACERBA* ON TWO COASTS AND IN DIFFERENT WATER DEPTHS AND SEASONS

4.1 INTRODUCTION

The champagne crab *Hypothalassia acerba*, together with the western rock lobster *Panulirus cygnus*, the southern rock lobster *Jasus edwardsii,* the king crab *Pseudocarcinus gigas* and the crystal crab *Chaceon bicolor*, are the main large benthic, crustacean predators in water depths greater than 20 m off the south-western Australian coast (George, 1962; Kailola *et al.,* 1993; Levings *et al.,* 1996, 2001; Koh and Ng, 2000; Jones and Morgan, 2002).

The acquisition of appropriate biological data is crucial for managing deep-sea crab species as these grow slowly and are long lived and are thus susceptible to becoming the subject of boom-and-bust fisheries (Hastie, 1995). Prior to the present study, no such data on features such as distribution patterns, size compositions and sex ratios were available for *H. acerba,* or for any other species of the family Eriphiidae except those provided in reports on the king crab *Pseudocarcinus gigas* by Gardner (1998) and Levings *et al.,* (2001).

However, such data are available for a number of deep-sea crab species elsewhere in the world, and particularly for certain species belonging to the Geryonidae and Lithodidae. The distribution of several of these species is known to be related to water depth, temperature and/or substrate type (Melville Smith and Bailey, 1989; Hastie, 1995; Comeau *et al.,* 1998) and the males tend to be more abundant in catches and grow to a larger size than the females (Lux *et al.,* 1982; Melville Smith, 1988; Attrill *et al.,* 1991; López Abellán *et al.,* 2002). Furthermore, body size has been shown to be inversely correlated with water depth in certain deep-sea geryonid species, implying that the individuals of these species are recruited into deeper water and subsequently move shorewards as they increase in size (Beyers and Wilke, 1980; Attrill *et al.,* 1990; Lockhart *et al.,*1990). In some species, such movements are apparently more pronounced amongst females than males, occur seasonally and/or are related to such factors as temperature and/or reproductive state (Melville Smith, 1987b; Lockhart *et al.,* 1990; Defeo *et al.,* 1991; Hastie, 1995). Moreover, differences between the compositions of the invertebrate fauna living on the shells of males and females of *Chionoecetes opilio* imply that, when not pairing, the two sexes of this species tend to occupy different niches off Newfoundland (Hooper, 1986). There is also evidence that the spatial resources in deep-sea waters are partitioned among two congeneric species of deep-sea crab in the Gulf of Mexico, with *Chaceon quinquedens* being more abundant in shallower waters and *Chaceon fenneri* being more numerous in deeper waters (Lockhart *et al.,* 1990; Hastie, 1995).

During the present study, we collected *H. acerba* during each season from seven water depths located at depth intervals of 55 m between 35 and 310 m on both the lower west and south coasts of Western Australia in order to test the following hypotheses. (1) *Hypothalassia acerba* will occur predominantly in a range of water depths that differ from those in which the other main large benthic invertebrate carnivores are predominantly found and thus reduce the likelihood of competition for resources amongst those species. (2) Since bottom water temperature declines with increasing water depth and overall is higher at corresponding depths on the lower west coast than south coast, the relative abundance of this species would be likely to peak at a deeper water depth on the lower west than south coast if temperature influences the distribution of *H. acerba*. (3) The distribution by depth will change seasonally in response to changes in bottom water temperature. The study also focuses on determining whether, as with certain representatives of two other families of deep-sea crabs, the following apply on both coasts. The males will be relatively more abundant and attain a greater size than females, the body size will be inversely correlated with water depth and there will be a certain degree of habitat segregation between the sexes. Since the “western rock lobster” traps used in our study caught few small *H. acerba*, as is often the case with the traps employed to catch deep-sea crabs (*e.g.* Lux *et al.,* 1982; López Abellán *et al.,* 2002), the question of whether the enclosure of these traps with a fine mesh would increase the catches of small crabs was also examined.

4.2 MATERIALS AND METHODS

4.2.1 Sampling Regime

The data used to determine the relative abundance of *Hypothalassia acerba* in different water depths were derived from the depth-stratified sampling regime, which was undertaken once per calendar season on both the lower west and south coasts using traps that were not enclosed in mesh (Chapter 2).

The data used to describe the relationships between carapace length and water depth, coast and season were derived collectively from the sampling described above, but in this case they included the data collected using traps enclosed in small mesh. Refer to chapter 2 for a full description of the sampling regime.

4.2.2 Data Analysis

Plots of $\log_{10}$ (mean) against $\log_{10}$ (standard deviation) showed that, prior to subjecting catch rates to Analysis of Variance (ANOVA), they required square root transformation (see Clarke and Gorley (2001) for rationale for this approach). These two values (*mean* and *s.d.*) were calculated from the catches per line of three traps in each water depth on each coast in each season. The transformed values for catch for each sex for each line of traps in each water depth on each coast in each season were subjected to ANOVA, with each factor being fixed. Note that since no crabs were caught at depths of either 35 or 365 m on either coast, these zero values were not employed in the ANOVA. Since the four-way interaction between coast, depth, sex and season was not significant ($P > 0.05$), this term was removed from the model and the data reanalysed. Results from the ANOVA were back-transformed before plotting.

The distribution of crabs with respect to bottom water temperature was explored by fitting a nonlinear regression model that related the catch *C(T)* by all three lines of traps to the bottom water temperature *T*°C recorded at the corresponding depth at which the traps were placed. The base model used, *i.e.*

$$C(T) = a + b\exp\left[-c(T-d)^2\right],$$

was intended to represent catches for the sampling unit that were proportional to a common base level of catch, *a (*where $a \geq 0$), over all temperatures, augmented by a 'normal distribution' of increased catches of crabs centred at a mean temperature of *d*°C. The parameters *a*, *b*, *c* and *d* were estimated by minimizing the weighted sum of squared deviations between transformed values of the observed and predicted catches, where each weight was calculated as the inverse of the predicted catch and a penalty function was used to ensure that $a \geq 0$. A likelihood ratio test was used to determine whether the above model provided a better description of the distribution of crabs than the simpler model $C(T) = a$, *i.e.* a distribution of crabs that was independent of water temperature. Likelihood ratio tests were also used to test whether the value of *a* in the base model differed significantly from zero and/or whether there were differences between the mean temperatures of the 'normal distributions' for the curves for the south and west coasts and, on the west coast, between those for the meshed and non-meshed traps.

The logarithms of the standard deviations of the carapace lengths for each sex on each sampling occasion on both coasts were plotted against the logarithms of the mean values for those carapace lengths. This demonstrated that the carapace lengths did not require transformation prior to subjection to analysis of covariance (ANCOVA). This latter analysis, which employed the General Linear Model (GLM) procedure within SPSS Version 10 (SPSS Inc., Chicago, Illinois, USA) and assumed a normal distribution of observation errors, was undertaken to ascertain whether there was a significant linear relationship between carapace length and water depth and whether this relationship was influenced by sex, coast and/or season. If the covariate in an ANCOVA is found to be significant, the absolute value of the dependent variable is dependent upon the value of the covariate and values of the dependent variable for the other factors must be adjusted to a standard value of this covariate before they are compared. In the SPSS analysis of the data for *H. acerba*, a water depth of 200 m was specified as the standard depth at which the comparison among other factors was to be made if the covariate, depth, was found to be significant. Likewise, if the other factors (or their interactions) are found in the ANCOVA to be significant, a plot of the values of the dependent variable against the values of the covariate will reflect both the linear trend associated with the covariate and the effects of the other significant factors and interactions. To remove these effects and thereby illustrate more clearly the relationship between the dependent variable and the covariate, the values of the effects of the significant factors and interactions, as calculated in the ANCOVA, were subtracted from the corresponding values of the dependent variable to transform the data to values that would be approximately "equivalent" to those recorded at the reference levels of the factors, *i.e.* females of *H. acerba* on the south coast during spring. The means and 95% confidence intervals of the transformed data were calculated and plotted against the values predicted for the corresponding depths for females on the south coast during spring.

A fully saturated statistical model was fitted to the carapace lengths, with sex, coast and season as factors and depth as a covariate. Higher order interactions that were not significant ($P > 0.05$) were then successively removed, with the term having the greatest P-value being selected as the next term to be eliminated. Next, lower-order interaction terms that were not significant were examined to determine whether they might also be removed to reduce the model further. Such lower-order terms were retained if they contained constituent variables that were included in the remaining significant higher-order interaction terms. The value for the Bayesian Information Criterion (BIC) was calculated for the resulting model as $BIC = n\log_e\left(\frac{SS_e}{n}\right) + p\log_e(n)$, where SS_e is the sum of squares of the errors, n is the number of observations, p is the number of parameters that were estimated by the GLM procedure and $\log_e$ is the natural logarithm (Schwarz, 1978). The highest-order interaction terms in the model were then removed and the BIC recalculated. If the latter value was less than the corresponding value for the preceding model, it was concluded that this latter model was the more appropriate description. In this case, the simpler model was accepted and re-examined to determine whether further non-significant terms could be removed, using the same procedure as described above.

4.3 RESULTS

4.3.1 Water temperature

Water temperatures declined with increasing water depth on both the west and south coasts (**Figure 4.1**). However, at each depth for which there are comparable data, the temperatures were appreciably greater on the west than south coast in both summer and spring, but not in autumn or winter. Temperatures in depths $\leq$ 255 m were greater in summer and autumn than in winter and spring on the west coast, whereas they were greater in autumn and winter than in spring and summer on the south coast.

4.3.2 Relative abundance of crabs in different water depths and temperature

ANOVA demonstrated that the catch rates of crabs differed significantly between sexes and among water depths and seasons (**Table 4.1**). However, the mean squares and significance

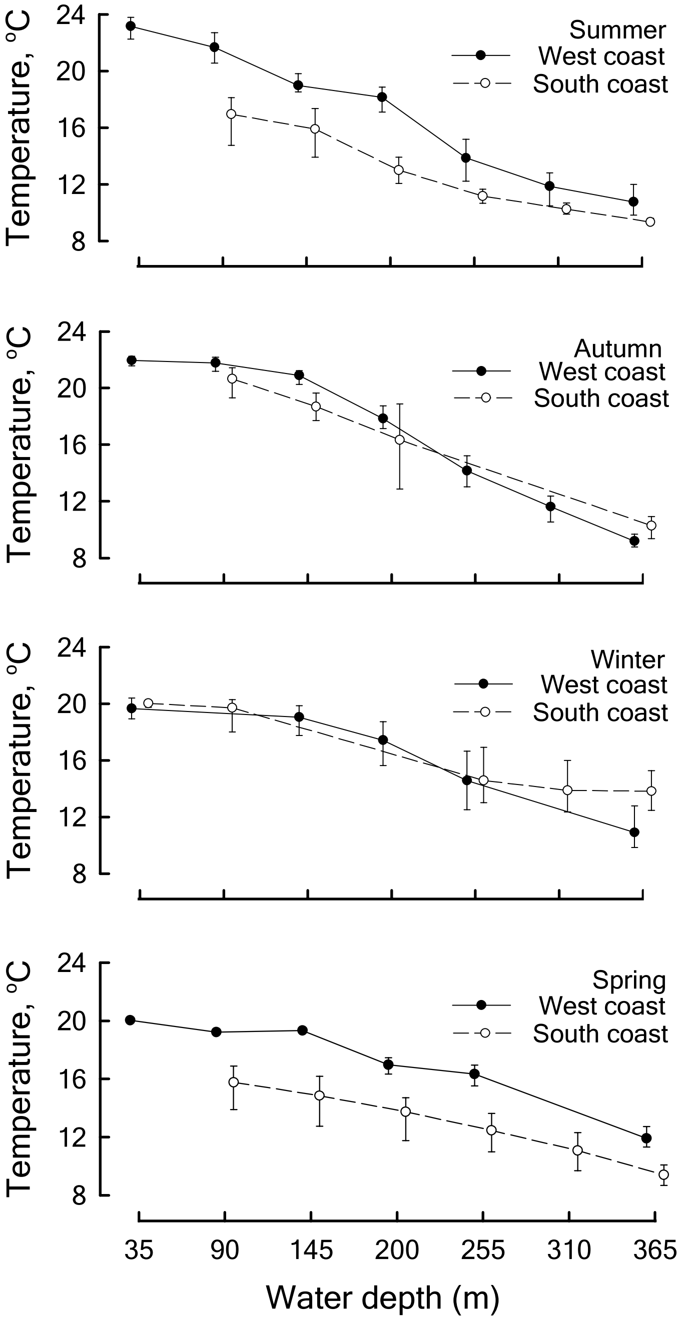


Figure 4.1 Mean bottom water temperatures ± 95% CIs in the water depths where *Hypothalassia acerba* was sampled off the lower west and south coasts of Western Australia in each season.

levels were far greater for water depth and sex than for season. All of the two-way interactions except sex × season and the three-way interactions sex × coast × water depths and coast × depth × season were significant (**Table 4.1**).

On both the west and south coasts, the mean catch rates were greater for males than females in those water depths in which the majority of crabs were caught, *i.e.* 200 and 255 m on the west coast and 90, 145 and 200 m on the south coast (**Figure 4.2**). These depth-related differences in the abundances of crabs on the west and south coasts, together with the fact that males were proportionately more abundant on the south coast, explain the sex × coast × depth interaction for catch rates (**Table 4.1**).

Table 4.1. Mean squares and significance levels for ANOVA of catch rates of female and male *Hypothalassia acerba* recorded in the seven water depths sampled on the lower west and south coasts of Western Australia during the four seasons of the year. **P*<0.01 ***P*<0.01 ****P*<0.001

	Mean squares	**d.f.**
Sex (S)	16.4***	1
Coast (C)	2.5	1
Depth (D)	23.6***	4
Season (T)	3.1**	3
S × C	7.4**	1
S × D	2.4*	4
S × T	0.2	3
C × D	26.3***	4
C × T	7.1***	3
D × T	7.0***	12
S × C × D	4.3***	4
S × C × T	1.2	3
C × D × T	3.5***	10
S × D × T	0.8	12
Residual	0.8	54

The catch rates of crabs on the west coast peaked at a water depth of 200 m in summer, autumn and winter and at 255 m in spring (**Figure 4.3**). In contrast, on the south coast, catch rates

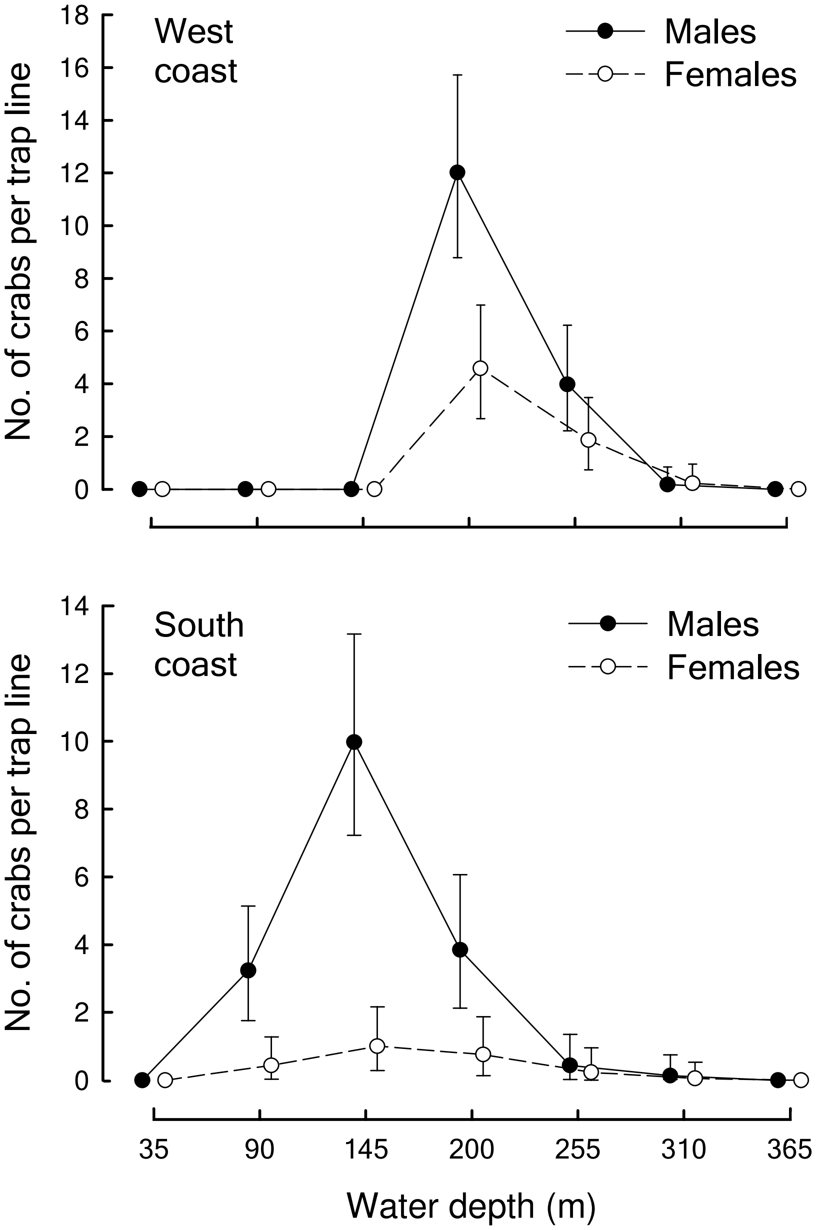


Figure 4.2 Mean numbers of male and female *Hypothalassia acerba* ± 95% CIs caught in trap lines in different water depths off the lower west (top) and south coasts (bottom) of Western Australia.

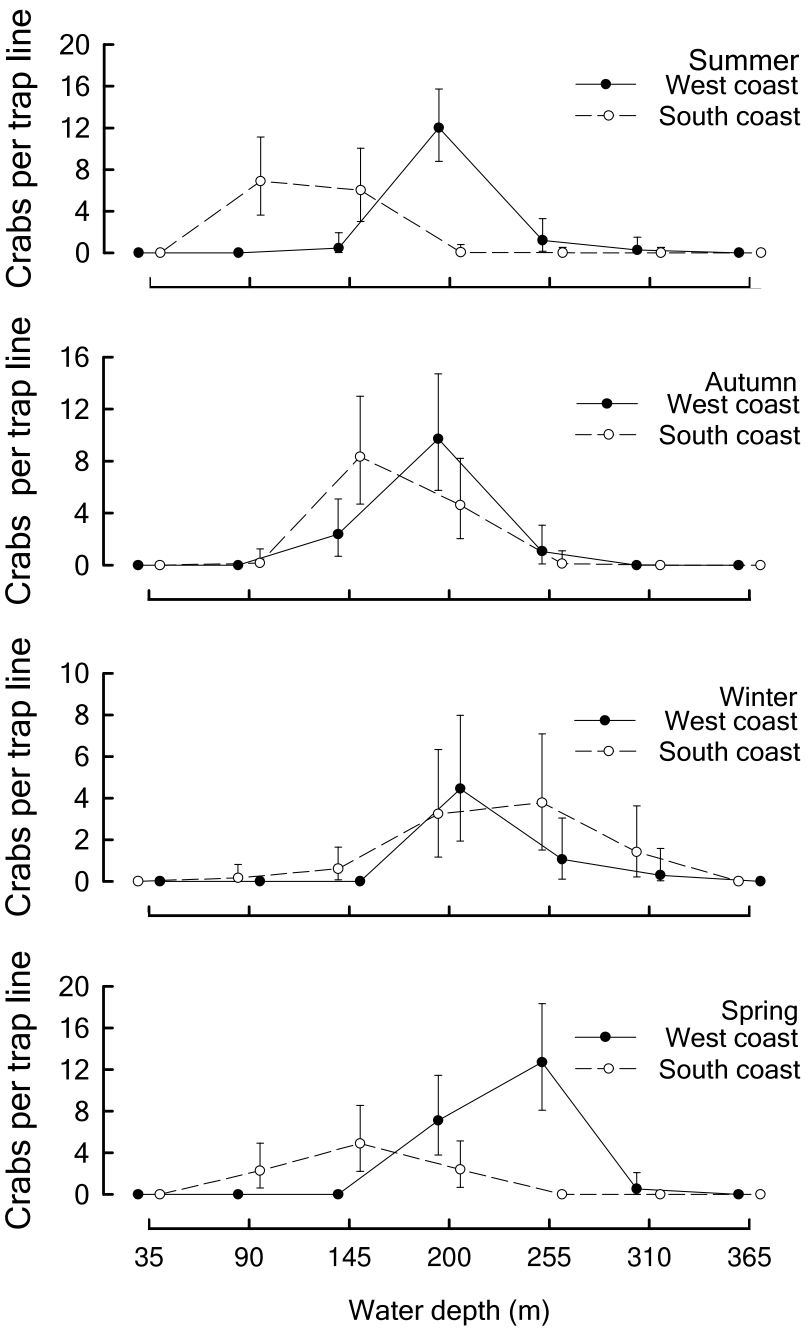


Figure 4.3 Mean numbers of *Hypothalassia acerba* ± 95% CIs caught in trap lines in different water depths off the lower west and south coasts of Western Australia in each season.

peaked at 90 or 145 m in summer, autumn and spring and at 255 m in winter. These differences explain the coast × depth × season interaction (**Table 4.1**).

Comparison of the fitted model with one that assumed a distribution of catch rates independent of temperature revealed that, on the south coast, catch rates were not significantly influenced by temperature (P>0.05). However, on the west coast, catch rates of champagne crabs were influenced markedly and significantly (P<0.001) by bottom water temperatures (**Figure 4.4**). While the value of the parameter *a* did not differ significantly from zero for either trap type on the latter coast (P>0.05), the mean temperatures of the 'normal distributions' fitted to the numbers of crabs caught using non-meshed and meshed traps, *i.e.* 17.1 and 16.1°C, respectively, differed significantly (P<0.01). Although the temperature distribution of the catches of the non-meshed traps on the south coast were not demonstrated to be significantly influenced by temperature, it should be noted that the mean temperature associated with the 'normal distribution' in the curve fitted to these catches was 16.4°C and did not differ significantly from that for non-meshed traps on the west coast (P>0.05). It is thus concluded that the mean temperature occupied by *H. acerba* of the size range caught by traps on both coasts lies between 16.1 and 17.1°C.

4.3.3 Relationship between carapace length and water depth, coast and season

The carapace lengths of male and female *H. acerba* caught during the study ranged from 50 to 135 mm and from 51 to 113 mm, respectively on the west coast and from 62 to 138 mm and from 69 to 120 mm, respectively, on the south coast (**Figure 4.5**). The size distribution of the females was skewed markedly to the left of males on the south coast but not on the west coast.

As the four-way interaction between the carapace lengths of crabs and sex, coast, depth and season was not significant ($P > 0.05$) in the ANCOVA to which these data were subjected, the analysis was repeated but excluding this interaction term. Season × depth × sex was the

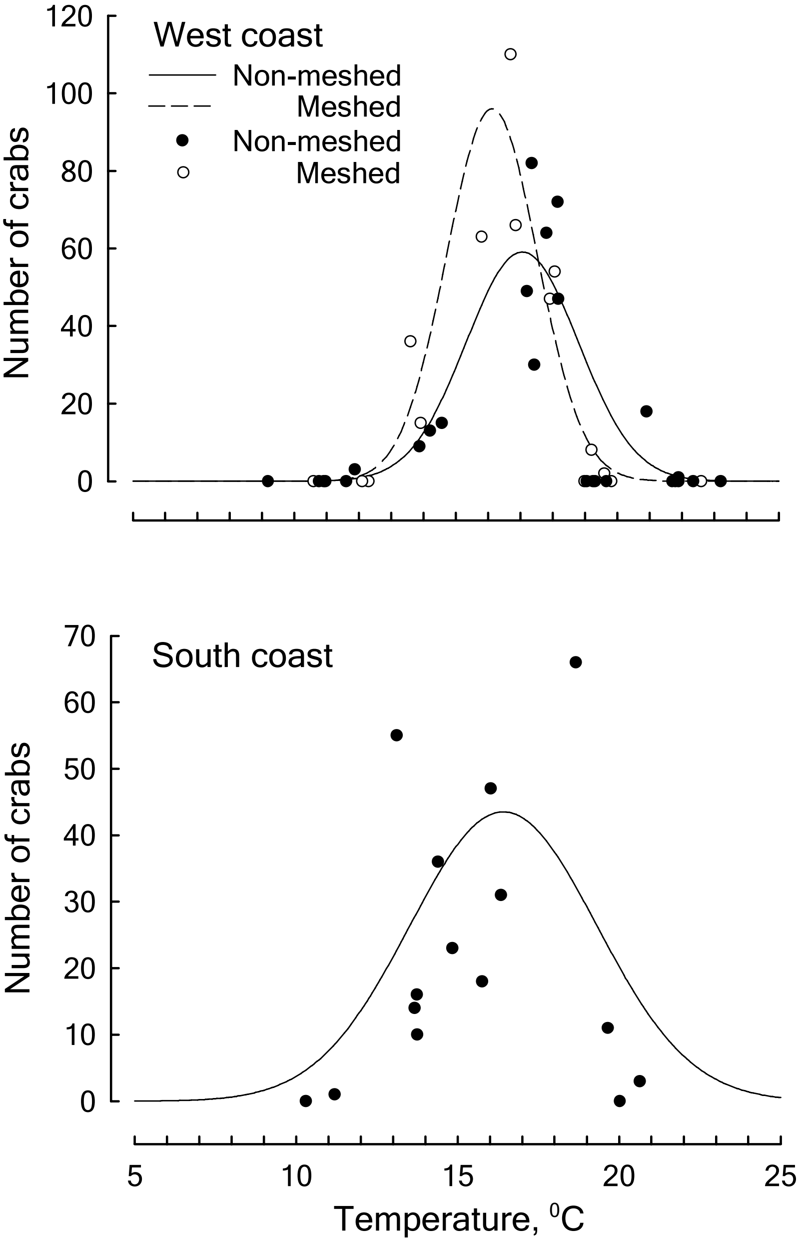
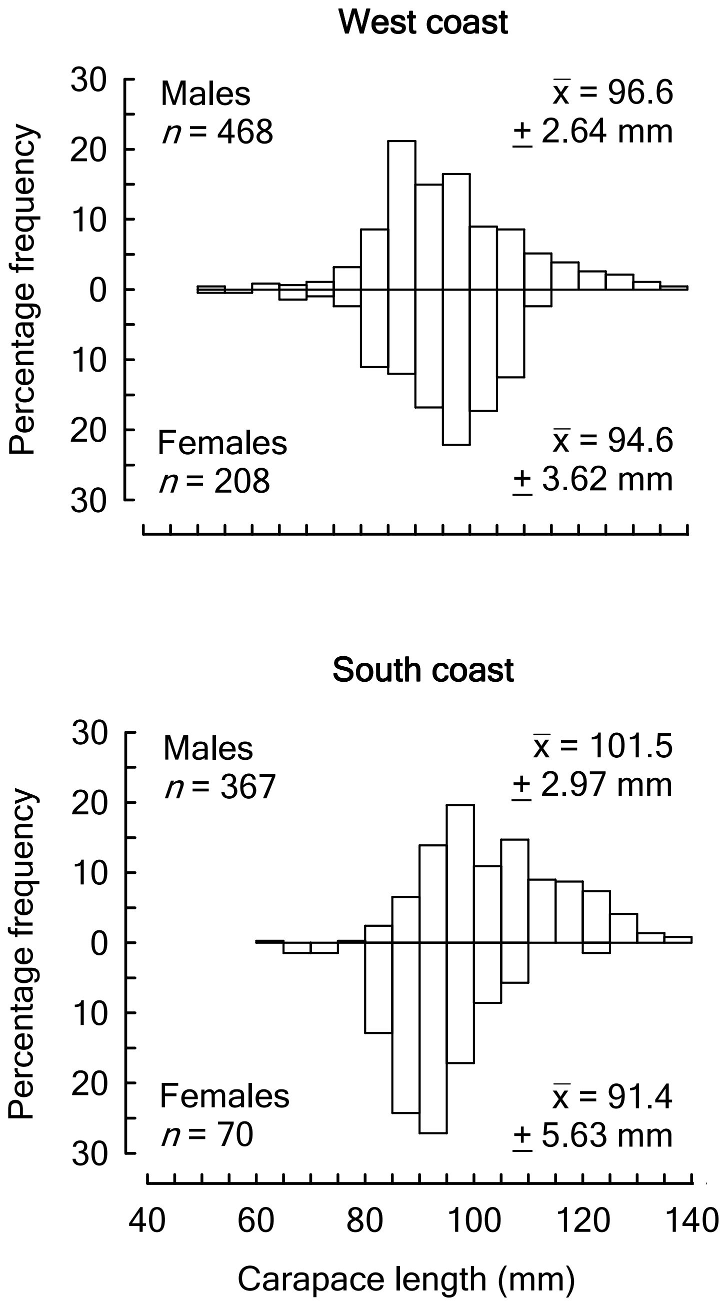


Figure 4.4 Distribution of numbers of champagne crabs caught at various bottom water temperatures in non-meshed and meshed traps off the lower west (above) and south (below) coasts of Western Australia.


West coast

South coast

Figure 4.5 Frequency distributions for the carapace lengths of male and female *Hypothalassia acerba* caught using non-meshed traps off the lower west and south coasts of Western Australia.

only three-way interaction term that was significant (*P* < 0.05). However, the value for the \BIC for this model, *i.e.* 5628, was greater than that for the model that excluded this three-way interaction term, *i.e.* 5616. Thus, this three-way interaction term was removed from the ANCOVA, together with non-significant two-way interaction terms.

Carapace length was significantly influenced by water depth and the relationship between these two variables did not exhibit a significant interaction with either sex, coast or season (**Table 4.2**). Thus, on average, the carapace length declined by 4 mm for every 100 m increase in water depth (**Figure 4.6a**). Sex × coast and coast × season were the only significant two-way interaction terms (**Table 4.2**). After adjustment of the data to a standard depth of 200 m, the mean carapace lengths of males and females were 96.6 and 94.6 mm, respectively, on the west coast, and 101.5 and 91.4 mm, respectively, on the south coast (**Figure 4.6b**), the latter difference being significant (*P* < 0.001). Although the mean carapace length of males on the south coast was significantly greater than that of males on the west coast (*P* < 0.001), no such significant difference was found between the mean carapace lengths of females on the two coasts (*P* > 0.05).

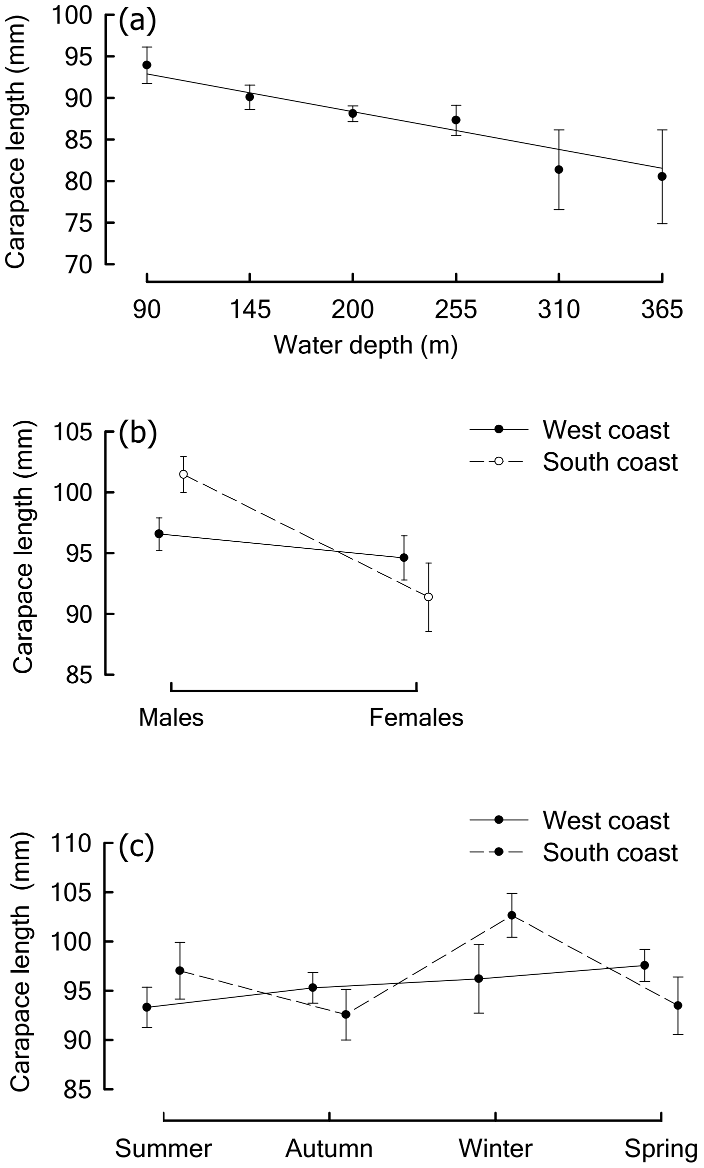


Figure 4.6 (a) Mean carapace lengths ± 95% CIs for *Hypothalassia acerba* caught in different water depths off Western Australia. The mean carapace lengths have been calculated after adjusting the data to represent the equivalent lengths that, after adjustment, would have been obtained for females on the south coast during spring. Mean carapace lengths ± 95% CIs of (b) male and female *H. acerba* caught off the lower west and south coasts of Western Australia and of (c) both sexes collectively off the lower west and south coasts of Western Australia in each season. The data in Figs 3.5b and 3.5c have been adjusted to a standard depth of 200 m.

Table 4.2 Mean squares and significance levels for ANCOVA of carapace lengths of female and male *Hypothalassia acerba* caught in the seven water depths sampled on the lower west and south coasts of Western Australia during the four seasons of the year. Depth was treated as a covariate. ****P*<0.001

	Mean squares	**d.f.**
Sex (S)	5906.0***	1
Coast (C)	82.0***	1
Depth (D)	2899.7***	1
Season (T)	882.4***	3
S × C	2684.4***	1
C × T	1251.4***	3
Residual	141.0	4

The mean carapace lengths of crabs caught during summer and winter off the south coast were greater than those of crabs caught during these corresponding seasons off the west coast, whereas the reverse pertained in autumn and spring (**Figure 4.6c**). During winter, the mean carapace length of crabs caught off the south coast was significantly greater than that of crabs caught during autumn and spring off that coast ($P < 0.001$).

4.3.4 Sex ratios

Males dominated the catches obtained from all water depths collectively in each season on both the west and south coasts (**Table 4.3**). However, in each season, the prevalence of males was not as great on the west coast as on the south coast, with the seasonal percentage contributions made by males to the catches of crabs in each season ranging from 64.8 to 76.9% on the west coast compared with 76.0 to 88.8% on the south coast. The overall percentages of males on the west and south coasts were 69.2 and 84.0%, respectively (**Table 4.3**).

Table 4.3. Percentage of females and males of *Hypothalassia acerba* caught in traps in each season and overall on the lower west coast and south coasts of Western Australia. *n* = number of crabs.

	West coast			**South coast**		
	Males %	Females %	*n*	Males %	Females %	*n*
Summer	76.9	23.1	143	87.2	12.8	102
Autumn	64.8	35.2	233	79.0	21.0	100
Winter	70.2	29.8	47	88.8	11.2	160
Spring	68.8	31.2	263	76.0	24.0	75
Overall	69.2	30.8	676	84.0	16.0	437

4.3.5 Results of enclosing traps with mesh

On the two occasions when crabs were caught in non-meshed and meshed traps, the mean carapace length of both male and female crabs obtained using meshed traps was significantly different ($P < 0.05$) from that of the corresponding sex collected using the same type of trap but without mesh (**Figure 4.7**). However, the differences in the mean carapace lengths of the crabs caught in meshed and non-meshed traps differed by only between 3.9 and 6.9 mm in each of the four comparisons. Furthermore, the number of crabs that were caught with carapace lengths of less than 75 mm still remained low.

4.4 DISCUSSION

4.4.1 Relationship between catch rates and water depth

The sampling regime used in this study was designed to collect *Hypothalassia acerba* from the range of water depths in which preliminary studies had indicated that this species occurred on the lower west and south coasts of Western Australia. Furthermore, particular attention was paid to ensuring that the seven sampling sites were aligned perpendicular to the shoreline and were located sequentially at even depth intervals of 55 m from the shallowest site at 35 m to

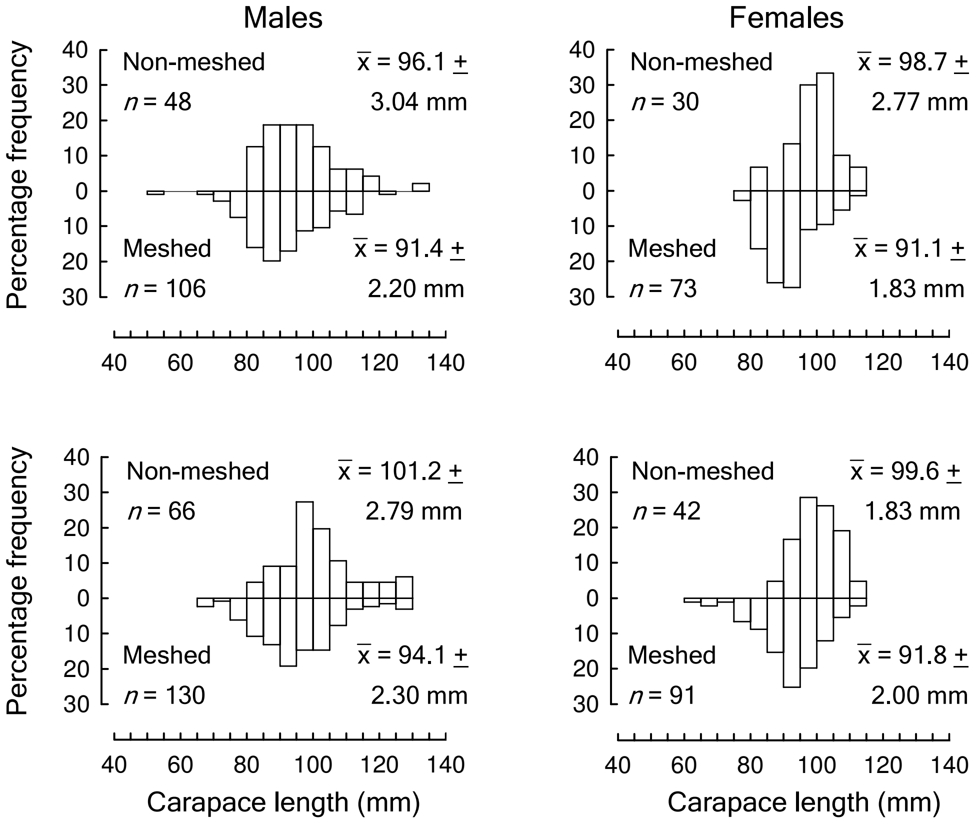


Figure 4.7. Frequency distributions for the carapace lengths of male and female *Hypothalassia acerba* caught off the lower west and south coasts of Western Australia using meshed and non-meshed traps in May (top) and November (bottom). Sample sizes (*n*) and mean ± 95% CIs are given on Figure.

the deepest site at 365 m. The sampling of seven sites (water depths) on both coasts in each season thus produced results that enabled conclusions to be drawn regarding aspects of the spatial and size distributions and sex ratios of *H. acerba.* This species of deep-sea crab was not caught in the shallowest depth and was rarely caught in the deepest waters in any season on either coast, and the catch rates at the intermediate depths rose progressively and then declined sequentially. This demonstrates that our sampling regime essentially encompassed the full range of depths at which at least all but the smaller members of this species occur in the sites sampled. Furthermore, the depths at which *H. acerba* were predominantly caught on both the west and south coasts are entirely consistent with those in which commercial fishers obtained their catches (R. Melville Smith, Department of Fisheries W.A., pers. comm.). The very strong relationship between catch rate and water depth is further illustrated by our finding that, in the case of the most abundant sex, *i.e.* males, the catches peaked sharply at 200 m on the west coast and at 145 m on the south coast. Furthermore, the catches of males at 200 and 255 m collectively on the west coast and at 90, 145 and 200 m collectively on the south coast contributed 90 and 92%, respectively, to the total catches of this sex on these two coasts. Although the females of *H. acerba* were less abundant than their males on both the west and south coasts, our data still clearly demonstrate that the trends exhibited by the abundance of females with water depth were the same as those for males on both coasts. Thus, the catches of females likewise peaked at 200 m on the west coast and at 145 m on the south coast. The presence of the same pattern of distribution of the two sexes of *H. acerba* in all seasons contrasts with the situation with certain other deep-sea crabs species in which, when unpaired, the sexes tend to occupy different water depths (Beyers and Wilkie, 1980; Melville Smith, 1987; Lockhart *et al.,* 1990; Defeo *et al.,* 1991). For example, the females of *Geryon maritae, Chaceon fenneri, Chaceon notialis,* and *Chionoecetes opilio* were relatively more prevalent than males in shallower waters (Melville Smith, 1987, 1988; Lockhart *et al.,* 1990; Defeo *et al.,* 1991).

Comparisons of our results with those for other species of deep-sea crabs suggest that *H. acerba* is restricted to a particularly narrow range of water depths for such species. For example, *Chaceon notialis* was caught in water depths of 300 to 900 m in the Argentinian–Uruguayan fishing zone and, in summer, the catch per unit of effort (CPUE) was still increasing at the upper end of this range in water depths (Defeo *et al.,* 1991). Although the catch rates of *Chaceon affinis* peaked at 800-900 m water depth, this species was caught in water depths of 500 to 1200 m and, from the data presented, presumably well beyond that latter depth (López Abellán *et al.,* 2002). *Geryon quinquedens* and *Geryon maritae* are also found in a wide range of water depths, *i.e.* from 275 to 1000 m off southern New England and from 270 to 924 m off Namibia (Lux *et al.,* 1982; Melville Smith and Bailey, 1989).

Since *H. acerba* appears to be largely restricted to water depths within the relatively narrow ranges of 145 to 310 m on the west coast and of 90 to 200 m on the south coast, it is relevant that other major large benthic crustaceans in this region are most abundant in water depths to either side of those in which *H. acerba* occurs. Thus, on the west coast, the western rock lobster *P. cygnis* is most common in depths up to 90 m (George, 1962), while off the south coast the southern rock lobster *J. edwardsii* is also most frequently caught in waters less than 90 m (Department of Fisheries, Western Australia, Catch and Effort Statistics, unpublished data). The crystal crab *Chaceon bicolor* is most abundant in depths exceeding 600 m on the west coast and 500 m on the south coast (K. Smith and R. Melville Smith, unpublished data), where our unpublished sediment analyses showed that the silt/clay fraction in the substrate was far greater than in the shallower waters where the champagne crab is found, *i.e.* 32 vs 5%. Furthermore, on the south coast, *P. gigas* also occurs mainly in water depths that, from Levings *et al.,* (1996, 2001) and Gardner (1996), lie at the upper end of the range of that in which *H. acerba* lives. The distribution patterns of these decapod species thus provide evidence of spatial partitioning among these major components of the benthic communities on the two coasts, thereby parallelling the type of partial partitioning by depth exhibited by *Chaceon fenneri* and *Chaceon quinquedens* in the Gulf of Mexico (Lockhart *et al.,* 1990).

4.4.2 Relationship between catch rates and water temperature

Since the density of *H. acerba* is related to water depth on both the west and south coasts and water temperature decreases with increasing water depth, it seems highly likely that the relative abundance of this species will also be influenced by water temperature. Such a conclusion is consistent with the fact that, while the overall catches of *H. acerba* peaked at a shallower water depth on the south coast (145 m) than lower west coast (200 m), those peaks in abundance corresponded to a similar water temperature, *i.e.* ~16.1-17.1ºC. Thus, by typically occurring in a shallower water depth on the south coast, *H. acerba* is located in the same temperature as would be the case on the west coast. It is thus not surprising that the distribution of catch rate of *H. acerba* by depth on the two coasts was most similar in winter when the water temperatures at the corresponding depths on the two coasts were most similar.

Although *H. acerba* was caught in water temperatures ranging from 11.9 to 21.9°C on the west coast and from 11.2 to 20.6°C on the south coast, over 85% of the individuals of this species were caught in temperatures of 15.8 to 18.2°C on the west coast and over 95% were collected at temperatures between 13.1 and 18.7ºC on the south coast. Furthermore, the water temperature at which the catches of *H. acerba* peak lies between 16.1 and 17.1°C on both coasts, which is ~6 to 10°C higher than those recorded for five *Chaceon* species, which live in deeper water (see Hastie, 1995).

4.4.3 Trap selectivity

Our failure to catch small *H. acerba* in traps parallels the situation recorded for several other species of decapod (Melville Smith, 1986; Miller, 1990). Furthermore, the mean size of crabs caught by the rectangular traps was only slightly reduced when these traps were enclosed in aviary mesh. This may reflect either trap shyness by small *H. acerba* or their exclusion from traps through the aggression of larger individuals or possibly their occupation of different water depths. The greater prevalence of males than females in our catches, and those of commercial fishers operating over a wide geographical area (K. Smith, unpublished data) may reflect females being less vulnerable to traps, as is the case in some other species of decapod (see Miller, 1990). Furthermore, the fact that only seven ovigerous *H. acerba* were caught during the present study, which is again consistent with the results for some other decapod species (Miller, 1990) and presumably reflects a tendency for the berried females of this species not to enter traps, also helps account for the predominance of males in our catches of *H. acerba.*

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5.0 COMPARISONS BETWEEN THE REPRODUCTIVE BIOLOGY OF FEMALES OF TWO SPECIES OF DEEP SEA CRABS WHICH LIVE IN DIFFERENT WATER DEPTHS

5.1 INTRODUCTION

Three species of deep-sea crab are fished commercially in Western Australian waters, namely the champagne crab *Hypothalasia acerba* Koh and Ng, the crystal crab *Chaceon bicolor* Manning and Holthuis and the king crab *Pseudocarcinus gigas* Lamarck (Anon., 2002). On the basis of catches obtained by commercial fishers, the distribution of *H. acerba* ranges from a latitude at least as far north as about 27ºS on the west coast, southwards and then eastwards along the south coast to a longitude of at least 129ºE (Anon., 2002). Although *C. bicolor* occurs in the same geographical region as *H. acerba*, its distribution in Western Australia extends further north to a latitude of about 22ºS (MelvilleSmith *et al.,* in press). In contrast, the distribution of *P. gigas* is essentially restricted to the south coast in Western Australia and extends eastwards across the full length of Australia, including Tasmania, and then northwards on the east coast to about 31ºS (Kailola *et al.,* 1993, Gardner, 1998).

Recent depth-stratified sampling off the south-western Australian coast has demonstrated that *H. acerba* occurs predominantly in waters where temperatures lie between 13 and 20ºC and the depths range from 200 to 255 m on the lower west coast and from 90 to 200 m on the south coast (Smith *et al.,* 2004a). Temperatures recorded during commercial fishing for *C. bicolor* show that, on the lower west coast of Australia, this species typically occurs in waters of 4 to 6.5ºC (K. Smith unpublished data) and at water depths of 450 to 1220 m (Melville Smith *et al.,* in press) and is thus located further offshore than *H. acerba*. *Pseudocarcinus gigas* is found in waters of 11 to 17ºC and at depths of 120 to 340 m (Levings *et al.,* 1996).

The commercial fisheries for *H. acerba* and *C. bicolor* in Western Australia started to develop during the late 1990s (Anon., 2002). However, in contrast to the situation with *P. gigas* (see Levings *et al.,* 1996, 2001; Gardner, 1997, Gardner and Williams, 2002), no biological studies have been conducted on the spawning period and location and fecundity of either of these two species.

The stages in development of the ovaries of several species of deep-sea crabs belonging to the Geryonidae, *e.g. Chaceon quinquedens* (Smith), *Chaceon maritae* (Manning & Holthuis) and *Chaceon affinis* (Milne Edwards & Bouvier), have been described on the basis of their macroscopic appearance and, in some cases, also on the stages of maturation of their oocytes as determined from histological sections (Haefner, 1977, Melville Smith, 1987a, Fernández-Vergas *et al.,* 2000, López Abellán *et al.,* 2002). No such combined macroscopical and histological studies have been carried out on any deep-sea species of the Eriiphidae, the family to which *H. acerba* belongs. Although some deep-sea crab species, such as *Chaceon fenneri* (Manning & Holthuis), have an annual reproductive cycle (see Hastie, 1995), no clear seasonal fluctuations in reproductive patterns were detected with *C. maritae* (Melville Smith, 1987a) and *C. quinquedens* (Wigley *et al.,* 1975, Haefner, 1978). It was proposed by Melville Smith (1987a) that the lack of a distinct reproductive cycle in *C. maritae* was attributable to the absence, in the deep waters in which this species is found, of changes in day length and temperature and other potential environmental reproductive triggers.

The aims of the present study were as follows. (1) Describe, on the basis of their macroscopic appearance, the sequential stages in the development of the ovaries of *H. acerba* and use histological sections to determine the stages of maturation of the oocytes in ovaries at each of those stages. Attention was paid to elucidating whether the criteria developed for categorizing the ovarian stages of *H. acerba* were the same as those we developed concomitantly for *C. bicolor* and those described for other species of deep-sea crab. (2) Use the trends exhibited throughout the year by the monthly prevalences of female crabs with ovaries at different stages in development and of females bearing either eggs or egg remnants, together with those of the mean monthly gonad weights of females, to determine the timing of reproduction in these two species. Particular emphasis is placed on testing the hypothesis that, as *H. acerba* lives in far shallower waters than *C. bicolor*, and thus lives in an environment which undergoes a greater degree of seasonal change and particularly in water temperature, it is far more likely to reproduce seasonally. (3) Determine the fecundities of *H. acerba* and *C. bicolor* and their relationships to the body size and body weight of these species. (4) Establish whether aspects of the reproductive biology of *H. acerba* on the lower west and southern coasts of Western Australia exhibit similar patterns. Since preliminary analyses indicated that *H. acerba* invests less in gonadal development on the south than west coasts, we examined whether the relative ovarian weights and diameters of the mature oocytes of females on the two coasts differed.

5.2 MATERIALS AND METHODS

5.2.1 Collection of samples

The reader is referred to Chapter 2 for details of the depth-related sampling regime and the onboard sampling which together yielded the *H. acerba* and *C. bicolor* used for the present study.

5.2.2 Laboratory processing

The reader is referred to Chapter 2 for description of measurements made on *H. acerba* and *C. bicolor* and the criteria used to designate female crabs as either immature or mature.

The ovary of each female was removed and allocated to a numerical developmental stage on the basis of macroscopic criteria (see Results). The stages in development of the testes and vas deferentia were recorded during another study aimed at determining the size at maturity of the males of these two species (Chapter 7).

The ovary of each female of *H. acerba* and *C. bicolor* was weighed to the nearest 0.1 g. The mean monthly ovarian weights (± 95% CIs) at standardised carapace lengths were determined for *H. acerba* on the lower west and south coasts and for *C. bicolor* on the former coast using analysis of covariance (ANCOVA) of the natural logarithm of the gonad weight as the dependant variable, month as a fixed factor and the natural logarithm of the carapace length as a covariate. Note that the standardised carapace length was calculated separately for the lower west and south coast assemblages of *H. acerba* and the lower west coast assemblage of *C. bicolor*. These constant carapace lengths were a default value calculated by the ANCOVA. ANCOVA was also used in the above manner to calculate the mean gonad weight (± 95% CIs) for *H. acerba* with ovaries containing previtellogenic, early vitellogenic and late vitellogenic oocytes on the lower west and south coasts. The standardised carapace length was calculated separately for each of these three developmental stages, but was common for a given stage on the two coasts. Data for the small individuals that were considered not to have mated were not used when calculating the monthly prevalences of females with ovaries at different stages in development, the mean monthly gonad weights for females at a standardized carapace length, and the mean gonad weights for west and south coast *H. acerba* with ovaries at different stages in development (see **Figures 5.2-5.5** in Results).

The method of Melville Smith (1987a) was used for determining the batch fecundity of *H. acerba* and *C. bicolor*. Thus, alternate pleopods were removed from the abdomen of each ovigerous female and soaked for 1 to 4 h in 0.5 M NaOH to facilitate the separation of eggs from the pleopod setae. All of the eggs removed from each crab were pooled, oven dried at 70°C for 24 h and then weighed to the nearest 0.001 g. Subsamples of ca. 0.1 g of eggs (= ca. 300 eggs) were then weighed and counted, and the average weight of a single egg in each subsample was calculated. When estimates of the weight of a single egg in three subsamples differed by less than 5%, the mean of those weight estimates was then used, in conjunction with twice the weight of all eggs removed, to estimate the fecundity of the crab.

The right posterior side of the ovary was removed from up to 20 females of both species in each season, ensuring that these subsamples covered the full size range of those species in the total catch in each season. The ovarian material was fixed in 4% glutaraldehyde in a 0.025 M phosphate buffer solution (pH 7.0), dehydrated in a series of increasing concentrations of ethanols, embedded in paraffin wax, sectioned transversely at 6 μm and stained with Mallory's trichrome. The ovarian material was fixed in glutaraldehyde since it was not fixed well by traditional fixatives used for light microscopy such as Bouin's and 10% formalin. The smallest and largest diameters of oocytes of *H. acerba* and *C. bicolor* at different developmental stages sectioned through their nuclei were measured to the nearest 5 μm. The smallest and largest diameters of each oocyte were then averaged.

In addition to the above laboratory processing of crabs, the senior author also recorded, when on board fishing vessels, the total number of mature female crabs caught and the percentage of both ovigerous females and of females with egg remnants attached to their pleopods. Note that, due to inclement weather, the commercial fisher with whom we mainly worked did not operate in September in the deep waters off the lower west coast of Australia where *C. bicolor* is found and thus there are no data on the above variables for that month.

5.3 RESULTS

5.3.1 Ovarian maturation stages

On the basis of their macroscopic appearance, the ovaries of the females of *Hypothalassia acerba* and *Chaceon bicolor* each followed essentially the same pattern of development (**Table 5.1**). Thus, for both species, six sequential stages were recognised (**Table 5.1; Figure 5.1**). As

Table 5.1. Macroscopic and microscopic characteristics of sequential stages in ovarian development of *Hypothalassia acerba* and *Chaceon bicolor*. Range in oocyte diameters at each stage of development are provided. Scheme has been adapted from that of Haefner (1977).

Ovarian stage	**Macroscopic description**	**Histological description**
Stage I Virgin/immature resting	Ovaries small but generally visible macroscopically, thin and 'H' shaped. (Shape is maintained for all latter stages except stage IV). Oocytes not visible through ovarian wall. Colour varies from pale grey to ivory.	Ovaries contain oogonia and small previtellogenic oocytes (chromatin nucelolar and perinucleolar oocytes). Connective tissue and oocytes stain blue with Mallory's trichrome. For *H. acerba*, oogonia 5-10 µm and small previtellogenic oocytes 10-60 µm. For *C. bicolor*, oogonia 5- 10 µm and small previtellogenic oocytes 10-70 µm.
Stage II Developing	Ovaries always visible macroscopically, larger than stage I and slightly dorso-ventrally compressed. Ovaries beginning to displace hepatopancreas. Oocytes not visible through ovarian wall. Colour varies from ivory to white.	Ovaries contain all oocyte stages present in stage I together with cortical alveolar oocytes. Cortical alveolar oocytes 60-200 µm in *H. acerba*, 70-210 µm in *C. bicolor*. Cortical alveolar oocytes stain blue with Mallory's trichrome, except for their lipid droplets and nucleolei, which stain dark red.
Stage III Maturing	Ovaries larger than at stage II and outer membrane has wrinkled appearance. Oocytes not visible through ovarian wall. Ovaries are pale pink in *H. acerba* while range from very pale yellow to yellowish orange in *C. bicolor*.	Large numbers of early yolk granule oocytes present. Yolk granules in peripheral region of oocyte cytoplasm. Yolk granules stain orange with Mallory's trichrome and are larger than lipid droplets. For *H. acerba,* yolk granule oocytes are 160 – 270 µm and for *C. bicolor* are 140-390 µm.
Stage IV Mature	Ovaries larger than at stage III and consequently are no longer 'H-shaped'. Ovarian wall more folded. Oocytes visible through ovarian wall. Ovaries pink to red in *H. acerba* and brown to purple in *C. bicolor.*	Large numbers of late yolk granule oocytes. Yolk granules distributed throughout cytoplasm. For *H. acerba* yolk granule oocytes are 200- 480 µm and for *C. bicolor* 350-560 µm.
Stage V Recently spent	Ovaries similar in appearance to stage II, but more flaccid and yellowish-grey in colour.	Ovary contains mainly connective tissue. Some yolk granule oocytes present undergoing atresia.
Stage VI Spent-recovering	Same as stage V.	Ovaries comprise mainly connective tissue and numerous small previtellogenic oocytes.

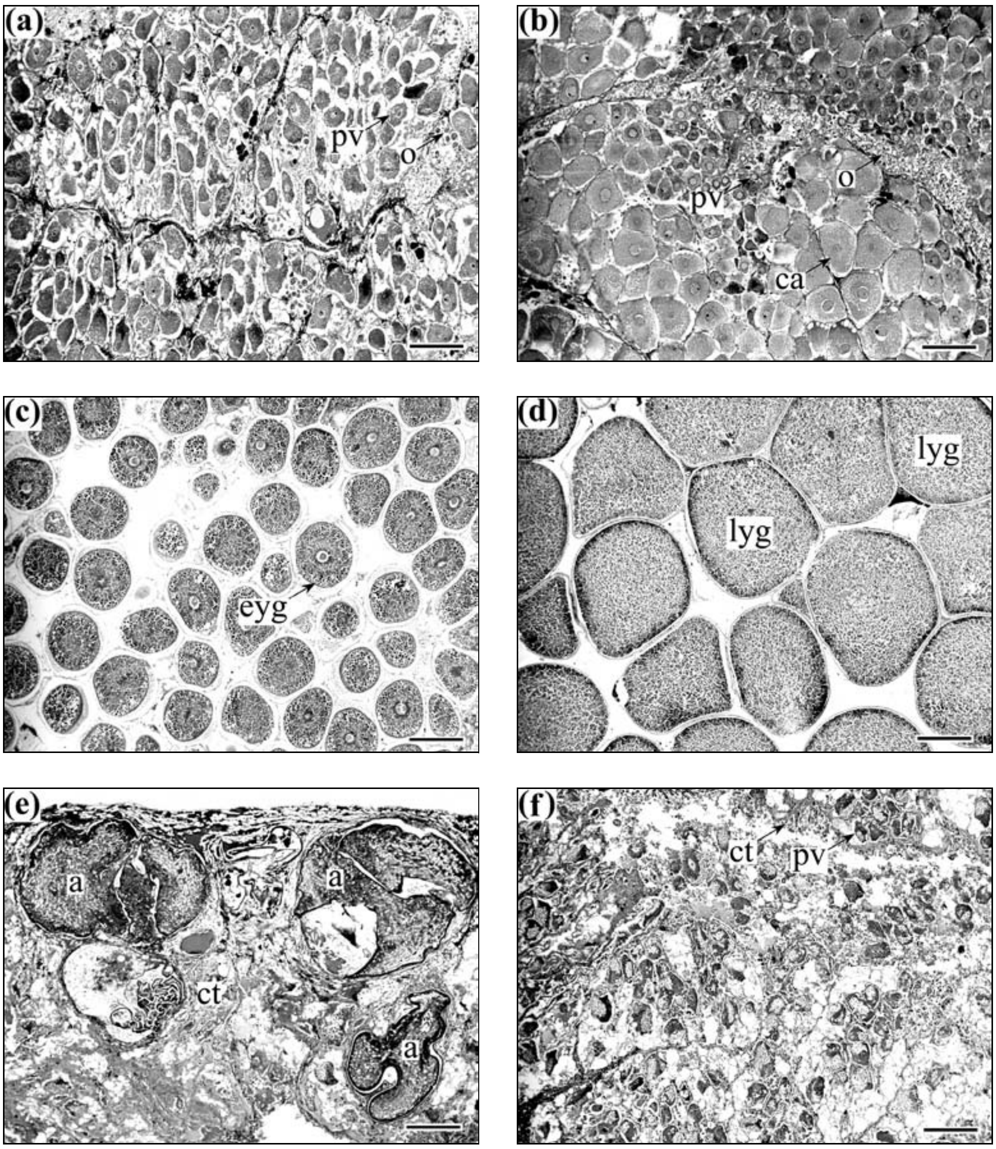

Figure 5.1. Histological sections of ovaries of *H. acerba* at (a) stage I, (b) stage II, (c) stage III, (d) stage IV, (e) stage V (recently-spent) and (f) stage VI spent-recovering. a, atretic oocyte; ca, cortical alveolar oocyte; ct, connective tissue; eyg, early yolk granule; o, oogonia; lyg, late yolk granule; pv, pre vitellogenic oocyte. Scale bar = 200 µm.

they progress from stages I to IV, the ovaries increase progressively in size and change colour (**Figures 5.1a-d**). However, the colours of the ovaries of the two species at stages III and IV differ. In both species, ovaries at stages V and VI are flaccid and could not be separated macroscopically.

At a histological level, cortical alveolar oocytes first appeared in stage II ovaries of *H. acerba* (**Figures 5.1a,b**), and the presence of early and late yolk granule oocytes characterised stage III (**Figure 5.1c**) and IV ovaries (**Figure 5.1d**), respectively. Ovaries of recently-spent females (stage V) of *H. acerba* contained some atretic oocytes (**Figure 5.1e**), while those of spent-recovering (stage VI) females possessed no such oocytes but did contain numerous early previtellogenic ooctytes (**Figure 1f**). The histological characteristics of the ovaries of *C. bicolor* are essentially the same as those shown for *H. acerba* in **Figures 5.1a-f**. However, the mean diameters of the mature oocytes, as measured in stage IV ovaries, are significantly greater ($P < 0.001$) for *C. bicolor* than *H. acerba.*

Comparisons of the macroscopic and microscopic characteristics of our ovarian stages for *H. acerba* and *C. bicolor* with those of Haefner (1977) demonstrate that the ovaries of the former two species undergo the same pattern of development as *Chaceon quinquedens*. However, the maximum diameter of the oocytes in our stage I (70 μm) is far less than that recorded by Haefner (1977) for his first stage for *C. quinquedens* (172 μm) and yolk granule oocytes are already present in his stage II whereas they do not appear until stage III of our categorization for *H. acerba* and *C. bicolor*. In essence, Haefner (1977) did not recognise the presence of the early stage we have termed virgin/immature resting. However, that stage was recognised by de Lestang *et al.* (2003) in their description of ovarian development in *Portunus pelagicus* (Linnaeus) in inshore waters in Western Australia. Furthermore, unlike the study of Haefner (1977), our histological staging criteria distinguish recently-spent ovaries from spent-recovering ovaries, which is useful for obtaining an idea of how recently ovulation had occurred.

5.3.2 Monthly trends in reproductive indices

On the lower west coast, the prevalence of female *H. acerba* with ovaries containing late vitellogenic oocytes was greatest in September to February, during which months their contributions ranged from 58 to 76%, and was least in March to June when their monthly contributions ranged from 11 to 50% (**Figure 5.2a**). The prevalence of female crabs with ovaries containing only previtellogenic oocytes was less than 12% in each month from September to February and in April and only exceeded 30% in March and August. Small numbers of spent females were collected between January and March and in May. The mean monthly gonad weight of *H. acerba*, standardized to a constant carapace length of 94.7 mm, rose progressively from 11.5 g in July to between 25.2 and 28.6 g in October to December and then declined sequentially to between 4.9 and 8.3 g in March to May (**Figure 5.2b**). The prevalence of female *H. acerba* bearing egg remnants declined sequentially from 12% in July to zero or close to zero in October to January before rising progressively to 21% in May. Small numbers of ovigerous females were caught in February, March and May (**Figure 5.2c**) and a commercial fisher provided six ovigerous females and two females with egg remnants which he had caught in January 2000.

On the south coast, the prevalence of female *H. acerba* containing late vitellogenic oocytes and the mean monthly gonad weights, standardized to a common carapace length of 95.2 mm, peaked in September (**Figures 5.3a-b**). The prevalence of *H. acerba* with ovaries containing late vitellogenic oocytes never exceeded 47% in any month other than September and the prevalence of ovaries with previtellogenic oocytes exceeded 50% in five months

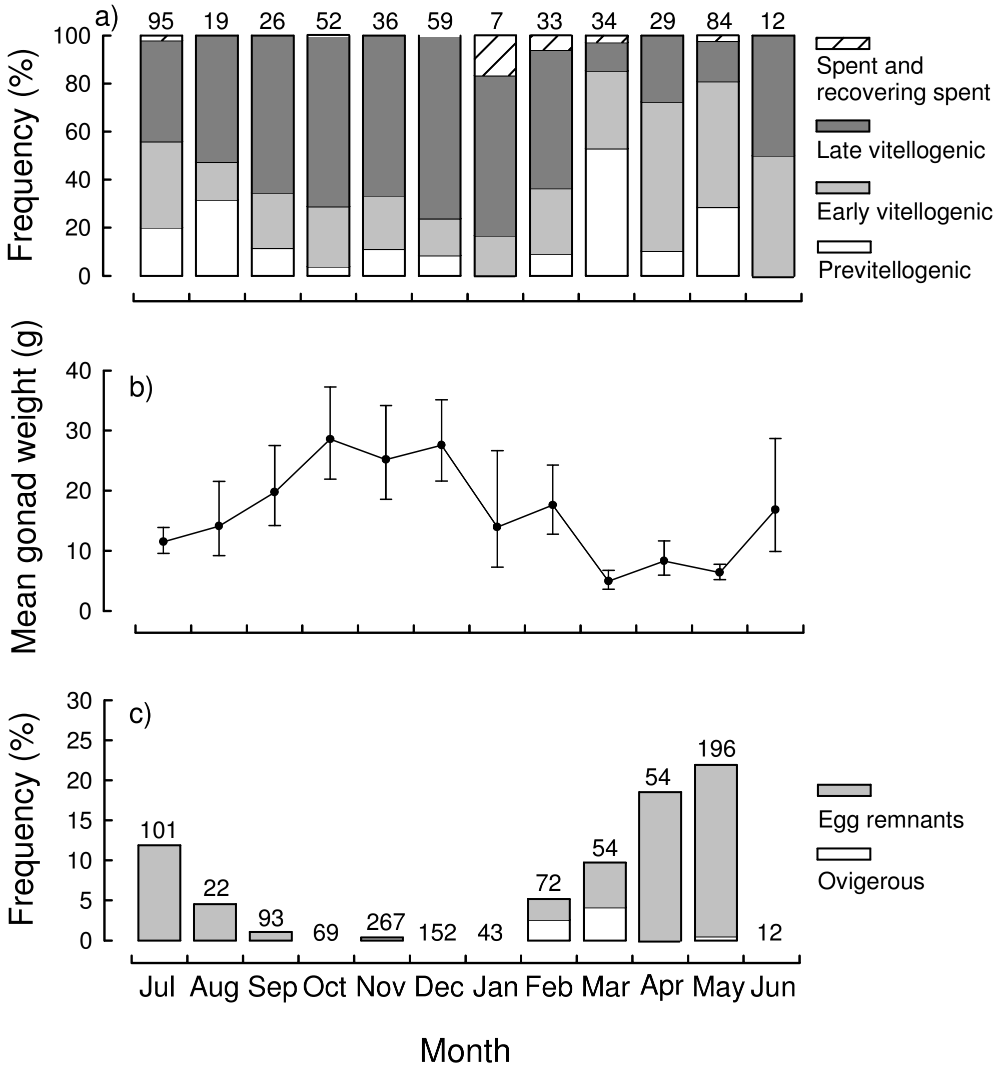

Figure 5.2. Monthly data for female *Hypothalassia acerba* on lower west coast of Australia. (a) Frequency of occurrence of crabs at different stages of development, (b) mean gonad weights ± 95 CIs standardised to a constant carapace length of 94.7 mm, as selected by ANCOVA and (c) frequency of occurrence of crabs with eggs and egg remnants. In this Fig. and Figs 3 and 4, the sample sizes for each month in (b) are the same as those given in (a).

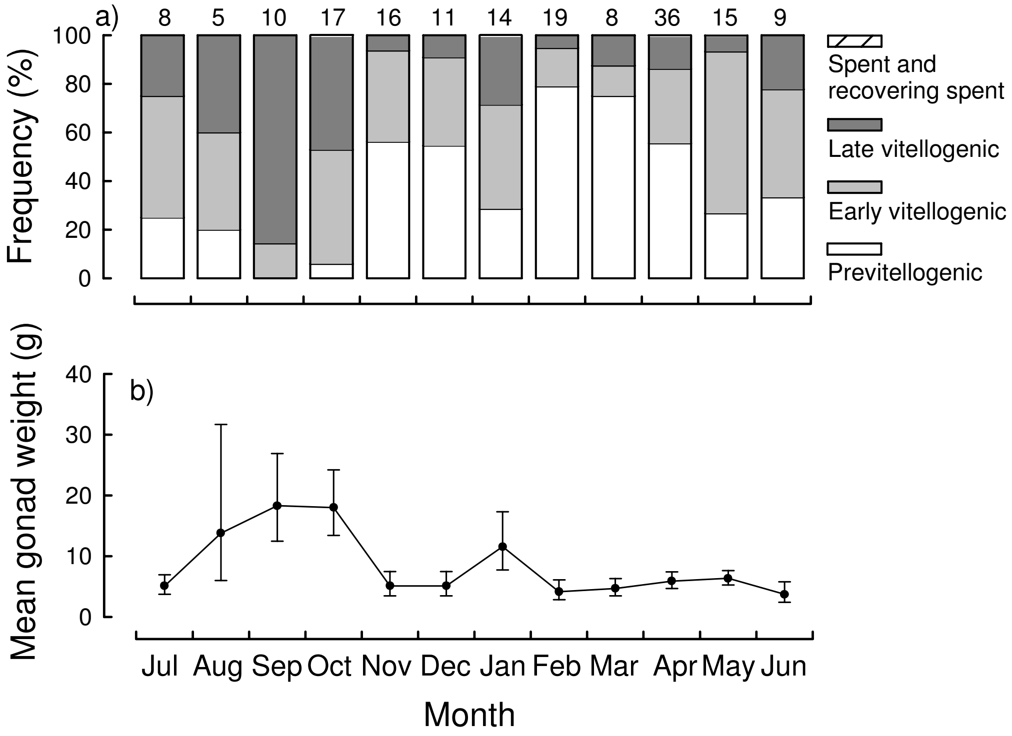

Figure 5.3. Monthly data for female *Hypothalassia acerba* on the south coast of Australia. (a) Frequency of occurrence of crabs at different stages of development and (b) mean gonad weights ± 95 CIs standardised to a constant carapace length of 95.2 mm, as selected by ANCOVA.

(**Figure 5.3a**). Samples from the south coast yielded no ovigerous females and only two females bearing egg remnants, both of which were caught in August.

The prevalences of females of *C. bicolor* with ovaries containing late vitellogenic oocytes were greater in July to December than in January to April and in June (**Figure 5.4a**). The mean monthly gonad weights, standardized to a constant carapace length of 110.0 mm, peaked at 42.2 g in September and 43.1 g in December before declining to 11.6 g in February, increasing to 37.1 g in May and then declining to 8.8 g in June (**Figure 5.4b**). Ovigerous females were caught in each of the 11 calendar months in which samples were obtained and females bearing egg remnants were found in six of those months (**Figure 5.4c**).

The mean gonad weight ± 95% CIs, standardized to a constant carapace length, did not differ significantly ($P > 0.05$) between the assemblages on the lower west and south coasts when the females contained ovaries with either previtellogenic or early vitellogenic eggs (**Figure 5.5**). In contrast, the mean gonad weight ± 95% CIs for females of *H. acerba* with ovaries containing late vitellogenic oocytes was significantly greater ($P < 0.001$) for the assemblage on the lower west coast, 26.4 ± 1.71 g, than that on the south coast, 16.0 ± 1.85 g (**Figure 5.5**).

The relationships between gonad weight (W) and carapace length (CL) of west coast and south coast females of *H. acerba* with ovaries containing late vitellogenic oocytes (**Figure 5.6**) are described by the following equations.

West coast: $\ln(W) = 2.561\ln(CL) - 8.130$; $P < 0.001$, $R^2 = 0.240$, $n = 228$

South coast: $\ln(W) = 6.430\ln(CL) - 26.311$; $P < 0.001$, $R^2 = 0.442$, $n = 34$

Although none of the females of *H. acerba* from the south coast, which had CLs < 90 mm, contained ovaries with late vitellogenic oocytes, many females of *H. acerba* from the lower west coast with CLs of 75 to 90 mm possessed ovaries with oocytes at this advanced stage. The use of ANCOVA demonstrated that, in the case of *H. acerba* for a standardized

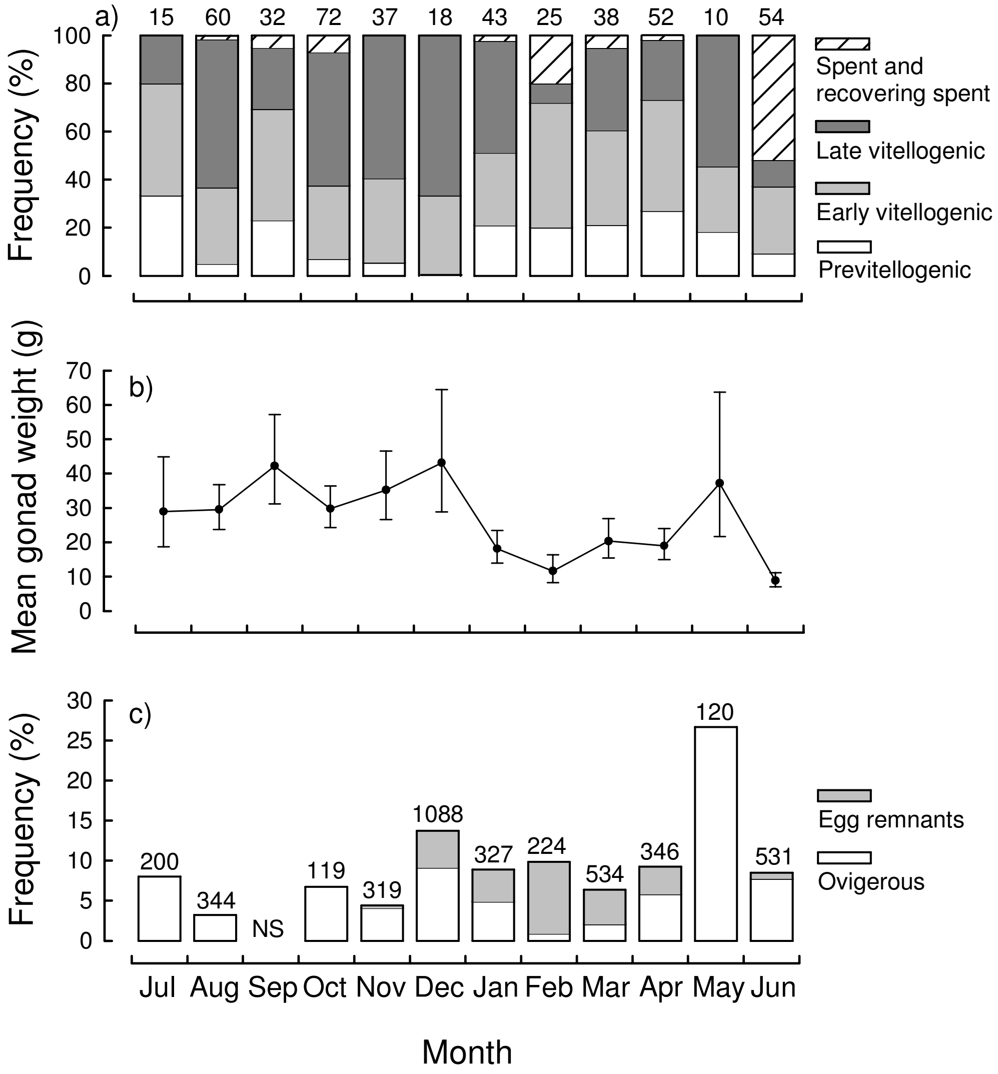

Figure 5.4. Monthly data for female *Chaecon acerba* on the lower west coast of Australia. (a) Frequency of occurrence of crabs at different stages of development and (b) mean gonad weights ± 95% CIs standardised to a constant carapace length of 110.0 mm, as selected by ANCOVA and (c) frequency of occurrence of crabs with eggs and egg remnants.

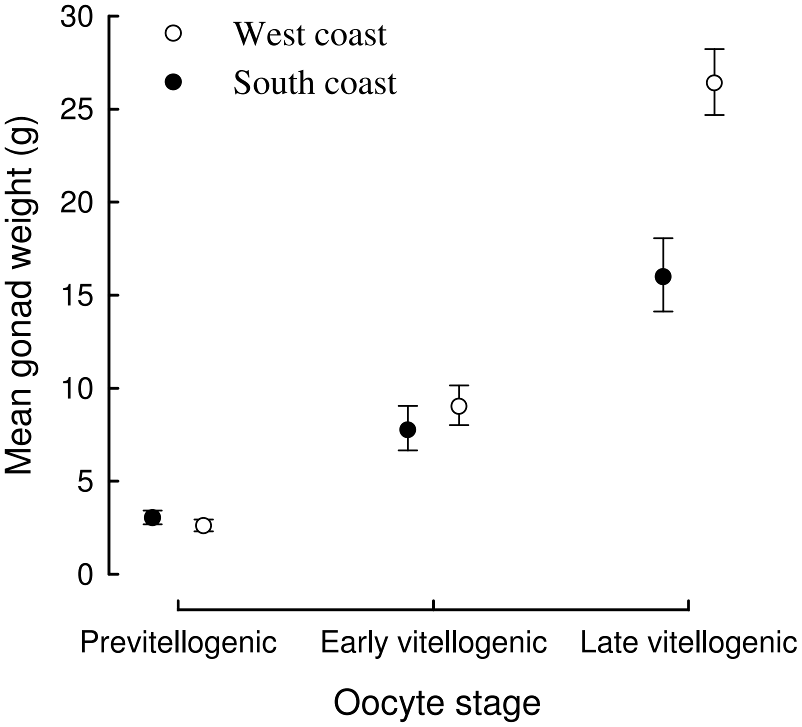

Figure 5.5. Mean gonad weights ± 95% CIs for female *Hypothalassia acerba* caught off the lower west versus south coasts and containing ovaries predominantly previtellogenic, early vitellogenic and late oocytes. The gonad weights of each of the ovarian categories on both coasts were standardised to constant carapace lengths as selected by ANCOVA.

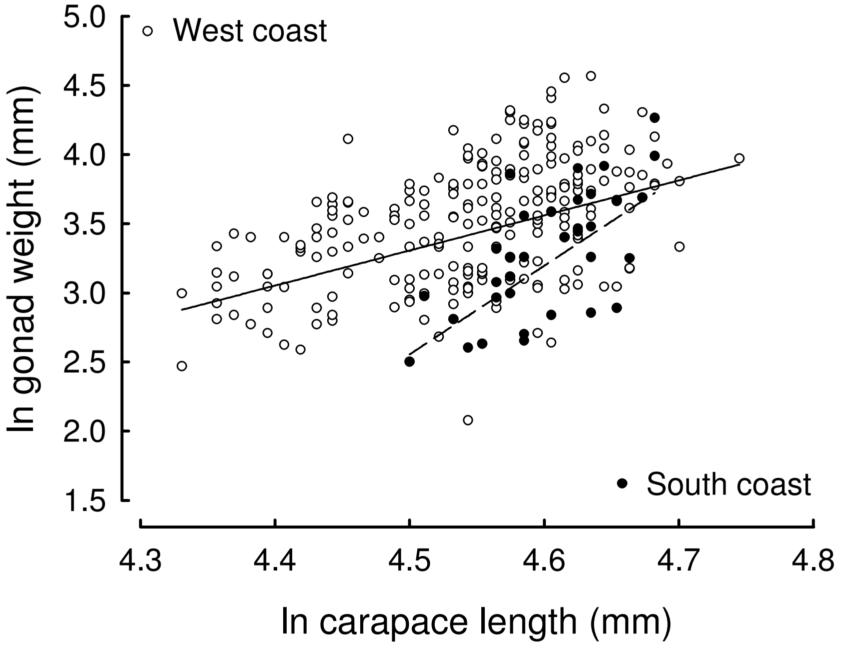

Figure 5.6. Relationship between the weights of ovaries containing late vitellogenic oocytes and carapace lengths for *Hypothalassia acerba* from both the lower west and south coasts of Western Australia.

selected carapace length, the mean gonad weight of crabs was significantly greater on the lower west coast than south coast ($P < 0.001$).

To enable predictions of *W* from *CL* for *H. acerba*, the regression equations relating these two variables are provided below,

West coast: $\ln(W) = 2.809\ln(CL) - 6.400$; $P < 0.001$, $R^2 = 0.946$, $n = 581$

South coast: $\ln(W)= 2.768\ln(CL) - 6.128$; $P < 0.001$, $R^2 = 0.893$, $n = 185$

The mean lengths (± 95% CIs) of females from the lower west (93.8 ± 2.02 mm) and south coasts (93.0 ± 1.39 mm) were not significantly different ($P > 0.05$) when the individuals contained previtellogenic oocytes, whereas the corresponding values of 94.7 ± 0.91mm and 99.1 ± 1.37 mm for females with late vitellogenic oocytes on those two coasts were significantly different ($P < 0.001$). These differences are reflected in the fact that the distributions of the carapace lengths of female *H. acerba* on the south coast were located more to the right than those on the lower west coast in the case of females with late vitellogenic oocytes, whereas this was not so with females with previtellogenic oocytes (**Figures 5.7a,b**).

The mean diameters (± 95% CIs) of late vitellogenic oocytes of *H. acerba* from the lower west coast (357.7 ± 10.79 µm, $n = 342$) and south coast (370.3 ± 8.16 µm, $n = 134$) were not significantly different ($P > 0.05$).

The fecundities of *H. acerba* ranged from 202 295 to 488 758 for crabs with CLs of 90 mm and 102 mm, respectively. The minimum and maximum fecundities for *C. bicolor* were 15 592 and 288 512 respectively, for crabs with CLs of 98 and 133 mm respectively. The mean fecundities (± 95% CIs) of *H. acerba*, *i.e.* 356 210 (± 64 297) and *C. bicolor*, *i.e.* 192 070 (± 33 640), were significantly different ($P < 0.001$). Although the mean body weights (± 95% CIs) of the ovigerous females of *H. acerba* used for the above fecundity estimates, *i.e.* 587.4 (± 96.5 g) were substantially less than that of *C. bicolor*, *i.e.* 651.9 (± 61.3 g), those means were not significantly different ($P > 0.05$). The relationships between fecundity (*F*) and the carapace

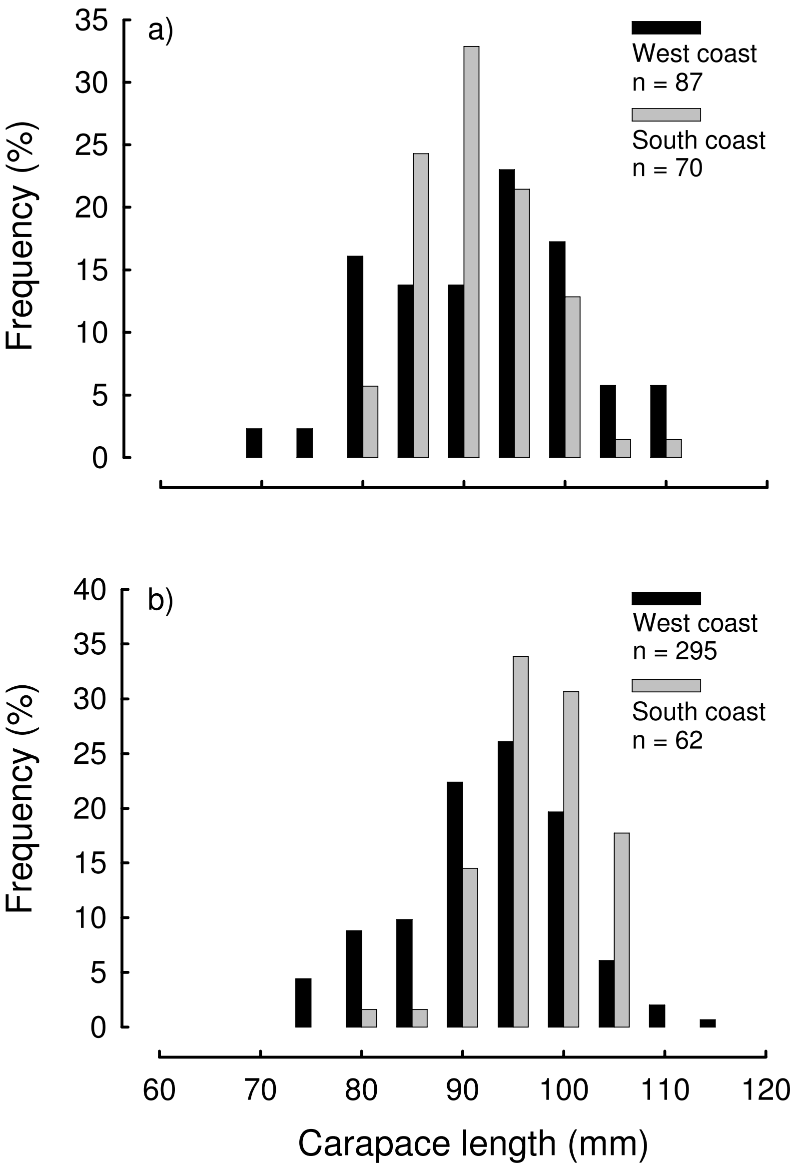

Figure 5.7. Carapace length-frequency distributions for female *Hypothalassia acerba* with ovaries containing (a) previtellogenic and (b) late vitellogenic oocytes off the lower west and south coasts of Western Australia.

length (*CL*) and wet weight (*W*) of the two species are shown in **Figures 5.8a-d** and are described by the following regression equations:

Hypothalassia acerba

$\ln F = 3.44\ln(CL) + 1.235, P < 0.05, R^2 = 0.486, n = 10$

$F = 0.005W + 0.608, P < 0.05, R^2 = 0.569, n = 10$

Chaceon bicolor

$\ln F = 2.957\ln(CL) + 1.686, P < 0.05, R^2 = 0.127, n = 40$

$F = 0.003W + 0.1572, P < 0.05, R^2 = 0.260, n = 40$

5.4 DISCUSSION

5.4.1 Comparisons between **Hypothalassia acerba** *on the west and south coasts*

The trends exhibited by the three reproductive variables recorded for the females of *Hypothalassia acerba* on the lower west coast of Australia were consistent with each other and clearly imply that reproduction in this deep-sea species is highly seasonal. Thus, the increase in the prevalence of females with ovaries containing late vitellogenic oocytes between July and October and subsequent levelling off to December was paralleled by a progressive rise and then levelling off in the mean monthly relative gonad weights. Likewise, the subsequent decline in the prevalence of females with this category of advanced ovary between December and March was accompanied by a pronounced decline in the mean monthly relative gonad weights. Furthermore, spent females were found in the relatively short period of January to March, which yielded most of the ovigerous females obtained during this study. It is also highly relevant that the prevalence of female *H. acerba* bearing egg remnants rose progressively from zero or very low levels in October to January to peak in May and subsequently declined sequentially to zero between July and October. The consistent trends exhibited by the monthly data for the three reproductive variables strongly suggest that oviposition occurs mainly in January to March.

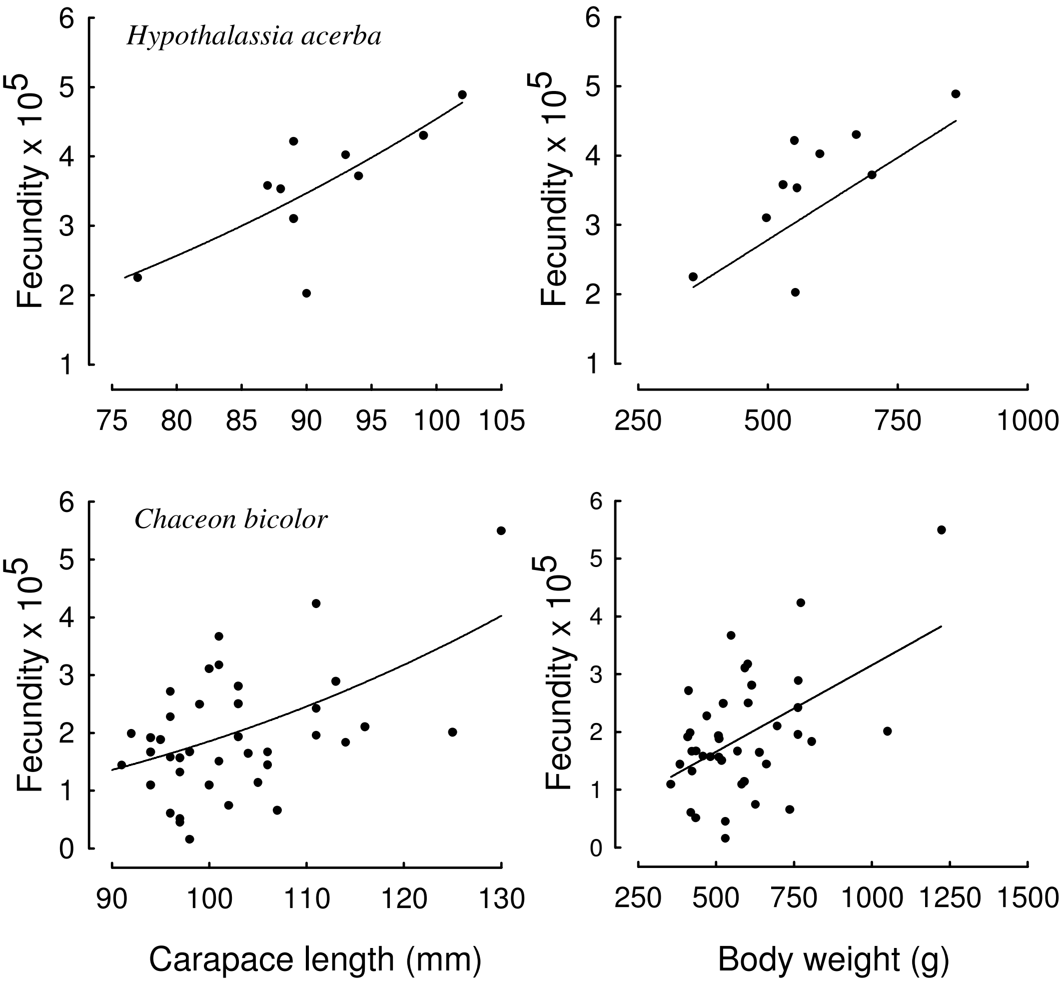

Figure 5.8. Relationships between fecundity and carapace length and body weight for *Hypothalassia acerba* and *Chaceon bicolor*.

The patterns exhibited by the reproductive variables for female *H. acerba* on the south coast of Western Australia differed markedly from those displayed by this species on the lower west coast. Thus, on the south coast, the prevalence of females with late vitellogenic oocytes and the mean monthly relative gonad weights both peaked in September rather than December and the overall prevalence of females with ovaries containing previtellogenic oocytes was far higher. Moreover, no ovigerous female crabs and only two females with egg remnants were collected on the south coast. This strongly suggests that very little reproduction occurs on the south coast.

The possibility that the lack of capture of ovigerous females of *H. acerba* on the south coast is due to females moving inshore prior to oviposition, as occurs, for example, with *Chaceon affinis*, *Chaceon quinquedens*, *Chaceon maritae* and *Chionoecetes opilio* (Fabricus) (Haefner, 1978; Hastie, 1995; Melville Smith, 1987a, Comeau *et al.,* 1998, López Abellan *et al.,* 2002) appears unlikely. This conclusion is based on the results of our stratified sampling in sequential water depth intervals from 35 m to 365 m, which showed that the females and males of *H. acerba* were both very largely concentrated in a relatively narrow range of water depths of 200 to 255 m off the lower west coast and of 90 to 200 m off the south coast, and that no crabs were caught in water depths of 35 m (Smith *et al.,* 2004a). However, it is relevant that, although the catches of *H. acerba* on both coasts contained a greater number of males than females, that difference was substantially greater on the south coast (Smith *et al.,* 2004a). The above data on *H. acerba* suggest that, at some stage prior to oviposition, the females of *H. acerba* on the south coast typically migrate westwards and then northwards on the lower west coast where they extrude their eggs.

The conclusion that the females of large and maturing *H. acerba* undergo considerable migratory movements is consistent with the observation that such movements are undertaken, in particular, by mature females of some other species of deep-sea crabs, *e.g. Chaceon fenneri*, *C. quinquedens* and *C. maritae* (Melville Smith, 1987b, Lockhart *et al.,* 1990). Some species of lobster also move substantial distances, including the western rock lobster *Panulirus cygnus* George along the west coast of Australia (Phillips, 1983; Melville Smith and Cheng, 2002). In decapods, these types of movements are often related to reproduction and enable those species to return to their spawning locations as mature adults after they have been transported as larvae or juveniles away from the areas of spawning (*e.g.* Bennett and Brown, 1983; Moore and Macfarlane, 1984; Stewart and Kennelly, 1988; Groeneveld and Branch, 2002). In the context of possible larval movement in south-western Australia, it is relevant that the important Leeuwin current flows southwards along the lower west coast of Australia and then eastwards along the south coast and extends to a depth of 350 m (Pearce and Griffiths, 1991). It is thus proposed that the larvae of *H. acerba* are planktonic, as has been shown by Gardner (1998) to be the case with those of the confamilial *Pseudocarcinus gigas*, and would thus be likely to be transported by this major current from the areas on the lower west coast where spawning occurs. The likelihood of such transport would be enhanced by the fact that the larvae of *H. acerba* on the west coast are released in autumn, when the Leeuwin current is strongest (Phillips *et al.,* 1991).

5.4.2 Comparisons between **Hypothalassia acerba** *and* **Chaceon bicolor**

The trends exhibited by the reproductive variables for *Chaceon bicolor* were far less seasonal than those displayed by *H. acerba*. Thus, although the prevalence of females of *C. bicolor* with ovaries containing late vitellogenic oocytes was high in October to December, it was also relatively high in August and May and, while the mean monthly relative gonad weight declined between December and February, it remained high from July to December. More importantly, however, *C. bicolor* with spent/spent-recovering ovaries were caught in eight months and in each season of the year, thereby indicating that oviposition occurs in most months of the year.

This conclusion is consistent with the fact that ovigerous females of *C. bicolor* were caught in each of the eleven months for which samples were obtained for deriving this variable and that, unlike the situation with *H. acerba*, the prevalence of such females did not exhibit a clear pattern of change during the year. The finding that, unlike the situation with *H. acerba,* and also *P. gigas*, which lives in similar water depths (Levings *et al.,* 1996), *C. bicolor* clearly does not reproduce within a restricted part of the year is consistent with *C. bicolor* occupying far greater depths and thus living in an environment that undergoes little seasonal change. The lack of conspicuous seasonality in the reproduction of *C. bicolor* parallels that found by Melville Smith (1987a) for *Chaceon maritae*, which likewise lives in deep water. It is also consistent with the fact that the physiological processes of the majority of organisms living in deep waters do not exhibit seasonality (Tyler, 1988).

5.4.3 Investment in gonadal development by **Hypothalassia acerba**

It was particularly noteworthy that the mean relative gonad weights of females with late vitellogenic oocytes were far greater for the assemblage on the west coast than for that on the south coast, especially as this did not apply to females with oocytes in earlier stages of development. This strongly indicates that the females of *H. acerba* on the west coast invest relatively less energy in ovarian development than those on the south coast. Furthermore, the lack of a significant difference between the size of the late vitellogenic oocytes of females on the south and lower west coasts implies that any differences in energy allocation to ovarian development on the two coasts is not reflected in differences in an allocation to individual oocytes. From the above data and comparisons, it appears reasonable also to assume that the number of eggs per batch produced by females of *H. acerba* that originated on the south coast are likely to be less than those of the individuals that spent at least most of their life on the west coast.

It is also evident from the data shown in **Figure 5.6** that the females of *H. acerba* on the south coast do not start producing mature (late vitellogenic) oocytes until they have reached a substantially larger size than those on the west coast. This implies that, with respect to size, the attainment of maturity by the females of *H. acerba* is delayed on the south coast compared with the west coast (69 mm CL).

In summary, our results provide good circumstantial evidence that conditions are less conducive for gonadal development and reproduction by *H. acerba* on the south than lower west coast of Western Australia. Furthermore, they also suggest that maturing females of *H. acerba* migrate from the south coast, which is at the southern and cool end of the distribution of this species, to the west coast for spawning. Reproduction on the lower west coast was shown to occur seasonally in *H. acerba*, but throughout at least much of the year with *C. bicolor*, which occurs in far deeper water and thus where environmental conditions remain more constant during the year. The seasonality of reproduction by *H. acerba* is accompanied by producing, at any one time, a greater number of eggs per given body weight than does *C. bicolor*.

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6.0 POTENTIAL BIAS IN ESTIMATES OF THE SIZE OF MATURITY OF CRABS DERIVED FROM TRAP SAMPLES

6.1 INTRODUCTION

The age at which fish and crustaceans are first caught should be at least as great as the age at first maturity if recruitment overfishing is to be avoided (Caddy and Mahon, 1995). Therefore, the size at which the individuals of a decapod species typically reach the onset of sexual maturity (SOM) is frequently used by fisheries managers as the basis for assigning a minimum legal size for the retention of that species (Watson, 1970). The criteria used to designate whether a female decapod is mature vary among species, and often reflect differences in the secondary sexual characteristics of those species. For example, because the abdomen of female portunid crabs becomes relatively wider and more loosely attached at the pubertal moult, this characteristic provides a sound criterion for assessing whether a female of this family has reached maturity (*e.g.* Van Engel, 1958; Somerton, 1981; de Lestang *et al.,* 2003a), whereas the shape of the gonopores (Melville Smith, 1987), or the presence of eggs under the abdomen (Levings *et al.,* 2001), have been employed for this purpose with the females of some deep-sea species of crabs.

The size at which 50% of the females of the stock of a crab species reach the onset of sexual maturity (SOM_{50}) is usually estimated by subjecting the proportions of mature females in sequential size classes to logistic regression analysis (*e.g.* Fisher, 1999; Muino *et al.,* 1999; de Lestang *et al.,* 2003a). The validity of this approach depends on both the immature and mature individuals of the stock in question having been sampled in an unbiased manner. As many crab fisheries employ only baited traps, scientists have often used the data obtained from the resulting catches to estimate the SOM_{50} (Brown and Powell, 1972; Melville Smith, 1987; Abbe, 2002; Gardner and Williams, 2002). However, traps yield samples that are biased in terms of both the size and sex composition of the population (Williams and Hill, 1982; Zhou and Shirley, 1997; Jury *et al.,* 2001).

Trap selectivity for decapod species typically occurs as a result of the larger individuals being more aggressive, thereby restricting the likelihood of smaller animals entering the trap (*e.g.* Bovbjerg, 1956; Rodhouse, 1984). In addition, the greater number of males than females typically found in the trap catches of decapods (Carroll and Winn, 1989; Potter and de Lestang, 2000) almost certainly reflects the greater aggression of males. Moreover, behavioural studies strongly indicate that, in the case of the portunid *Callinectes sapidus*, females are more likely to enter traps containing males once they have become mature (Jivoff and Hines, 1998). Hence, trap catches of the females of this species will almost certainly contain a disproportionately greater number of mature than immature females. Therefore, subjection of the proportions of trap-caught mature females of *C. sapidus* in successive size classes to logistic regression analysis would presumably underestimate the SOM. Similar biases in the estimates of SOM would be expected to result from analyses of trap catches of other crab species if there is likewise a greater likelihood of the capture of the mature females of those species than their immature females of the same size.

The commercial fishery for the blue swimmer crab (*Portunus pelagicus*) in Western Australia is the largest for this portunid in Australia, a total catch of 673 t being taken in 1999–2000, yielding a wholesale value of approximately $A3 million (Anon., 2002). The SOM of female *P. pelagicus* in Shark Bay, the location of the largest fishery for this portunid in Western Australia, has been estimated using data from samples obtained by baited traps, seine-netting and otter trawling collectively (de Lestang *et al.,* 2003a). However, because of trap selectivity, the samples of *P. pelagicus* collected by baited traps in Shark Bay may have contained an atypically high proportion of mature females and, consequently, a logistic regression analysis using data from trap catches may have underestimated the SOM of the females there. In contrast, the size composition of samples of *P. pelagicus* collected by seine-netting and otter trawling would be far more representative of the population in Shark Bay.

The champagne crab (*Hypothalassia acerba*) and the crystal crab (*Chaceon bicolor*) are fished commercially using baited traps in water depths of about 150-360 m and 600-800 m, respectively, off the west and south coasts of Western Australia (Smith *et al.,* in press; unpublished data). Although estimates of the SOMs can be derived from the trap catches of the females of these populations, no data are available from catches obtained using other fishing gear that could be used to determine whether vulnerability to capture by traps was greater among the mature females of these species.

This study aimed to determine whether the SOM_{50} estimated for female *P. pelagicus* in Shark Bay was significantly lower when data derived from trapping were used in preference to data from seine-netting and otter trawling collectively. If this was the case, it would demonstrate that, as with *C. sapidus*, the mature female *P. pelagicus* are more vulnerable to capture by traps than the immature females of the same size. Consequently, a SOM_{50} derived from trap catches will be an underestimate for species such as *P. pelagicus* and *C. sapidus*. However, the only method used for catching *H. acerba* and *C. bicolor* in Western Australia is trapping. Although it is recognized that the SOM_{50}s derived from these trap catches may represent underestimates, we derived such values so that fisheries managers have data that, with discretion, can be used for determining, for example, the minimum legal size for capture of these species.

6.2 MATERIAL AND METHODS

6.2.1 Sampling and measurement of crabs

The data for *P. pelagicus* used in this study were extracted from the database constructed for the samples of this species collected in Shark Bay (26°S, 113.5°E), at bimonthly intervals between July 1998 and May 2000 (de Lestang *et al.,* 2003a, b). Samples were collected with a seine-net 21.5 m long with a bunt made of 3 mm mesh, a small otter trawl with a net containing a codend constructed of 25 mm mesh, and a series of crab traps consisting of either 12 or 76 mm mesh (for further details see Potter and de Lestang, 2000). The crab traps, which were the same as those used by most professional fishers in Western Australia, were ca. 630 mm high and 1000 mm in diameter. They were joined together in four lines of four, separated by a distance of 15 m. The traps were baited with fish, usually *Sardinops neopilchardus*, and set for ca. 24 h. The carapace width (CW) of each female *P. pelagicus*, *i.e.* the distance between the tips of the two lateral spines of the carapace, was measured to the nearest 1 mm.

The *H. acerba* and *C. bicolor* used in this study were derived from the depth-stratified sampling regime and from commercial catches as described in Chapter 2. That chapter also describes the measurements made on these two species of crab.

As the morphology and tightness of the abdominal flap of the immature and mature females of both *H. acerba* and *C. bicolor* do not differ markedly, abdominal flap characteristics could not be used to determine the maturity status of the females of those deep-sea crabs. Moreover, as the morphology of the gonopores of immature and mature females of *H. acerba* does not differ markedly, which contrasts with the situation in some other species of deep-sea crab (Melville Smith, 1987), this structure could not be used to determine the maturity status of the champagne crab. Therefore, female *H. acerba* were classified as having reached maturity when their ovaries were relatively large and pale yellow to pink (and shown by histology to contain yolk granule oocytes), rather than being either inconspicuous or thin and white (and shown by histology to contain oogonia and primary oocytes). As the gonopores of female *C. bicolor* are elliptical and compressed in immature individuals, and circular and open in mature individuals, it was possible to use this criterion to determine whether an individual crab was immature or mature.

6.2.2 Data analysis

The SOM_{50}s of female *P. pelagicus* taken by trap, and by seining and trawling collectively, were estimated using logistic regression analysis of the proportions mature at each CW. The probability that the j^{th} crab is mature (P_j) is

$$P_j = 1/\{1+\exp[-\ln(19)(CW_j - SOM_{50})/(SOM_{95} - SOM_{50})]\}$$

where CW_j is the CW of that crab, SOM_{50} and SOM_{95} the CWs at which 50 and 95% of the assemblage reach maturity, and ln is the natural logarithm of the specified value. This equation represents a simple reparameterization of the logistic equation, which employs the parameters SOM_{50} and SOM_{95} that may be more readily interpreted than the traditional parameters of this equation. The SOM_{50} and SOM_{95} were determined through use of a computer program that maximizes log-likelihood, and employs AD Model Builder (Fournier, 2000). The confidence limits of these parameters and of the estimated percentages of mature crabs at different CWs were determined from likelihood profile distributions calculated using AD Model Builder. Similarly, estimates of the SOM_{50}s were derived for trap-caught females of both *H. acerba* and *C. bicolor*. Note that, in the case of each of these latter species, CW is replaced by CL in the above equations.

A likelihood-ratio test (see Cerrato, 1990) was used to determine whether the SOM_{50}s of *P. pelagicus* estimated from samples caught by trap, and by seining and trawling collectively, were significantly different.

6.3 RESULTS

6.3.1 Size composition

The 272 female *P. pelagicus* caught in traps in Shark Bay, of which only 2.9% were immature, ranged from 74 to 178 mm CW (**Figure 6.1a**). In contrast, the size range of the 238 female *P. pelagicus* caught by seining and trawling collectively, of which as many as 57% were immature, ranged from 12 to 160 mm CW (**Figure 6.1a**). The mean CWs of mature females

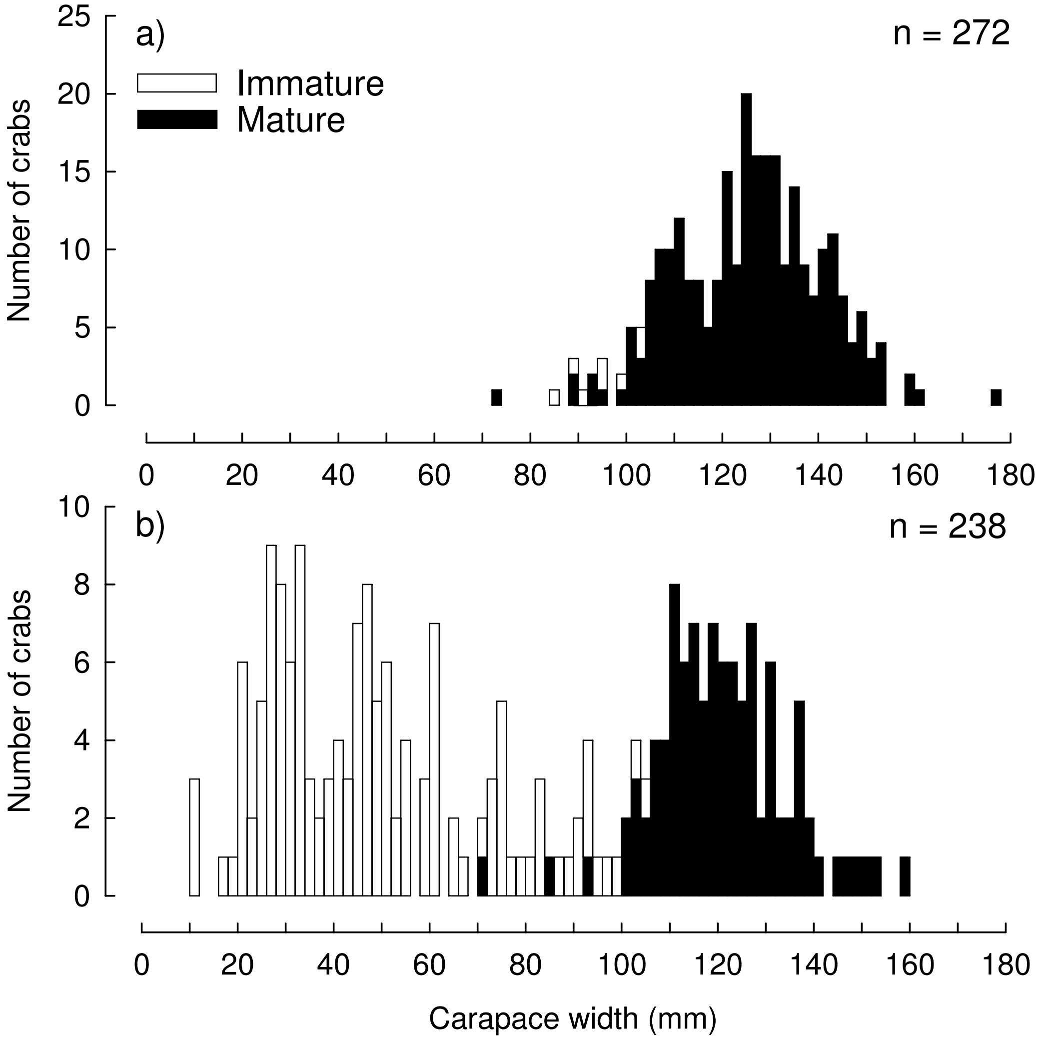

Figure 6.1 Size compositions of immature and mature female *Portunus pelagicus* caught in (a) traps, and (b) seine-nets and otter trawls collectively, in Shark Bay, Western Australia.

collected by trapping (127.5 mm), and by seining and trawling collectively (125.5 mm), were not significantly different ($P > 0.05$).

The CLs of the 598 female *H. acerba* and the 2981 female *C. bicolor* caught by traps ranged from 50 to 114 mm and from 34 to 148 mm, respectively (**Figure 6.2**). The size distributions of both of these species were essentially unimodal, peaking at ~ 95 and ~ 110 mm CL, respectively. The number of immature individuals in the samples of female *H. acerba* and *C. bicolor* were 20 and 186, respectively, thus contributing only 3.3 and 6.2% to the total catch of the females of these two species (**Figure 6.2**).

6.3.2 Size at maturity

A logistic regression analysis of the proportions of mature female *P. pelagicus* in sequential CWs in trap samples yielded a SOM_{50} of 86.1 mm, with lower and upper 95% confidence limits of 59.7 and 97.2 mm, respectively (**Figure 6.3a**). A far greater SOM_{50}, *i.e.* 101.1 mm, and a far narrower 95% confidence interval, *i.e.* 96.1-105.4 mm, were obtained when subjecting the proportions of mature crabs in seine and trawl samples to the same analysis (**Figure 6.3b**). The above two SOM_{50}s were significantly different ($P < 0.001$). As the mean CW of ovigerous female *P. pelagicus* in trap catches did not differ significantly ($P > 0.05$) from that recorded in seine and trawl catches collectively, the size frequency data for these methods were pooled. The CWs of ovigerous females caught in Shark Bay ranged from 104 to 157 mm, with a mean and 95% confidence limits of 131.3 ± 3.4 mm (**Figure 6.3c**).

Logistic regression analyses of the proportions of mature females of *H. acerba* in sequential CLs in samples collected by traps yielded a SOM_{50} of 69.7 mm (**Figure 6.4a**). The CLs of ovigerous females and females with egg remnants collectively ranged from 75 to 114 mm, producing a mean and 95% confidence limits of 96.6 ± 3.0 mm (**Figure 6.4b**). Subjection of the proportions of the mature females of *C. bicolor* in trap catches to logistic regression

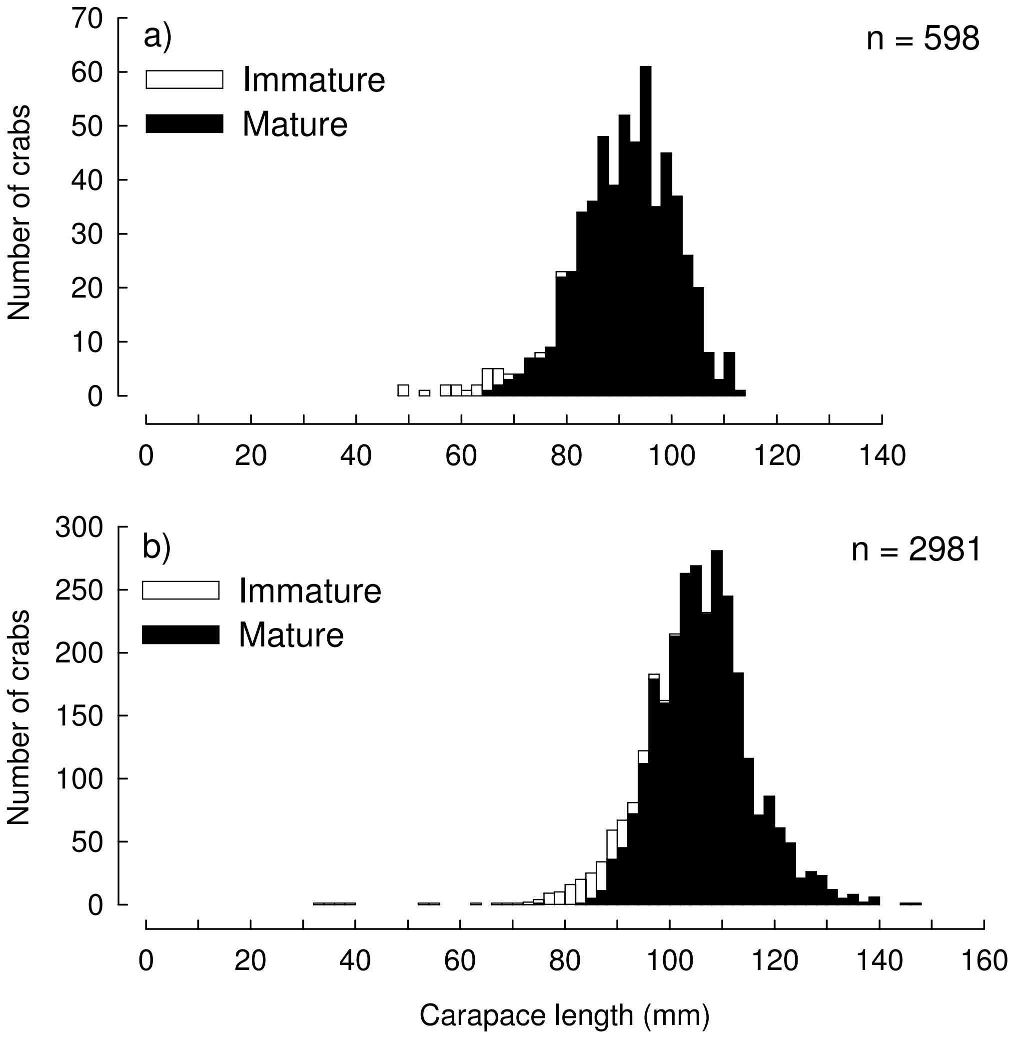

Figure 6.2 Size compositions of immature and mature females of (a) *Hypothalassia acerba*, and (b) *Chaceon bicolor* in samples collected by traps on the lower west coast of Australia.

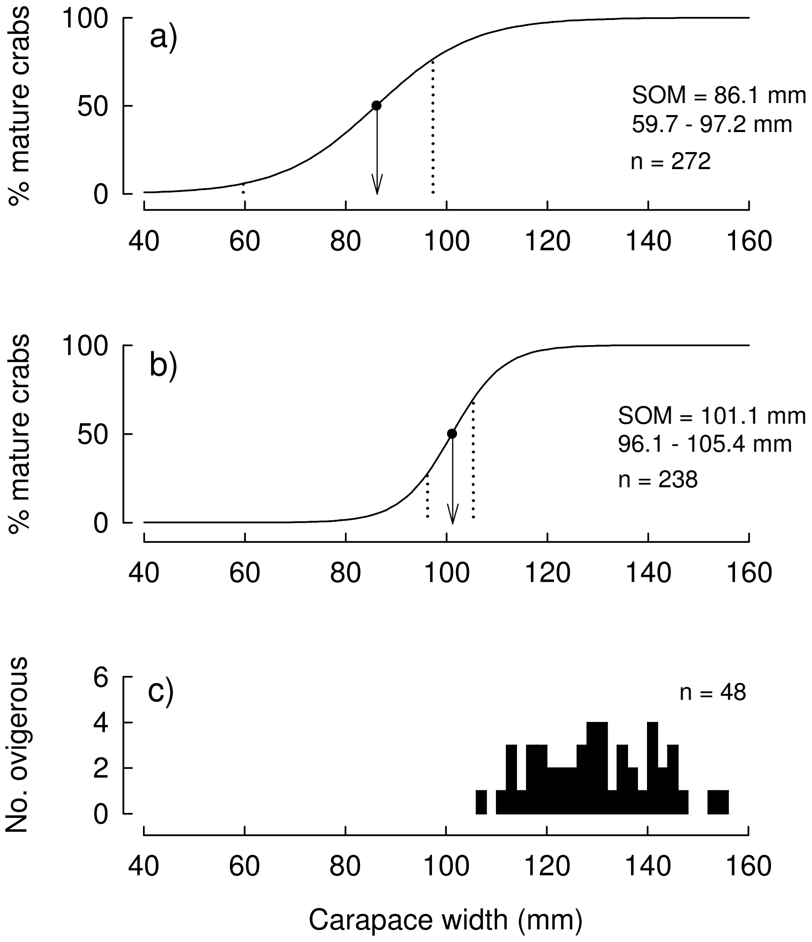

Figure 6.3 Logistic regression analysis of the proportions of mature female *Portunus pelagicus* caught in (a) traps, and (b) seine and otter trawl nets collectively. (c) Size composition of ovigerous female *P. pelagicus* caught using all three sampling methods. The estimates of the SOM_{50}s and 95% confidence limits are denoted by the arrows and dashed lines, respectively. Values for the SOM_{50}s and 95% confidence limits are also presented.

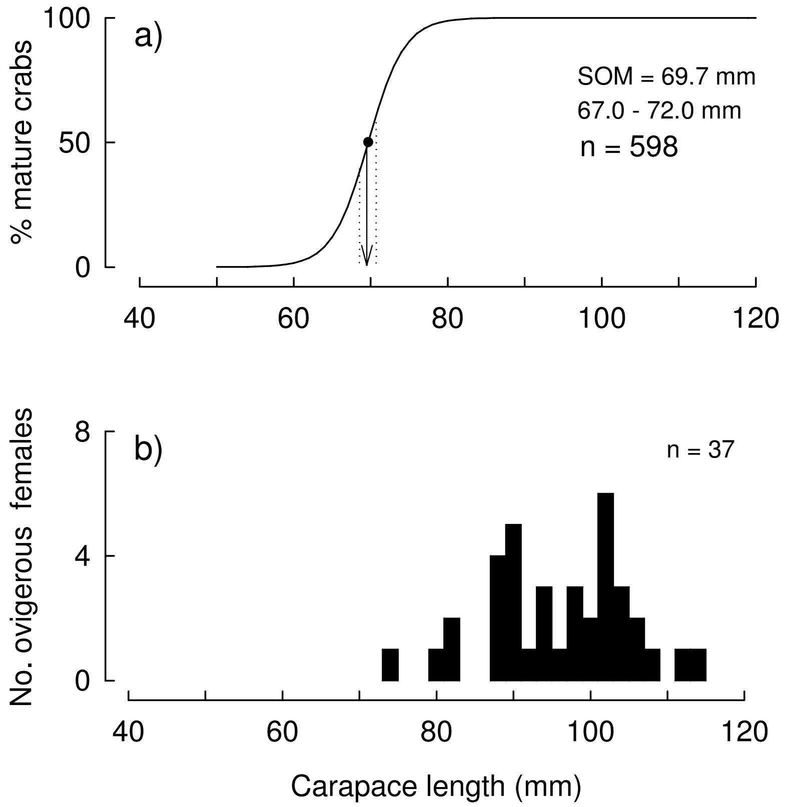

Figure 6.4 (a) Logistic regression analysis of the proportions of mature female *Hypothalassia acerba* caught in traps. (b) Size composition of ovigerous female *H. acerba.* The estimate of the SOM_{50} and 95% confidence limits are denoted by the arrows and dashed lines, respectively. Values for the SOM_{50} and 95% confidence limits are also presented.

analysis yielded a SOM_{50} of 90.5 mm (**Figure 6.5a**). The CLs of ovigerous females and females with egg remnants collectively ranged from 91 to 140 mm, with a mean and 95% confidence limits of 108.2 ± 1.0 mm (**Figure 6.5b**).

6.4 DISCUSSION

The proportion of small female *P. pelagicus* obtained by trapping in Shark Bay is far less than that obtained by seine-netting or otter trawling in the same environment. Indeed, the percentage contribution made by female *P. pelagicus* with a CW < 100 mm to the total catch of females was only 3.3% in trap catches, whereas it exceeded 57.6% in the combined catches obtained by seine-netting and otter trawling. The proportion of large female crabs that entered traps was also high in the case of the two species of deep-sea crabs. Therefore, the proportions of female *H. acerba* < 70 mm CL and of *C. bicolor* < 90 mm CL among all females of each of those species were only 3.3 and 4.4%, respectively. It should be noted that the numbers of small deep-sea crabs caught were low, even when the traps were enclosed in a smaller mesh or plastic covering and had their entrances narrowed.

The size composition data for *P. pelagicus* for Shark Bay, and also for the Leschenault Estuary much farther south (Potter and de Lestang, 2000, unpublished data), demonstrate that, in contrast to mature females, few immature females of this species enter traps. This finding is consistent with the implications of the results of behavioural studies on *Callinectes sapidus* by Jivoff and Hines (1998), which indicated that an immature female of this portunid would be more likely to avoid any male(s) of this species present in traps than would a mature female. Furthermore, male American lobster (*Homarus americanus*) do not allow the immature females of the same species to occupy their shelter (Salmon, 1983). If the proportion of mature females in any size category is greater in trap samples than in the environment, the SOM_{50} derived from such samples would underestimate this parameter as a result of the sample being biased towards those mature individuals. This conclusion is strongly supported by the fact that

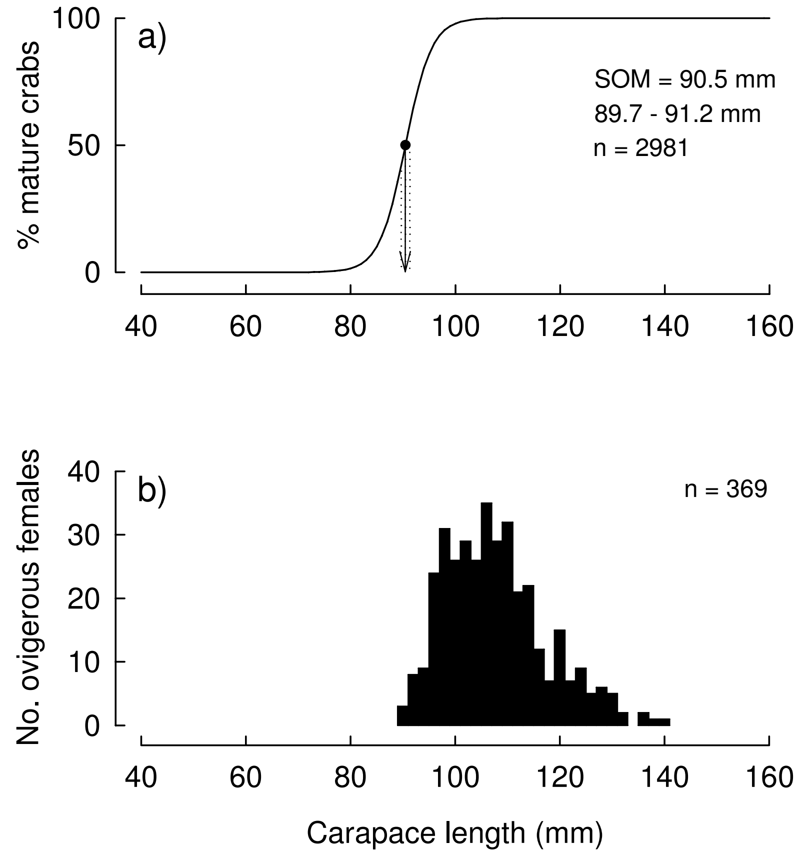

Figure 6.5 (a) Logistic regression analysis of the proportions of mature female *Chaceon bicolor* caught in traps. (b) Size composition of ovigerous females of *C. bicolor*. The estimate of the SOM_{50} and 95% confidence limits are denoted by the arrows and dashed lines, respectively. Values for the SOM_{50} and 95% confidence limits are also presented.

the estimated SOM_{50} of female *P. pelagicus*, based on data from trapping (86.1 mm CW), was significantly less than that of 101.1 mm CW estimated with the data derived from seine-netting and otter trawling, which would have caught a far more representative sample of the population. The CW of the smallest ovigerous female *P. pelagicus*, 104.0 mm, was substantially greater than the SOM_{50} of 86.1 mm, estimated from the proportions of mature females in trap catches, which, as argued above, is an underestimate.

As with *P. pelagicus*, the estimates of SOM_{50} for *H. acerba* and *C. bicolor,* 69.7 and 90.5 mm, respectively, calculated using the proportions of mature females in trap catches, were lower than the sizes of the smallest ovigerous females. Catches of those species obtained using active fishing methods are not available, so precluding investigation of the possibility that the vulnerability of the females of these species might be greater for mature than for immature crabs. Until this hypothesis can be tested for each species, the values of the SOM_{50}s for *H. acerba* and *C. bicolor* calculated from trap catches should be considered lower “bounds” of the true SOM_{50}s rather than accurate estimates of these crucial reproductive parameters.

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7.0 DO THE CHELAE OF THE MALES OF THREE CRAB SPECIES UNDERGO ALLOMETRIC CHANGES THAT CAN BE USED TO DETERMINE MORPHOMETRIC MATURITY?

7.1 INTRODUCTION

The size at which the individuals in fished stocks become mature is one of the most important parameters used by managers to develop plans for ensuring the sustainability of those stocks. Indeed, concerns that the reduced number of males found in crab fisheries, that exploit only or predominantly males, might influence the sustainability of the stocks of certain species have highlighted the need for information on the sizes at which the males of those species attain maturity (Conan and Comeau, 1986; Ennis *et al.,* 1988; Gardner and Williams, 2002).

Studies aimed at determining the size at maturity of male crabs have used data on whether individual crabs have become functionally, physiologically and/or morphometrically mature (*e.g.* Goshima *et al.,* 2000; Conan *et al.,* 2001; Comeau and Conan, 1992; Gardner and Williams, 2002; de Lestang *et al.,* 2003a). Evidence of functional maturity is derived from observations that copulation has occurred (Goshima *et al.,* 2000; Gardner and Williams, 2002), whereas demonstration that males are physiologically mature is provided by their production of spermatophores (Warner, 1977; Melville Smith, 1987). The attainment of morphometric maturity by a male crab is identified by determining whether certain body parts, *e.g.* chelae**,** undergo a conspicuous change at the pubertal moult (Somerton, 1981; Comeau and Conan, 1992; Gardner and Williams, 2002).

A male crab must become both functionally and physiologically mature before it can reproduce and the ability to mate may depend on the crab having become morphometrically mature. In an aquarium study involving males of *Chionoecetes opilio* with carapace widths (CWs) in excess of the size at physiological maturity and mature females, precopulatory pairing behaviour was found to be initiated only by the larger of the males that had become morphometrically mature, *i.e.* > ~95 mm CW (Conan and Comeau, 1986). It was thus concluded that, although physiological maturity is attained by the males of *C. opilio* before they reach a CW of ~60 mm, functional maturity is not attained until individuals have moulted to become morphometrically mature and attained a CW of ~95 mm. However, Paul (1992) has queried why physiologically mature males would produce sperm if they were not to be used immediately. Subsequently, Sainte-Marie *et al.,* (1995) found that males of *C. opilio* from the Gulf of Saint Lawrence became physiologically mature at a CW of only 38.5 mm and that, in non-competitive aquarium studies, males that were physiologically mature but morphometrically immature were functionally mature, *i.e.* mated successfully.

The changes undergone in the allometry of a body part of a male crab may not be sufficiently well defined to be able to be used with confidence for estimating the size at which morphometric maturity is attained (Clayton, 1990; Goshima *et al.,* 2000). For example, in some decapod species, the changes in the "level of allometry" *sensu* Hartnoll (1978) are gradual and the logarithms of the measurements appear to follow a curvilinear trend. Consequently, the straight lines that are fitted to the presumed juvenile and adult data may be artefactual and cannot thus provide a reliable means for distinguishing between pre- and post-pubertal moult animals (Conan *et al.,* 2001). Indeed, Somerton (1980) has pointed out that it is essential to test whether a difference between the patterns of growth of that body part in juveniles and adults can be detected.

Somerton (1980) fitted separate, overlapping lines, rather than a single straight line, to the logarithms of the dimensions of various body parts of juvenile and adult crabs and used a *F*-test to determine whether the difference between the sums of squares of those two models was statistically significant. However, the objective function calculated by Somerton (1980), using his iterative approach to fit separate overlapping lines, relies on the allocation of intermediate points to one or other of the straight lines, based on the value of the dependent variable and the predicted values of the lines at that body size. It was thus inappropriate to employ statistical tests, such as the *F*-test, to compare his models of differing complexity using the value of this objective function and that obtained from a traditional regression model. However, several earlier studies on the maturity of male crabs, including our own on *P. pelagicus* (de Lestang *et al.,* 2003a), have used an overlapping-lines model without validating that it was appropriate.

In Western Australia, the blue swimmer crab *Portunus pelagicus* is fished in estuaries and protected coastal waters, whereas the champagne crab *Hypothalassia acerba* and the crystal crab *Chaceon bicolor* are fished predominantly in water depths of 90 to 310 m and 450 to 1220 m, respectively (de Lestang *et al.,* 2003b; Smith *et al.,* 2004a; Melville Smith *et al.,* in press). The main aim of the current study was to determine statistically whether the allometry of the chelae of the males of *P. pelagicus*, *H. acerba* and *C. bicolor* underwent a change that could be assumed to reflect a morphological transition from an immature to a mature state. The Akaike and Bayesian Information Criteria were thus used to explore which of a linear, quadratic, broken stick or overlapping-lines model was the most appropriate for representing the relationship between the natural logarithms of the length of the dorsal propodus and body size of the male crabs of each species (Akaike, 1973; Schwartz, 1978). A linear model would imply that allometry does not change as body size increases, whereas a quadratic model would indicate that the pattern of growth changes continuously with increasing body size and the broken stick or overlapping-lines models would imply that there is a distinct change in allometry during growth. If there was found to be a change in allometry, the resulting estimate of the body size at which this change occurred was compared with the size at which the animal becomes physiologically mature. This required the determination of the size at which physiological maturity is attained by the males of *H. acerba* and *C. bicolor* to provide data, which would complement that already derived for this variable for *P. pelagicus* (de Lestang *et al.,* 2003a).

7.2 MATERIAL AND METHODS

7.2.1 Collection of crabs

Male *P. pelagicus*, with CWs ranging from 21-154 mm, were collected from Cockburn Sound (32°12'S, 115°48'E) at monthly intervals between February 1997 and March 2000. The crabs were caught using a 21.5 m seine net with a bunt made of 3 mm mesh and a small otter trawl net with a cod end constructed of 25 mm mesh (see de Lestang *et al.,* 2003a).

The *H. acerba* and *C. bicolor* used for this study were collected during the depth-stratified sampling regime and sampling onboard commercial fishing boats (for details, see Chapter 2).

7.2.2 Measurements

The carapace width of each male *P. pelagicus*, *i.e.* distance between the tips of the two lateral spines of the carapace, and the carapace length of each male *H. acerba* and *C. bicolor, i.e.* distance across the gastric region from the midpoint between the bases of the two anterior medial spines and the posterior margin of the carapace, were each measured to the nearest 1 mm. Carapace length rather than carapace width is typically measured in deep-sea crabs (*e.g.* Levings *et al.,* 1996; Gardner, 1997; Goshima *et al.,* 2000) as it overcomes the problems of using the distance between the two lateral spines of the carapace, which are particularly prone to wear. For all three species, the length of the dorsal propodus from the proximal edge of the depression below the upper articulation knob to the proximal edge of the depression at the articulation with the moveable finger of the molariform cheliped of each male was measured to the nearest 0.1 mm using vernier calipers. The choice of chela propodus length to provide data aimed at determining whether or not changes in allometry occur was based, in part, on the demonstration by Gardner and Williams (2002) that this was the most suitable of several variables for assessing morphometric changes in the giant crab *Pseudocarcinus gigas*. The latter species belongs to the same family (Eriphiidae) as *H. acerba*.

7.2.3 Relationship between propodus length and body size

The natural logarithms of the lengths of the dorsal propodus of the males of each species were plotted against the natural logarithms of body size, *i.e.* carapace length or width. In each case, the trend exhibited by the points with increasing body size appeared continuous and without marked disjunction. This suggests that the data for each species might be adequately described by a linear or quadratic regression or a broken-stick regression, *i.e.* a piecewise linear function that is continuous at the point of intersection, or a model comprising two overlapping lines in combination with a logistic function. The logistic function determines the probability that an observation is drawn from the distribution of points around either the first or the second of these overlapping lines. The straight line implies that there is no change in the level of allometry, whereas the quadratic model represents a continuous and smooth change in the level of allometry as body size increases. The broken stick and overlapping-lines models represent two distinct and constant levels of allometry, reflecting the different patterns of growth of morphometrically immature and mature crabs. For the broken stick model, the change occurs when the animals attain the length corresponding to the point at which the two lines intersect. For the model using overlapping lines, the change is gradual and its rate is determined by the parameters of the logistic curve that determine the proportion of the mixture of points associated with each of the overlapping lines. The linear and quadratic models are written as $\ln DP = a + b \ln S$ and $\ln DP = a + b \ln S + c(\ln S)^2$, respectively, and the broken-stick model as

$$\ln DP = \begin{cases} d + e\ln S & \text{if } \ln S \leq X \\ d + eX + f(\ln S - X) & \text{otherwise} \end{cases}$$

The overlapping-lines model is

$$\ln DP = (1 - P_S)(a' + b'\ln S) + P_S(c' + d'\ln S),$$

where

$$P_S = \{1 + \exp[-\ln(19)(S - S_{50})/(S_{95} - S_{50})]\}^{-1}.$$

In these equations, DP = length of the dorsal propodus, *S* = body size (*i.e.* CL or CW), *a*, *b* (and *c*) = parameters of the linear (and quadratic) model(s), *d* and *e* = intercept and slope, respectively, of the first line, and *f* = slope of the second line of the broken-stick model, *X* = value of ln *S* at the point of intersection of the two straight lines that form the broken stick, a' and b' = intercept and slope, respectively, of the first of the overlapping lines, c' and d' = intercept and slope of the second of the overlapping lines, P_S = probability that a crab with body size *S* is associated with the second of the overlapping lines, S_{50} and S_{95} = body sizes at which 50 and 95%, respectively, of crabs are associated with the second of the overlapping lines, and ln = natural logarithm of the associated variable.

It was assumed that observation errors ε were independent, identically distributed random variates drawn from a normal distribution, *i.e.* where $\varepsilon \sim N(0, \sigma^2)$. Ignoring constants, the log-likelihood was calculated as $\lambda = -\frac{n}{2}\ln\left(\frac{SS}{n}\right)$, where *n* is the number of observations and *SS* is the sum of squared deviations of the observed value of $\ln DP$ from the value predicted using each model. The models were fitted to the data for each species using Solver in Microsoft Excel, and maximising the log-likelihood for each model to estimate the two parameters of the linear model, *a* and *b*, the three parameters of the quadratic model, *a*, *b* and *c*, the four parameters of the broken-stick model, *d*, *e*, *f* and *X* and the six parameters of the overlapping-lines model, a', b', c', d', S_{50} and S_{95}. 95% confidence intervals for each parameter in each model were estimated as the 2.5 and 97.5 percentiles of 200 estimates of each of the parameters that were obtained by random resampling, with replacement, of the data for each species and then refitting each model to the resulting set of data. When fitting the overlapping-lines model, a penalty function was used to ensure that, for crabs with a body size less than a specified minimum or greater than a specified maximum, the values of S_{50} and S_{95} were such that (1 - P_S) > 0.99 or P_S > 0.99, respectively. This emulates the approach used by Somerton (1980) whereby crabs with sizes below or above some intermediate size range were assumed to be immature or mature, respectively. For *P. pelagicus*, the values of these specified minimum and maximum body sizes were set at 60 and 110 mm CW, respectively, as these were the values used by de Lestang *et al.,* (2003a). For *H. acerba* and *C. bicolor*, the values specifying this intermediate size range, *i.e.* 67 to 110 mm CL and 81 to 134 mm CL, respectively, were selected from plots of the data for each species and appeared to bracket the range likely to contain the point of inflection of the lines, if such a point exists.

As the four models are not nested, they cannot be compared using the likelihood-ratio test to determine the most appropriate and parsimonious model, *i.e.* that possessing the fewest parameters, but which is consistent with the data. Accordingly, the selection of the most appropriate model to describe the data for each species was based on the Akaike and Bayesian information criteria, *i.e.* AIC and BIC, which were calculated as

$$AIC = -2\lambda + 2k$$

$$BIC = -2\lambda + k \ln n$$

where *k* is the number of parameters, *i.e.* 2 for the linear, 3 for the quadratic, 4 for the broken stick regression and 6 for the overlapping-lines model (Akaike, 1973; Schwartz, 1978). The model with the smallest value for the information criterion was accepted as providing the best, most parsimonious fit to the data for that species and for that information criterion.

7.2.4 Probability of selecting an incorrect model

The parameters that were estimated when the linear model was fitted to each set of randomly resampled data for each of *P. pelagicus*, *H. acerba* and *C. bicolor*, and the resulting standard deviation of the observation errors were then used to generate a synthetic value of the logarithm of dorsal propodus length for each recorded body size. For this, a random normal variate with a mean of zero and standard deviation of 1 was generated. This was multiplied by the standard deviation of the observation errors to produce a random "observation error", which was then added to the value predicted using the linear model and the recorded body size to produce a randomly-generated value of the logarithm of dorsal propodus length for the crab. The resulting data are thus formed from the linear model fitted to the resampled data, *i.e.* to data randomly drawn from the population from which the original data set was obtained. Linear, quadratic, broken-stick and overlapping-lines models were then fitted to the synthetic data and, for each of the AIC and BIC, the best, most parsimonious model was selected as that with the lowest value of that information criterion. This process of generating a synthetic set of data, fitting the three models and selecting the more appropriate model was repeated using each set of results obtained from refitting the linear model to each of the resampled data sets. The probability of erroneously selecting either the quadratic, broken-stick or overlapping-lines model as the best model was calculated as the proportion of these 200 runs for which each of these models was selected as the best model, *i.e.* the correct conclusion that there was no change in the level of allometry was rejected.

The same process was then repeated for each species, using the parameter estimates obtained when fitting the quadratic, then the broken-stick, and finally the overlapping lines, models to generate the random data to which the other models were fitted and to determine whether or not the model that matched that used to generate the synthetic data was correctly selected using the AIC and the BIC.

We have considered four hypotheses concerning the relationship between the logarithms of the length of the dorsal propodus and of body size, *i.e.* H_1 - the relationship is linear, H_2 - the relationship is quadratic, H_3 - the relationship is a broken stick or H_4 - the relationship is one that is formed by overlapping lines. The conclusion from our analysis is that most appropriate relationship for describing the data is either D_1 - linear, D_2 - quadratic, D_3 - a broken stick, or D_4 - one that is formed by overlapping lines.

The results obtained from the simulations described in the preceding paragraphs were used to calculate the probability of each conclusion, *D*, given that the relationship used to generate the synthetic data was known to be of each specific form. This has been denoted as $P_{\mathrm{AIC}}(D \mid H)$ or $P_{\mathrm{BIC}}(D \mid H)$. Thus, for example, $P_{\mathrm{BIC}}(D = D_1 \mid H_3)$ is estimated as the proportion of data sets that were generated using the broken stick relationship in which, employing the BIC, it was concluded that the relationship was linear.

A Bayesian approach was employed to assign probabilities to each of the hypotheses regarding the form of the relationship between the logarithms of the length of the dorsal propodus and the body size. It was assumed that, prior to the study, the four hypotheses were equally likely, *i.e.* $P(H) = 0.25$ for each hypothesis, *H*. The posterior probabilities of these hypotheses were then calculated as

$$\mathrm{P}(\mathrm{H_j}) = \frac{\mathrm{P}(\mathrm{D} \mid \mathrm{H_j})\mathrm{P}(\mathrm{H_j})}{\sum_{\mathrm{k}} \mathrm{P}(\mathrm{D} \mid \mathrm{H_k})\mathrm{P}(\mathrm{H_k})}.$$

7.2.5 *Physiological maturity*

Collected individuals of *H. acerba* and *C. bicolor* were transported to the laboratory where they were euthanased in a bath of seawater and clove oil. The gonads of these crabs in a randomly-selected subset of the males of each species, which could be readily distinguished from females by the shape of their abdomen, were examined macroscopically and classified as immature or mature using the following criteria. They were recorded as immature if either the reproductive tract, *i.e.* the testes and/or vas deferens, was not visible or if the middle and posterior vas deferens were present but were thin and either straight or loosely convoluted, and were classified as mature when the middle and posterior regions of the vas deferens were enlarged and highly convoluted (Ryan, 1967; de Lestang *et al.,* 2003a). Note that, when examined microscopically, segments of the anterior vas deferens of large subsamples of each species always contained spermatophores in individuals designated as mature, but that this was never the case with immature crabs.

7.2.6 Size at physiological maturity

The sizes by which 50% of the males of *H. acerba* and *C. bicolor* have become physiologically mature was calculated by logistic regression analysis, using the equation

$$p_j = \left\{1 + \exp\left[-\ln(19)\left(CL_j - CL_{50}\right)/\left(CL_{95} - CL_{50}\right)\right]\right\}^{-1},$$

to calculate p_j, the probability that a male crab of carapace width CL_j is mature and where CL_{50} and CL_{95} are the carapace widths at which 50 and 95% of the males are expected to be mature. This equation is a reparameterised version of the logistic model, in which the traditional parameters are replaced with the parameters CL_{50} and CL_{95}. The model was fitted by maximum likelihood using a nonlinear subroutine in SPSS^{TM}.

7.3 RESULTS

7.3.1 Relationship between propodus length and body size.

Comparison of the values of the AIC and BIC, calculated by fitting each model to the logarithms of *DP* and *CW* for the males of *P. pelagicus*, demonstrated that the relationship between these measures was described better by a broken stick regression than by either a linear, quadratic or overlapping-lines model (**Table 7.1, Figure 7.1**).

Table 7.1. Estimates of the parameters (and 95% confidence limits) for the linear, quadratic, broken stick and overlapping-lines models fitted to the logarithms of the lengths of dorsal propodus versus logarithms of body sizes for *P. pelagicus*, *H. acerba* and *C. bicolor*, and values of the log-likelihood (λ) and of the Akaike (AIC) and Bayesian (BIC) Information Criteria.

		P. pelagicus			*H. acerba*			*C. bicolor*		
		Estimate	Lower	Upper	Estimate	Lower	Upper	Estimate	Lower	Upper
Linear	a	-3.003	-3.103	-2.917	-3.029	-3.196	-2.884	-1.741	-1.814	-1.656
	b	1.374	1.355	1.396	1.539	1.507	1.576	1.147	1.128	1.162
	λ	2270	2228	2314	1018	988	1058	1692	1642	1750
	AIC	-4536	-4623	-4452	-2033	-2111	-1971	-3380	-3495	-3279
	BIC	-4526	-4614	-4443	-2025	-2103	-1963	-3371	-3487	-3270
Quadratic	a	0.699	-0.154	1.732	-3.619	-5.958	-1.116	0.265	-0.986	1.756
	b	-0.374	-0.858	0.018	1.807	0.693	2.854	0.285	-0.346	0.822
	c	0.205	0.161	0.259	-0.030	-0.148	0.099	0.092	0.035	0.161
	λ	2390	2340	2461	1019	989	1058	1694	1643	1755
	AIC	-4774	-4916	-4674	-2031	-2109	-1972	-3382	-3504	-3280
	BIC	-4760	-4902	-4660	-2019	-2097	-1960	-3370	-3491	-3267
Broken stick	d	-2.384	-2.559	-2.256	-3.143	-12.916	-0.060	-1.335	-1.677	5.268
	e	1.222	1.190	1.267	1.565	0.801	4.162	1.055	-0.521	1.133
	f	1.566	1.539	1.626	1.258	0.616	1.606	1.169	1.149	1.562
	X	4.382	4.344	4.479	4.705	3.879	4.804	4.511	4.205	4.991
	$\exp(X)$	80.000	77.000	88.167	110.495	48.361	122.000	91.000	67.000	147.025
	λ	2402	2356	2463	1022	992	1062	1695	1644	1758
	AIC	-4796	-4919	-4704	-2036	-2115	-1976	-3383	-3507	-3280
	BIC	-4777	-4900	-4685	-2020	-2099	-1960	-3365	-3490	-3263
Overlapping lines	a'	-2.403	-2.583	-2.259	-2.675	-3.136	-2.223	-1.380	-2.010	-1.110
	b'	1.227	1.191	1.272	1.453	1.345	1.561	1.066	1.006	1.212
	c'	-3.891	-4.156	-3.751	-2.557	-2.891	-1.427	-1.724	-2.405	-1.358
	d'	1.566	1.536	1.623	1.438	1.199	1.511	1.144	1.070	1.279
	S_{50}	76.535	73.221	88.610	85.891	83.743	97.876	106.093	86.467	132.911
	S_{95}	77.304	74.039	91.543	86.754	84.585	104.900	107.159	87.336	134.247
	λ	2402	2357	2465	1026	996	1066	1698	1647	1760
	AIC	-4792	-4918	-4701	-2041	-2121	-1979	-3384	-3508	-3282
	BIC	-4764	-4890	-4673	-2017	-2097	-1956	-3358	-3482	-3257
		BS			Overlap			Overlap		
		BS			Linear			Linear		

However, the use of the AIC suggested that, for the males of both *H. acerba* and *C. bicolor*, the overlapping-lines model provided the best description of the relationship between the

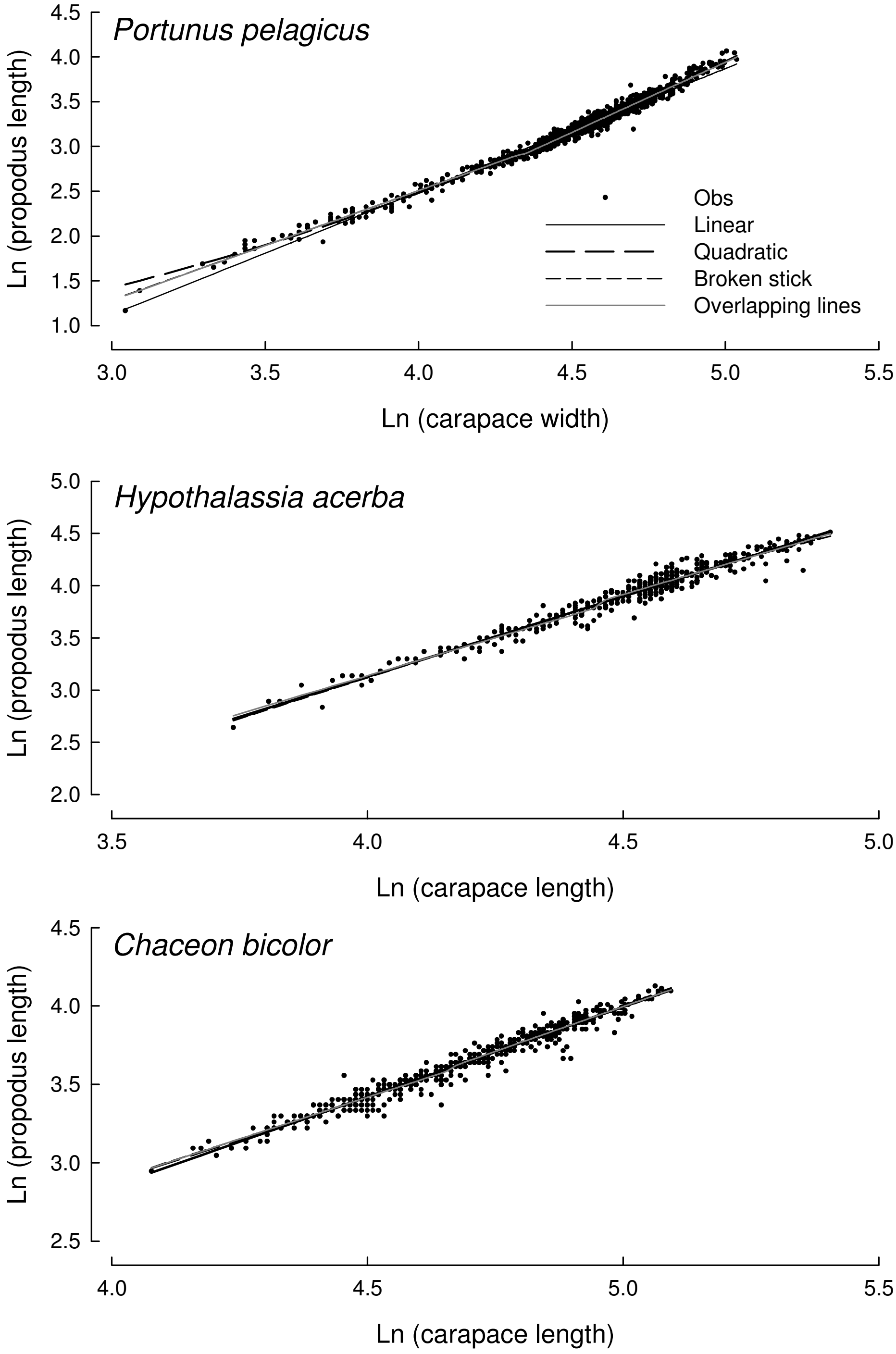

Figure 7.1. Alternative model forms (linear, quadratic, broken stick and overlapping lines) fitted to the relationship between the natural log of the length of the dorsal propodus of the largest cheliped and the natural log of the carapace width of *Portunus pelagicus* and the natural log of the carapace length for *Hypothalassia acerba* and *Chaceon bicolor*.

logarithms of *DP* and *CL*, whereas the use of the BIC indicated that the linear model was more appropriate (**Table 7.1**).

7.3.2 The probability of selecting an incorrect model form

The percentages of synthetic data sets for which each model was correctly or incorrectly identified by the AIC or BIC as providing the best description of the relationship between the ln(*DP*) and ln(CW) or ln(CL) are presented in **Table 7.2**. These data were then used to generate the posterior probabilities shown in **Table 7.3**, the implications of which are considered in the discussion.

7.3.3 Size at physiological maturity

The estimates of CW_{50} and CW_{95} for *Portunus pelagicus*, based on the percentages of male crabs with mature gonads, were 88.4 (95% confidence interval 87.8 – 89.1 mm) and 99.9 (95% C.I. 98.2 – 101.6) mm, respectively (de Lestang *et al.,* 2003a) (**Figure 7.2**). Males of *H. acerba* attain physiological maturity at a carapace length of 68.1 (95% C.I. 67.8 - 68.3) mm, and 95% are physiologically mature when they have reached a carapace length of 72.0 (95% C.I. 71.2 – 72.7) mm. For male *Chaceon bicolor*, the estimates of CL_{50} and CL_{95} were 94.3 (95% C.I. 93.7 - 94.9) and 99.9 (95% C.I. 98.2 – 101.6) mm CL, respectively (**Figure 7.2**).

7.4 DISCUSSION

7.4.1 Morphometric and physiological maturity of **Portunus pelagicus**

Our results show that, irrespective of whether the selection of model form was based on AIC or BIC, the relationship between the logarithms of the dorsal propodus and carapace width of *P. pelagicus* was described better using the broken stick approach rather than either linear, quadratic or overlapping-lines models. Although the posterior probabilities estimated for the broken stick and overlapping-lines models for this species differed only slightly, but were both

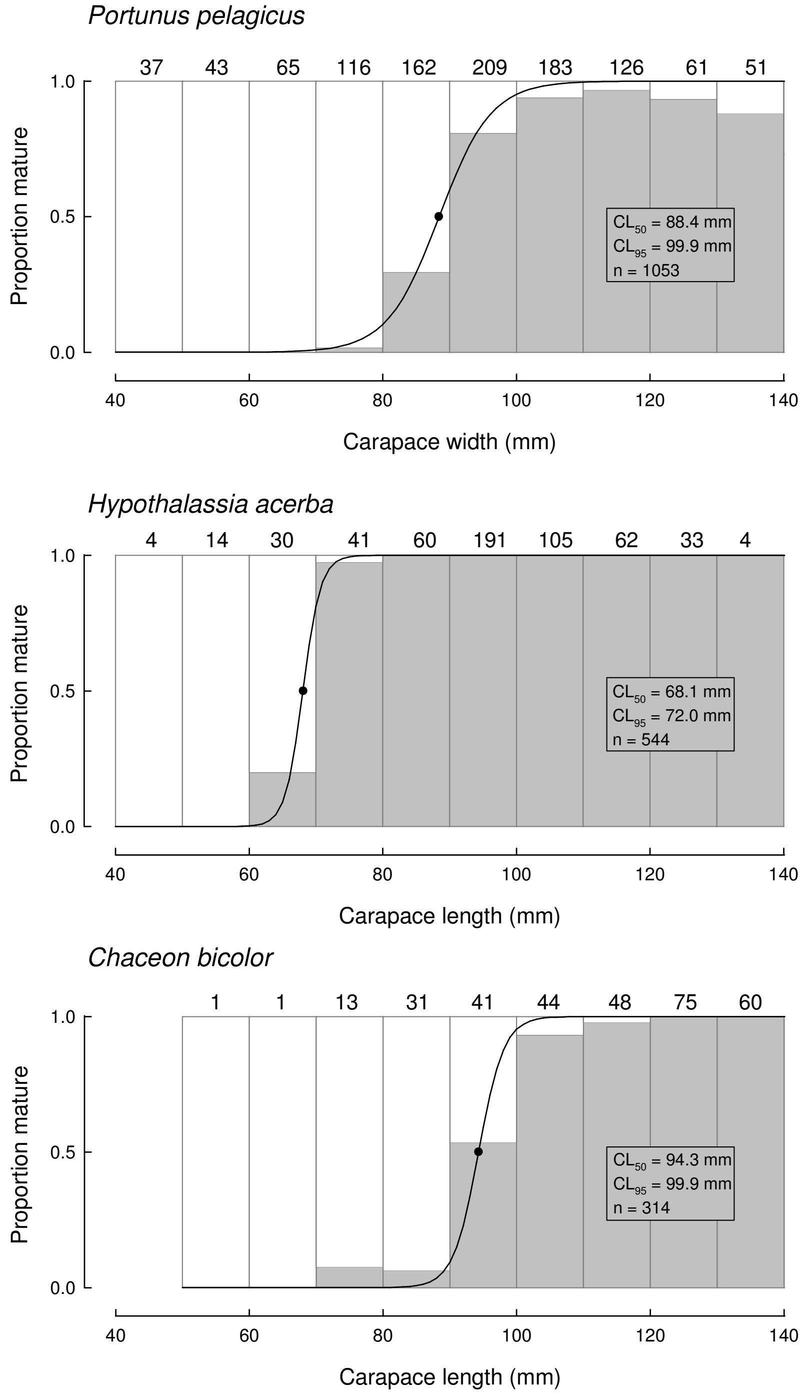

Figure 7.2. Logistic regressions fitted to the proportions of males of (a) *Portunus pelagicus* (b) *Hypothalassia acerba* and (c) *Chaceon bicolor* which at each size possessed mature gonads.

Table 2. Percentage of data sets in which, using either the Akaike (AIC) or Bayesian (BIC) Information Criterion, each model was selected as the model of appropriate complexity that best described the 200 sets of synthetic random data generated using each of the linear, quadratic, broken stick and overlapping-lines models. The correct classification is identified by the shading.

		Model used to generate synthetic data							
		Linear		Quadratic		Broken stick		Overlap	
Species	Selected model	AIC	BIC	AIC	BIC	AIC	BIC	AIC	BIC
P. pelagicus	Linear	64.5	98.5	0.0	0.0	0.0	0.0	0.0	0.0
	Quadratic	9.0	1.0	99.0	100.0	0.0	0.0	0.0	0.0
	Broken stick	21.0	0.5	1.0	0.0	85.5	100.0	72.0	99.5
	Overlap	5.5	0.0	0.0	0.0	14.5	0.0	28.0	0.5
H. acerba	Linear	62.5	98.5	44.0	87.0	7.0	35.5	2.0	43.0
	Quadratic	10.5	1.0	21.0	11.5	15.0	30.5	0.5	0.0
	Broken stick	19.5	0.5	25.5	1.5	69.5	33.5	11.0	10.0
	Overlap	7.5	0.0	9.5	0.0	8.5	0.5	86.5	47.0
C. bicolor	Linear	63.5	99.0	21.5	54.5	10.5	44.5	2.5	42.5
	Quadratic	7.5	0.5	39.5	43.5	22.5	38.5	8.5	29.0
	Broken stick	19.5	0.5	32.0	2.0	51.5	17.0	33.5	20.0
	Overlap	9.5	0.0	7.0	0.0	15.5	0.0	55.5	8.5

Table 3. Posterior probabilities of the model forms describing the allometric data for each species calculated from the fact that, using both the Akaike (AIC) and the Bayesian (BIC) Information Criterion, the broken stick model was selected as the most appropriate model to represent the allometric data for *P. pelagicus*, and that, using the AIC, the overlapping-lines model was selected as the most appropriate model to describe the data for *H. acerba* and *C. bicolor* whereas the linear model was chosen when the BIC was employed.

	Posterior probability of each model form for each species					
	P. pelagicus		*H. acerba*		*C. bicolor*	
Model form	AIC	BIC	AIC	BIC	AIC	BIC
Linear	0.117	0.003	0.067	0.373	0.109	0.412
Quadratic	0.006	0.000	0.085	0.330	0.080	0.227
Broken stick	0.476	0.500	0.076	0.134	0.177	0.185
Overlapping lines	0.401	0.498	0.772	0.163	0.634	0.177

higher than those of either the linear or quadratic models, the broken stick is less complex than the overlapping-lines model (four as opposed to six parameters) and is thus the better and more appropriate model.

From our use of the broken stick approach, it is concluded that the growth of the largest cheliped of male *P. pelagicus* clearly undergoes an inflection when individuals reach a carapace width of about 80.0 mm (95% confidence limits 77.0 to 88.2 mm). This value is ~ 6 mm less than that derived previously by de Lestang *et al.,* (2003a), *i.e.* 86.2 mm CW, when subjecting the same data to Somerton’s (1980) overlapping-lines method. However, in this context, it is relevant that the parameter estimates of the overlapping-lines model for *P. pelagicus* have been found to be very sensitive to the values selected as the upper and lower “limits” of the body sizes associated with morphometrically immature or mature individuals. Thus, the estimate derived from the previous study is unlikely to have been precise.

The males of *P. pelagicus* become physiologically mature at 88.4 mm CW (de Lestang *et al.,* 2003a), and thus ~8 mm after they have attained morphometric maturity. Thus, the males of this species would appear, at least on the basis of cheliped measurements, to have developed the potential to mate just prior to the time when their gonads become fully mature. From a management perspective, it would be appropriate to base management strategies and assessment on the size at which *P. pelagicus* has attained both morphometric and physiological maturity, *i.e.* 88.4 mm CW.

7.4.2 Morphometric and physiological maturity of **Hypothalassia acerba** *and* **Chaceon bicolor**

The values estimated for the AIC and BIC for the males of *H. acerba* and *C. bicolor* gave no consistent indication of which of the four models provides the best description of the relationship between the logarithms of the length of the dorsal propodus and CL. For both species, the value of the AIC suggested that the overlapping-lines model was best, whereas the value of the BIC indicated that the linear model was best. Since the values of the posterior probabilities that were estimated for each model showed the same inconsistency, there is a no conspicuous change in the level of allometry of the males of either *H. acerba* or *C. bicolor*, that could be related to the attainment of morphometric maturity.

The absence of both distinct changes in the patterns of allometry of the chelae of the males of *H. acerba* and *C. bicolor* and direct information on the sizes at which these deep-sea crabs are capable of mating, *i.e.* functional maturity, leaves only the size of physiological maturity as a basis for assessing the "reproductive" status of their stocks and as a measure of reproductive potential for developing management plans for these species. Thus, since *H. acerba* and *C. bicolor* become physiologically mature at 68.1 and 94.3 mm CL, respectively, it would be appropriate for managers to consider these lengths when reviewing management plans involving the use of a minimum legal size.

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9.0 BENEFITS

Managers now have the reliable data on the following which will enable them to produce much more effective and appropriate methods for managing the resources for the deep sea crabs *Hypothalassia acerba* and *Chaceon bicolor* (see 11.0 Planned outcomes).

1. Trends exhibited by annual and monthly catches, effort and catch per unit effort for *H. acerba* and *C. bicolor* on both the lower west and south coasts of Western Australia.
2. The distribution of *H. acerba* and *C. bicolor* by water depth and temperature.
3. The reproductive biology of *H. acerba* and *C. bicolor*.
4. Demonstration that some traditional approaches for estimating the size at maturity of *H. acerba* and *C. bicolor* are inappropriate and this may be the case for some other crustacean species.

The data will also enable fishers to make more informed decisions regarding investment in fishing for *H. acerba* and *C. bicolor*.

10.0 FURTHER DEVELOPMENT

Once the final report has been accepted by the FRDC, it will be provided to the Western Australian Department of Fisheries. Thus, when developing management plans for *H. acerba* and *C. bicolor*, fisheries managers will be able to take into account the annual and monthly trends exhibited by the fisheries catch and effort statistics and the quantitative information on key aspects of the biology of these two deep sea crab species. The final report will also be provided to WAFIC and professional fishers for deep sea crabs.

A poster will be produced describing the main findings of this study. An account of these findings will also be supplied to PROWEST so that professional fishers are made aware of the results and their implications.

11.0 PLANNED OUTCOMES

The implications of our results will require managers to consider the following when they are reviewing plans for the management of *H. acerba* and *C. bicolor*.

1. Estimates of the size at maturity of males should be based on physiological (gonadal) maturity.
2. Estimates of the size at physiological (gonadal) maturity of females are likely to be artificially low.
3. Values selected as the minimum legal sizes for retention of *H. acerba* and *C. bicolor* are likely to be based on the sizes at physiological maturity of males and females of these species. However, since estimates of the sizes at physiological maturity of males and females are likely to be low, an adaptive approach will be required to ensure that the numbers of mature crabs are maintained at a level sufficient to sustain the stocks.
4. Protection should be considered for the assemblage of *H. acerba* on the south coast as there is strong evidence that females in these waters do not typically reach maturity and apparently move to the west coast for breeding.
5. Restriction of both *H. acerba* and *C. bicolor* to a narrow depth range makes these species particularly subject to depletion through focussed fishing.
6. As the *H. acerba* and *C. bicolor* that are caught in traps appear to have approximately attained their asymptotic body size, yield per recruit will be an asymptotic function of fishing effort (of a form determined by the Baranov catch equation). Similarly, spawning biomass per recruit will decline exponentially with fishing effort. Since natural mortality cannot be estimated, it is impossible to estimate the value of fishing mortality from the available data. However, the implications of declining spawning biomass per recruit with fishing effort is that catch per unit of effort (CPUE) will need to be sustained above some reference value determined from either the virgin CPUE or

from historical levels of CPUE. Thus, decision rules for the fishery will need to be based on CPUE rather than being model-derived estimates of fishing mortality or biomass.

7. If CPUE is to be used as the primary indicator for fisheries management decisions, factors that increase the efficiency of fishing effort will need to be carefully monitored. The potential for spatial depletion also exists and CPUE will need to be estimated appropriately.
8. Although there are no data on growth or mortality, evidence from other deep sea crab species suggest that *H. acerba* and *C. bicolor* are likely to be slow growing and long-lived. Thus, minimum legal size regulations are very likely to be inadequate unless they are accompanied by management strategies that ensure that the stocks of mature crabs are sustained at adequate levels. Since such slow growing and long-lived species are likely to be prone to becoming part of boom and bust fisheries, there is a need for constant monitoring to ascertain whether, at any stage, their catch statistics are deviating from those recorded during more recent years and thus provide evidence that the abundance of the stocks are declining. There is a strong need to consider the specification of appropriate limit and target reference points for the estimates of catch per unit of effort and for the implementation of appropriate decision rules, based on current estimates of catch per unit of effort, that will ensure that the stocks of *H. acerba* and *C. bicolor* are conserved. The decision rules should ensure that, as catch per unit of effort approaches the limit reference point for this variable, exploitation is reduced appropriately.

12.0 GENERAL CONCLUSIONS

We have met the vast majority of the objectives listed in the original applications for FRDC 2001/055 and those that were our obligations for FRDC 2001/055. Please note that work associated with objectives 1, 4, 7, 8, 9 and 10 of the second proposal (FRDC 2001/055) is being undertaken by the Western Australian Department of Fisheries. The results of that work will be produced by that department in a separate final report after that project has been completed on 30 June 2005.

The only objectives we were unable to meet in FRDC 2001/055, which focused on the champagne crab *Hypothalassia acerba*, were Objectives 2 on growth and 7 on diets. Because small crabs were unable to be caught using traps, there was insufficient information in the length composition data to allow determination of the growth of individuals of either species. Without such life history data, no estimates are possible of the longevity of the individuals of either species and hence of their natural mortality. As the length composition data reveal no change that can be related to growth, yield per recruit of each crab species will increase asymptotically towards the average body weight of the individuals caught in the traps as fishing effort increases. Since the females that are caught in the traps are likely to represent the mature individuals of the stocks, the spawning female biomass per recruit of each species of crab will decrease exponentially with increasing fishing effort. The rate of increase of yield per recruit or decrease of biomass per recruit will be determined by the level of fishing mortality relative to the level of natural mortality. However, neither of these mortalities can be determined from data that can currently be collected for these species.

The diets could not be elucidated because the dietary items in the stomachs had become too decomposed for identification by the time they were examined in the laboratory. All of the objectives of FRDC 2001/055, which focused on the champagne crab *Chaceon bicolor*, were achieved. Attention is drawn to the fact that we have demonstrated that, for both *H. acerba* and *C. bicolor*, the traditional method for determining the size of males at morphometric maturity is not valid. This raises the strong possibility that, in the case of some other species, inappropriate methods may have been used to determine this important variable, which is widely used by fisheries managers when developing management plans. Likewise, we have demonstrated that the use of trap samples leads to underestimates of the size at maturity of *H. acerba* and *C. bicolor*. Although far better estimates can be obtained for the size of female portunids at maturity by using data from active methods of fishing, *e.g.* seine netting and trawling, these methods were not available for collecting *H. acerba* and *C. bicolor* from the deep waters in which these crabs live.

During this study, we have described the catch, effort and catch per unit for *H. acerba* and *C. bicolor* since the inception of the fisheries for those species on the lower west and south coasts of Western Australia. We have also studied the biology of those species, placing particular emphasis on determining their distribution and the factors influencing their distribution, and (2) the key aspects of the reproductive biology as they relate to management. The major findings are as follows.

- The fishery for *Hypothalassia acerba* in south-western Australia commenced in the early 1990s and peaked in 1998, with catches of ~73 000 kg. The catches subsequently declined due to fishers on the lower west coast switching their effort to catching *Chaceon acerba*. A decline in effort for *H. acerba* on the lower west coast was partially compensated for by an increase in effort on the south coast.
- The catch per unit effort for *H. acerba* has declined in recent years, suggesting that fishing might have had a detrimental influence on the stocks of this species.
- The catches of *H. acerba* on the south coast underwent a cyclical change during the year, declining to minimal levels between late autumn and mid-spring, largely

reflecting a decline in effort due to the harsh weather conditions that prevail in that period.

- The catch per unit effort of *H. acerba* on the lower west coast rose progressively from April to November, suggesting that this species gradually became more abundant and/or accessible to fishing in that period.
- The fishery for *C. bicolor*, which has been almost entirely based on the lower west coast, essentially commenced in 1997. Catches subsequently rose to reach a peack of 222 500 kg in 2000 and remained close to this level in the ensuing years.
- The sharp rise in the annual CPUE during the early years of the fishery probably reflects an increasing knowledge by fishers of the best areas to fish.
- The commercial catches of the males of both *H. acerba* and *C. bicolor* outnumbered those of their females.
- The size of the males caught by traps was greater than that of females in the case of both *H. acerba* and even more particularly *C. bicolor*.
- Traps did not catch many individuals of either *H. acerba* or *C. bicolor* which had a carapace length <80 mm, even when the traps were covered in a fine mesh.
- The catch rates of *Hypothalassia acerba* peaked in water depths of 200 m on the lower west coast and at 145 m on the south coast and in temperatures of ~16-17ºC on both coasts.
- The size (carapace length) of *H. acerba* decreased slightly with increasing water depth.
- *Hypothalassia acerba* reproduces seasonally on the lower west coast, with egg extrusion occurring mainly in summer and early autumn. Since *H. acerba* does not typically appear to reproduce on the south coast, it is proposed that, maturing females migrate to the lower west coast.

- In contrast to *H. acerba*, *C. bicolor* reproduces throughout at least most of the year. This continuity of reproduction probably reflects the occupancy by this species of deeper waters than *H. acerba* and thus an environment which undergoes less conspicuous seasonal changes.
- Although the mean body weights of ovigerous females of *H. acerba* (587 g) and *C. bicolor* (652 g) were not significantly different ($P > 0.05$), the fecundities of these two species, *i.e.* 356, 210 and 192, 979, respectively, were significantly different. The relatively high fecundity of *H. acerba* may reflect an adaptation of this seasonal spawning species to optimise egg production.
- The passive sampling method of trapping was the only method available for catching *H. acerba* and *C. bicolor*. We thus used data collected for *Portunus pelagicus* using both the above passive fishing method and the active fishing methods of seine netting and trawling to determine whether they yielded comparable data for estimating the size at maturity of female crabs. The trap caught samples contained predominantly mature crabs and were thus biased, leading to an underestimate of the size at maturity. It is reasonable to assume that the estimates of maturity of *H. acerba* and *C. bicolor* using data derived from trap-caught samples are likewise underestimates. This point will need to be taken into account by managers when they are developing management plans for *H. acerba* and *C. bicolor*.
- We have demonstrated that the chelae of the males of *H. acerba* and *C. bicolor* do not undergo a detectable change in allometric growth at the pubertal moult. Thus, it is inappropriate to use the traditional method, which is based on this assumption, to determine the size at morphological maturity. Managers will thus have to use the size at 50% of females when they attain physiological maturity, *i.e.* 68.1 and 94.3 mm carapace lengths, respectively.

13.0 APPENDICES

Appendix I

Intellectual Property

The value of the intellectual property will be 54.38% based on PART C of the FRDC project proposals.

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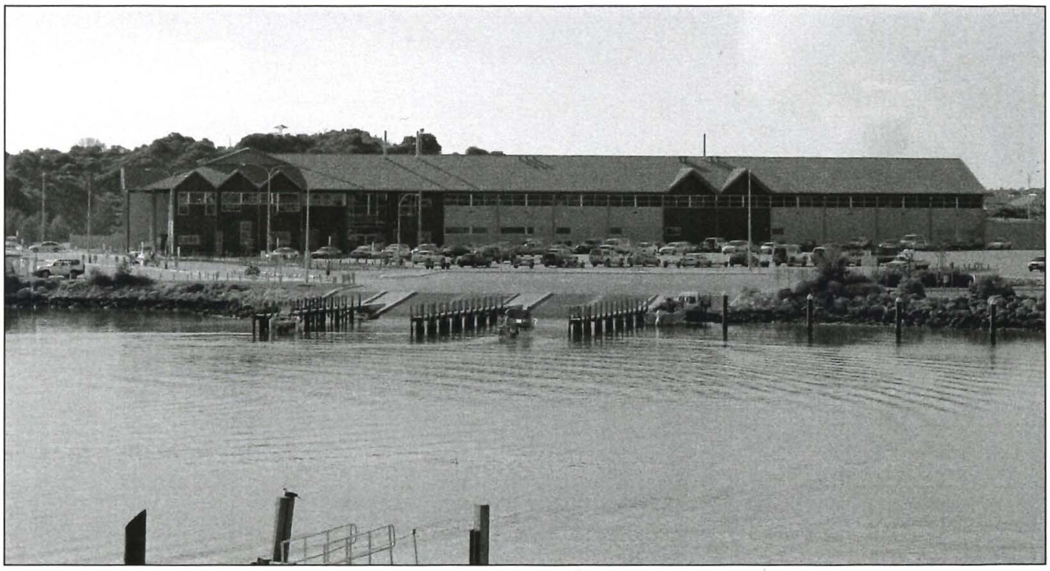
Dr Alex Hesp

Dr Simon de Lestang



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