FRDC FINAL REPORT

DEVELOPMENT OF THE TOOLS FOR LONG TERM MANAGEMENT OF THE GIANT CRAB RESOURCE: DATA COLLECTION METHODOLOGY, STOCK ASSESSMENT AND HARVEST STRATEGY EVALUATION

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November 2007

FRDC Project No. Project 2001/042

Australian Government

Fisheries Research and Development Corporation

National Library of Australia Cataloguing-in-Publication Entry

Author:	Gardner, Caleb.
Title:	Development of the tools for long term management of the giant crab resource - data collection methodology, stock assessment and harvest strategy evaluation : tools for giant crab assessment/ authors, Caleb Gardner ... [et al.].
Publisher:	Hobart : University of Tasmania, 2007.
ISBN:	9781862954311 (hbk.)
Notes:	Includes index. Bibliography.
Subjects:	Crabs--Australia. Crab fisheries--Australia--Management. Fish stock assessment--Australia--Research. Fisheries--Australia--Research.
Dewey Number:	333.95556

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2001/042 Development of the tools for long-term management of the giant crab resource: data collection methodology, stock assessment and harvest strategy evaluation.

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OBJECTIVES:

1. To develop a low cost, long term, giant crab resource assessment and data collection methodology.
2. To quantify biases in the historical logbook data to increase its value for resource assessments.
3. To obtain industry's understanding/observations of basic biological and market processes (eg. moulting, egg-bearing, mating, migration, beach price influences) and how their fishing effort is adapted to this knowledge (eg. targeting of size classes, seasonality of effort, etc.).
4. To develop the ability to investigate alternative harvest strategies (sustainability of different TACs; closed seasons etc.).

NON-TECHNICAL SUMMARY:

OUTCOMES ACHIEVED TO DATE

The project has developed tools for low cost assessment of the giant crab resource across southern Australia.

Stock assessment and management response is now increasingly based on biomass estimates from this project. Risk of poor management decisions is thus reduced, which contributes to greater business certainty.

This project was constructed with the awareness that the resource was small and the fishery would have little ability to fund expensive data collection systems in the future, beyond catch rate data from logbooks. Size structure data from the fishery was considered the main data type to be valuable for ongoing assessment, but also expensive to collect. Fishers have adopted electronic calipers combined with an electronic data logger, the solution developed in this project. This system has dispensed with paper records so that work at sea is easier, and costs for data management (e.g. data entry) are reduced.

Specialised software was developed for conducting model runs to facilitate altering parameters, running a range of alternative scenarios, and plotting

outcomes.

Giant crab stock assessments are utilizing outputs from this model. The fishery performance indicators in Tasmania are being re-written in a new management plan to formalize the adoption of the model outputs.

The improvements in stock assessment processes through this project have contributed to approval for export and consequently the maintenance of higher beach price than could be obtained from local markets. Business planning and investment has been assisted by greater certainty in management structures for the fishery.

KEYWORDS: giant crab, *Pseudocarcinus gigas*, harvest strategy, population model, data collection.

ACKNOWLEDGMENTS:

This project was completed with the help of numerous people. Most significantly, Michel Bermudes completed much of the database review and analysis of serial depletion, David Mills worked on methods for ongoing data collection, and Andrew Levings made available extensive tag recapture and size structure data, which was vital for the development of the stock assessment model. Many fishers participated in data collection and providing information/observations about their operations including Bill Tober, John Hammond, John Hammond Jr., Charles Willis, Theo Hairon, Mick Stacy, Michael White, Roger Fox, Shannon Churchill, John Cull, Sam Greg and Ross Wisby.

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1. Background

1.1 Development of the fishery

Giant crabs have been collected as bycatch of the rock lobster fishery since the late 1800's although in small volume. A royal commission into the state of Tasmanian fisheries in 1882 concluded that though they were a splendid animal, they were only brought to market occasionally and were not of much commercial importance (Saville Kent, 1882). At around the same time in Victoria, McCoy (1889) reported that giant crabs, especially females, were occasionally brought to market and were especially common along the Victorian coast near Portland. This is the region where most of the Victorian catch is harvested today, which demonstrates that fishers were rapidly able to locate productive grounds. William Saville-Kent was appointed fisheries commissioner in 1882 and was keen to see the harvest of crustaceans diversified to provide greater variety of seafood to the developing Tasmanian colony. He was exasperated by the reluctance of lobster fishers to use gear other than rings because this limited crab catch and wrote:

"*The use of crab pots, as utilised in almost every other country on the face of the globe, might be advantageously recommended to the fishermen of Tasmania*" (Saville-Kent, 1884).

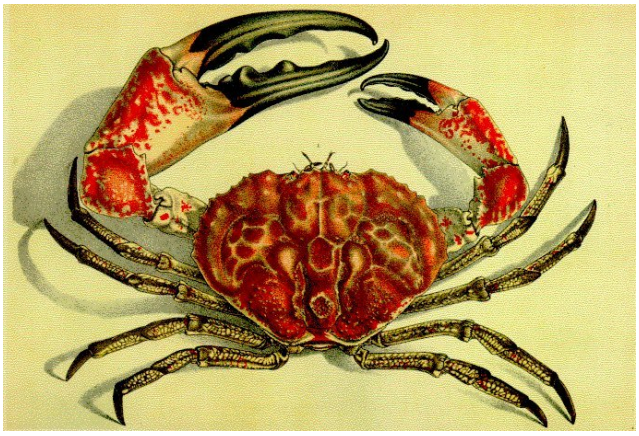


Figure 1. Male giant crab landed in the Victorian fishery, McCoy (1889).

The potential for expansion of the giant crab fishery was evaluated in the 1970's through two projects: "Development of Small Scale Invertebrate Fisheries in Tasmanian Waters" (by the Tasmanian Fisheries Development Authority; Sumner and Dix, 1980); and "Experimental Trapping of the Giant Crab *Pseudocarcinus gigas*" (by the Fisheries and Wildlife Division, Victoria; Winstanley, 1979).

The Tasmanian project, headed by Colin Sumner and Trevor Dix, was funded by the predecessor of FRDC. That research concluded that there was potential for development of a fishery for giant crabs, primarily as bycatch from the rock lobster

(*Jasus edwardsii*) fishery, rather than as a targeted species. The development of a fishery was considered to rest on marketing because prices were generally too low to warrant fishers retaining giant crabs (20c/kg, 1977/78). Crabs were processed by hand picking the meat and marketing trials were also made with whole cooked crabs.

Although rock lobster fishers took most crab bycatch, trawlers also captured some giant crabs on muddy substrates and these were generally discarded. Crabs collected by rock lobster fishers were often smashed so that they could be removed more easily from the wicker lobster pots and also because they were considered to interfere with the entry of rock lobsters (Sumner and Dix, 1980).

Research conducted to improve live transport of rock lobsters in the late 1980's allowed processors to gain higher prices for live rock lobster exports to Asia. The improved methods also enhanced survival of giant crabs so that they could be sold for far higher prices than was previously possible (VDCNR, 1995a). This opened the way for the development of a giant crab fishery as processors began to offer prices that were high enough to allow large vessels to fish the deeper waters at the edge of the continental shelf profitably (Yasuhara, 1995). Tasmanian catches grew from 133 kg in 1990 to 243 tonnes in 1995 and Victorian catches also increased dramatically (VDCNR, 1995b; TDPIF, 1995). As the market became increasingly aware of giant crabs, prices steadily climbed. The higher prices were based on the red colour of giant crabs, rather than their large size, as small crabs of less than 3 kg could receive considerably more than crabs greater than 5 kg (on a per kg basis).

By the late 1990's, giant crab fisheries off South Australia, Victoria and Tasmania had stabilised to become small operations with most catch taken by only a handful of fishers in each state. Fishers targeting giant crabs operate in deep water around the shelf break at 150-350m (Levings *et al.*, 1996).

Management measures have evolved as the crab fisheries have grown and stabilised. Controls have been largely adopted from those for rock lobster. Access to the fishery has been largely based on ownership of a rock lobster license with associated constraints such as limited entry and gear limitations. Trap design has been restricted based on rules developed for rock lobsters. Input controls of closed seasons and restrictions on the taking of berried females largely mirror those for lobster. Minimum size limits were developed based on limited information early in the fishery and have remained unaltered at 150 mm CL. Individual transferable quota was introduced to prevent unsustainable levels of effort being shifted from quota managed rock lobster fisheries, although initial TAC levels appear to have been set too high for sustainability.

1.2 Project development

This project provided giant crab resource managers with the tools for conducting stock assessments in the future on small budgets. It was based largely on collating and utilising existing catch and effort data. It also involved the collection of new data by fishers and the construction of a stock assessment model. The stock assessment model

will assist in identifying research needs or information gaps in the fishery, that when filled will improve the accuracy of model estimates.

Giant crabs are distributed all across southern Australia. The fishery is concentrated in Victoria and Tasmania where over 70% of the total yield is caught, equivalent to a GVP of around $4.5 million per annum. Both States have implemented management that incorporates individual transferable quota. Total allowable catches (TACs) in each State were initially based on a proportional reduction in catch from that being taken when the fisheries were managed by input controls alone. Little stock assessment data was available for the setting of initial TACs.

The project was directed to research needs identified by the Tasmanian Crustacean Fishery Advisory Committee and the Tasmanian Crustacean Research Advisory Group. The issues identified by these groups fell within the FRDC program of Natural Resource Sustainability. Specifically, the research addressed strategies of "*stock assessment methods – to increase and apply knowledge of stock assessment methods*" and "*fisheries and ecosystems management methods – to increase and apply knowledge of sustainable fisheries and ecosystem management methods*".

1.2.1 Relationship to the FRDC strategy: stock assessment methods

While the setting of TACs on the basis of previous catches appeared to be a prudent and conservative management measure, it was crude for long-term management. Modern management aims to be responsive to changes in the fishery so that TACs are based on the state of the fishery. In giant crab fisheries, TACs aims to balance maximising yield with ensuring long-term sustainability. There is also the need to assess the impact of management changes and to monitor the resource over time.

Stock assessment is fundamental for sustainable management of any fishery, and is perhaps especially important in longer lived/slower growing species such as giant crab. This is because any error in management will take many years to reverse. The Department of Environment and Heritage (DEH), in this fisheries EPBC strategic assessment, has noted the need for effective assessments of giant crab to fulfil requirements for export.

The ability of fisheries agencies to conduct stock assessments and to evaluate management strategies was discussed by participants at a giant crab workshop organised by DPIWE (Tasmania) and held in Adelaide, November 1998. Stock assessment was considered crude in all States as it relied solely on catch rate data collected through fishers logs. At the time this project commenced, performance measures had only been defined in the Tasmanian giant crab management plan and were based on trends in non-standardised commercial catch and effort data (CPUE), and data from processors on the size of crabs landed. No State had a stock assessment model or used data from sources other than commercial logs for stock assessment.

Commercial logbook data is generally of great value for assessments but there were specific concerns with giant crab due to possible biases that may have been unrelated to crab abundance. For example, fishers often captured crabs as bycatch during lobster fishing operations so that effort directed to crab fishing was difficult to quantify. Other

suspected biases of raw CPUE data in the giant crab fishery included historical changes in fishing region, historical changes in fishing skill and gear, variation in soak time, seasonal variation in catchability, indications of depth migration, depth stratification of size classes, effort targeted at smaller crabs, errors in the reporting of effort, and susceptibility of any trends to the influences of individual fisher behaviour as few participants were involved. Assessments at the time recognised that these possible biases existed, but it was not possible to assimilate them without catch rate standardisation and analysis through a stock assessment model.

Four main areas that required research to improve the assessment of giant crabs were identified at the Adelaide workshop and in subsequent discussions between researchers, fisheries managers and industry and are as follows:

(1) Improved understanding of giant crab biology was required, especially in aspects that may influence data collected for stock assessment (e.g. growth). It was anticipated that progress could be made in this area through compiling industry knowledge.

(2) Errors in earlier catch and effort records were problematic for assessments in Tasmania and Victoria. Part of this was believed to be associated with deliberate misreporting of effort.

(3) The construction of a stock assessment model that combined data from a range of sources would assist assessments. An assessment model was also required to evaluate alternative harvest strategies with immediate application in the setting of TACs.

(4) Although a range of data was collected through compulsory logbooks, size structure data required additional sampling.

Research was required to evaluate low cost yet effective options for collecting this data on an ongoing basis. It was also noted that there was commitment from all three states to align data collection and management methods.

1.2.2 Relationship to the FRDC strategy: fisheries and ecosystem management methods

The project developed a stock assessment model as a tool for evaluating different management methods and options. The most important application was for evaluating alternative TACs, although other issues such as the harvest of females with eggs or alternative maximum size limits were also discussed. The model is fitted to data from several sources, most importantly catch rate and length-frequency data.

Information relating to the interaction of the crab fishery with the ecosystem was collected where possible including monitoring bycatch and determining the spatial distribution of fishing effort.

1.3 Building on previous research

Considerable resources had been directed to giant crab research prior to this project, primarily through the Universities of Deakin and Tasmania. Much of that previous research was used in the research described here, especially in defining parameters in the assessment model. Examples included weight/length relationships, length/ fecundity relationship, reproductive patterns and information on growth. Tag recapture data from research at Deakin University by Andrew Levings and colleagues were reanalysed for growth analyses where previous analyses were limited by insufficient tags. Records of population structure from earlier in the fishery were also important.

Previous modelling research was undertaken by Rick McGarvey, Janet Mathews and Andrew Levings (FRDC 1993-220; 1997-132). That modelling was a complex extension of egg- and yield-per-recruit modelling that developed options for dealing with some of the unique aspects of giant crabs, in particular their extended intermoult, which can span several fishing seasons. Management applications of that modelling included evaluating size limits and seasons on stocks and fishery economics (Levings *et al.*, 2001; McGarvey *et al.*, 1999).

Much of the earlier research relied on sampling aboard commercial vessels by observers. That sampling involved collecting data to examine a broad range of biological issues. For the research conducted in this study, we were focused on collecting length-frequency data for stock assessment. Although observer sampling provides accurate length-frequency data, it is expensive and was considered unsuitable for ongoing monitoring of the fishery. This was because the number of animals captured per day by commercial fishers was typically less than 80. In contrast, observers in Tasmanian rock lobster fishery catch sampling often measure over 2000 animals per day. Difficulty in accessing crab vessels also increases the cost of deploying observers so that alternative sampling techniques were required to those used previously.

It was considered that the key to obtaining low cost length-frequency data in the future was industry participation. A quick, simple and targeted process was required for fishers to participate in sampling . For this reason, data collection was restricted to recording only length and sex. Relationships with fishers that were established through previous research assisted in developing methods.

2. Need

This project was initiated to develop stock assessment procedures for giant crab. The ability to conduct stock assessments of the giant crab resource and to evaluate management strategies is fundamental for sustainable development and management of the giant crab resource.

Stock assessment of giant crab across southern Australia is a requirement for state management and is also required to meet federal expectations on export of wildlife under Schedule 4 of the Wildlife Protection Act. Our ability to conduct assessments was limited by the data and analytical tools that were available.

Agencies involved in managing giant crabs require information on the setting of meaningful fishery performance indicators, and they also require the ongoing collection of information to evaluate these indicators. It is important to have the ability to track changes in biomass (or an index of biomass), recruitment of sized animals into the fishery, and reproductive output. Managers require information on how to balance the goals of optimising yields and ensuring adequate reproductive output is maintained.

Each of the States uses ITQ plus a series of input controls including a minimum legal length. The similar structure of management presents an opportunity for pooling of assessment resources – including the development of a general giant crab model. Management needs in each state are similar as they require information on the size of the current stock plus advice on alternative harvest strategies, in particular the effect of different size limits and TACs.

A low-cost approach was the over-riding requirement for the assessment of giant crab fisheries. Because the fishery is low-value, biologists conducting future assessments will have access to only limited levels of funding. Future assessments will need to rely on commercial logbook data and the industry data collection methods developed through this proposal.

3. Logbook data validation and correction

3.1 Introduction

Historical datasets on the crab fishery contained numerous aspects that could bias future assessments of the fishery. These included structural problems in catch and effort data base (such as for calculated shot weight based on vessel unloadings), deliberate mis-reporting of effort, data-entry errors and biases in catch rate data from crabs taken as bycatch in lobster pots. Correcting this data was an important first step in the project.

3.2 Methods

3.2.1 Tasmania

Historical catch and effort data from the Tasmanian giant crab fishery is split into three series and stored in different databases. These series are the pre-1995 records (monthly catch with no record of effort), 'General Fish' logbook records from 1995 to 1999 entered in the 'General Fish' (GF) database, and current giant crab logbook records from 2000 until now entered in the 'Integrated Catch and Effort' (ICE) database. Pre-1995 data cannot be used in catch per unit effort standardisation given the absence of effort recording at the time. Audits were conducted on the GF and ICE databases to check the integrity of the data to be used for standardisation and assessment purposes.

Audit of the GF database (5422 records)

An overall 18.1% of the GF database records (~1 in 5 records) contained entry errors. Entered records, which had a high CPUE, were more likely to be the result of entry error than records with low CPUE (Figure 2). Searches based on outliers with abnormally high CPUE were effective in detecting a large number of data entry errors. Other types of entry errors, which were corrected or excluded, were:

- grouped entries: the catch for a fishing trip comprising several shots (as shown on original records) was reported as one shot with one set of traps. Given the reduced effort this resulted in very high CPUE;
- double entries;
- entries for other species (eg. spider crabs);
- misreporting of effort: three fishers were identified as consistently under-reporting fishing effort. No solution to this problem could be found so their records were excluded from further analysis, and
- the absence of species targeting information: this information is essential for further analysis in order to distinguish between fishers targeting crabs and fishers reporting crabs as bycatch. In the GF database, targeting was first set according to fishing

depth (in ICE, 95% of records by fishers targeting crabs were deeper than 173 on the east coast and 131 on the west coast) and refined by looking at soaktime, fishers' fishing history and catch rate.

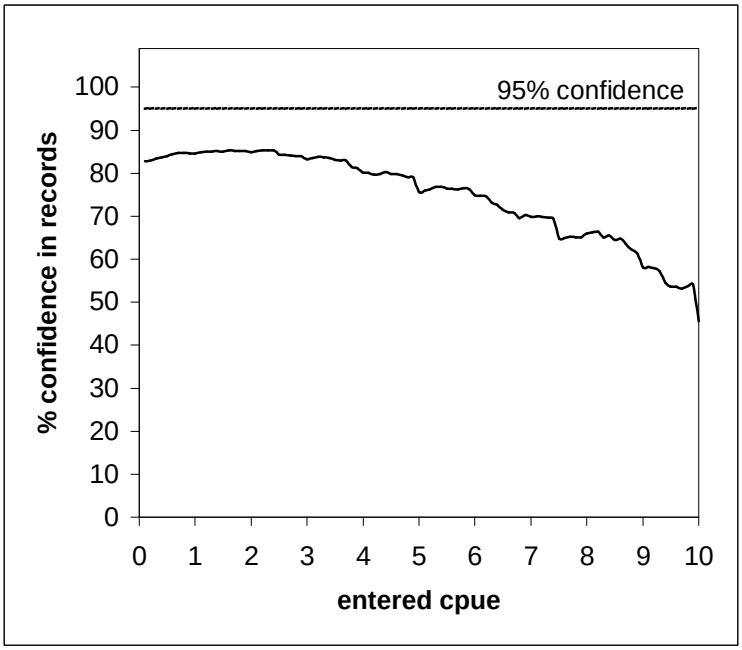


Figure 2. Accuracy (confidence) of records in the General Fish Database producing a CPUE ranging from 0.1 to 10 prior to audit.

Audit of the ICE database (5674 records)

The audit of the ICE database had direct implications for modifications of the current recording system. The problems identified in ICE included:

- discrepancies between the numbers of crabs caught by fishers (recorded in ICE) and the number of crabs unloaded (recorded in the 'Quota Management System' database);
- a significant number of vessels with low trap numbers (eg. 1 – 5, where fishers were actually indicating number of longlines rather than number of traps per longline);
- unusually high or low average weights for certain areas at various times; and
- unclear distinction between records when fishers were targeting crabs or reporting bycatch.

Comparison between records from the giant crab catch and effort database (ICE, Nov 1999 – Feb 2002) and the QMS (quota management system) database highlighted data entry errors and discrepancies in unloading data. This identified missing data, which has now been entered into ICE, and identified errors have been corrected. The changes

resulted in a net increase in the total number of crabs retained from 69,070 to 71,990 and the number landed from 66,774 to 71,634; after correcting, the difference between the recorded number kept and the recorded number unloaded was small (n=356, 0.5%).

Total landed weight of crabs has increased from 226,000 kg to 244,500 kg. The absolute difference in numbers of crabs caught (ICE) and landed (QMS) was 1592 crabs with a net difference of –452 crabs. The net difference in landed weights between ICE and QMS has been reduced from about –22,000 kg to –3,100 kg; the gross difference has been reduced from 23,604 kg to 4,538 kg. Total fishing effort has increased from a pre-audit level of 97,848 pots @ total soak time of 185,180 pot days to a post-audit level of 105,629 pots @ 201,264 pot days.

Following this review, very few entry errors were subsequently found in ICE, and entered records matched original logbook records with an overall 98.5% confidence. However, the need for a flag was identified for records with a CPUE above 4.6 as these are likely (more than 5% chance) to be the result of entry errors (Figure 3) and should be checked against originals.

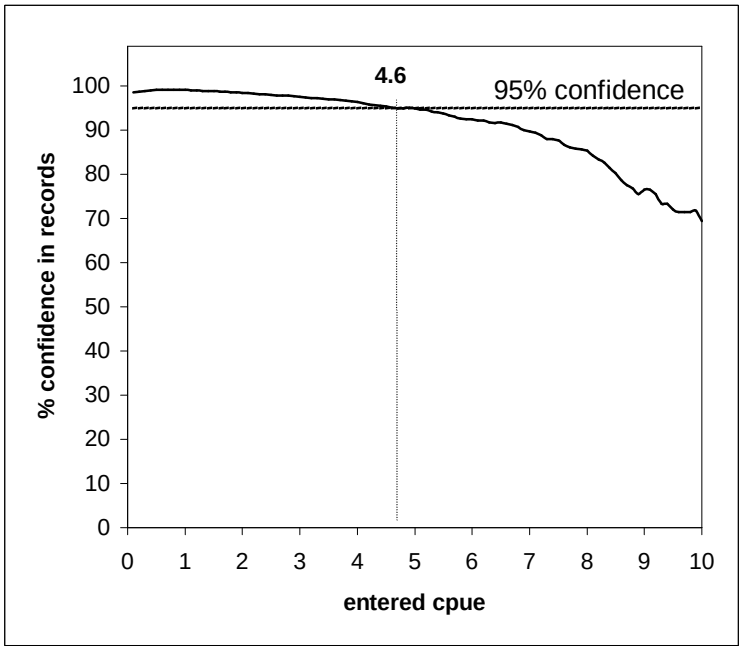


Figure 3. Accuracy (confidence) in records for entries in ICE producing a CPUE ranging from 0.1 to 10 prior to the audit. All records with a CPUE above 4.6 were checked against original logbooks.

Proposed changes to logbook data collection

Following the identification of problems in data collection and management, a number of changes to the logbook and ICE database were proposed to:

- aid fishers in correctly calculating the number of fish caught during a trip,
- reduce fisher confusion over the number of traps entered per location,

- account for discrepancies between number of crabs caught and unloaded (ie. 'missing crabs'),
- identify and quantify the sources of 'missing crabs' (mortalities, returns to sea, personal possession), and allow for the weight of crab unloadings to be distributed among the precise locations where crabs were caught;
- allow for crab targeting to be recorded for each shot.

A revised logbook was introduced in 2006.

Some modifications to the ICE database were made to improve future data entry; most significantly, the calculation of catch weights for discrete sets has been incorporated, which allows for the distribution of landed weights to the precise locations where crabs were caught. The source of some other errors was systematic and continued to occur in the ICE database so that this exercise needed to be repeated in 2004. Recommendations to correct the database were provided to DPIWE.

Effect of the data correction process

The audit of the Tasmanian giant crab fishery records resulted in marked changes in the trend in catch rate with the various time-series becoming more stable (Figure 4 and Figure 5). Trends in data now appear less erratic, which provides confidence that the data audit has been successful. It is also noteworthy that the proportion of data that can be utilised in assessments increases in more recent years (Figure 5).

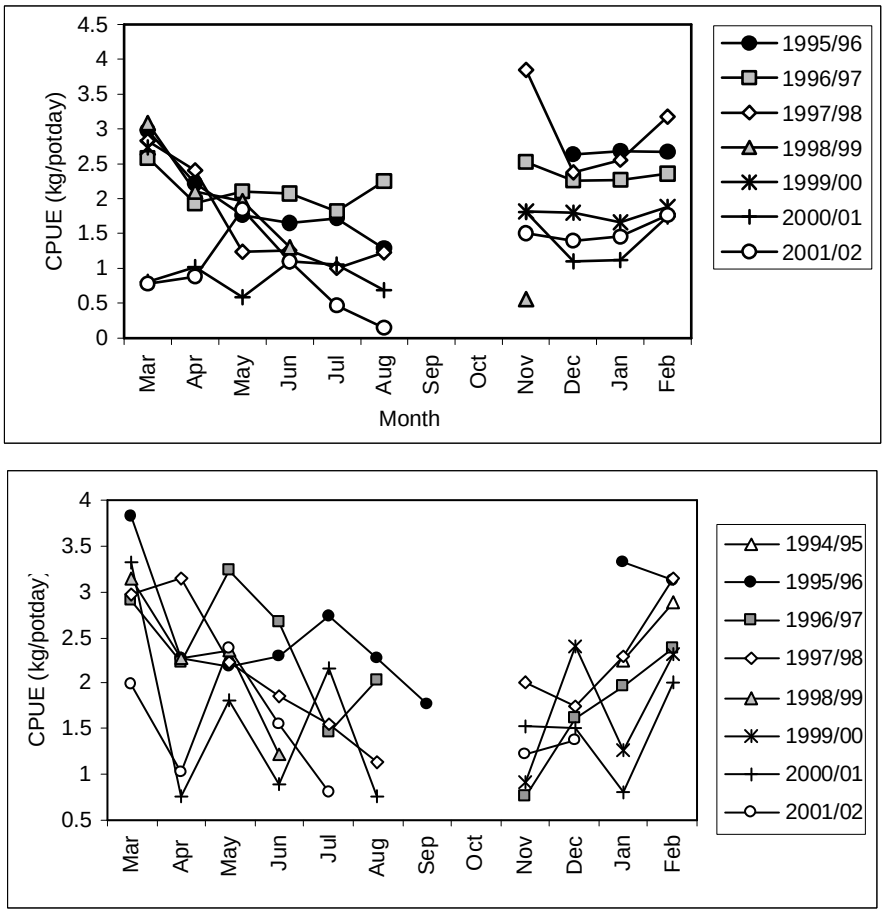


Figure 4. Seasonal patterns in CPUE since 1995. The upper plot shows values from data after correcting for database errors as described in text. The lower plot shows the same information, but generated with the catch and effort data available for the previous giant crab assessment. Note that the process of correction of errors has improved the signal to noise ratio – so that seasonal patterns more indicative of the biology of giant crabs have become apparent. For example, catch rates in November now appear higher, which is consistent with the opinion of fishers.

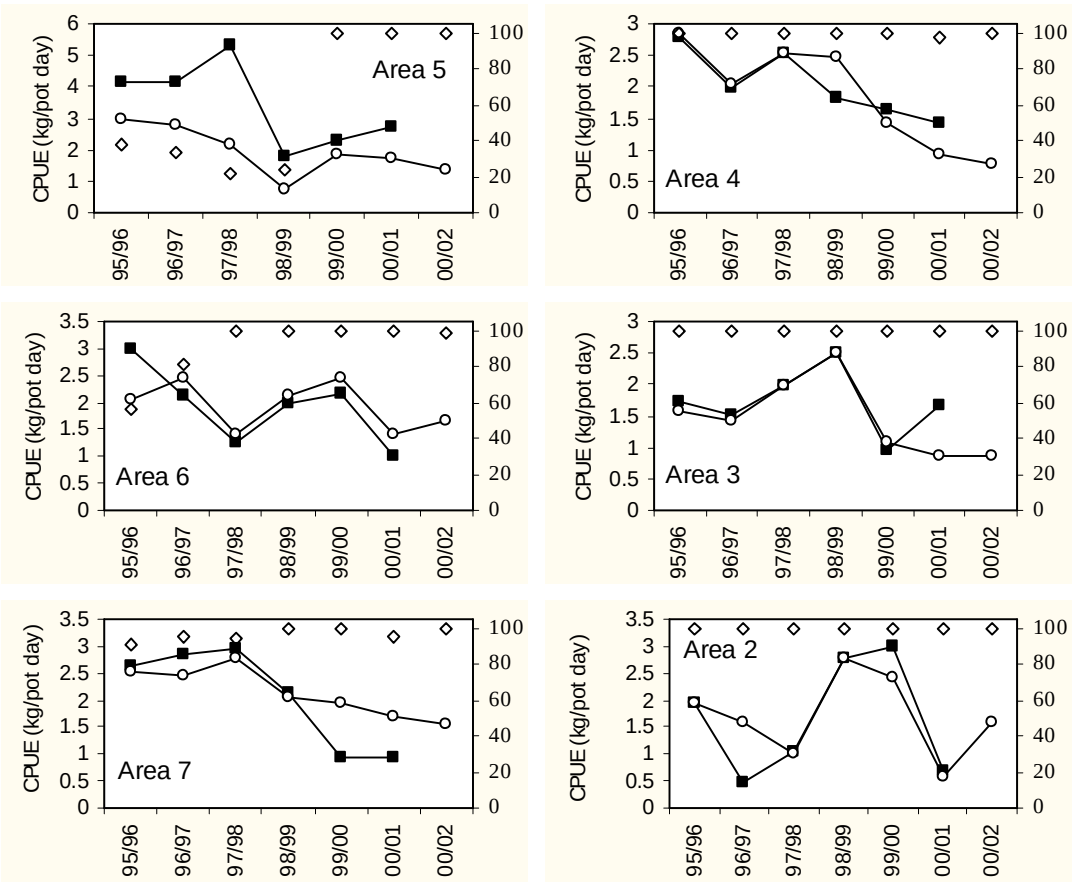


Figure 5. Trends in catch per unit effort (CPUE) from each of the 6 main assessment regions (the assessment regions are the same as for rock lobster). Years are split by quota years (March - February). Effort is pot days. Each plot shows the CPUE trend as shown in the 2002 assessment report (black squares) and the corrected catch rate values as calculated for the 2003 assessment (hollow circles). In the process of correcting these data, some records of catch were associated with records of effort that could not be corrected; these data were excluded. The percentage of total catch data that was useable and could be incorporated into CPUE calculations are shown by the hollow diamonds measured against the right axis.

3.2.2 Victoria and South Australia

The Victorian and South Australian giant crab data was assessed following the template set for Tasmania. Few outliers were detected in the Victorian records although this data series suffered the same problem as per Tasmania in the separation of crab catch taken through targeted effort vs as bycatch. As per Tasmania, targeted effort was separated on the basis of block, depth of fishing, soak time, and volume of catch.

South Australian data was derived almost exclusively from two fishers, both of whom were unable to fish for lobsters. Thus the issue of targeted effort vs bycatch was not relevant for this series. Data errors were not apparent in the South Australian data set, that is, outliers were not common and the occasional records that were possibly spurious could not be evaluated against a parallel quota monitoring database.

Reporting of effort remains inconsistent across States as it varies between man-days and trap numbers in South Australia vs calculated soaktime and trap numbers in Tasmania. This would be worthwhile addressing in future reviews of the fishery so that temporal trends in CPUE can be compared between States and a collaborative approach to management fostered.

3.2.3 Revised catch and effort database

Giant crab catch and effort data held by State fisheries agencies serve many purposes, some of which are defined by law. These databases are intended to provide an accurate record of the information supplied by fishers on their commercial logbooks. This requirement can be contrary to the needs for stock assessment – for instance, deliberately misreported effort data must be retained in the databases held by fisheries agencies, but excluded or adjusted for stock assessment. For this reason, a new Access database was created to store combined catch and effort data that had been corrected for errors. A summary of the database is given in Appendix 3 (page 143).

3.3 Conclusions

The collection of catch and effort data from giant crab fisheries in each State since inception of commercial harvests is a valuable resource for future assessments because it provides information about the unfished stock. However, the value of this data was compromised through a series of problems, most of which have been corrected through this project. Current logbook data is much improved, primarily as a result of the introduction of ITQs and the associated need for better quality record keeping.

4. Industry surveys

This chapter summarises results from interviews with fishers. These interviews were intended to facilitate the catch rate standardisation described in Chapter 7.

Interviews were completed with 12 fishers accounting for over 80% of the Victorian and Tasmanian giant crab catch. A range of issues were addressed in relation to factors affecting fishers catch rates (and thus interpretation of CPUE), quantification of effort, logbook efficacy, and some biological issues relevant to stock assessment modelling. The questionnaire is attached at Appendix 4.

The key questions relating to change in fishing efficiency produced a consistent response. Gear had changed little and fishers attributed little effect of changing catch rates to this. The issue that most fishers identified as important was simply improved fisher knowledge. Most fishers attributed gains of between 15 and 25% to this over the period of 2 years since commencement. They consistently noted that the level of skill development required was less than for rock lobsters, which implies that effort standardisation is less complex.

A summary of responses from the interviews relevant to the process of effort standardisation is shown below.

EFFORT STANDARDISATION	
How long did it take to learn to fish to the current level of skill?	50% of the fishers considered they reached full skill level within the first year. One fisher said it took three years and the remainder said two years.
Where fishers felt their efficiency changed over more than 1 season, how large was this effect?	Most felt the change was between 15% and 25%, one felt the change was 100% (*i.e.* double effective effort).
What was the change in efficiency attributed to?	All fishers that considered they had changed their efficiency attributed it to locating better areas and understanding seasonality.
Are seasonal cycles in catch rate consistent between years?	2/3 said yes, 1/3 no. Where respondents said no, they felt there was variation of around 4 weeks (*e.g.* there may be variation of a month for catch rates to increase after the release of larvae in Spring).
Did fishers follow the same spatial pattern in effort direction each year?	All said yes except two fishers operating off western Tasmania, which was attributed to the introduction of quota and encroachment of trawlers.

Did the introduction of QMS in 1999 in Tasmania affect timing of effort?	2/3 of respondents said yes. Quota had less effect on east coast fishers. The effect was driven by price maximisation. No consistent timing shift was apparent (some shifted effort to Nov, others to February).
Did the introduction of the QMS in 1999 in Tasmania affect the size of crabs targeted?	50% the respondents said yes – most increased targeting of smaller crabs, one increased targeting of larger crabs.
Did the QMS influence where effort was directed?	All fishers said it had no effect.
Other effects of introduction of the QMS?	7 fishers reported that they no longer retain 1-armed crabs, 1 reported the opposite (*i.e.* that they used to discard them but now retain them).
What other fisheries influenced direction of effort into crab?	All fishers reported that prices and catch rates in the lobster fishery affected their effort directed towards crab. Other fisheries include scallop and drop line.
BIOLOGICAL ASPECTS	
Has there been an increase in the incidence of crabs with black shells?	Only one fisher reported an increase.
When does moulting occur?	In contrast to rock lobsters, fishers had less idea of when moulting occurs. 5 of 12 said they had no idea, 2 thought most moulting was in winter, 1 thought it was in summer, and 1 felt females moulted in spring. 3 felt moulting occurred at low levels throughout the year.
Other issues relevant to CPUE standardisation	
	Several fishers noted that they believe the crabs are highly mobile which explains the benefit of long soak times. They explained that localised depletion around the traps was not an issue as it is for rock lobsters.

5. Low cost length-frequency data collection

5.1 Introduction

This Chapter reports on comparison of different techniques for measuring crabs. The aim was to develop a technique that would enable fishers to collect information on the size-structure of their catches to assist with stock assessment. The need for fisher-based data collection arose because of the high cost of placing observers aboard crab fishing vessels. Observer based sampling is less viable in the crab fishery than the rock lobster fishery because of the smaller value of the fishery and the lower number of crabs landed each day (*i.e.* fewer data per day of observer time).

We recognised that fishers would be more willing and able to participate in data collection if the method used to collect data were easy and could be integrated with daily deck operations. However, the easiest method for collecting size-structure data may not necessarily be the most accurate – clearly a balance needs to be established. Validation of sample methods was intended to assist this process.

5.2 Methods

Comparison between options for measuring crabs was done in two steps. First, three systems for collecting measurements were tested for accuracy. Options that appeared promising were then further developed to find electronic options to make data collection easier.

Options considered were:

- callipers
- measuring boards; and
- disposable cameras.

Callipers were standard plastic or metal vernier callipers, measuring to the nearest millimetre (Figure 6) and represent the current system adopted for catch sampling. Note that large 400 mm callipers are required for crab sampling rather than the standard 250 mm callipers used for sampling rock lobsters. Measuring boards were designed specifically for measuring giant crabs, to be permanently attached to a convenient surface in the sorting area on crab boats. Readings were taken to the nearest centimetre.

Photos were taken with Kodak waterproof, single use cameras and scanned for measuring using image analysis software. Operators were instructed to take the photo from directly above the crab to avoid parallax error in measurements, and to allow the full carapace to be seen in the photo. An object of known dimension must be included in each photo to provide appropriate scaling when measuring the crab. The accuracy of measurement of this scaling object will have considerable effect on the accuracy of crab measurements. Three different scaling devices were compared in laboratory trials (Figure 7). Two devices, a scaling grid and a black square were placed on the ground

(or deck) beneath the crab while the third, a black bar was placed on the crab and thus was at the same distance from the camera as the carapace. Crabs measured in this trial were undersize crabs retained by a fisher over a number of fishing trips.

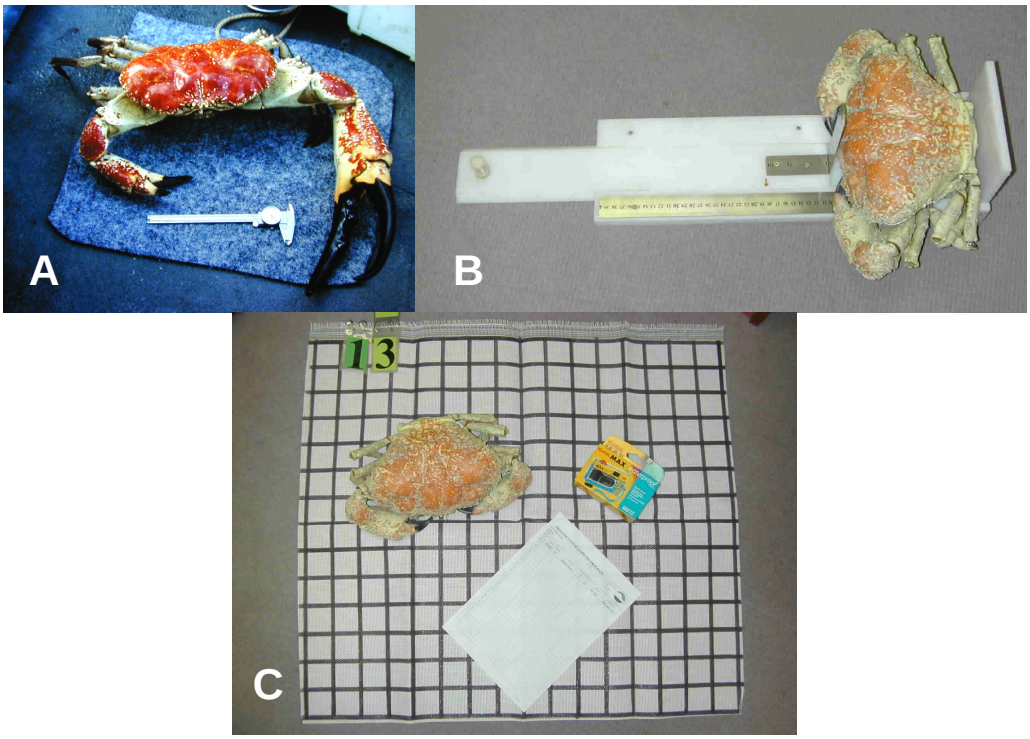


Figure 6. Systems tested for accuracy in data collection. Callipers (A), measuring board (B), and disposable camera combined with scaling system (C).

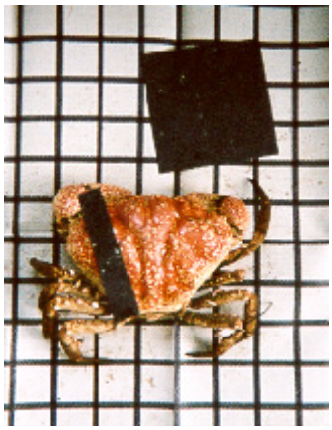


Figure 7. Three scaling methods tested for use with disposable cameras in measuring the size of giant crabs: square, grid and bar (placed on crab carapace).

5.3 Results and Discussion

5.3.1 Callipers

Precision of calliper measurements was assessed in the laboratory. Three operators each measured the same group of 84 live giant crabs. For 81 crabs, all measurements were within 1 mm of each other (Figure 8). For two crabs, maximum measurement error was 2 mm, and on a third an apparent misread of the callipers by person A resulted in a discrepancy of 10mm. Consequently correlations between person A and the other measurers are reduced (Table 1), but were still high.

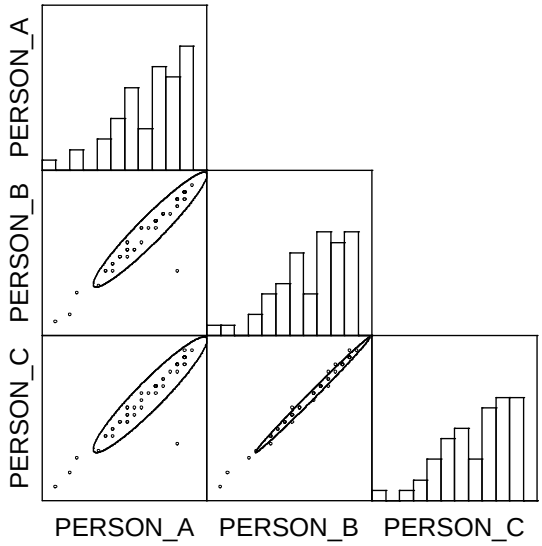


Figure 8. Correlations and frequency distributions for calliper measurements taken by 3 operators on the same crab specimens.

Table 1. Pearson correlation matrix for three people using callipers to measure the same group of 84 crabs.

	PERSON_A	PERSON_B
PERSON_B	0.962	
PERSON_C	0.955	0.995

These results highlighted the inherent opportunities for inaccuracy when using callipers, but also potential problems with misreading. This trial was performed by experienced operators in laboratory conditions. Error rates under field conditions may be considerably higher, and consideration should be given to methods of decreasing error rates such as highlighting the 'pointer' where measurements are read on the callipers.

5.3.2 Measuring boards

As with the callipers, three operators measured a sample of 84 live crabs.

Precision: An indication of precision is given by the degree of overlap of subsequent board-measured size groups in Figure 9. The width of the confidence limits around the middle two size groups indicate that the chance of incorrectly assigning a crab to either of these groups is low, and therefore precision is acceptable. However crabs measured by boards to be in the largest size group (≈15.5cm) fall entirely outside the confidence limits, and overlap almost entirely with the 14.5cm size group. This is not attributable to the measuring technique, but rather to the non-normal distribution of crabs measured (see frequency distributions in Figure 8).

Accuracy: Measuring boards do not measure carapace length, but rather the distance from the outside curvature of the tail to the tips of the rostral horns. For a given carapace length, this distance may vary due to factors such as sex or reproductive state of females (for instance - tail protrudes further when in berry). For the purposes of these trials, a linear adjustment based on the discrepancy in means of board measurements and calliper measurements was applied to board measurements. The resulting regression line of slope approximating 1, and with intercept close to zero (Figure 9) indicates that this adjustment was appropriate for the size range of crabs measured.

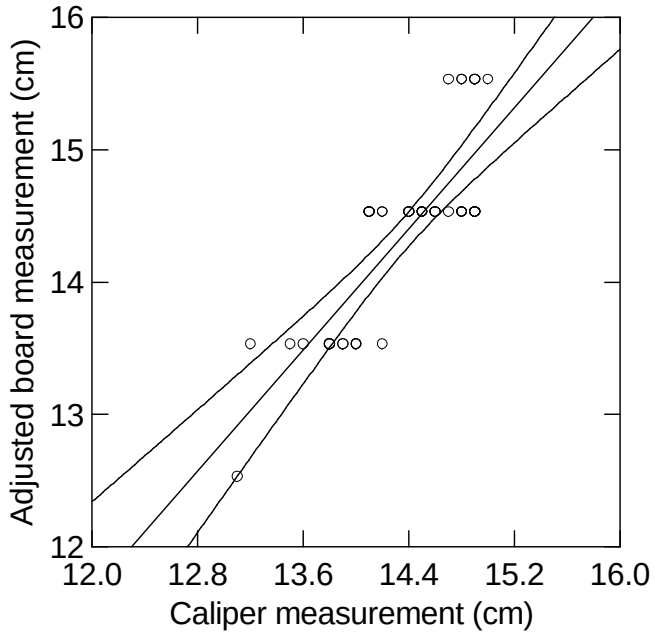


Figure 9. Adjusted board measurement (adjusted by comparing means of calliper and board measurements) vs calliper measurement. 95% confidence limits are shown.
Due to the layout, construction and size of measuring boards, the chance of a misread is minimal, representing an advantage over callipers.

5.3.3 Disposable cameras

Photographic techniques had the advantage of provision of physical evidence of crab size to researchers/managers so that chances of gross misreads of crab size were minimal. Effort required by deck hands was also reduced. A disadvantage was that scanning and digital measurement of photos was time consuming, taking 30 to 45 minutes to process a single film. This could be decreased significantly if photos were

scanned as they were processed, a service offered by many photography shops, however costs would increase.

Quality of photos had a considerable bearing on ultimate accuracy of measurements. Field trials showed that light levels were important, as photos became more 'grainy' at lower light, resulting in poorly defined edges of the crab carapace and scaling object. As the single use cameras are not equipped with a flash, data cannot be collected from any shots hauled at night. Photos taken using deck lights were inadequate.

Laboratory trials clearly showed that scaling of photos was most accurate using a scale bar placed on top of the crab carapace. While fewer photos were taken with this device than with the square and grid, resulting in broad confidence limits towards the extremes of sizes measured (Figure 10), the correlation with calliper measurements was best using this method (Table 2).

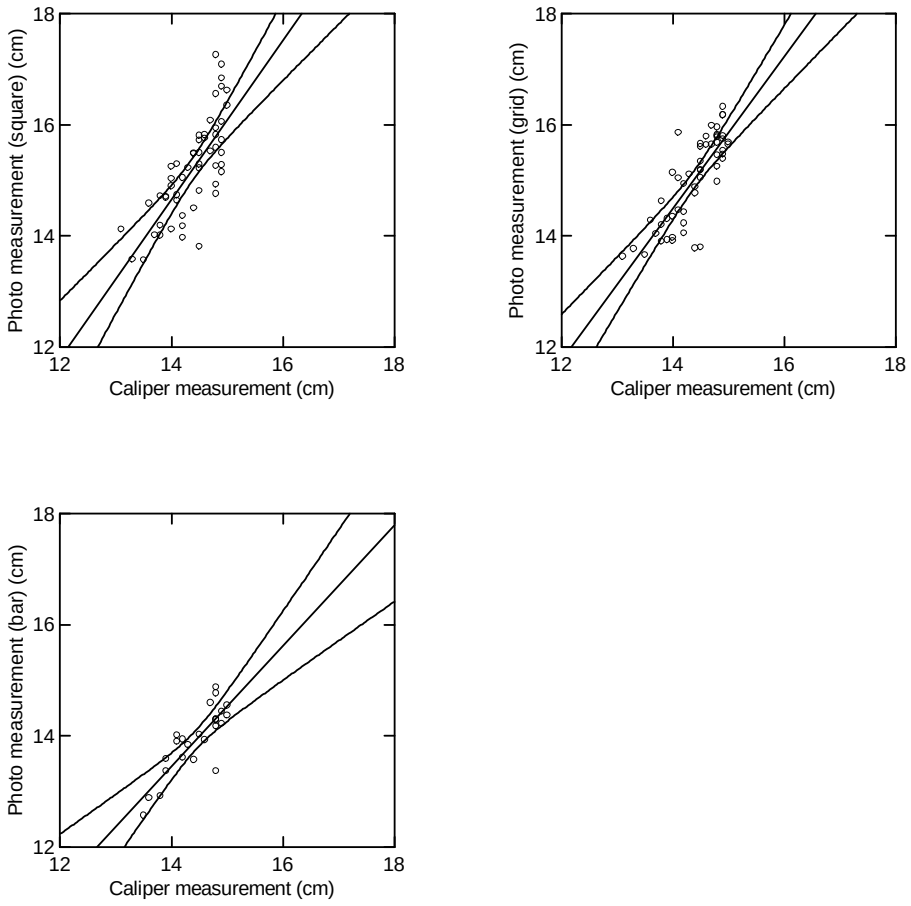


Figure 10. Regression of calliper measurements against photo measurements scaled using the square, grid and bar in photos. Linear regressions and 95% confidence intervals are shown.

Table 2. Pearson correlations between caliper measurements and photo measurements taken using the three scaling methods.

	Grid	Square	Bar
Calliper	0.815	0.759	0.839

5.3.4 Field testing by fishers

Fishers field-tested all three options to evaluate their use in a normal fishing operation. All methods were readily integrated with normal operations and used at the point where claws were cable-tied. Callipers were preferred above measuring boards due to their smaller size. In addition, callipers provided a measure of carapace length rather than total length so fishers were able to use these for determining whether crabs were legal size. Photographic systems were slightly more awkward as crabs are disturbed and highly mobile after being removed from traps so that two people were sometimes required – one to hold the crab and the other to photograph (Figure 11). Movement of crabs also led to difficulty in determining the size of crabs from photos. Given these results, callipers were selected as the preferred option for deployment with fishers.

5.3.5 Electronic solutions based on measurement by callipers

Fishers noted that the photographic measurement option had the benefit that there was no paper or pencils involved in the recording of data. This presented a problem with the use of callipers as measurements needed to be recorded on datasheets –and pencils and datasheets could be lost on the deck. We addressed this by developing electronic options for recording calliper measurements. A private company (Scielex - www.scielex.com.au) conducted this development and two options are now commercially available. Both utilise waterproof electronic callipers connected to a data-recording unit (Figure 12) so that data entry from paper records is eliminated. Data is downloaded and stored in fisheries databases.

Waterproof vernier calliper logbook: this stores gender, berried state, length and units, date, time. Location and depth information is linked to length records by later database links based on date and fisher ID. This unit was adopted as the basic system for fishers to record size structure data.

Touch screen logbook: this unit can be easily programmed to store more extensive data than the simple waterproof logbook, such as tag number, damage (missing limbs), individual pot ID, and bycatch. This system is used where fishers wish to record additional information or where observers are present.

Figure 11. Images collected by fishers aboard the Rachel Maree and Petuna. A white calibration square was used to provide contrast to the black deck mats. Movement of crabs created problems with this system.

Figure 12. Electronic options developed for recording length measurements from callipers. The waterproof vernier calliper logbook (left) stores gender, berried state, length and units, date, time. The touch screen logbook (right) can be connected to electronic callipers and easily programmed to store more extensive data, such as tag number, damage (missing limbs), individual pot ID, and bycatch. The basic calliper logbook has been deployed with several fishers and now serves as the main system for obtaining size-structure data for the crab fishery.

5.3.6 Conclusion

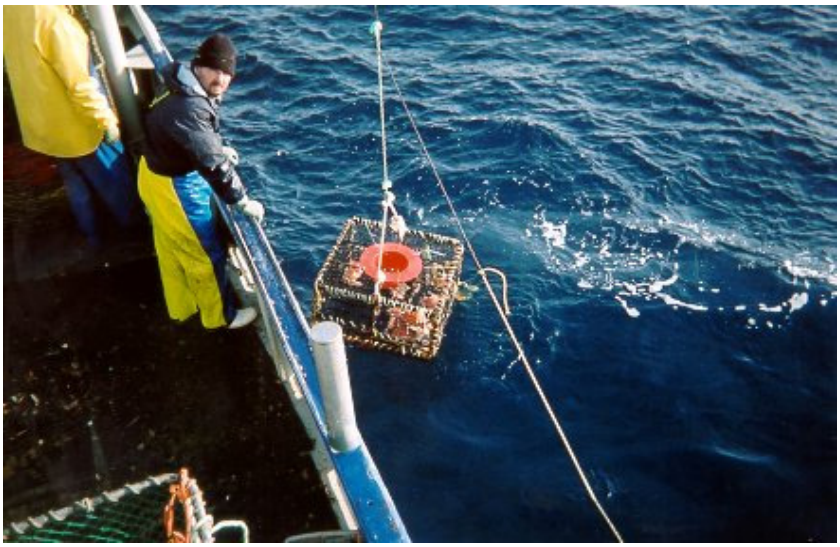
The waterproof vernier calliper logbook provides an accurate system for collecting size structure data and has been well received by fishers due to the ease of use. This system has been deployed in Victoria and Tasmania.

The units consist of a set of digital calipers and small data storage unit (both IP 67 rated) capable of storing 5000 entire records from its rechargeable 12v power supply. An advantage of this setup is that it allows the straightforward collection of data to occur on commercial vessels without the presence of a researcher onboard. Fishers simply measure and assign a sex (either male, female or berried female) to the crab. By recording details from as little as only one pot per shot a considerable data set is quickly generated from only a small number of trips.

Once the unit is full (indicated by a small red light on the logger) or the fisher wants to find out details about their catch, the unit is returned to TAFI for downloading and then reposted. To keep the user of the loggers informed of their catch the data downloaded is sent to them via a standard set of graphs and spreadsheets.

We have developed a series of operational and support procedures for these units. If a mistake is made with measurements the fisher closes the callipers and records another measurement of 0 mm length. These two records are then deleted when the data is downloaded. Graphs are generated automatically when data is downloaded. The length data retrieved from these units is stored in the crab database for use in stock

assessments. Links from this size data to other details of the fishers operation such as depth and location of fishing (from logbooks) are made automatically in the database on the basis of date of fishing.



6. Risk of serial depletion

6.1 Introduction

Serial depletion occurs when fishers progressively deplete one area and then move to the next to maintain stable catch rates. Serial depletion can be masked in logbook returns if the spatial resolution of reporting is much larger than such an area, *i.e.* if there is a substantial spatial mis-match between fishery processes and reporting. This situation is problematic for fisheries management because the fish stocks can collapse without much prior warning of problems. The extent to which this is a concern in the crab fishery was assessed from logbook data. These analyses were intended to evaluate the need for tracking of spatial patterns in future assessments.

The fishers interviewed for Chapter 4 were asked about their spatial patterns of fishing. All stated that they deployed their gear at a targeted depth along the shelf-break, although this depth varied from trip to trip. Fishers generally responded to catch rates in gear at different depths from shot to shot. Spatial movement of effort around the coast tended to be constrained to regions with most fishers having their own "patch" around the coast – typically the region closest to home.

Fishers stated that they tended to set gear in a line along the targeted depth without targeting specific bottom features (as per rock lobsters); after the shot was hauled the gear would be moved further along the shelf-break. In this manner they would work their gear along the coast until they reached a point where the direction of movement would be reversed. The trigger for moving back included encountering someone else's gear, moving too far from port, or the need to return to port and land the catch. This pattern of fishing implies that fishers have tended to work in the same area, which suggests that likelihood of serial depletion is low.

We examined the fishing patterns of the fleet by first portioning the fished region into patches or regions where effort is concentrated. We then examined how mobile fishers were between these patches – did they remain in their preferred region year after year?

6.2 Methods

Analysis of spatial distribution of effort in the fishery involved the mapping of effort and then analysis of the transfer of effort of individual fishers between areas. The first step of mapping of effort was complicated by changes in the spatial resolution of data recorded in fisher's logbooks.

6.2.1 Mapping

Since 1999, commercial Tasmanian giant crab fishing logbooks have included entry of vessel ID, catch, effort and GPS location for each shot. Using these records compiled for the 4-year period of 1999-2003 we have defined hot spots of giant crab fishing effort around Tasmania. Using Arcview GIS 3.2, we first created a grid to compute the sum of

number of traps per each 4 km^2 cell. The grid shown in Figure 13 highlights giant crab fishing hotspots between 1999 and 2003.

From the fishing intensity grid it was possible to define several fishing areas along the west and east coasts of Tasmania (Figure 14). Areas that had few records and showed similar trends in catch rate to adjacent areas were grouped to provide a final grouping of five areas (Figure 14). These groupings enabled the use of data for the period 1995 to 1999 when geographical information of catch was recorded in half-degree block (Figure 15 left). Extending the southern areas southward to cover the entire Tasmanian fishing zone we obtain the statistical areas shown in Figure 15 right.

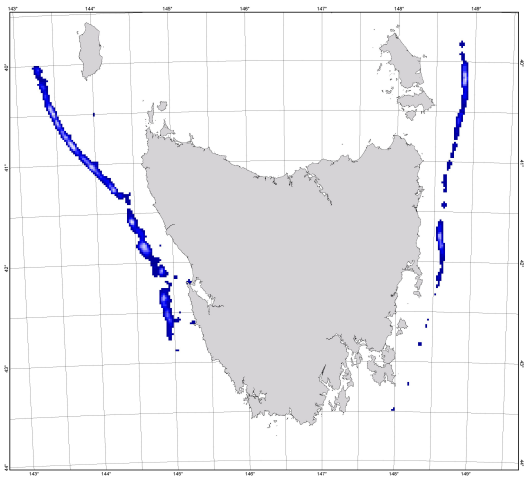


Figure 13. Distribution of effort 1999-2003. The colour gradient indicates light (dark blue, >350 traps km^{-2} in 4 years) to heavy (light blue, >3000 trap km^{-2}) fishing effort.

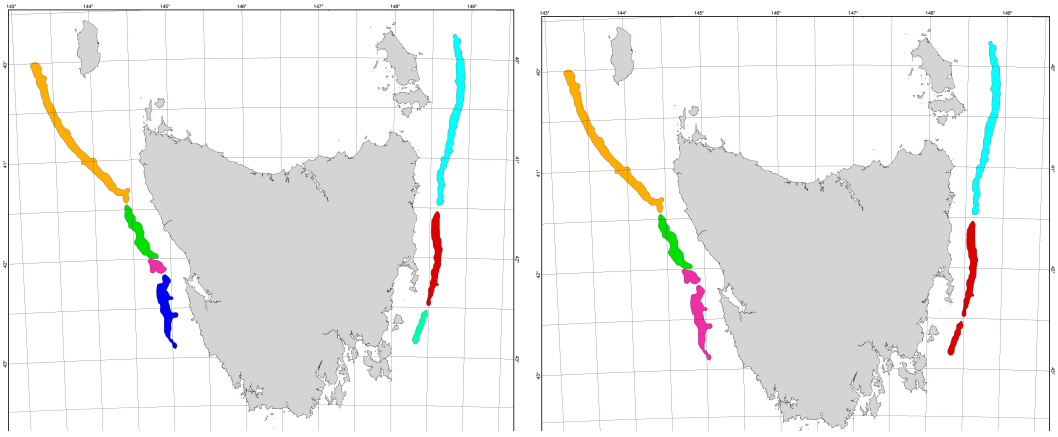


Figure 14. Regional division of effort and the participants. This analysis initially produced seven regional areas (left), which were further pooled to 5 areas (right) to enable comparison with lower resolution logbook data prior to 1999.

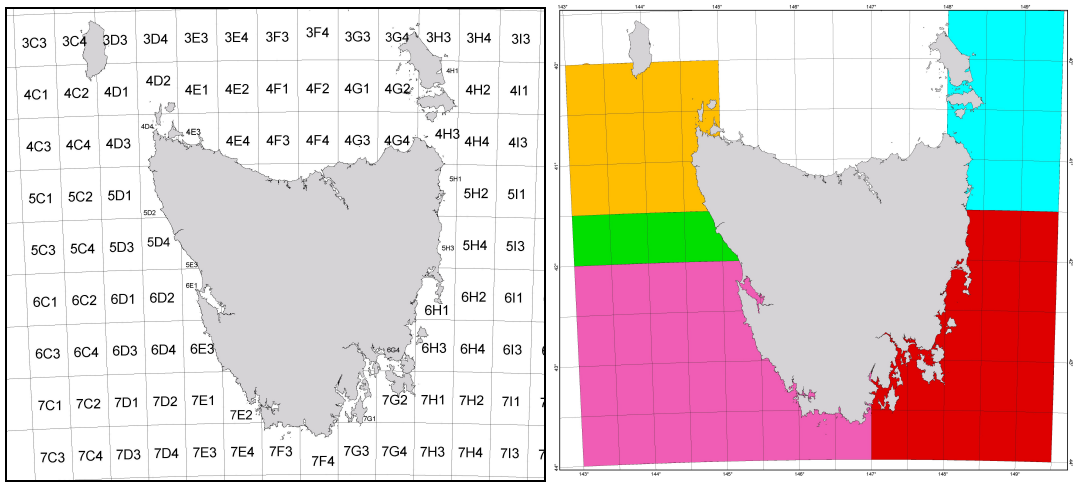


Figure 15. Boundaries for effort - 1995 to 1999. Data for were recorded in ½ degree grids (left). Groupings in Figure 14 were related to grid cells to produce extended areas.

6.2.2 Spatial distribution of fisher's effort

Fishers effort was mapped into four km cells as described for combined catch data above. This data is not presented here to protect confidentiality, however, this information was used to describe movement in effort between regions in Section 6.3.2.

Change in location of crab fishing effort was evaluated for fishers who were ranked as major players (caught more than 10 tons between 1995 and 2003 or that they caught two tons per year for at least two consecutive years) and were active in the fishery for more than three years. The spatial distribution of the effort of these operators was assigned to the five fishing areas. Effort that was not targeting giant crabs was excluded.

6.3 Results and Discussion

6.3.1 Temporal changes in regional catch and catch rate

Trends in catch statistics were not indicative of serial depletion, as temporal patterns were not hyper-stable (Figure 16 and Figure 17). Rather, volatility existed both temporally and between spatial areas. Temporal changes in catch rates between regions were occasionally substantial, which would be expected to provide motivation for fishers to transfer effort between regions (Figure 17).

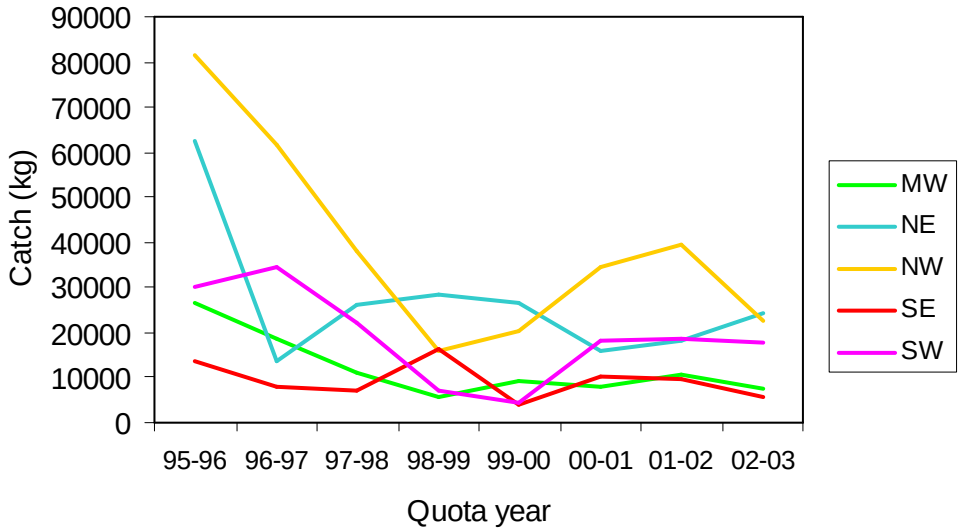


Figure 16. Total catch per zone. Quota year is for the period March to February inclusive. Colour categories relate to regions shown in Figure 15b.

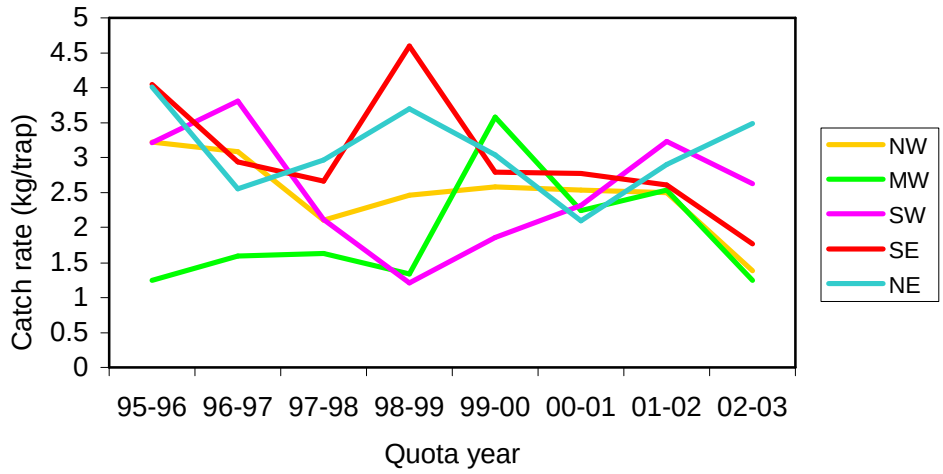


Figure 17. Historical catch rate (geometric mean) trend for each zone. Quota year is for the period March to February inclusive. Colour categories relate to regions shown in Figure 15b.

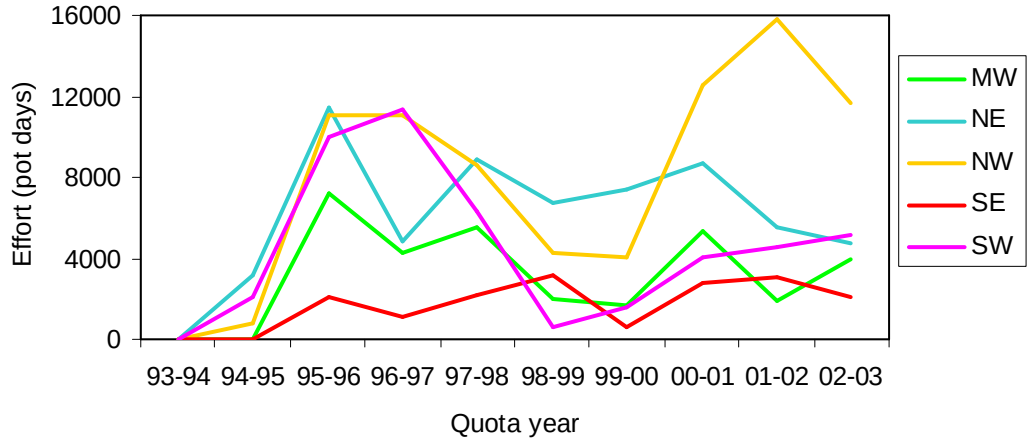


Figure 18. Temporal change in effort in each of the five regions identified in Figure 15b.

6.3.2 Regional transfer of effort

Logbook records indicate considerable temporal volatility in effort in most regions (Figure 18). Effort on the east coast tended to be more stable than that on the west, which may be a function of the smaller number of operators targeting crabs in this region, and the stable fishing behaviour of those operators (Figure 19).

Temporal change in effort on the west coast displayed a clear pattern for the southwest and northwest regions (Figure 18). Both these areas had similar temporal pattern and magnitude of effort until 1998/99. After this, effort in the northwest increased dramatically relative to that in the southwest. Several factors may have accounted for this change including improved reporting of effort in the northwest following the introduction of quota management and interactions with benthic trawlers. In interviews reported in Chapter 4, crab fishers operating in the northwest region reported that the increased activity of trawlers from 2001 onwards had led to their effort being displaced to areas with lower catch rate. Under a quota management system this displacement of effort to areas with lower catch rate is a mechanism for increased effort.

Temporal patterns in fishing effort of individual operators shown in Figure 19 indicate that most fishers have operated in only one or two regions. Examples of fishers shifting from one region to another, in a pattern consistent with serial depletion, occurred in only two cases, fishers C and H. Both of these fishers shifted effort towards the northwest. In two other cases (Fishers L and M), the fishers shifted effort around the State. The spatial stability of the majority of fishers argues against serial depletion.

6.4 Conclusion

The risk of serial depletion in the Tasmanian giant crab fishery appears low due to several factors.

Firstly, effort is widely distributed along the shelf break with effort in all available fishing grounds where catch rates are economically viable. An exception is that little effort has occurred in the southwest, which fishers report is due to uneconomically low catch rates. Crabs are present in this region and numerous individuals have been observed on the seafloor in this region using deep-water video (unpublished results from FRDC 2004/066). However, either catchability or abundance is insufficient to enable economical harvests so that this southwest region appears to be a spatial refuge.

Secondly, the pattern of fishing reported by fishers in interviews argues against serial depletion. Fishers tend to deploy gear with only limited attempt to target specific bottom features – a target depth is the primary consideration. Gear is moved along the coast in a regular pattern so that the entire shelf break is fished. Exceptions are southern regions with low catch rates and local regions unsuitable for deploying gear, such as where trawler activity is common.

Lastly, although regional variation in catch rates from year to year appears to provide motivation for fishers to shift effort between regions so as to stabilise catch rates, this does not seem to have occurred. Most individual fishers expend their effort in the same region for periods spanning many years and do not vary the location of their effort from year to year.

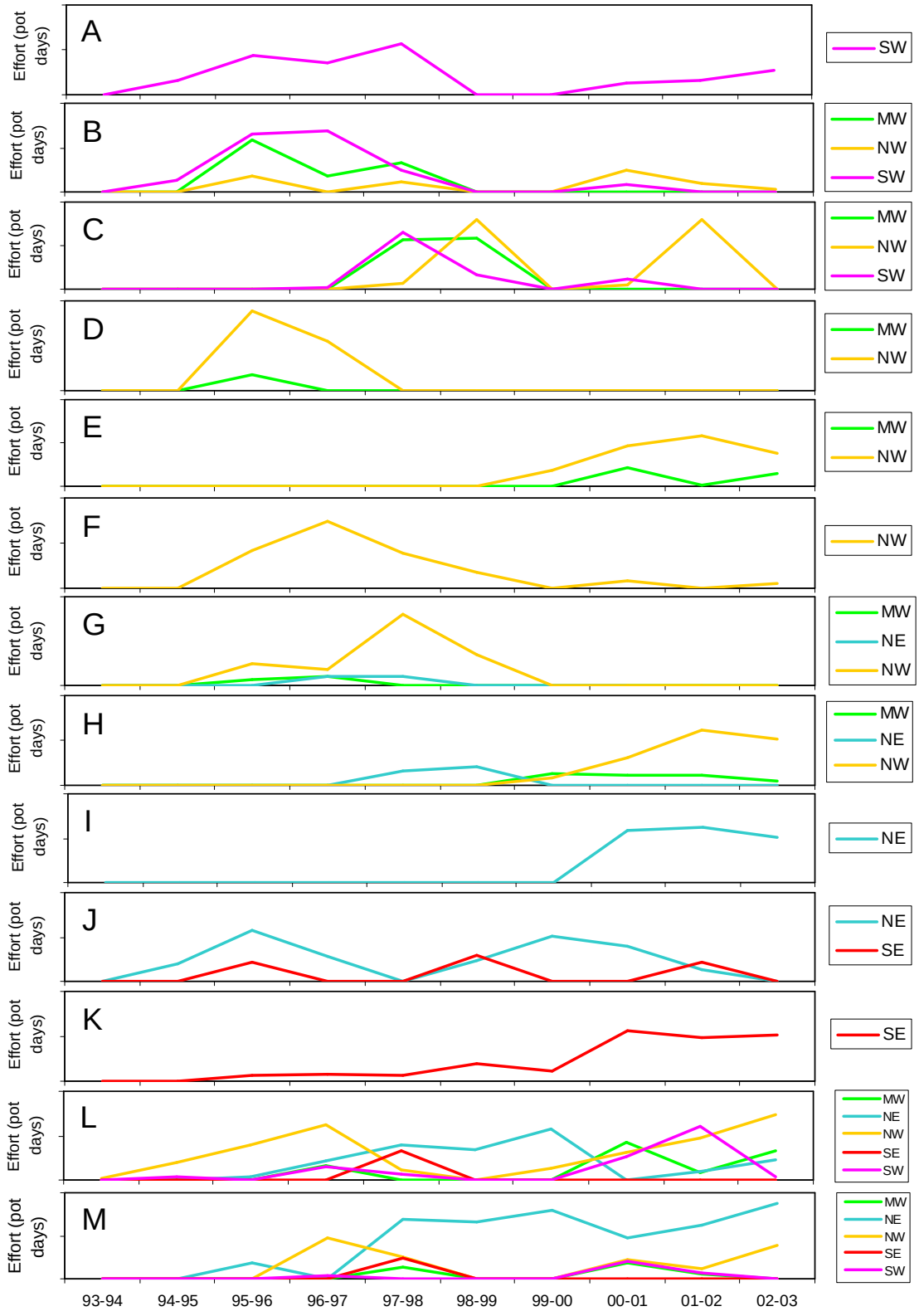


Figure 19. Regional distribution of effort for individual Tasmanian fishers with historical records of effort targeting giant crabs of more than 7000 trap days. Units of effort are not displayed to protect confidentiality.

7. Catch rate standardisation

7.1 Introduction

The need for catch rate standardisation was identified at the commencement of the project due to concerns of industry about the value of standard CPUE data. Concerns included:

- misreporting of effort led to errors, especially in data prior to 1999 (dealt with in Chapter 3);
- variation in soak time of traps between fishers and between shots - for example buoys can be submerged for extended periods with strong tidal movement;
- variation in the capability of operators within the fleet - some operators holding a small amount of quota are poorly equipped for deep water fishing;
- variation in targeting of crabs – some crabs are captured as bycatch by lobster fishers in deep water but has not always been identified as such;
- seasonal variation in catchability and expenditure of effort caused in part by interaction with other fisheries, especially scallop season openings; and
- the effect of depth on catch rates, especially in the context of crab fishers avoiding preferred depths to avoid interaction with trawlers.

The need for standardisation of CPUE was also apparent from the observed statistical distribution of logbook catch and effort data (Figure 20). Frequencies of individual catch rate records for each year since 1995 were clearly non-normal, which implies that the statewide values of CPUE calculated by arithmetic mean (that is, total catch divided by total effort) are biased. This bias was confirmed by a Q-Q plot of the residuals where the fit using arithmetic means is extremely poor (Figure 23).

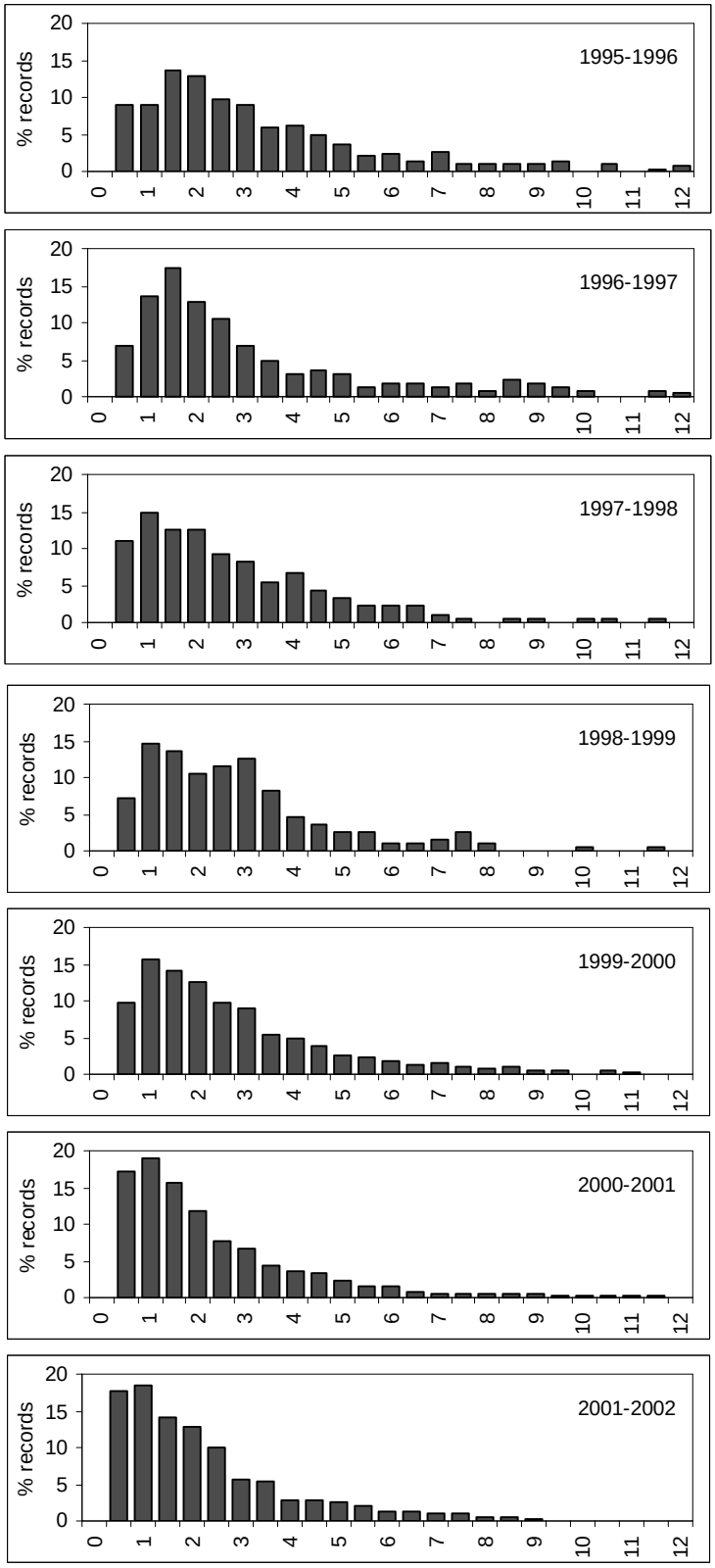


Figure 20. Frequencies (x-axis; kg/potday) for individual catch rate records in fisher log book returns (split by quota years). Note that the distribution of these is not normal, which implies that the arithmetic means of catch rate will be biased. Also note a shift towards lower catch rates through time. Both of these observations implied standardisation was required. Frequencies of catch rates of zero crabs per shot are excluded.

7.1.1 Historical patterns in catch and effort data

The commercial fishery for giant crab began in Tasmania during the 1992/1993 quota year (defined as the period from the start of March to the end of the following February) after a live export market to Melbourne, Sydney and Asia was established (Gardner, 1998). Giant crab had previously appeared as occasional bycatch by rock lobster fishers operating in deeper waters but were generally regarded more as a nuisance than a target. Once giant crab became a targeted species, catches increased dramatically and by the 1994/1995 quota year, total reported catch in Tasmanian waters peaked at 291 tonnes. While some of this total may be attributed to misreporting of catch in anticipation of a change in management (moving to quota), it was clear that a large virgin stock was being fished down. By the end of the 1997/1998 quota year the total catch had fallen to 110 tonnes (Table 3, Figure 21) and there was concern that the stock was over exploited. A management plan was introduced in November 1999 and an Individual Transferable Quota system was introduced in 2000/2001.

Table 3. Reported catch totals, in tonnes, by quota year from before the beginning of the Tasmanian fishery in 1992/1993 until the present. The quota year runs from March 1st to the end of February the following year. East and west are defined as either side of longitude 147° East.

Quota Year	Total	West	East
1989/1990	0.202	0.002	0.105
1990/1991	1.706	1.598	0.108
1991/1992	1.483	1.410	0.073
1992/1993	118.157	112.794	5.363
1993/1994	224.233	223.413	0.819
1994/1995	291.226	217.755	73.471
1995/1996	224.932	147.904	77.028
1996/1997	147.380	125.231	22.149
1997/1998	113.283	77.431	35.852
1998/1999	75.607	30.410	45.197
1999/2000	64.212	33.883	30.329
2000/2001	86.510	60.606	25.904
2001/2002	96.593	68.640	27.953
2002/2003	75.242	45.118	30.123
2003/2004	59.057	39.104	19.953

All of the targeted fishing for giant crab in Tasmanian waters takes place on the edge of the continental shelf on both the east and west coast. There are modes of catches in the 180m and 280m depth categories on the west coast while on the east coast the only major modal depth was the 280m depth category (Figure 22). Although it is quite probable that there is some larval exchange between coasts (Gardner and Quintana, 1998), it is unlikely that there is any significant mixing of the adult populations.

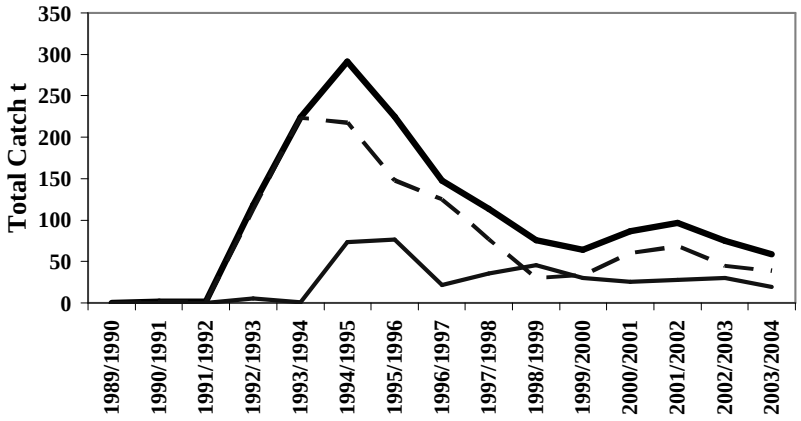


Figure 21. Total catches, and catches from the eastern (solid line) and western (dashed line) regions, of the Tasmanian giant crab fishery (Table 3). The management plan was introduced in November 1999. The quota year is from March 1st through to February 28/29th.

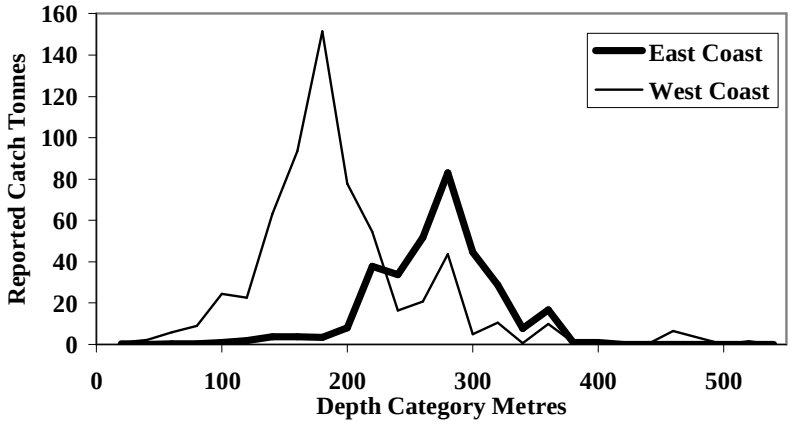


Figure 22. The distribution of total catches relative to 20m depth category for the west and east coasts separately across the history of the fishery.

The majority of the catch on each coast is taken mainly by different groups of about ten operators, however, there is also a small amount of bycatch taken by rock lobster fishers on the west coast (Gardner, 1998).

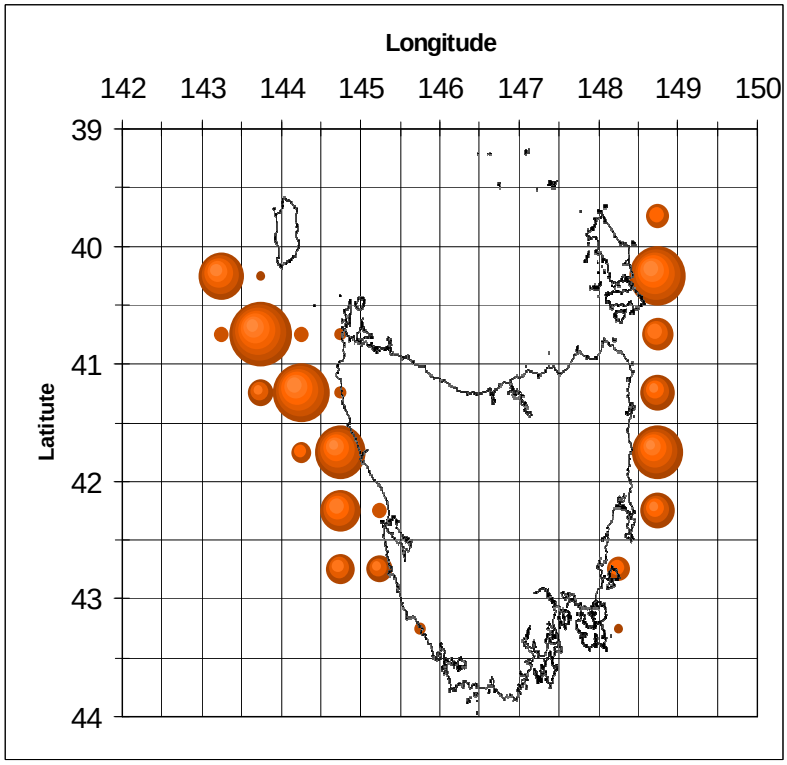


Figure 23. Spatial distribution of effort of fishers targeting crabs from 1999 to 2002; larger circles denote greater effort. Effort is measured as number of shots and grouped by statistical reporting blocks.

As with most fisheries, catch rates obtained by the fishers are assumed to constitute an index of relative abundance through time. However, there are many other factors that can influence catch rates besides the relative stock abundance. In the case of giant crabs, whether the fisher is targeting the crabs, the location, season and depth of fishing, and who is fishing are all likely to be important factors influencing observed catch rates. Once any effects of these factors are statistically accounted for by standardization the relative changes in catch rates that remain are more likely related to changes in stock abundance than without the standardization. While there is the risk that not all important factors have been included, the standardization of catch rates should provide an improvement over raw catch rates.

The option of identifying shots targeted at giant crabs has been included in logbooks only in the most recent year. In order to restrict the analysis to those records most likely to have been targeted at giant crabs a number of criteria were developed for data selection.

Only those vessels that had been in the fishery for a minimum of two years with a median catch of at least one tonne per annum during that period were considered for analysis. Any data from remaining vessels were removed from consideration as they primarily contribute only noise to the assessment. The assumption is that relatively small contributors are not representative of the general state of the fishery. Applying these criteria when selecting the dataset to be used accounted for about 86.6% of the total catch by weight and 75.7% by number of records (Table 4).

7.2 Methods

7.2.1 Catch Rates

In Tasmania, the catch rates were measured as kilograms per pot day, where a pot day was defined as the soaktime in days for each trap. This CPUE was estimated for each record in the database as:

$$\text{CPUE} = \frac{\text{Weight of Catch Kg}}{\text{Number of Traps} \times \text{SoakTime}} \qquad 10.1$$

Soaktime is the recorded number of days the traps are in the water before being hauled. There is a belief that a soaktime greater than 7 days does not lead to any increases in catch but the reported soaktimes were used in calculating the CPUE because the normality of the log-transformed data was reduced if soaktimes were limited to 7 days.

The period under analysis included two different management arrangements with fisheries data being recorded in different logbooks. Before July 1998, fishing was restricted to fishers with Commonwealth permits issued by AFMA with effort limited by gear restrictions. A total of 106 permits were issued to holders of Tasmanian rock lobster endorsements (Gardner, 1998) and catch effort data was recorded in the general fish logbook. The general fish logbook was updated in 1995 and before this time no effort was recorded, hence data from before March 1995 (the 1995/1996 quota year) cannot be included in this analysis. In the new general fish log-book, introduced in January 1995, the data recorded included the weight of the catch, the number of traps used, the time the traps were in the water, the location of fishing by 30 minute block, the average depth of fishing and the date of fishing. In November 1999 a new management plan for giant crab was introduced by the State Government that set the total allowable catch (TAC) to be 100 tonnes and created a new type of fishing licence (giant crab). A new logbook for giant crab was introduced at the same time and required additional information. The new logbook included the latitude and longitude of fishing and whether a fisher was targeting giant crab or not. All data fields recorded in the previous logbook were retained and information was recorded in the ICE data base (see Section 3). Along with the introduction of a TAC, a maximum size limit of 215mm carapace length for both males and females was also introduced (the minimum legal length of 150mm for both sexes, introduced in 1993, was retained).

It is important to note that the quota allocation system and the logbook recording do not correspond completely. Quota is considered to have been used only when the animals are sold/landed whereas an entry in a fisher's logbook only records date of capture, not date of sale. It is quite common for a fisher to hold animals until the market price improves (Gardner, 1998). This appears to be one of the reasons that the full quota does not appear to have been taken since it was introduced in 1999.

Data from the General fish log-book and the ICE log-book databases were extracted and combined into a single Access database for use in the following analyses.

Table 4. The number of records used in the analyses for each quota year. Data from 1994/1995 were not used in the analyses. "Total All" relates to all records whereas Total and East and West relate only to those records for vessels in the fishery for more than two years and catching a median catch in each year of greater than 1000 kg.

Quota Year	Total All	Total	West	East
1994/1995	288	191	114	77
1995/1996	1390	853	576	277
1996/1997	1393	765	621	144
1997/1998	1127	797	555	242
1998/1999	510	392	180	212
1999/2000	1085	909	317	592
2000/2001	1513	1231	685	546
2001/2002	1431	1254	881	373
2002/2003	539	464	335	129
2003/2004	944	879	521	358

7.2.2 Statistical Transformation

The catch rate data was not normally distributed so before statistical treatment the data was first natural log transformed, which greatly improved normality (Figure 24 and Figure 25).

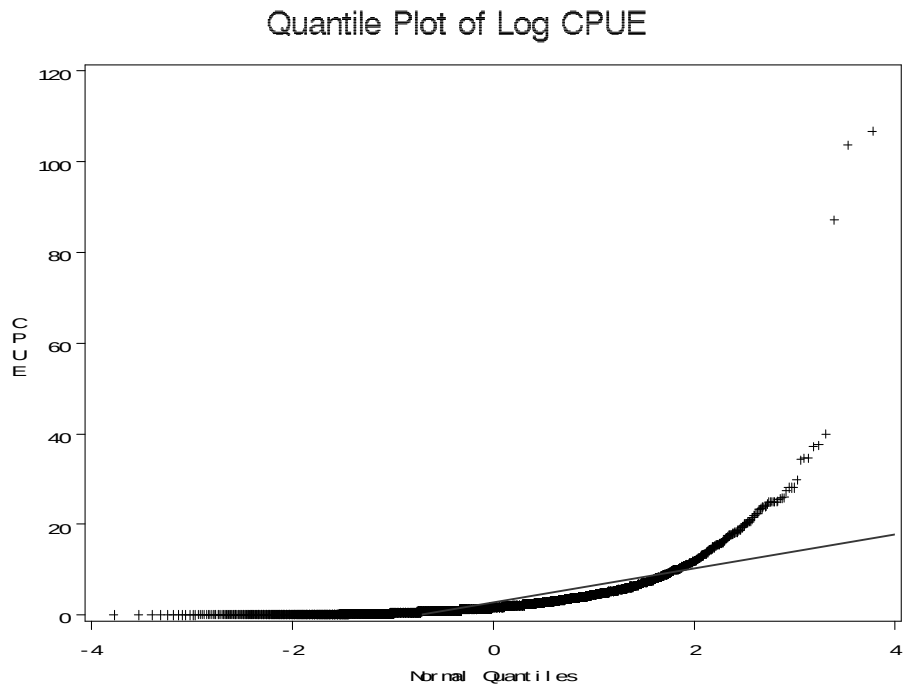


Figure 24. Quantile-Quantile plot of the untransformed CPUE data (that is, total catch/total effort). The distribution of these residuals is curved, rather than straight, which indicates a poor fit from the arithmetic means and demonstrates standardisation was required.

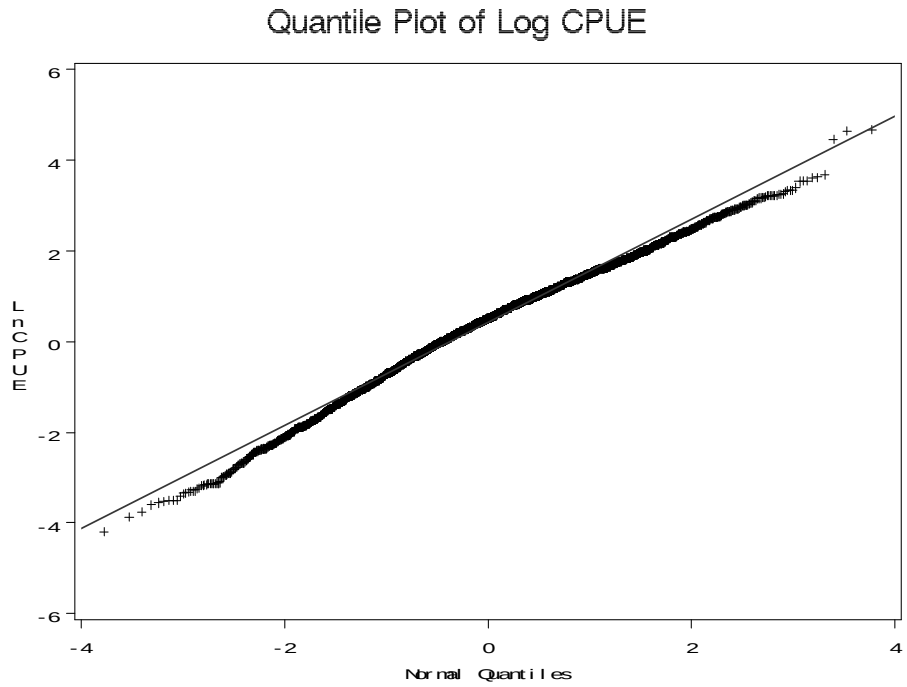


Figure 25. Quantile-Quantile plot of the Natural–log transformed catch rate data for Tasmanian Giant Crab. Catch rates were defined as : CE = Catch/(Traps*SoakDays).

PROC GLM (General Linear Modelling) inside SAS 9.1 was used for the statistical analyses and the standard form of the statistical models used was:

Ln(CPUE) = Const + QYear+Skipper+DepCat+Month+Traps+Block+Month*Block+Skipper*Month

With fewer or more factors used as the relative contributions of the different factors was explored. QYear was quota year, DepCat was a series of 20m depth categories, Traps was the number of pots used, Block was the 30' statistical block. The use of Block captured all that was implicit in the East/West distinction.

A series of GLMs, sequentially adding each factor, were then fitted to the data until the optimal model, or best description of the data was identified. Optimality cannot be guaranteed simply by selecting the model that describes the maximum amount of the variation in the data. This becomes clear from considering that it would be possible to fit the data exactly if one used a model with the same number of parameters as there were data points. The definition of optimum requires some criterion that counter-balances the amount of variability accounted for with the number of parameters used to describe the data. The approximate aim is to maximize the variation accounted for using the fewest number of parameters. Generally, the more independent parameters that are added the greater the amount of variability explained. Therefore, it is necessary to penalise a more complicated model in some way when compared to a simpler one. In this situation where we are trying to account for variability in a relatively large data set, Ripley (unpublished manuscript) recommends fitting by lowest AIC and retaining all models within two of the best model. The AIC is the Akaike Information Criteria and can be defined in two ways. The first is:

$$\mathrm{AIC} = n.\mathrm{Ln}\left(\frac{\mathrm{SSE}}{n}\right) + 2p \qquad 10.2$$

where where SSE is the sum of the squared residuals, n is the total number of observations, and p is the number of parameters. The second definition is:

$$\mathrm{AIC2} = \mathrm{Ln}\left(SSE\right) + \frac{2p}{n} \qquad 10.3$$

In addition, the adjusted R^2, gives a better estimate of total variability described by the statistical model (Neter *et al*, 1996) than the simple R^2, with *n-p* degrees of freedom, and SSTO, with *n-1* degrees of freedom, is the SSE plus the variation due to the statistical model:

$$R^2 = 1 - \frac{SSE}{SSTO} \quad R_A^2 = 1 - \frac{\frac{SSE}{n-p}}{\frac{SSTO}{n-1}} = 1 - \left(\frac{n-1}{n-p}\right)\left(\frac{SSE}{SSTO}\right) \qquad 10.4$$

"This adjusted coefficient of multiple determination may actually become smaller when another X variable is introduced into the model; because any increase in SSE may be more than offset by the loss of a degree of freedom in the denominator *n-p*" (Neter *et al*, 1996, p. 231).

All models were fitted using a forwards process, the initial factor that fitted the data best would be added to the model first, then the next best factor would be added and so on until additional factors or interactions no longer improved the AIC. When the optimal model had been identified, residual plots and QQ-plots were examined to confirm that the data still conformed to the statistical assumptions under the model.

7.3 Results

Given the factors available, nine different statistical models were considered (Table 5). The geometric mean, by itself (Model 1), only accounted for about 6.5% of unadjusted variability. The skipper doing the fishing and the depth in which fishing occurs both had greater influences than quota year. The month of fishing was also important. It should be noted that the interaction terms between skipper and month and block and month were also very influential. So seasonality of activity by different skippers was important as was the block fished in each month.

The use of statistical block in the model meant that adding the east/west factor made no difference to the analysis (all the variation accounted for by east/west was described by Block).

Apart from two central years 1998/1999 and 1999/2000 the standardized catch rates declined steadily from 1995/1996 to 2003/2004 (Figure 26). The effect of the standardization is relatively minor with the trends described by the simple geometric mean being fairly similar to the optimum two models.

Table 5. Descriptions of the none statistical models compared for giant crab around the whole of Tasmania at a time step of quota years. LnCE is the natural log of catch (kg) per pot-day, Qyear is quota year (Mar 1st to Feb 28th/29th), DepCat is a series of 20m depth categories, Traps is the number of pots used, and Block is the 30' statistical reporting area. Model 1 is equivalent to the geometric mean average catch rate, and acts as a Base Case against which the other models are compared.

Model 1	LnCE =Const + Qyear
Model 2	LnCE =Const + Qyear + Skipper
Model 3	LnCE =Const + Qyear + Skipper + DepCat
Model 4	LnCE =Const + Qyear + Skipper + DepCat + Month
Model 5	LnCE =Const + Qyear + Skipper + DepCat + Month + Traps
Model 6	LnCE =Const + Qyear + Skipper + DepCat + Month + Traps + Block
Model 7	LnCE =Const + Qyear + Skipper + DepCat + Month + Traps + Block + Month*Block
Model 8	LnCE =Const+Qyear+Skipper+DepCat+Month+Traps+Block+Month*Block+Skipper*Month
Model 9	LnCE =Const+Qyear+Skipper+DepCat+Month+Traps+Block+Month*Block*Skipper

Table 6. Statistical results from the standardization of giant crab data from Tasmania. Model definitions are given in Table 5. N is the number of data records (*n*), Var% is the raw R^2 value, AdjustR^2 is the adjusted R^2 as per Eq. 10.4, df Params is the degrees of freedom for the statistical model, df resids is the residual degrees of freedom (*n*-*p*), ModelSS is the variation described by the model, Resid SS is the sum of squared residual errors, #param is the number of parameters (*p*), AIC is the Akaike's Information Criterion Eq. 10.2, and AIC2 is Eq. 10.3. Model 8 and 9 are very similar while the factors in Model 8 are simpler to understand. The three way interaction term in Model 9 makes this difficult to obtain an intuitive understanding of what the terms mean. The vertical line separates simple models from those that include interaction terms. The adjustedR^2 values for Models 7 to 9 are relative to Model 6.

Model	Model 1	Model 2	Model 3	Model 4	Model 6	Model 7	Model 8	Model 9
N	7544	7544	7544	7544	7544	7544	7544	7544
Var%	6.5	30.21	39.08	44.88	50.86	59.28	64.13	69.47
df Params	8	51	74	85	202	416	627	911
df Resids	7535	7492	7469	7458	7341	7127	6916	6632
ModelSS	628.8	2924.1	3782.9	4344.1	4922.9	5738.6	6207.8	6725.2
Resid SS	9051.4	6756.03	5897.3	5336.1	4757.3	3941.6	3472.4	2955
# Param	9	52	75	86	203	417	628	912
AdjustR2	6.3965	29.7321	38.4756	44.2479	49.5031	56.9051	**60.8768**	**65.2806**
AIC	1392.27	-728.23	-1712.29	-2440.17	-3072.33	-4063.31	**-4597.44**	**-5246.64**
AIC2	9.1131	8.8320	8.7021	8.6050	8.5213	8.3899	**8.3191**	**8.2330**
DAdjR2	6.3965	23.34	8.74	5.77	2.91	7.40	11.37	15.78

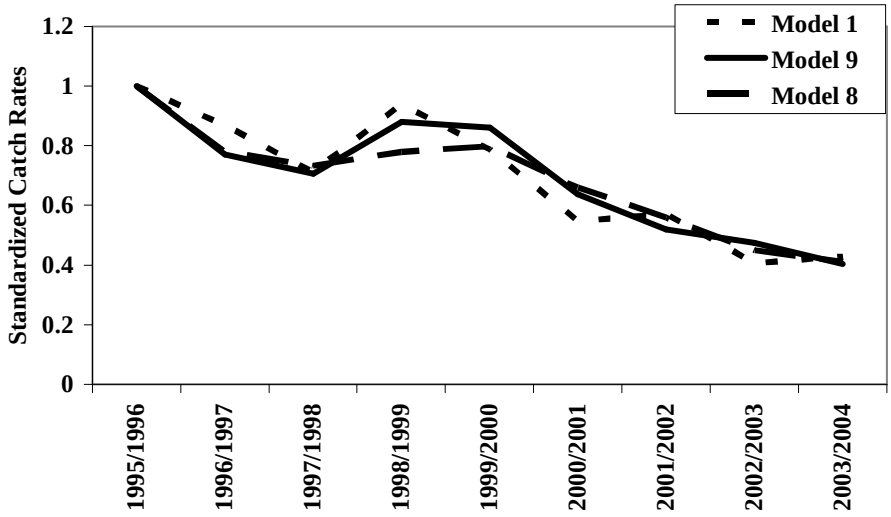


Figure 26. The standardized catch rates deriving from Models 1, 8, and 9 relative to the Quota Year to which they relate, all relative to catch rates in 1995/1996. Data restricted to vessels in the fishery for at least two years and with a median annual catch greater than 1000 kg.

Most of the effect of the standardization was brought about by the original selection of data to those vessels in the fishery for at least two years and catching a median of 1 tonnes per year during that time. If no data selection is made the same two models are optimal but the standardized time-series are rather different (Figure 27). The major difference is with the geometric mean catch rates (Model 1) while the other models, especially Model 8, are relatively close to the restricted data analysis.

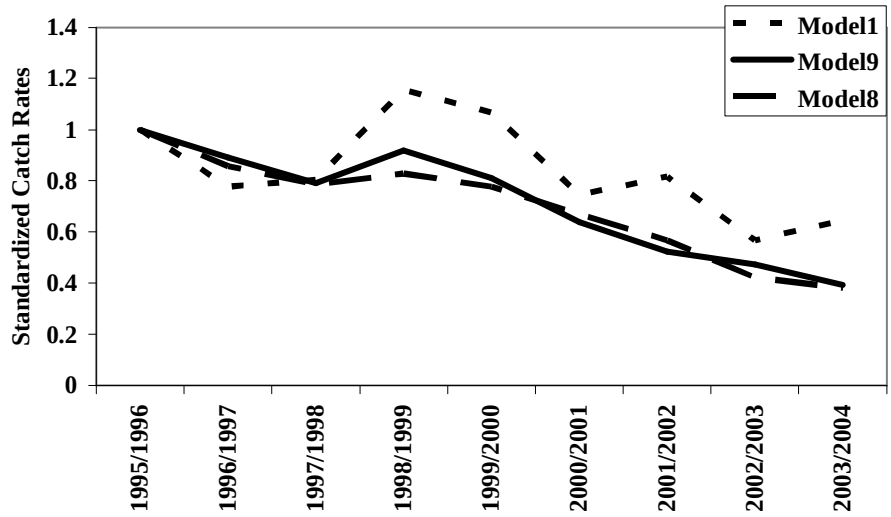


Figure 27. The standardized catch rates deriving from Models 1, 8, and 9 relative to the Quota Year to which they relate, all relative to catch rates in 1995/1996. All available data included in the analysis.

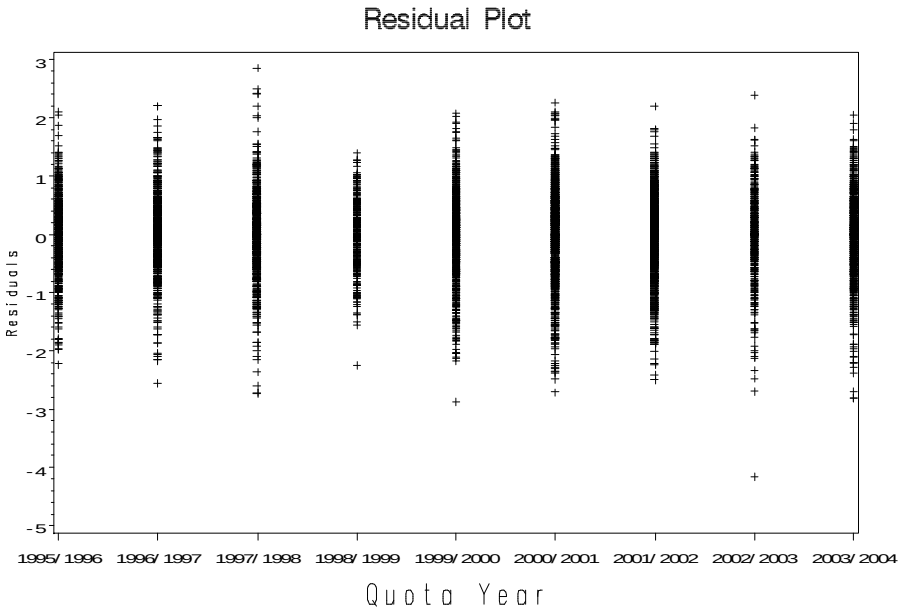


Figure 28. Residual plot for Model 8 for each of the quota years.

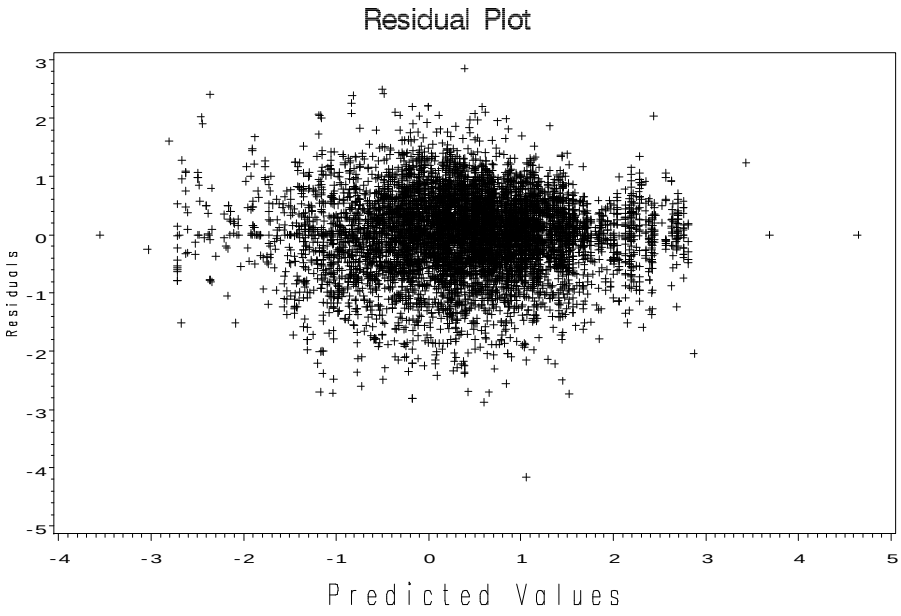


Figure 29. Residual plot against the predicted values showing the relatively even spread of values for Model 8.

Table 7. Predicted standardized catch rates for each of the statistical models (Model 5 is omitted). Models 8 and 9 are optimal; their definitions are in Table 3 and Models 1, 8, and 9 are illustrated in Fig. 3. Qyear is the quota year.

Qyear	Model1	Model2	Model3	Model4	Model6	Model7	Model8	Model9
1995/1996	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
1996/1997	0.7780	0.8661	0.9306	0.9364	0.9442	0.8786	0.8566	0.8923
1997/1998	0.8042	0.7503	0.8032	0.8114	0.8017	0.7962	0.7853	0.7919
1998/1999	1.1558	0.9756	0.9497	0.9274	0.8932	0.8728	0.8290	0.9188
1999/2000	1.0666	1.2678	1.0060	0.9587	0.7980	0.7092	0.7777	0.8107
2000/2001	0.7451	0.8967	0.7874	0.9009	0.7065	0.6459	0.6691	0.6388
2001/2002	0.8156	0.8074	0.6787	0.7705	0.5945	0.5232	0.5671	0.5238
2002/2003	0.5675	0.5743	0.4762	0.4828	0.4277	0.3795	0.4228	0.4734
2003/2004	0.6456	0.6838	0.5788	0.5402	0.3977	0.3661	0.3817	0.3944

7.4 Discussion

Standardisations were conducted by generalised linear models investigating the effects of skipper, vessel, ½ degree block, month within the year, depth, number of traps fished, and interactions where feasible. Not surprisingly, skipper and vessel were highly correlated and treated as a single factor - skipper. Skipper was considered to be more influential on CPUE as greater consistency was expected between a skipper fishing two or more boats than a vessel fished by two or more skippers.

The general trend of standardised catch rates was one of consistent decline and this provided management groups with justification to recommend a reduction in quota. Previous discussion about trends in catch rates had been clouded by uncertainty about the effects of factors such as the participation of minor fishers and the effect of effort shifting to other fisheries, especially scallop. This was clearly a useful process for stock assessment and the models developed are to be run in future assessments.

The statistical analysis only led to minor changes to the geometric mean values, however, the original data selection made by restricted data to those vessels in the fishery for at least 2 years with median catches of at least 1000 kg made the greatest impact. An analysis with this restriction still led to a time-series of catch rates very similar to Model 8.

While Model 9 was statistically a better fit it is recommended that Model 8 be used in any stock assessment as its factors have easily understood meanings and there was little difference between Model 8 and Model 9, which had a three way interaction term (month by block by skipper) that was intrinsically difficult to understand. At very least this term implies that different skippers fish different blocks at different times of the year but how the statistical interactions occur is less clear; these interactions may simply be the difference between the two coasts.

7.4.1 Difficulties with the Analysis

The fishery has two distinct areas, being the east and west coasts. By including statistical block in the analysis, this influence was accounted for, however, it may be better to conduct separate assessments for the two coastlines of Tasmania, as each fishery appears to have different characters. Care will need to be taken, as the amount of data available from the East coast is often far less than available for the West coast. Initially it is recommended that comparisons be made between combined and separate analyses. At very least a separate coast analysis will determine whether the skipper by block interaction is being driven by the separate coasts of whether the separation of effort by skipper along each coast is enough to generate the effect.

In addition, the annual time step of using quota years may create inconsistent standardisation because the effort permitted has varied greatly through the history of the fishery. Inclusion of Month as a factor in the analysis will have alleviated this problem to some extent, but it would be advantageous to explore the outcomes by using perhaps a two-month time period as the base time step.

8. Updating giant crab growth information

8.1 Introduction

Growth information is an essential input for the assessment model and a summary of key findings in relation to giant crabs is given here. These analyses rely on tag-recapture data supplied by Andrew Levings with the help of numerous commercial fishers. A subset of these data were analysed and reported on by Mc Garvey *et al.* (2002) who were able to characterise growth of giant crabs in Western Australia, South Australia and Victoria, but had few records of moulting crabs from Tasmania – the most important region of the fishery. This difficulty was due to lack of tag returns where moulting had occurred, for example, at the time of their analysis only two male tag returns were from animals that had moulted in Tasmania – clearly insufficient data to model growth. Since that time the number of tag returns has increased so that data was available from 167 males that appeared to have moulted. Analyses shown below are for Tasmanian data only and relate to tag recapture data of male crabs generally greater than 80 mm carapace length.

Other sources of information on growth of giant crabs include tank-based observations of juveniles (Gardner and Welsford, 2003) and radiometric analyses of shell age to estimate intermoult (Gardner et al., 2002).

The availability of tagging data from the Tasmanian fishery for giant crabs permitted the development of a description of the growth of giant crabs in a format suitable for inclusion in a size-based stock assessment model. Because of the extended intermoult periods exhibited by the larger giant crabs the description of growth involved a separate consideration of the dynamics of the expected moulting increment and of the intermoult intervals for different sized crabs.

Instead of using one of the standard growth curves to describe the expected average growth increment for each size-class it was found that the relationship between moult increment and size-class could be described well using simple linear regressions. This suggests a similarity with the growth increment version of the von Bertalanffy growth model (Fabens, 1965) but no benefit would have accrued from using the slightly more complex model so the expected growth increments were described by straight lines. A simple method was devised for using data from both single and double moults in the estimation of the regression lines in describing moult increments. The variation of moult increment about the average increment was best-described using normal distributions and was not held constant as with ordinary regression analysis. The optimum models were produced when the variability around the expected moult increment was linearly related to the premoult carapace length. Sufficient data was available to estimate the growth transition matrix up to the legal size for both females and males but little or no information was available from crabs above legal sizes. The linear regressions of size-class to expected moult increment were extrapolated to generate the expected moult increments for the larger size-classes. Using the data and the extrapolations it was possible to generate the required annual growth transition matrices for males and

females. Of course the extrapolation may have introduced a degree of uncertainty into the predicted growth patterns but the regressions between moult increment and initial size were relatively clear so this source of uncertainty may only have been minor. Far more critical was the estimation of the intermoult periods for the larger crabs.

The intermoult periods of giant crabs become longer as the size of crab increases. This could potentially lead to problems if, for example, fouling organisms grow across a suture line and prevent successful moulting. It seems likely that a moulting event would constitute a significant source of natural mortality, which also seems likely to become greater as the crabs become larger. To include this, a linear relationship between moulting related mortality rates and size-class was included in the model of growth. The columns of the growth transition matrix were multiplied by the survivorship for each size-class following this natural mortality so that the growth and the implicit mortality were coordinated. In the size-based stock assessment model, this source of natural mortality was in addition to a background constant rate of annual natural mortality. The inclusion of this source of natural mortality is based upon intuition only as there is only anecdotal evidence that moulting mortality increases with size.

The description of the intermoult dynamics was more difficult to develop as this had not been attempted before in such detail. It was found that the proportion of giant crabs in a particular size-class that moulted through time was described well using a logistic curve. In addition, the larger size-classes took much longer for all animals to moult than the smaller animals with the moulting of larger crabs being less synchronized and spreading out over a longer period (the logistic curves were flatter).

A matrix of size-class against years-to-moult was generated containing the logistic curves describing the cumulative proportion of animals in each size-class moulting with the passing years. A simple transformation converted this cumulative proportion through time to the expected proportion of the animals remaining in a given size-class that would moult in a given year. This matrix of moulting proportions for each size-class and year-since-last-moulting could be used in conjunction with a matrix of number-at-size by years-since-last-moulted to determine the numbers in each size class that would moult in any one year. These would be grown using the transition matrix to form the first column of the numbers-at-size matrix while the remainder would stay in their original size-class but move a year forward in the years-since-last-moulted axis of the numbers-at-size matrix. The innovations were the matrix of proportions moulting and converting the numbers-at-size vector normally used in size-based models into a matrix of number-at-size by years-since-last-moulted. Large amounts of data are required to generate the logistic curves describing the moulting dynamics for the different size-classes. In practice, for females there was only enough data to describe four size classes and only two size-classes for males. Once again extrapolation was possible but this time there were non-linear relationships involved and thus there was a high level of uncertainty introduced into the final description of growth. While it was possible to generate the necessary description of growth it must be emphasized that the description of the intermoult dynamics was very dependent upon interpolation and extrapolation of non-linear relationship fitted to very few data points.

8.2 Introduction to Crustacean Growth

Species with internal skeletal structures or no skeletal structures tend to grow in size in a gradual, continuous fashion. Crustacea, on the other hand, have a hard exoskeleton or carapace, which they need to shed or moult before they can grow in size. In essence, Crustacea grow through an iterative process of moulting, hydraulic body expansion, carapace hardening, an intermoult period, and then moulting again. Some species repeat this process until the intermoult period becomes so long they die before moulting, while other species have what is termed a terminal moult, sometimes associated with maturation, after which they do not moult again (Hartnoll, 1985). Crustacean growth has been described in many different ways, some of which were related to methods used to describe continuously growing species (such as fitting a von Bertalanffy growth curve to growth increment data obtained from tagging experiments; Fabens, 1965) while other methods attempt to describe both the intermoult interval and the moult increment. Verdoit *et al*. (1999) provided a review of many of the mathematical models that have been used to describe the moult increment and the intermoult interval in Crustacea. There do not appear to be very many attempts to combine a description of the moulting interval and the growth increment into a size-based stock assessment model.

Crustacea are often difficult to age with any accuracy so any description of growth cannot be made by a direct comparison of size against age. Instead, the indirect methods used to describe growth include the tracking and description of modal progressions in length frequency information (Wenner *et al*, 1987; Sheehy *et al*., 1998), the use of tag and recapture experiments (Punt *et al.*, 1997), and retaining individuals in captivity and following their growth histories (Thomas, 1965; Gardner and Welsford, 2003). The primary purpose for describing the growth of harvested species is to obtain insight into the potential productivity of the species concerned and, ideally, to provide a way for inclusion of growth processes into stock assessment models for the stock. This latter can be either as weight-at-age or, as in length-based models, numbers-at-size through time.

There is a fishery for the Australian giant crab, *Pseudocarcinus gigas* (Lamarck, 1818), in the States of Western Australia, South Australia, Victoria, and Tasmania with the largest catches coming from Tasmanian waters. This present study is restricted to a consideration of animals taken in Tasmania. The growth of giant crabs has previously been considered in some detail by McGarvey *et al*. (2002) who used a tag and recapture data set in their study. They found that in all States except Tasmania the moult increment in males was relatively constant up to a given size beyond which there was no information available. For females, again in all States except Tasmania, there was an identifiable decrease in moult increment in females with increasing premoult carapace length up to some maximum size beyond which there was little data. In addition, McGarvey *et al*. (2002) found that the intermoult period increased dramatically with premoult carapace length, with larger animals having intermoult periods of many years. Unfortunately, because of unavoidable limitations in the data set at that time, McGarvey *et al*. (2002) were not able to conclude anything about the growth of Tasmanian male giant crabs (there were only two tag returns for males from Tasmania). Furthermore, the limited data available for females from Tasmania indicated that the moult increment was relatively constant with premoult carapace length, which was different from the females in every other State. This lack of information about Tasmanian giant crabs prevented the

development of a suitable stock assessment model for the largest giant crab fishery in Australia.

There have now been many more tag returns from Tasmanian waters and this present work aims to produce a description of the growth of Tasmanian giant crabs. This will be formulated in such a way as to simplify its inclusion into a size-based model akin to those used with southern rock lobster (*Jasus edwardsii*) in Australia and New Zealand (Punt and Kennedy, 1997; Starr *et al*, 1999). A novel structure was required for this model because of the extended intermoult period in giant crabs. A standard growth transition matrix (Punt *et al*. 1997) would only inadequately capture the complex interaction between the changing intermoult periods and the moult increments in different sized giant crabs. In this study both the intermoult periods and the moult increments for different sized crabs of both sexes will be considered and one way of including both these processes into a stock assessment model will be demonstrated.

8.3 Growth Transition Matrices

When it is not possible to age a species with any accuracy a good alternative modelling option to standard age-based models is to construct a size-based model (SBM). Thus, instead of modelling the changes in numbers-at-age through time, SBMs follow the changes in expected numbers-at-size. Obviously, such SBMs require a method of describing the expected changes through time of the size-distribution of the population under study. One method of doing this is to multiply the vector of numbers at size by a size-transition matrix to generate a new vector of numbers at size:

$$\mathbf{N}_{t+1}^{k} = \mathbf{G}^{k}\mathbf{N}_{t}^{k} \qquad 11.1$$

where $\mathbf{N}_{t}^{k}$ is the vector of numbers in each size-class at time t for sex k, and $\mathbf{G}^{k}$ is the square growth transition matrix containing the transition probabilities of particular size-classes growing into other size-classes. One of the problems to be solved in such a stock assessment model is how best to estimate the growth transition matrix.

Because of their variable and extended intermoult period, only a proportion of the population of Tasmanian giant crabs would be expected to moult in any one year. For that small proportion of animals it will be necessary to generate a growth transition matrix. For the animals that do not moult, which therefore remain in their original size class, it will be necessary to maintain some form of accounting of the numbers in each size class and how many years they have lived without moulting. What is needed is a description, through the maximum number of years required, of the annual proportions moulting from each size class.

To describe the transition matrix, there will be an expected mean growth increment for each size-class about which there is expected to be some degree of spread (Figure 29). A transition matrix contains the predicted distribution of expected growth for each size-class being considered. Size- or Length-Based Assessment models (Sullivan *et al*,1990; Sullivan, 1992) follow the fate of the numbers in each size-class as opposed to numbers in each age-class (Haddon, 2001). In the usual situation where a SBM is being used, a population being modelled is described by a vector of the numbers in each size class at

time *t*, $\mathbf{N_t}$ (in what follows, bolded characters are used to denote vectors and matrices). At some point during each time-step in the model, at least some individuals grow, which implies that animals either stay in their original size class or move into a larger one (Figure 30).

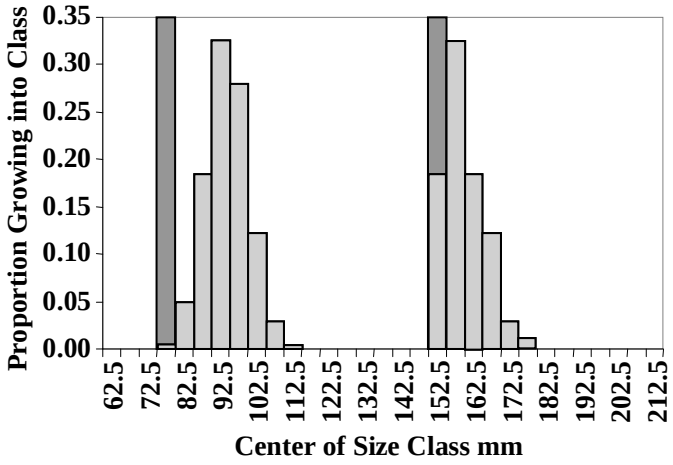


Figure 30. The expected growth increment from two different initial size-classes in an hypothetical crustacean species. The grey bars represent the initial sizes while the light coloured bars represent the size distribution after growth of animals originally in the single grey bars. Note, in this instance, the smaller animals are expected to grow, on average, more than the larger animals. Some of the larger animals do not grow out of the size-class in which they begin.

Mathematically, the numbers-at-size at time *t* are usually represented by a vector of size-classes:

$$\mathbf{N_t} = \begin{bmatrix} N_{1,t} \\ N_{2,t} \\ . \\ N_{n,t} \end{bmatrix} \qquad 11.2$$

where N_t is the vector of *n* size classes indicating the numbers in length-class *l* at time *t*. A stage- or size-structured model provides a description of the calculation of N_{t+1}.

The foundation of such stage-structured models is the transition matrix with which the population vector is repeatedly multiplied to describe the changing population size-structure through time. The transition matrix contains the probability that the individuals in length class *l* at time *t* have grown into length class *l** by time *t*+1, and can be combined, if desired, with survivorship probabilities and recruitment relationships. There are often variations in the exact contents of the transition matrix to reflect the particular circumstances of the fishery being modelled. In matrix notation the effect of growth alone would be represented thus:

$$\mathbf{G} = \begin{matrix} G_{1,1} & 0 & . & . & . & 0 \\ G_{2,1} & G_{2,2} & . & . & . & . \\ G_{3,1} & G_{3,2} & G_{3,3} & . & . & . \\ G_{4,1} & G_{4,2} & G_{4,3} & G_{4,4} & . & . \\ . & . & . & . & . & 0 \\ G_{n,1} & . & . & . & G_{n,n-1} & G_{n,n} \end{matrix} \qquad 11.3$$

where **G** is the transition or projection matrix in which the $G_{i,j}$ are the probabilities that an animal in size class or column *j* will grow into size class or row *i*. Multiplying the numbers-at-size vector, $\mathbf{N_t}$ by the square transition matrix leads to Eq. 11.1, which describes growth in the population without recruitment or mortality. In a model of rock lobster, where the sexes grow differently, separate vectors of numbers-at-size and separate growth transition matrices would be required for each sex.

Clearly, the key to the formation of any growth transition matrix is in how the individual cell probabilities ($G_{i,j}$) are defined. Sullivan *et al* (1990) and Sullivan (1992) used the Gamma distribution to describe the expected distribution of growth increments for each size class. Punt *et al* (1997) compared the use of the Gamma probability density function (PDF) with the Normal PDF and found that the Normal distribution provided an optimum fit when describing the growth of Tasmanian rock lobster. McGarvey *et al* (2002) compared the Normal, the LogNormal, and the Gamma PDFs as descriptions for the moult increment of giant crabs. They found that the Normal PDF provided the best fit in 6 out of 7 single moulting distributions, and this occurred even in the female populations where the moult increment being described was greatly confounded with the declining moult increment relative to premoult carapace width. Nothing in the new data available for the Tasmanian giant crabs indicated an asymmetry to the distribution of moult increments. In male giant crabs only, where the moult increments were only slightly influenced by the carapace length, a formal comparison of the Normal, the Log-Normal, the Gamma, and the Beta distributions demonstrated that the Normal PDF provided the best description of moult increment. However, all distributions were able to be fitted acceptably well.

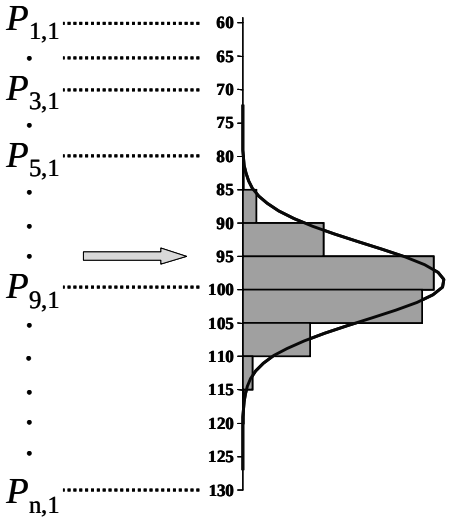


Figure 31. Diagrammatic representation of the derivation of the relative probabilities of the animals from a particular size class growing into any one of a range of size classes.

The average of the normal distribution is the average expected moult increment (Figure 31). The transition probabilities are simply the cumulative normal distribution to the upper size limit of each size class minus the cumulative normal distribution to the lower size limit of each size class in turn:

$$G_{i,j}^{k} = \int_{-\infty}^{L_i+\frac{\Delta L}{2}} \frac{1}{\sqrt{2\pi}\sigma_j^k} e^{-\left[\frac{\left(L_i-\bar{L}_j^k\right)^2}{2\left(\sigma_j^k\right)^2}\right]} dL \qquad L_i = L_{Min}$$

$$G_{i,j}^{k} = \int_{L_i-\frac{\Delta L}{2}}^{L_i+\frac{\Delta L}{2}} \frac{1}{\sqrt{2\pi}\sigma_j^k} e^{-\left[\frac{\left(L_i-\bar{L}_j^k\right)^2}{2\left(\sigma_j^k\right)^2}\right]} dL \qquad L_{Min} < L_i < L_{Max} \qquad 11.4$$

$$G_{i,j}^{k} = \int_{L_i-\frac{\Delta L}{2}}^{+\infty} \frac{1}{\sqrt{2\pi}\sigma_j^k} e^{-\left[\frac{\left(L_i-\bar{L}_j^k\right)^2}{2\left(\sigma_j^k\right)^2}\right]} dL \qquad L_i = L_{Max}$$

where $G_{i,j}^{k}$ is the transition probability of a crab growing from size class j into size class i for sex k, L_i is the mid-size of size class i, ΔL is the size class width, σ_j^k is the standard deviation of the normal distribution of moult increments for sex k (there is a sub-script j in case variability around the moult increment varies with premoult carapace length j), and $\bar{L}_j^k$ is the expected average moult increment for sex k for premoult carapace length j. The sum of the transition probabilities for all n size classes is standardized to equal one (that is the columns of the matrix all sum to one:

$$\sum_{i=1}^{n} \frac{G_{i,j}}{\sum_{i=1}^{n} G_{i,j}} = 1.0 \qquad 11.5$$

8.3.1 Natural Mortality at Moulting

The intermoult periods found for giant crabs both in this study and by McGarvey *et al*. (2002) are extremely long relative to most Crustacea. This is remarkable because the shells must maintain their integrity for the years between moults. In addition, there is always the risk of fouling organisms establishing themselves on the carapace, which becomes critical if the fouling grows across one of the suture lines that must open for moulting to occur (unpublished tank observations; Gardner, TAFI). Natural mortality in fisheries assessment models is most often implemented by assuming a constant mortality rate across all ages or size classes for each time period in the model. This seems inappropriate in the case of giant crabs, where natural mortality during the intermoult period is likely to be very low while moulting mortality could be relatively high. Because the intermoult period increases with size, it also seems likely that the mortality rate at moulting will increase with size-class. It was therefore decided to implement natural mortality, in the model of giant crab dynamics, as having two components. The first is the traditional constant background of natural mortality set at a low level. The second is a mortality rate associated with the moulting process that increases in a linear fashion with size-class. Thus, the background natural mortality, M_B, is included in the usual way but the moulting associated mortality and implied survivorship were set up as a function of size class *i*:

$$M_i = b + \delta L_i \quad S_i = e^{-M_i} \qquad 11.6$$

This is implemented by populating the diagonal of a square matrix by the S_i values and multiplying the growth transition matrix by the result:

$$\mathbf{T^k} = \mathbf{G^k S^k} \qquad 11.7$$

where $\mathbf{T^k}$ is the transition matrix for sex **k** that combines growth and the natural mortality associated with that growth, $\mathbf{S^k}$ is the square matrix of survivorships from Eq. 11.6.

8.4 Methods

8.4.1 Tagging Data

All tagging data were derived from an extension to the study that provided data to McGarvey *et al*. (2002). The tagging of giant crabs required the use of specially modified tags having a double T-bar (Levings *et al*. 1996). Tags are inserted into the epimeral suture line and without the double T-bar the tags could be drawn into the large branchial chamber of the crabs causing tag loss (McGarvey *et al*. 2002). The second T-

bar, about 10 mm below the terminal T-bar, acts as a stopper to prevent such unwanted tag movement. Vernier callipers were used to measure the carapace lengths, defined as the shortest distance from the centre of the anterior margin of the dorsal carapace between the eyes to the posterior margin of the carapace at the junction with the abdomen (McGarvey *et al*. 2002). Data were primarily available for giant crabs tagged at sizes below the legal minimum length of 150 mm carapace length (Table 8), although some data exist for larger females that most likely had been ovigerous at the time of capture (ovigerous females cannot be landed).

8.4.2 Moult Increment

The moult increments were investigated for both sexes by determining how many moults each animal had experienced in its time at liberty and then characterizing the relationship between the moult increments and the pre-moult carapace length. Some tags were recaptured more than once. In these cases the time taken till first moulting was considered as a single observation. If there was then another recapture, without a moult event this was also considered as an observation providing information about the moulting interval of the new sized animal (Figure 32). There were no occasions of multiple returns with multiple moults implied.

Table 8. The relative frequency of female and male giant crab tag returns from Tasmanian waters. The maximum number of recaptures on a single tag was three. The size classes were convenient divisions. A total of 2221 tags were placed into males with 220 unique returns, while there were 4964 placed into females with 625 unique returns. This implies a total tag return rate of 9.9% for males and 12.6% for females. The numbers in the table are greater than 625 and 220 because some multiple returns could be counted twice (see Figure 32).

Females	**Count**	**Minimum**	**Maximum**	**Average**
<131	110	81	130	121.95
131-149	437	131	149	141.55
>=150	94	150	199	163.22
Total Females	641			141.37
Males	**Count**	**Minimum**	**Maximum**	**Average**
<131	103	81	130	119.80
131-149	119	131	149	138.86
>=150	7	155	179	170.14
Total Males	229			131.24

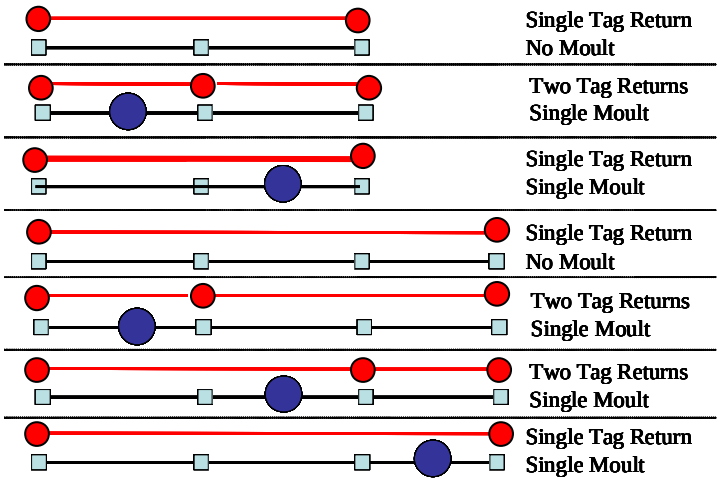


Figure 32. No more than a single moult increment was observed in recapture data, although some crabs were captured moulted twice. For those crabs observed two or even three times it was possible to obtain up to two valid observations from the same tagged animal. This included the time taken up to and including the first observed moult increment, followed by the time from recapture out to its final capture. In the diagram the large circles indicate a moult and the small circles indicate a recapture. Yearly time steps are divided by the small squares. The text describes how each combination of recapture and moult was interpreted.

Over the data range available, the average moult increment in males, of about 30 mm, decline slightly with increases in pre-moult carapace length. This is similar to the pattern seen in males from South Australia and Victoria (McGarvey *et al*, 2002). However, the females from Tasmanian waters exhibit a definite decline in moult increment with increasing pre-moult carapace length (Fig. 4), this differs from the conclusions drawn from the limited number of observations available to McGarvey *et al* (2002).

By plotting the moult increment against premoult carapace length distinct patterns become apparent (Figure 33). There are clear groupings of animals, those that appear not to have moulted, those that appear to have moulted once, and a few that appear to have moulted at least twice (Figure 33). Some females were tagged and recaptured at sizes above the 150mm minimum legal length because they were either ovigerous or badly damaged when first captured. Only a very few males were tagged above the legal size and these may have been damaged or deformed animals of lower value, which presumably biases their moulting ability.

8.4.3 Characterization of Moult Increment

One standard method for characterizing the predicted moult increment would be to fit the tagging version of the von Bertalanffy growth curve to the moult increment data (Fabens, 1965; Haddon, 2001). However, this requires a steady decline in observed moult increment with premoult size and so, for males, even though there is a slight decrease in average increment over the observed range of observations the von Bertalanffy curve would imply a ridiculously large maximum size. Strictly, all that is required to generate a transition matrix is a predictive relationship between premoult

size and moult increment. Therefore, instead of an explanatory model being fitted, simple linear regressions were used to provide an empirical estimate of the expected growth increments for each size-class for which there was information.

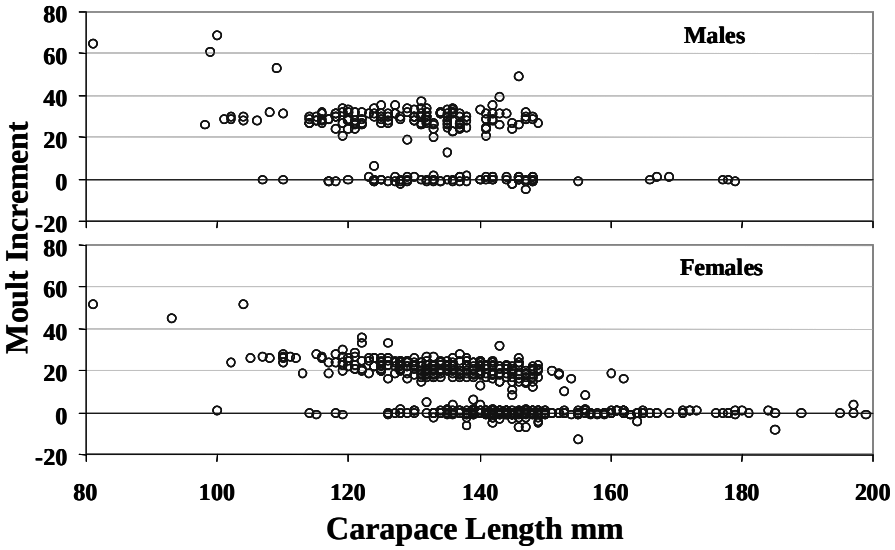


Figure 33. Plots of the moult increment of giant crabs from Tasmanian waters relative to premoult carapace length.

Before the moult increments were estimated, each observation had to be classified with regard to how many moults they represented; *i.e.* to what groupings of data should regression lines be fitted. A visual inspection of the data (Figure 33) indicated animals that obviously have not moulted, there are others that have moulted once, some appear to have moulted twice, and then there are others that appear to be intermediate between the average moult intervals and which, therefore, are difficult to classify (Figure 33).

The classification strategy adopted was to make an initial hypothesis about moult category membership for each point. By inspection of the data for growth increment (Figure 33) it was concluded that for both sexes, lengths > 40 mm appear to indicate two moults, lengths > 9 mm and < 40 mm suggested single moults, and anything < 10mm would be a non-moulting animal. Using this initial classification, separate linear regression lines were fitted to each data set for the no-moult and single-moult animals. The data were assumed to be normally distributed around the expected values and the regressions were fitted using maximum likelihood methods. This provided estimates of the standard deviation of the data around the expected regression lines, which, in turn, was used to generate confidence bounds around the data to aid in the identification of potential outliers or misclassifications. In each case, the suspect points were either re-classified into a different moulting category or considered to be outliers.

Reclassification of a particular point from one moulting category into another was only done when the reclassification improved the maximum likelihood fit of the resulting regressions. McGarvey *et al* (2002) did something very similar to this but with a somewhat different method of identifying potential outliers.

Unlike the analysis by McGarvey *et al* (2002), double moulting animals were included in the analysis by determining the predicted increment for one moult and then determining the predicted increment for the initial premoult length plus the implied single increment. Thus, where MI_1 is a single moult increment, MI_2 is a double increment, Int is the intercept, Grad is the gradient of the straight line regression, and PCL is Premoult Carapace Length, then for one moult:

$$MI_1 = Int + Grad*PCL + \varepsilon$$

And for two moults: 11.8

$$MI_2 = MI_1 + [Int + Grad*(PCL+MI_1)] + \varepsilon = 2MI_1 + Grad*MI_1 + \varepsilon$$

The gradient is negative so Eq. 11.8 implies the second moult will be less than the first. The variance of the normal random errors around the second moult increments was assumed to be the same as that around the first moult and the straight lines describing both the single and second moults were fitted at the same time using maximum likelihood to estimate all parameters for each line. Note that in estimating the line for double moults the variation around the predicted first moult increment is ignored.

As an alternative to the usual assumption behind linear regression, of constant error variances, alternative lines were fitted using an assumption of a linear relationship between premoult carapace length and the variance of the residuals around the expected mean increment. The lines generated, their relative quality of fit (using AIC) and the residuals generated were all compared. The optimum was that which gave rise to the maximum likelihood while minimizing the number of parameters, and this was characterized using the minimum Akaike's Information Criterion.

$$AIC = -2LL + 2k \qquad 11.9$$

where *LL* is the negative log-likelihood and k is the number of parameters.

The linear regressions and their associated standard deviations were used to generate the required growth transition matrices for each sex using the equations described in Eq. 11.4 and Eq. 11.5. The straight lines describing moult increment for a given premoult carapace width were extrapolated into the larger size classes for which no information was directly available.

8.4.4 Intermoult Interval

A plot of moult increment versus time exhibits a number of properties that must be accounted for in any analysis of moulting interval (Fig. 5). The first obvious property is that tag recaptures tend to be grouped in time. As well as being a reflection of the existence of a distinct moulting season, this is also a reflection of the seasonality of the giant crab fishery. Secondly, there are no tag returns with zero growth, indicating no moulting, after about 4 years. Finally, the proportion of recaptures exhibiting a moult increases through time from no moults to 100% moulted.

The obvious method for determining the intermoult period for the different size-classes selected is to collate the numbers recaptured in various time intervals and calculate the proportion that have moulted. To this data a logistic equation can be fitted using non-linear fitting techniques.

8.4.5 Log-Likelihoods for Logistic Regressions

When conducting logistic regressions on binomial data (true/false, mature/not-mature, moulted/not moulted) the optimum approach is to use a logit transformation to linearize the data. Despite this linearization it is still necessary to use a binomial residual error structure (Neter *et al*, 1990). The logistic model can be represented as:

$$E(Y) = P(Y) = \frac{e^{(B0+B1X)}}{1+e^{(B0+B1X)}} = \frac{1}{\left(1+e^{(-(B0+B1X))}\right)} \qquad 11.10$$

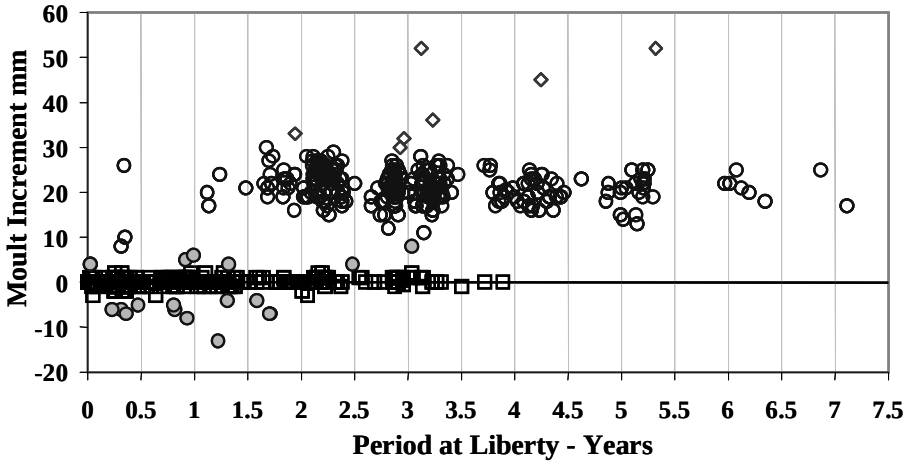


Figure 34. Moult increment against period at liberty for all female Tasmanian giant crab tag returns. The obvious periodicity in the returns reflects the seasonality of the fishery. From the analysis of moult increment, diamonds are double moults, open circles are single moults, squares are no moult, and filled circles are outliers.

For a monotonically increasing curve, *B0* would be negative and *B1* would be positive, while for a monotonically decreasing curve the reverse would be true. This logistic curve can be linearized using the Logit transformation (Neter *et al*, 1990); setting $P(Y) = \pi$, we have:

$$\pi' = Ln\left(\frac{\pi}{1-\pi}\right) \qquad 11.11$$

which, combined with Equation 14 leads to:

$$\pi' = B0 + B1X \qquad 11.12$$

The derivation of this turns out to be relatively simple (Appendix 5).

From the fitted logistic parameters we can derive the median interval and the inter-quartile distance:

$$L50 = \frac{-B0}{B1} \qquad 11.13$$

$$L75 - L25 = 2Ln(3)/B1 \qquad 11.14$$

8.4.6 Logistic Regressions for Giant Crab Moult Intervals

Even with the number of tag returns now available the information available to characterize the intermoult interval is limited. It was possible to categorize the moults into a number of size ranges and develop logistic regressions for each of these. The ranges were 100-130 mm, 131-139 mm, 140-145 mm, and 146-162 mm for females with 100-130 mm and 131-150 mm for males.

Giant crabs grow to much larger sizes than for which data was available. The best available strategy for describing the moult interval of these larger sizes was to extrapolate from the properties of the known size classes to those of the unknown. The logistic regression parameters altered with size class and from the initial fitting process to the female data it was found that an exponential relationship best described the relation between the B0 and B1 parameters.

Table 9. Number of tag returns relating to the estimation of the intermoult interval and the description of the proportion moulting through time. Nobs is the total number of tag returns, Nmoult is the number of returns where the animals have moulted.

Gender	Size Range	Midpoint	Nobs	Nmoult
Female	100-130	115	104	88
Female	131-139	135	147	87
Female	140-145	142.5	177	54
Female	146-162	152	164	37
Male	100-130	115	92	68
Male	131-150	140	141	63

These exponential relationships were fitted to the available data and projected to generate implied parameters for the logistic curves describing the proportion moulting of those size classes for which there was no data. The unknown B0 parameters for the larger size classes were derived by determining the optimum relationship existing

between the size class and the B0 parameters for the available size classes (this was a linear relationship for both males and females). Using this relation, an additional source of likelihood was added to the fitting process to constrain the logistics to lie on the same exponential relationship. For females, all four logistic regressions were fitted at the same time by varying the B0 parameters for each regression and the parameters of an exponential relationship between the B0 and B1 parameters. By knowing the exponential relationship between the B0 and B1 parameters of the various logistic regressions it was possible to generate an estimate of the B1 parameters as predicted by the assumed exponential relationship. In this way, it was possible to constrain the solutions for each logistic such that, using the additional linear relationship between size class and the B0 parameter, it was possible to project the parameters expected from unknown size classes.

The logistic regressions characterize the cumulative proportion of crabs moulting from each size class relative to years available. Using this it was possible to determine how many from each size class were going to moult in a particular year i.e. the proportion moulting as a fraction of those remaining rather than a cumulative proportion. In the stock assessment model the proportion moulting in a particular year were subtracted from the non-moulting crabs and grown to generate the first column of the numbers-at-size by year-to-moult matrix (the numbers matrix). The remaining non-moulting animals stayed in the same size class but were moved one year across the year-to-moult rows of the numbers matrix. To include this probability of moulting matrix into an assessment model it was necessary to determine from the cumulative proportions (the logistic regression) what proportion of the numbers remaining in a cohort/size class would moult each year. This could be determined using:

$$\begin{aligned} M_i^L &= C_i^L && \text{moult year } i = 1 \\ M_i^L &= \frac{C_i^L - C_{i-1}^L}{1 - C_{i-1}^L} && \text{moult year } i > 1 \end{aligned} \qquad 11.15$$

where for a given size class L, C_i^L is the cumulative probability of having moulted by year i, determined from the logistic regression, and M_i^L is the actual proportion of animals remaining in year i that are expected to moult. When the logistic curves for all n size classes are converted to these absolute proportions it generates an n x Y matrix, where Y is the maximum number of years required by the slowest growing giant crabs to pass completely through a moult.

8.5 Results

8.5.1 Moult Increment

Both males and female giant crabs exhibit a decline in average moult increment with increasing premoult carapace length. With the females (Figure 35) there is a marked decline from 27.5 mm increment at 100 mm carapace length down to 16.0 mm at 162 mm (a total decline of 11.5 mm), while with the males (Figure 36) only a minor decline

occurs from 30.44 mm at 98 mm down to 28.05 mm at 150 mm (a total decline of 2.4 mm).

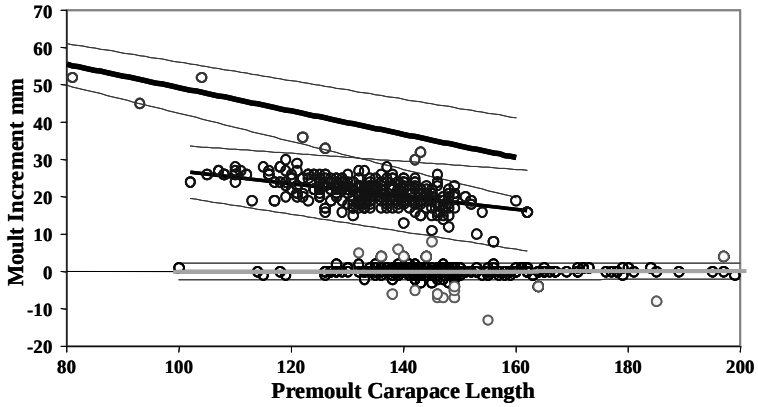


Figure 35. Moult increment versus premoult carapace width for female giant crabs off Tasmania. The lower flat line and black circles relates to females deemed not to have moulted. The central lines and blue circles represent the data for crabs deemed to have moulted once. Finally, the upper 7 red circles and associated lines represent crabs that are deemed to have moulted twice. The confidence intervals represent 3x the standard deviation (StDev) for each size class obtained through the maximum likelihood fitting process. The green and yellow circles are outliers that could not be classified into a particular moulting category. Parameter values are described in Table 10.

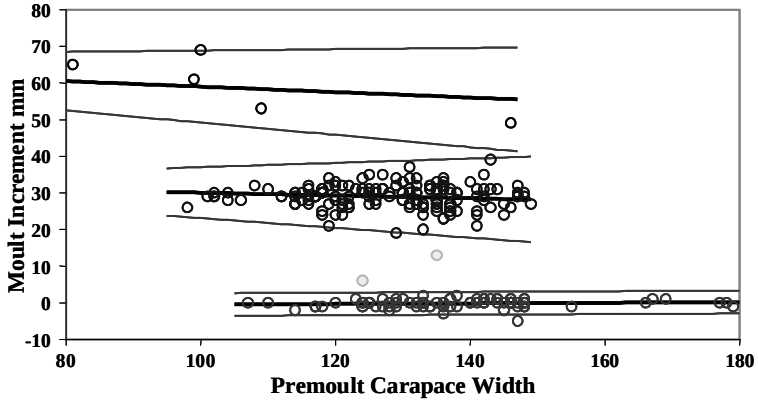


Figure 36. Lines describing the average moult increment for male crabs with either no moult, a single moult, or a double moult. The 99.7% confidence intervals were 3 times the Standard Deviation for each size class. The parameters are described in Table 10. The double moult is described in the text and is assumed to exhibit the same StDev as the single moult. Only two outliers were identified.

Table 10. Parameters from the regression lines fitted to the Tasmanian giant crab tagging data. Ideally, both the gradient and the intercept of the no-moult lines should have been zero. The assumption of constant variance was not tested in the no moult case. For the male and female single moult regressions, which also defined the double moults, the assumption of a constant variance was tested against the alternative of a linear relation between standard deviation and size class. Thus, if $\sigma_{gradient}$ is absent then the regression assumes a constant variance (σ_{const} only). AIC is the Akaike's Information Criterion and –veLL is the negative log-likelihood of the line fit. In both sexes the optimum fit, as indicated by the smallest AIC, was produced by including a relationship between the variability of the moult increment and the premoult carapace length (Figure 35 and Figure 36).

	Male			Female		
	Single	**Single**	**No Moult**	**Single**	**Single**	**No Moult**
Gradient	-0.04593	-0.03798	0.00894	-0.17651	-0.17055	0.00105
Intercept	34.94102	33.84391	-1.41124	44.73915	43.97422	-0.10141
σ_{const}	3.26020	-0.88163	1.03447	3.02145	0.17339	0.72864
$\sigma_{gradient}$		0.03199			0.02120	
AIC	869.4418	**863.9974**		1497.558	**1493.607**	
Parameters	3	4	3	3	4	3
-veLL	412.7085	408.1796	126.3964	744.779	742.8033	447.5588

The regression lines were fitted with either constant variances (the normal assumption with linear regressions) or with the addition of a linear relationship between the variance of the moult increment and the premoult carapace length. There was a significant difference between the negative log-likelihoods for the two models in both males and females. In each case the slightly more complex model with changing variance had the smaller AIC and was therefore selected. Given the balance between the number of parameters and the total negative log-likelihood, the assumption of changing variation of moult increment with premoult carapace length produced the best fitting line.

The linear relationships and their standard deviations were used to generate the required size transition matrices.

8.5.2 Moult Interval - Females

Far more data were available for estimating the intermoult intervals for females than for males. Because of this it was possible to consider four separate size classes for female but only two for males (Section 8.8; Table 13 and Table 14). There were slightly fewer animals available for determining the intermoult periods than for determining the moult increment because to avoid biasing the results, double moulting animals were not included in the analysis. In addition, there were some very large animals that were not included in the analysis because they were few in number and none had moulted.

Initially, logistic regressions were fitted to the available data for the different size classes in each sex of giant crab (parameters were B0 and B1; see Eq. 11.10). For females all four logistic regressions were fitted at the same time by varying the B0 parameters and

the parameters of an exponential relationship between the B0 and B1 parameters for each regression (Figure 37; Table 11).

At the same time, the relationship between the middle of each size class and the B0 parameter from the logistic regressions was obtained (for females this was a linear relationship; Table 11). The total time for all animals to moult out of each size class increases (Table 11) from about 2.7 years for the smallest size class (100-130mm) up to about 5.5 year for the largest class with data (145-162mm). The seven projected size classes were predicted to take between 1.9 and 14.0 years to completely moult (Table 11). The steepness of the logistic regression also decreases with size class, as evidenced by the increase in the inter-quartile distance with increasing size class (Table 11).

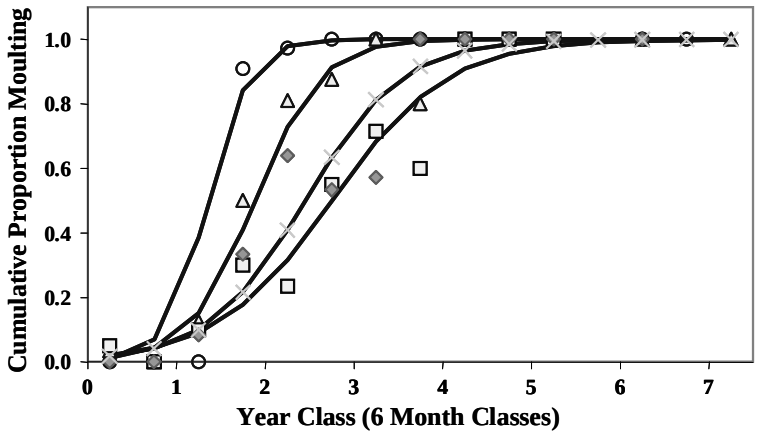


Figure 37. The cumulative proportion of female giant crabs moulting from four size classes. The four lines and data points represent the logistic regressions for the size classes 100-130mm (circles), 131-139mm (triangles), 140-145mm (crosses), and 146-162mm (squares) (Table 4).

Table 11. Properties of the four logistic regression curves fitted to female data (Figure 37). The size classes are listed with the average in brackets, InterQ is the inter-quartile distance, 2 x 50% is an estimate of the maximum time for all animals in the size class to moult, 50% is the estimate of when 50% will have moulted, B0 and B1 are the logistic regression parameters from Eq. 11.10, -veLL is the negative log-likelihood, finally, SC is the size class. The two equations at the bottom of the table are the logarithmic relationship between size class and B0, and the exponential relationship between the two logistic regression parameters.

Size Class	InterQ	2 x 50%	50%	B0	B1	-veLL
100-130(115)	0.5142	2.7182	1.3591	-5.8077	4.2731	3.43212
131-139(135)	0.8116	3.7706	1.8853	-5.1041	2.7074	11.4585
140-145(142.5)	1.1944	4.9016	2.4508	-4.5084	1.8396	15.2735
146-162(152)	1.4290	5.5046	2.7523	-4.2321	1.5376	13.8203
80-105(100)	0.3283	1.9421	0.9711	-6.4994	6.6932	
110-135(120)	0.5803	2.9693	1.4846	-5.6212	3.7862	
140-155(140)	1.0259	4.4289	2.2145	-4.7429	2.1418	
160-175(160)	1.8135	6.3796	3.1898	-3.8647	1.2116	
180-195(180)	2.4407	8.4422	4.2210	-3.8000	0.9003	
200-215(200)	3.4628	11.0319	5.5159	-3.5000	0.6345	
220-250(220)	4.8245	14.0527	7.0263	-3.2000	0.4554	

Equations used in projecting the logistic regressions into different size classes.

B0 = 0.043913 SC – 10.890732	Linear
B1 = 0.0987609EXP(-0.648693 B0)	Exponential

When the relationships between size-class and B0, and between B0 and B1, are used for interpolation into size classes bounded by the available data, plausible logistic curves are generated. When they are used to extrapolate into smaller size-classes (100mm) this also produces a plausible curve. However, when used to extrapolate up to 180, 200, and 220 mm implausible logistic curves are produced that have high tails implying that a significant proportion of animals moult in the first year (Figure 38). An alternative method was required to generate plausible logistic regressions for the largest size classes.

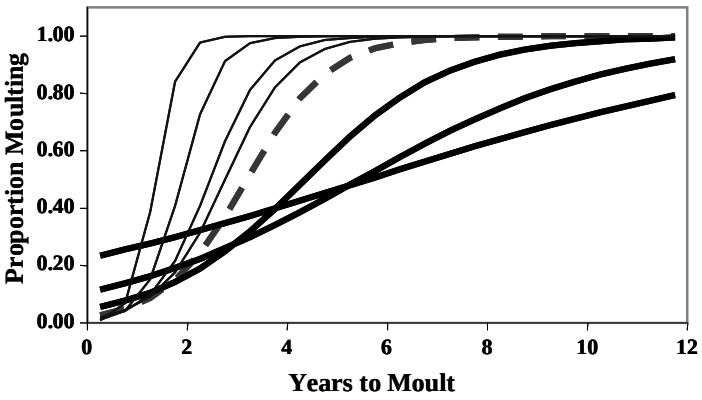


Figure 38. The fine lines are the four fitted logistic regression curves between proportion moulted and total time. The dashed line represents the projected curve for a size-class centred on 160mm. The three curves to the right of the dashed line represent projected curves for 180mm, 200mm, and 220mm. Extrapolating the relationships between size-class and B0, and between B0 and B1 logistic curves are generated that imply implausibly high proportions moulting in the largest size-classes in the first one to three years.

Reasonable curves were generated when interpolating or when only extrapolating by small amounts (*e.g.* between 100mm and 160mm). The implied maximum time to 100% moulting form an increasing series providing a power relationship between the size-class and the time to 100% moulting (Table 11). By fitting this relationship (Figure 39) and using it to predict the expected maximum time for moulting for the larger size classes, it was then possible to search for logistic curves that generated the required time to 50% moulting but that also did not have excessive proportions moulting in the earliest years (Figure 40). By plotting the fitted curves and comparing them with the interpolated and extrapolated curves a stable pattern is observed (Figure 40).

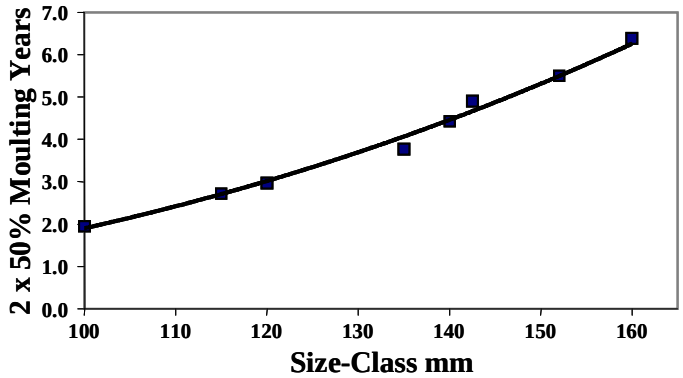


Figure 39. Relationship between size-class in mm and the maximum time for 100% moulting in female giant crabs. The power relationship was $1.5833e^{-5}$ SC $^{2.53933}$, and this was used to predict the maximum time taken for 100% moulting in the largest giant crab size classes (Table 11).

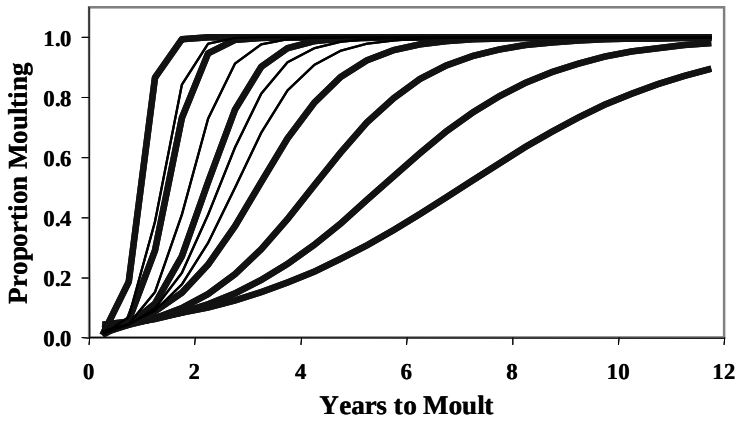


Figure 40. The fitted, the interpolated, and extrapolated logistic regressions of proportion moulted against years to moult for female giant crabs. The fine lines relate to the four fitted curves. The thick lines are the sequence of size classes 100m, 120mm, 140mm, 160mm, 180mm, 200mm, and 220mm (see Table 11).

8.5.3 Moult Interval - Males

For male giant crabs there was only enough data to generate two logistic regressions (Figure 41). With only two points it was not possible to determine the characteristic of the relationships between the various parameters and the size-classes. Therefore, the relationships between size class and the B0 parameter, and between the B0 and B1 parameters, were assumed to be linear and exponential, respectively, as with the female crabs. Using these assumptions with the males, interpolating the relationships produced plausible sets of projected logistic regressions (Table 12). As with the females, reasonable curves were generated when interpolating or when only extrapolating by small amounts (*e.g.* between 85mm and 145mm). The implied maximum time to 100% moulting forms an increasing series providing a power relationship between the size-class and the time to 100% moulting (Table 12). By fitting this relationship (Figure 42) and using it to predict the expected maximum time for moulting for the larger size classes, it was then possible to search for logistic curves that generated the required time to 50% moulting but that also did not have excessive proportions moulting in the earliest years (Figure 43).

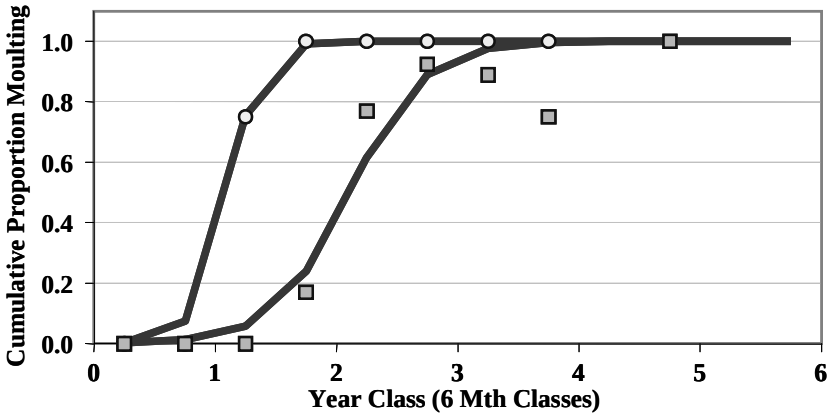


Figure 41. The cumulative proportion of male giant crabs moulting from two size classes plus the fitted logistic regression lines associated with each size class. The two lines and data points (Section 8.8) represent the size classes 100-130mm (circles) and 131-150mm (squares) (Table 12).

Table 12. Properties of the two fitted logistic regression curves along with the projected curves for male giant crabs (Figure 41 & Figure 43). The size classes are listed with the average in brackets, InterQ is the inter-quartile distance, 2 x 50% is an estimate of the maximum time for all animals in the size class to moult, 50% is the estimate of when 50% will have moulted, B0 and B1 are the logistic regression parameters from Eq. 11.10, -veLL is the negative log-likelihood, finally, SC is the size class. The two equations at the bottom of the table are the linear relationship between size class and B0, and the exponential relationship between the two logistic regression parameters.

Size Class	InterQ	2 x 50%	50% Moult	B0	B1	-veLL
115	0.3052	2.1809	1.0904	-7.8491	7.1982	1.2708
140	0.6923	4.2072	2.1036	-6.6764	3.1738	12.9352
80-90(85)	0.1143	0.9627	0.4813	-9.2563	19.2307	
91-100(95)	0.1585	1.2681	0.6340	-8.7872	13.8592	
101-110(105)	0.2200	1.6656	0.8328	-8.3182	9.9881	
111-120(115)	0.3052	2.1809	1.0904	-7.8491	7.1982	
121-130(125)	0.4236	2.8453	1.4226	-7.3800	5.1876	
131-140(135)	0.5877	3.6971	1.8485	-6.9110	3.7386	
141-150(145)	0.8155	4.7818	2.3909	-6.4419	2.6943	
151-170(160)	1.1772	6.1488	3.0745	-5.7383	1.8664	
171-190(180)	2.0097	8.7798	4.3904	-4.8002	1.0933	
191-210(200)	3.4347	12.0743	6.0372	-3.8620	0.6397	
211-250(220)	4.6569	16.1079	8.0540	-3.8000	0.4718	

Equations used in projecting the logistic regressions into larger size classes.

B0 = 0.0469066 SC – 13.2433678 Linear

B1 = 0.02997574 EXP(-0.69832109 B0) Exponential

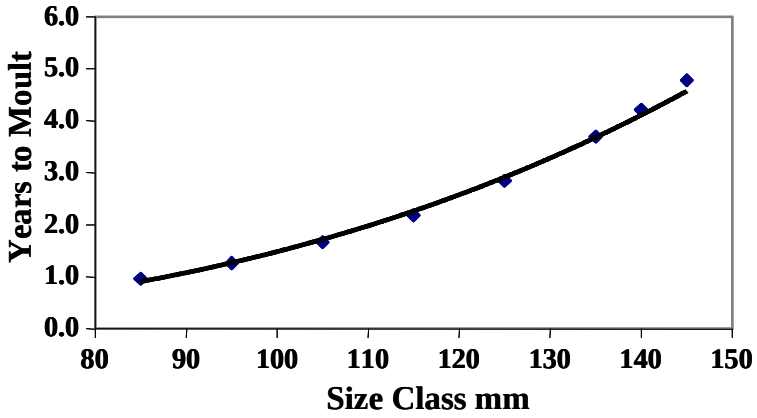


Figure 42. Relationship between size-class in mm and the maximum time for 100% moulting in male giant crabs. The power relationship was $1.32801e^{-6}$ SC 3.024149, and this was used to predict the maximum time taken for 100% moulting in the largest (>145mm) giant crab size classes (Table 12).

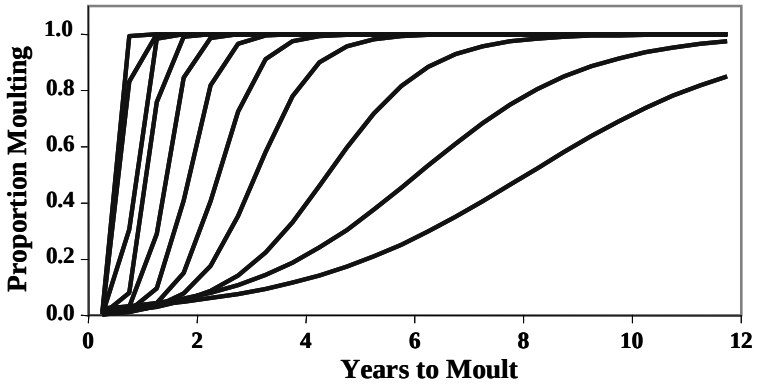


Figure 43. The interpolated, and extrapolated logistic regressions of proportion moulted against years to moult for male giant crabs. While series of logistic curves relate to the sequence of size classes 85mm, 95mm, 105mm, …., and 220mm. The parameters and properties of all curves are described in Table 12.

8.5.4 Implied Equilibrium Size Distribution

One approach to determine whether the suggested moult increments and consequent transition matrices are realistic is to compare the implied size distribution in the absence of fishing to that observed in the very early days of the fishery. The assumption is that selectivity is described well by a logistic. If the predicted equilibrium size structure deriving from constant recruitment in the absence of fishing is matched against the proportional size structure from early in the fishery then it should be possible to set the moulting mortality and see how well the growth dynamics can match the observed size distributions.

Data on the size-distribution of the complete catch is available for both males and females from catch sampling on-board commercial fishing vessels prior to 1995 (Figure 44). This provides an indication of the expected size distribution at the start of the

fishery. For males the size-class with the maximum number of observations was 135mm but 130 was close, so for males the range compared between observed and model predicted was 130mm to 220mm. For females the maximum was at about 145mm, but again 140mm was close, so the range compared was 140mm to 215mm.

Using an outline stock dynamics model (see later) without fishing mortality, it was possible to determine the equilibrium size structure by iteratively adding recruitment, growing the animals and killing them naturally. Using the sub-set of size-classes selected the proportional distribution of numbers-at-size were compared between the predicted equilibrium size-structure and that observed. The comparison was made using simple least squared residuals. By varying the parameters of the linear regression describing the moulting mortality relative to size-class it was possible to iteratively optimize the match between the observed and predicted size distributions.

Setting the background instantaneous natural mortality to a constant 0.05, it was found that a linear regression of the form:

$$M_i = 0.001 + 0.00795 L_i \qquad 11.16$$

optimised the match between observed and expected size distributions (Figure 45).

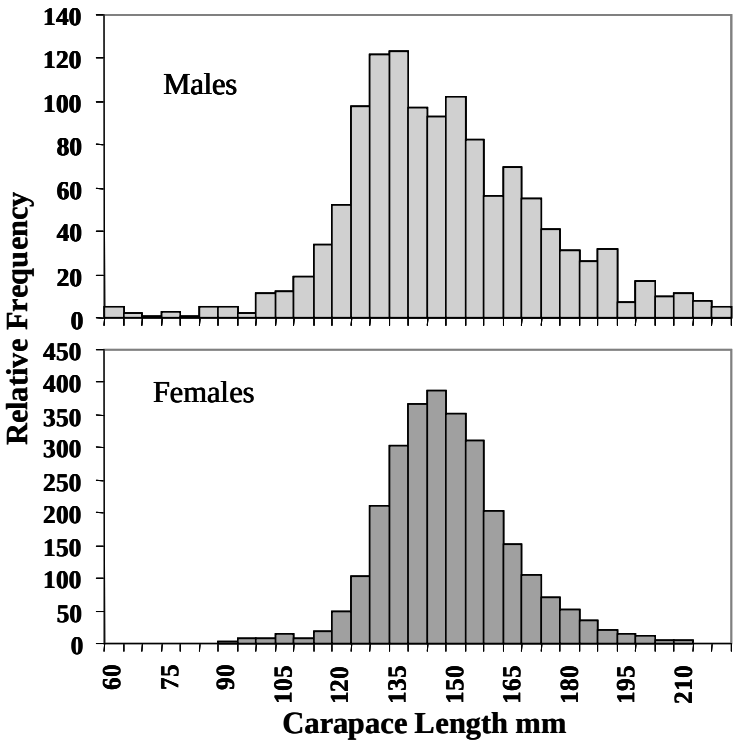


Figure 44. Comparison of the size-distribution of the commercial catch of Giant Crab in Tasmania prior to 1995.

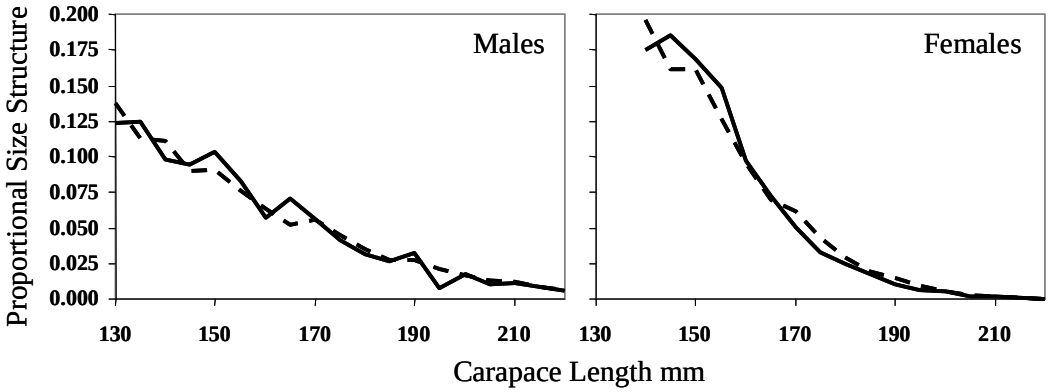


Figure 45. Comparison of the predicted proportional size structure (dashed lines) with the observed proportion size structure (solid lines) from the Tasmanian giant crab fishery before 1995.

8.6 Discussion

The growth analyses shown here provide a substantial improvement on that previously available due to both the increased number of records and the increased time at large. The outcomes from this analysis will contribute to management of this fishery as critical input data to yield and egg per recruit models and also for length based population modelling.

While this information will be of value for population modelling of the giant crab resource, some aspects of the analyses were limited by data availability. The most critical aspect is that data for legal sized crabs is scarce as no males of above 150 mm CL were observed to moult and no females of above 165 mm CL. Although the largest size category of tagged crabs ranged between 146 and 200 mm CL, and thus includes large crabs well above the minimum legal size, few recaptures were obtained for that group.

Improving data coverage of legal size crabs would be valuable and should be considered in future research programs. However, the difficulty in increasing coverage of tagging data for legal sized crabs is the costs, as noted by Levings *et al.* (2001). Fishers retain legal-sized crabs so they would require compensation for lost revenue if these crabs were to be tagged and released. Giant crabs have a very high individual value, typically above $100 per crab, so the eventual cost of moult data then becomes extremely high, given that only a small portion of the crabs released will be recaptured, reported and have moulted. Compounding the problem of obtaining moult data is that legal size crabs are vulnerable to exploitation for many years before a moult occurs.

Levings *et al.* (2001) attempted to improve data coverage of legal sized crabs by tagging crabs that were legal sized but were discarded. This can occur when crabs have one or no chelae, or when female crabs are ovigerous and cannot be landed. However, as noted by Levings *et al.* (2001) and also McGarvey *et al.* (2002), this strategy introduces biases and would ideally be avoided in favour of the release of legal-sized crabs selected randomly from the catch.

A consequence of the distribution of data for the current analysis is that our conclusions are much more robust in relation to crabs below the minimum size limit than those above. The risk of this data scarcity affecting our conclusions is likely to differ for moult increment and intermoult period estimates.

Moult increment estimates are likely to be the more reliable aspect for several reasons. Our estimates are well supported by those made by McGarvey et al. (2002) using data for other States, in particular the remarkably flat relationship between release size and moult increment for males appears to hold true across the range. Females in this study were observed to have a declining increment with length, which McGarvey et al (2002) reported for all States except Tasmania, where they observed a pattern more similar to that of males. That observation now appears to have been an artefact of the smaller sample sizes they had available.

It is also noteworthy that the distribution of increment data for Tasmania now appears more consistent with that for other parts of the range. We observed that a normal distribution fit to moult increments was most appropriate. McGarvey *et al.* (2002) detected an asymmetrical distribution in the maximum likelihood fit in their analysis of the smaller sample of females from Tasmania although they observed that data from all other regions were normally distributed.

Lack of moult data for legal size crabs is probably more critical in relation to intermoult period as there may be non-linearities with size, as a substantial increase in intermoult duration with size would be expected. Other studies have indicated that intermoult of large giant crabs becomes so extended that crabs effectively reach a terminal moult. Gardner and Williams (2002) examined changes in chelae morphometry and observed that males moulted into a "morphologically adult" stage at sizes above 175 mm CL. Given the moult increment documented here, it appears possible that some males could moult directly from below 150 mm CL into this state of morphological maturity. McGarvey et al. (2002) and Levings et al. (2001) observed very few moults of crabs tagged above legal size and also considered that intermoult period may become significantly longer for legal-sized crabs. Evidence also comes from radiometric analysis of shell age, which gave estimates of around 8 years intermoult duration for female giant crabs between 150 and 160 mm CL (Gardner et al., 2002).

Intermoult period estimates from this study were similar to those estimated from South Australia (McGarvey et al., 2002) with smaller females (<130 mm CL) estimated to moult around 3 years, while those in the larger class required 7 years. This indicates that growth around Tasmania is more rapid than other regions examined by McGarvey et al. (2002), Victoria and Western Australia. Tasmania appears to have the highest density of crabs of any of the states and this may be a function of higher productivity in part due to higher growth. "Faster" growth in this context is of course relative to populations of giant crab in other states. Relative to other exploited species the growth of giant crabs is low and their productivity would appear to be correspondingly low.

The description of the growth dynamics for giant crabs is complicated by the extremely long intermoult periods plus the inherent increased likelihood of moulting mortality associated with the long intermoult periods. Developing the growth transition matrix was relatively straight forward although due to the lack of data with respect to legal sized animals (>149mm carapace length) the predicted average moult increments could

only be obtained for the larger size classes through extrapolation of the linear regressions used to describe the relationship between average moult increment and original size-class. This extrapolation obviously has the potential for adding uncertainty into the description of growth dynamics; discussion of any consequent results must remember this.

Describing the dynamics of the intermoult periods required the development of a novel method of accounting for the years required for members of a given size class to moult. This moulting probability matrix requires that the numbers-at-size vector, normally used in size-based stock assessment models, be converted into a number-at-size by years-to moult matrix.

It was found that logistic curves provided good descriptions of the cumulative proportions moulting through time and a simple relationship then renders the expected proportion of animals remaining in a size-class in a given year that will moult. Unfortunately, the data requirements for developing the suite of logistic curves required is greater than that required for the growth transition matrices. The tagging information available only described the intermoult dynamics of smaller size-classes. Interpolation of the parameters from these curves worked well but extrapolation led to unrealistic predicted moulting proportions. Instead, the intermoult period was extrapolated and these were used instead to search for logistic curves producing plausible moulting descriptions. Some of the intermoult periods for the larger crabs are extremely long, and this led to the development of the notion of moulting mortality, which was assumed to be related to the duration of the intermoult period or size-class. The most convenient way of coordinating the moulting mortality into the growth dynamics was to include the survivorship for each size-class into the growth transition matrix to generate a transition matrix that both grew the vector of animals that were due to grow but also killed off different proportions of them depending on size-class.

8.7 Growth Appendix 1. Derivation of Logistic Transformation and Likelihood.

We first make two simplifications for ease of typing:

$$E(Y) = P(Y) = \pi \qquad \text{and} \qquad Z = B0 + B1X \tag{11.17}$$

using these we translate 11.10 into:

$$\pi = \frac{e^Z}{1+e^Z} \tag{11.18}$$

we note that:

$$1-\pi = 1-\frac{e^Z}{1+e^Z} = \frac{1+e^Z-e^Z}{1+e^Z} = \frac{1}{1+e^Z} \tag{11.19}$$

therefore, from Equation 14:

$$\frac{\pi}{1-\pi} = \frac{e^Z}{1+e^Z}.\frac{1+e^Z}{1} = e^Z \tag{11.20}$$

continuing Equation 14:

$$\pi' = Ln\left(e^Z\right) = Ln\left(e^{B0+B1X}\right) = B0 + B1X \tag{11.21}$$

In cases where there are repeat observations of the dependent variable (e.g. moulting, yes=1 or no=0) for each level of an independent variable X (e.g. recapture interval) the log-likelihood function required is relatively simple (Neter *et al*, 1990). Assuming there are a total of t different recapture interval of duration X (in this case, for example, X might be 6 months), then for each of the t X's there will be N_t observations (where N_t can vary for each of the classes concerned) and only n_t will have moulted. For each of the X_t the proportion moulting equals:

$$p_t = \frac{n_t}{N_t} \tag{11.22}$$

in which case the log-likelihood function can be described as:

$$LL(a,b) = \sum_{i=1}^{t}\left\{ Ln\left(\frac{N_i!}{n_i!(N_i!-n_i!)}\right) + n_i\left(B0 + B1X_i\right) - N_i Ln\left(1+e^{B0+B1X_i}\right)\right\} \tag{11.23}$$

8.8 Growth Appendix 2. Tagging Data Results

Table 13. Number of observations used in determining the intermoult intervals for three size classes of female giant crabs (100-130mm, 131-139mm, 140-145mm, and 146-162mm). Year is the period between tagging and recapture, Nobs is the number of observations and N_Moult is the number of moulting animals in the total. Double moults were ignored and outliers were treated as not moulting.

Size Class	100-130		131-139		140-145		146-162	
Year	Nobs	N_Moult	Nobs	N_Moult	Nobs	N_Moult	Nobs	N_Moult
0.25	10		29	1	50		40	2
0.75	2		16		25		47	
1.25	2		8	1	24	2	10	1
1.75	11	10	4	2	6	2	10	3
2.25	36	35	21	17	25	16	17	4
2.75	15	15	16	14	15	8	20	11
3.25	17	17	23	23	14	8	7	5
3.75	3	3	5	4	3	3	5	3
4.25	4	4	12	12	7	7	5	5
4.75			3	3	2	2	2	2
5.25	2	2	7	7	4	4	1	1
5.75					1	1		
6.25	1	1	2	2	1	1		
6.75	1	1						
7.25			1	1				
Total	104	88	147	87	177	54	164	37

Table 14. Number of observations used in determining the intermoult intervals for two size classes of male giant crabs (100-130mm and 131-150 mm). Year is the period between tagging and recapture, Nobs is the number of observations and N_Moult is the number of moulting animals in the total. Double moults were ignored and outliers were treated as not moulting.

	100-130		131-150	
Year	Nobs	N_Moult	Nobs	N_Moult
0.25	20		21	
0.75	3		11	
1.25	4	3	2	
1.75	12	12	41	7
2.25	33	33	26	20
2.75	10	10	26	24
3.25	9	9	9	8
3.75	1	1	4	3
4.25				
4.75			1	1
Totals	92	68	141	63

9. A Size Based Stock Assessment Model for Giant Crabs

9.1 Summary

- A size-structured stock assessment model has been produced although outcomes could be improved by information on growth, through the collection of representative length data, and a greater time series of informative data. As increased quantities of better quality data accumulate then the uncertainty in the assessment from the model should decrease.

- Model fits indicate that the Tasmanian giant crab stock has declined steadily since the introduction of the targeted commercial fishery; it may have reached as low as 27.87% of the unfished exploitable biomass, which for such an unproductive species appears to be quite heavy depletion.

- If no further negative effects are imposed on the Tasmanian giant crab stock and recruitment is approximately average over the next ten years, then the current TAC of 62.1 t appears to have the potential to permit some rebuilding of the stock and hence of the catch rates.

- The TAC of 62.1 t appears to be sustainable under the present conditions of exploitation in the stock, which suggests that the catch rates should at least stabilize in the next year or two and may begin to rise. If they do not then the stock would need reassessment under the assumption of lower productivity than currently assumed.

- The TAC of 103.5 t , which was in operation prior to 2004, appears likely to continue the depletion of the stock and would not be considered sustainable.

- The model requires further exploratory development but emphasis must be placed on the collection of more and better quality data from the fishery.

9.2 Introduction

The giant crab, *Pseudocarcinus gigas* is an extremely large and heavy crab fished across Southern Australia. In Tasmania, this is now a fishery with a 60.1 t TAC, which relates to 1035 units at 60kg a unit. This implies that with an average weight of over 2.5kg, the fishery is based on less than 24,000 retained individual animals. This small number of individual animals restricts the available information about the biology, growth, and population dynamics of this species. Nevertheless, research efforts conducted with tremendous cooperation from the fishing industry have now enabled the production of a detailed stock assessment model for investigating the implications of different harvest strategies (different TACs, different minimum and maximum size limits, different seasonal closures).

While a stock assessment model has been produced it must be emphasized that it was generated on the basis of a minimum of data and there are many uncertainties in the parameters fitted and the model structure selected. That is, the model produced has a suitable form but the parameters fitted in the descriptions, particularly of growth, are limited due to available data. Despite these caveats, the model provides indications of the likely productivity of giant crabs relative to commercial fishing, and alternative growth descriptions (apparent optimum and more productive) can be compared to determine the range of possible behaviour.

The model has been produced using data for the Tasmanian fishery, the largest of the State fisheries. This is reported in parts, the first being this summary of the assessment of the Tasmanian stock. This assessment is based on an analysis of catch rates, with the standardization process for this data given in Section 7. The most critical driver of population dynamics in a size-based model is the description of growth, and this was presented in Section 8. Growth in crustaceans is made up of the intermoult period and the moulting increment. In giant crabs the intermoult intervals can be very long so a detailed description of this process was required along with the need to estimate an annual time step growth transition matrix for those crabs that do moult.

Natural mortality was modelled in two ways. The first was the classical method of constant rate imposed across all size classes each year. The second form of natural mortality explicitly modelled was a moulting mortality associated with the act of moulting. Given the extremely long intermoult periods relatively to most other crustaceans, it seemed likely that the moulting event would be much more hazardous to the crabs than the intermoult intervals. No knowledge is available concerning natural mortality so this division into two distinct processes is essentially speculation. It does, however, lead to plausible dynamics and is intuitively more realistic than using a simple constant natural mortality imposed each year. Finally, a formal description of the model structure is provided. This summarises the algorithm used to define the population dynamics and associated processes such as selectivity and fecundity at size.

9.3 Formal Stock Assessment of Tasmanian Giant Crab Fishery

9.3.1 Data Available

There are two main sources of data that can be used in a stock assessment model of giant crabs. Firstly there is the standardized catch rates and catches provided by the commercial catch return log-books (Table 3 and Figure 26; Chapter 7). Secondly, catch sampling by observers and by commercial fishers provides the size distribution of the commercial catch through the years of the fishery (Section 9.7).

There are 20 parameters fitted by the model (Table 15). The model fails to fit the final five years of recruitment residuals because there can be a time-lag of up to five years for new recruits to enter the fishery and there is little information prior to their entry to the fishery to influence the parameters. Similarly, the first five years were relatively small catches and these provided too little information to fit the first few years of the time series. This bias in information towards animals just above legal-size is similar to aging bias where individuals at either end of the curve are under-represented.

Table 15. The twenty parameters used in the fitting of the giant crab model. Their descriptions are given in the model specification section, under Recruitment and Selectivity. The rows with quota years listed are the log-normal recruitment residuals in each year; 1 = average recruitment.

Average Recruitment	229550.3
Selectivity *L50* Female	149.6068
Selectivity *L95* Female	151.5490
Selectivity *L50* Male	152.1214
Selectivity *L95* Male	154.1188
1989/1990	1
1990/1991	1
1991/1992	1
1992/1993	1
1993/1994	1.872168
1994/1995	0.673044
1995/1996	0.478676
1996/1997	0.385602
1997/1998	0.346226
1998/1999	0.37247
1999/2000	1
2000/2001	1
2001/2002	1
2002/2003	1
2003/2004	1

With the set of optimum parameters in Table 1, the fit to catch rates was reasonable with a deviation in 1994/1995, 1998/1999 and 1999/2000 (Figure 46). The decline is down to just over 30% of catch rates in 1994/1995.

The comparison of the available length frequency information requires a large number of graphs (Figure 47 and Figure 48).

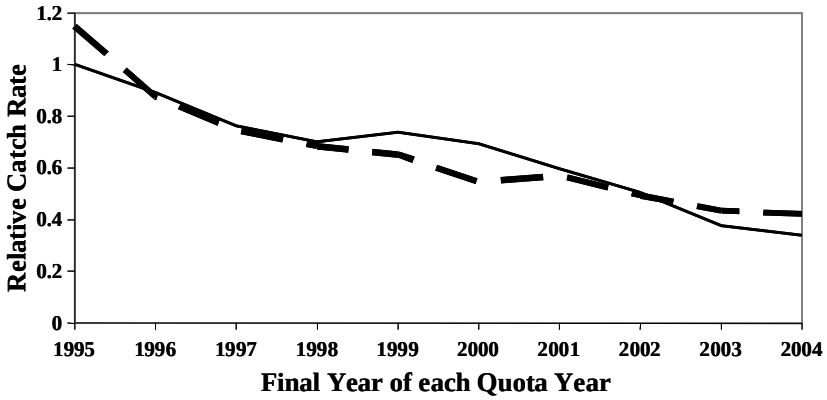


Figure 46. Comparison of the standardized catch rates (fine solid line) and the predicted catch rates from the model (thick dashed line).

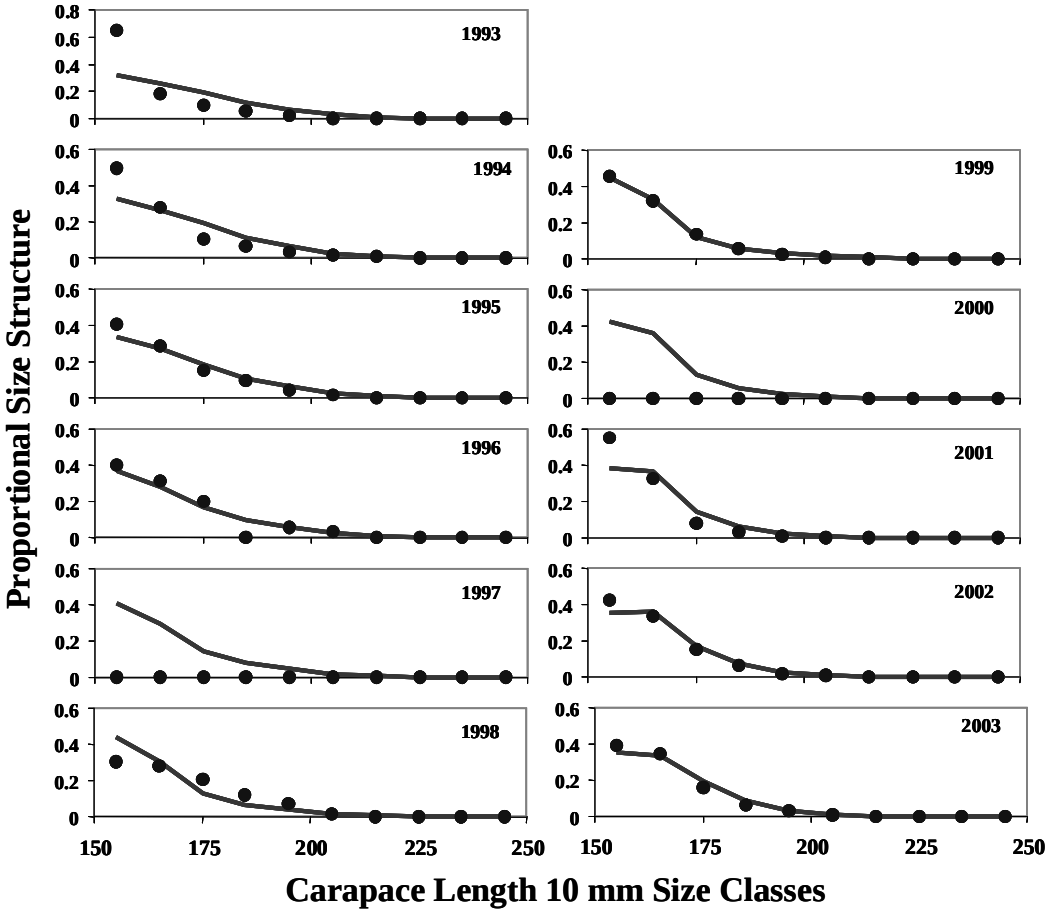


Figure 47. The observed proportional size structure of female giant crabs (blue dots) relative to the predicted proportional size structure (solid line). The slight bump at 160-170 is brought about by the inherently incremental growth of the giant crabs, which is not expressed very strongly in females. The years are the final years in the Quota year combinations, *e.g.* 2003 denotes the 2002/2003 quota year. Quota years with no observations are depicted where the blue dots align with the X-axis.

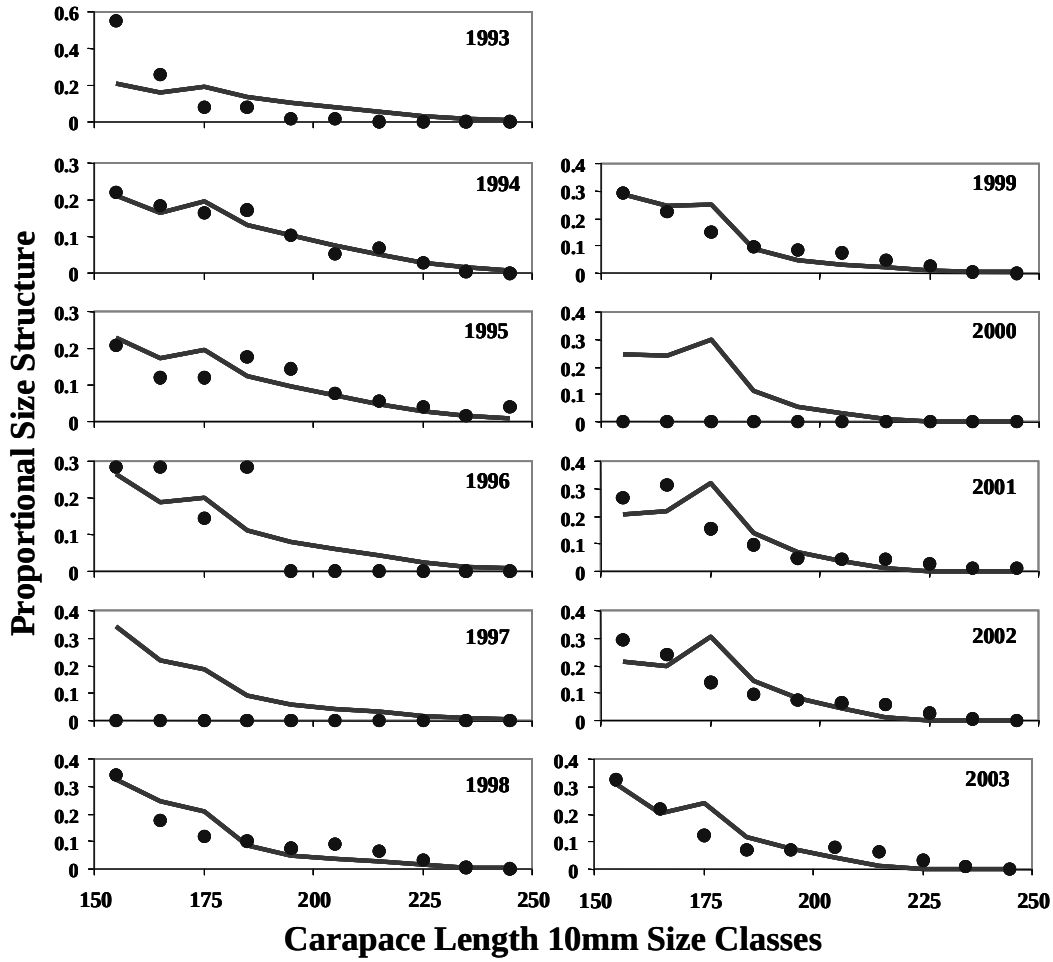


Figure 48. The observed proportional size structure of male giant crabs (blue dots) relative to the predicted proportional size structure (solid line). The bumps at the 170-180 size class are brought about by the inherently incremental growth of the giant crabs, which is expressed relatively strongly in males. The years are the final years in the Quota year combinations, *e.g.* 2003 denotes the 2002/2003 quota year. Quota years with no observations are depicted where the blue dots align with the X-axis.

In addition, the assessment model permits a comparison of the original, effectively unfished size distribution with the predicted current size distribution (Figure 49). The depletion brought about by fishing is clear from the separation of the two lines beyond the legal limit. The coincidence of the lines for the size classes below 140mm is brought about by the recruitment levels defaulting to the average recruitment in the absence of information that would permit the recruitment residuals for the last five years from being fitted (Figure 49). The appearance of a number of modes in the size distributions reflects the rapid growth of the crabs at the smaller sizes. The dynamics of growth interacts with the implementation of recruitment (divided into the first six size classes, to produce the modal structure below the legal sizes). This can influence the fit to the proportional size structure (*e.g* .Figure 48) by producing minor peaks in the expected size distribution of the catch. As the moult increments decline in the females the affects of this reduce. The progression of modes continues for larger sizes in the males until the variation in growth increment acts to smooth out the distribution (Figure 49).

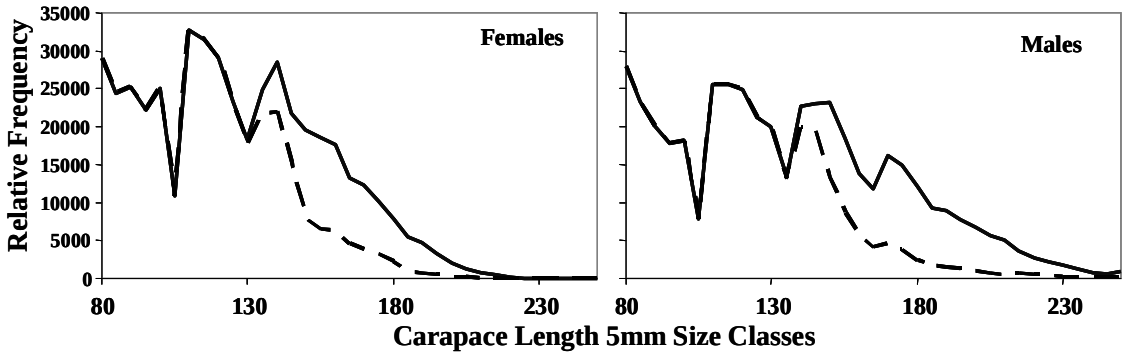


Figure 49. The unfished size distribution (solid line) relative to the predicted size distribution following the fishing up until 2003/2004.

The assessment generates an implied time series of total and exploitable biomass (Figure 50), which when combined with reported catches leads to an implied time series of harvest rates (Figure 51). In addition, the mature biomass was also followed, which enabled a time series of relative egg production to be described (Figure 52).

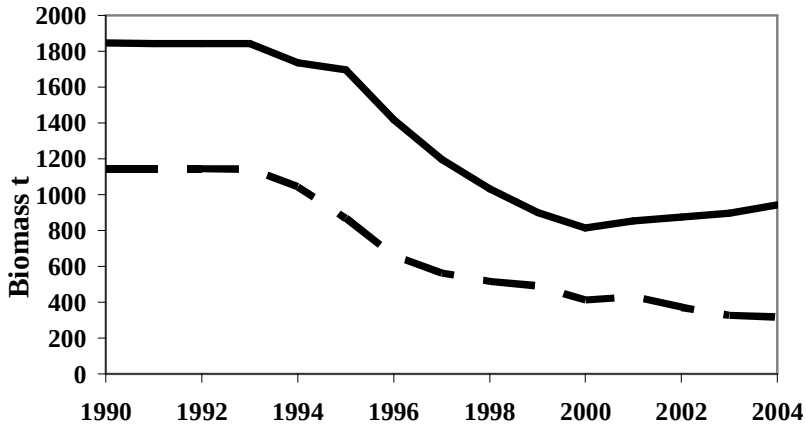


Figure 50. The predicted time series of total biomass (solid line) and exploitable biomass (dashed line). The exploitable biomass has declined to about 27.87% of unfished levels. The slight rise in total biomass in the final years is an artefact of average recruitment being implied for the final five years.

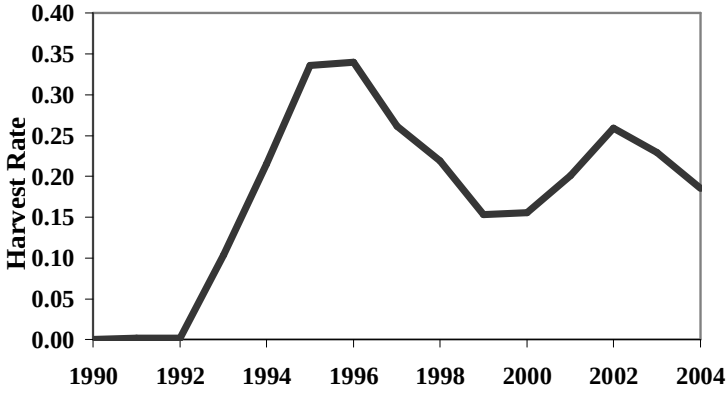


Figure 51. Implied time series of harvest rates (proportion of exploitable biomass taken each year by the commercial fishery. A level of approximately 20% would appear to be unsustainable.

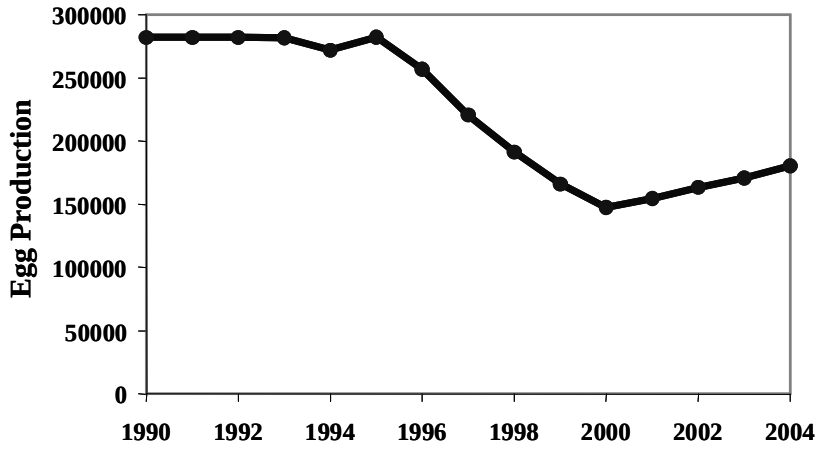


Figure 52. The time series of egg production implied by the trajectory of stock biomass through time. The final four years are highly uncertain because the model cannot fit those years well due to the time lag between recruits joining the populations and entering the fishery. At its lowest level there was only about 52% of unfished egg production being produced.

9.4 Model Projections

Using the fitted recruitment residuals to define the expected recruitment variation it is possible to project the population forward under different TAC and size limit scenarios to determine the likely outcomes of different management arrangements. This assumes that the dynamics as described by the assessment model continue to apply and that no new factors come into operation. A possibly significant omission from the assessment and the projections is the potential interaction between giant crabs on the west coast of Tasmania and members of the trawl fleet operating in the South East Fishery. However, their omission may have unexpected implications. The model fits the catch rates and size structure relative to the given extractions. If the actual amounts of giant crab removed were higher then the stock would, in fact, be that much more productive than the current assessment indicates. This would imply that if the trawl/crab interaction stopped the stock would recover faster than expected. If, however, the interaction became stronger the implications would be harder to predict.

Because of the five-year time lag in the recruitment residuals leading to the average recruitment being implied for the final five years, in the projections, a set of recruitment residuals for those five years are generated along with a set for the years of projection. In this way, the population is placed in a more realistic state at the state of each projection. 1,000 simulations were used in the forward projections and two scenarios were considered: the current 62.1 tonnes, and the older 103.2 3 tonnes. The predicted time-series of recruitment levels, exploitable biomass, total biomass, and total egg production were plotted to determine the relative performance under the different TAC scenarios. The current size limits were retained into the future. Projections were made for ten years into the future.

9.4.1 Current TAC 62.1 t

The current TAC of 62.1 t derives from 1,035 units set at 60kg a unit. When the assessment model is projected with this TAC from the optimum fit there are indications that at least the stock should stabilize and if average recruitment occurs over the ten year projection period (plus the five years for which no fit was possible), then exploitable biomass should increase along with total biomass, catch rates and egg production. Conversely, the harvest rate should drop. The confidence with which these claims are made relates to the recruitment variation. If poor recruitment happens often in the future then exploitable biomass may stay roughly the same as now, or decline slightly, with consequent stability in catch rates and other fishery performance indicators (Figure 53 and Figure 54).

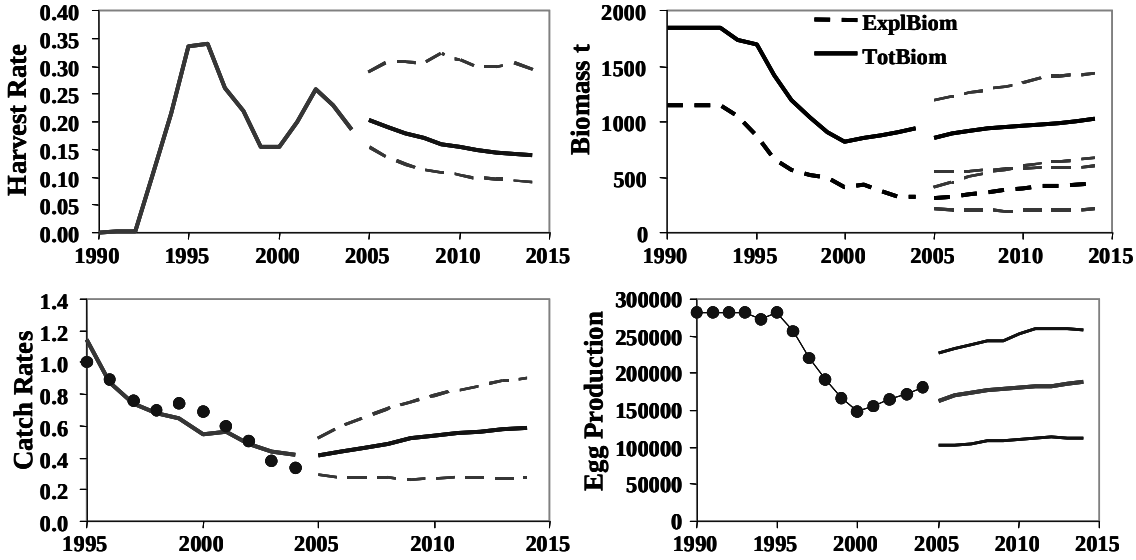


Figure 53. Ten year projection of the current TAC of 62.1 t using the optimally fitting model. Illustrated are the predicted exploited biomass levels (ExplBiom), the total biomass (TotBiom), implied harvest rates, implied catch rates, and implied egg production. In each case the year is the last part of the quota year, thus 2001 is 2000/2001. The projections are in each case surrounded by the 95% percentile confidence intervals, shown as dotted lines. After ten years catch rates are predicted to have recovered to the levels observed in 2000/2001.

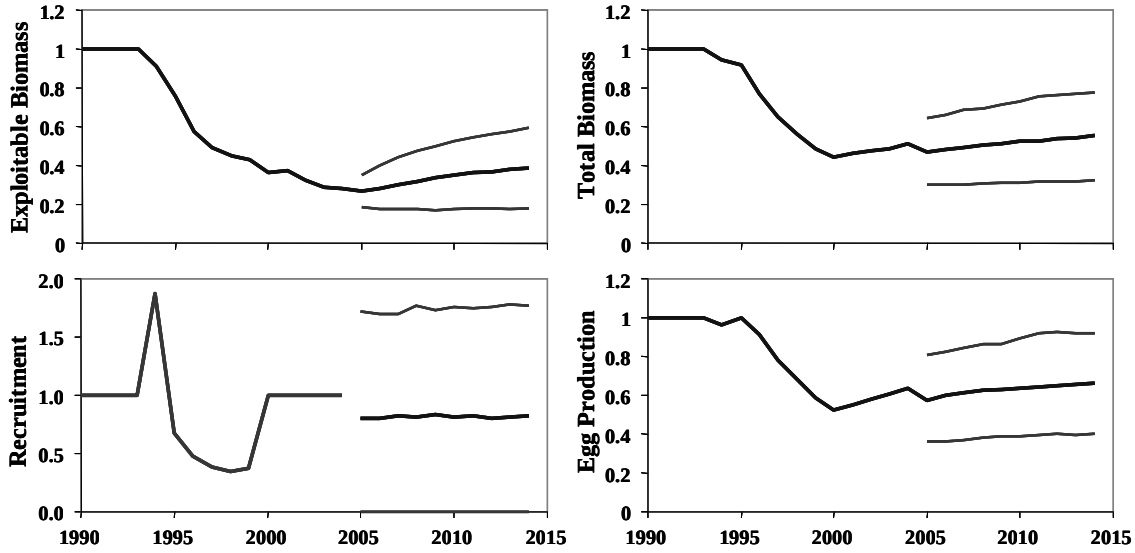


Figure 54. Projections for exploitable biomass, total biomass, recruitment levels, and egg production graphed as proportion of the unfished levels. The projected TAC remains at the present TAC of 62.1 t. The low point of exploitable biomass was 27.88% of unfished and after ten years, if we only consider the median value, this could recover to 38.75%. Recruitment ranges across two orders of magnitude on a log scale.

9.4.2 Old TAC 103.5 t

The old TAC of 103.5 t derives from the 1,035 units each giving the right to take 100kg. When projections are made with this TAC the exploitable biomass continues its slow decline with consequent declines in total biomass and catch rates. Egg production remains relatively stable but harvest rates increase dangerously (Figure 55 and Figure 56). After only three years, under conditions of poor recruitment destructive declines in catch rates can occur as can the maximum harvest rate permitted in the model (95% of all exploitable biomass being commercial taken each year).

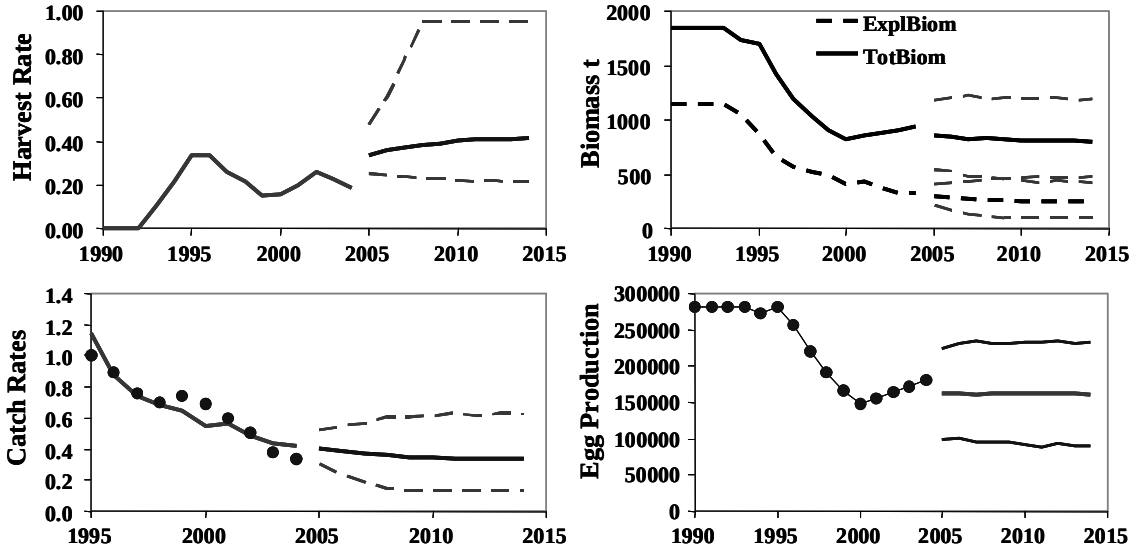


Figure 55. Ten year projection of the old TAC of 103.5 t using the optimally fitting model. Illustrated are the predicted exploited biomass levels (ExpBiom), the total biomass (TotBiom), implied harvest rates, implied catch rates, and implied egg production. In each case the year is the last part of the quota year, thus 2001 is 2000/2001. The projections are in each case surrounded by the 95% percentile confidence intervals, shown as dotted lines. After ten years catch rates are predicted to have recovered to the levels observed in 2000/2001.

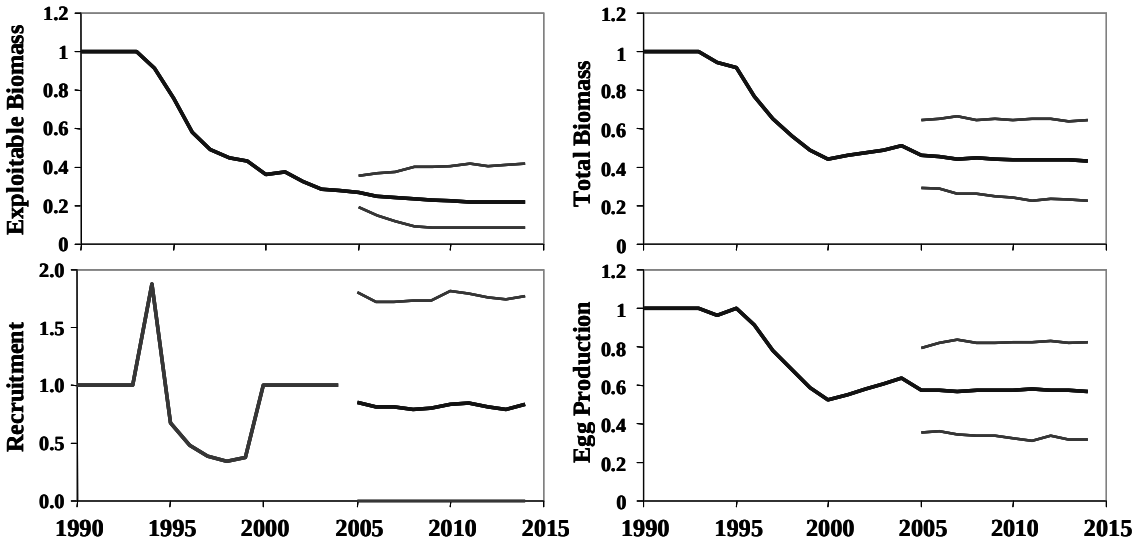


Figure 56. Projections for exploitable biomass, total biomass, recruitment levels, and egg production graphed as proportion of the unfished levels. The projected TAC was set at the old TAC of 103.5 t.

9.5 Discussion

9.5.1 Stock Assessment

The stock assessment model produced consistent results that indicated that the fishery for giant crabs in Tasmania has led to a steady decline in exploitable biomass with corresponding declines in catch rates. The model was fitted to catch rate data and to size distribution of the catch data by varying the estimates of the selectivity parameters, the average recruitment, and the annual recruitment residuals that characterized the recruitment variability.

At their lowest points the exploitable biomass reached 27.87% of unfished exploitable biomass in 2003/2004, catch rates were reduced to 34% of unfished catch rates also in 2003/2004, while egg production was reduced to 52.36% in 1999/2000 (Figure 53 and Figure 55). From 1992/1993 to 2003/2004 there was an average harvest rate of approximately 22%. Fortunately, over the last three years the harvest rate has been dropping, which reflects the reduced catch levels during that period. It may be argued that many fisheries based upon Crustacea are reduced to much lower levels than this, but invariably these species are much more productive than the giant crab. The very low depletion levels of unfished exploitable biomass seen in some rock lobster species should not be used as a guideline for one of the largest crabs in the World.

It must be remembered that it takes up to five years for new recruits to enter the fishery and influence catch rates and size distributions of the catch. Because of this the recruitment residuals for the last five years did not deviate from 1.0 implying that there was average recruitment over that time (Figure 55). The influence of this can be seen in the total biomass and egg production graphs (Figure 55). These apparently positive signs of increased egg production and increasing total biomass are misleading because if recruitment has not been as high as the predicted average recruitment then they will be high. That recruitment will have been low appears likely if the period from 1994/1995 to 1998/1999 is indicative of recent recruitment levels. The recent increases in total biomass are due to increases in the under-sized component of the stock due to recent recruits (Figure 49 and the absence of any increase in exploitable biomass as in Figure 55). Similarly, the apparent increase in egg-production is due to increases in the number of under-sized but mature crabs generated by recent recruitment.

9.5.2 Harvest Strategies

Given the uncertainties in the assessment model only two scenarios were compared to see the effect of projecting different TACs into the future. The assessment permitted the recruitment variability to be characterized. The projection entailed generating a random set of new recruitments using the characterization from the assessment. In addition, the recruitment residuals for 1999/2000 to 2003/2004 were also generated anew for each simulation to start the population at a different potential situation.

All the characteristics of the fishery, that is the predicted exploitable biomass, the total biomass, the catch rates, and the harvest rates, suggested that with a TAC of 62.1 t there were opportunities for the stock to recover as long as recruitment was average over the

next ten years. Given the worst set of real recruitment levels in the years ahead, this scenario suggests that the stock would at least remain stable in its current position.

Under a continued TAC of 103.5 t the exploitable biomass would continue to decline as would the expected catch rates. The predicted increase in harvest rate, especially given poor recruitment, suggests that catch rates would decline so much (harvest rates would increase catastrophically) that it would be extremely unlikely that the fishery would be economically viable, let alone sustainable. In short, 103.5 t was not considered a sustainable catch level but 62.1 t may be. If new factors begin to have significant effects (*e.g.* the potential interaction between bottom trawlers and giant crabs on Tasmania's west coast), then even a TAC of 62.1 t may become unsustainable.

If the giant crab stock is as productive as the model suggests, then a modest improvement in catch rates would be expected in one or two years at the lower TAC. If this did not happen, it would be necessary to reassess the stock assuming a model structure that was less productive than currently used.

9.5.3 Weaknesses of the Assessment

Assumptions and weaknesses of the current assessment model include the description of growth, interaction between growth and recruitment, fitting the final five years of recruitment residuals, and other data problems.

The most obvious weaknesses in the model is the description of giant crab growth, as growth is central to the dynamics of any size-based stock assessment model. As detailed in the section describing the growth of giant crabs, data was primarily available for under-sized crabs so that the growth and dynamics of legal sized crabs had to be extrapolated from what was known of the undersized crabs. In addition, part of natural mortality was implemented as a moulting mortality rate. This factor had a major influence on the potential productivity of the stock. While the description of growth is plausible (though the intermoult periods are very long), this description is nevertheless a major source of uncertainty in the model. This is both model uncertainty (are the dynamics really operating in the way described) and parameter uncertainty (have the parameters been estimated with sufficient precision to provide an accurate description of growth). The parts of the description of growth that influence the productivity of the stock include:

- the variability around the average moult increment for a given premoult carapace length,
- the gradient of the line describing the relationship between moulting mortality and premoult size class, and
- the rate at which the intermoult period increases with premoult carapace length.

A model weakness related to the description of growth is that the current equilibrium size distribution has a modal structure to it that reflects the large moulting increments of the crabs. At the smaller sizes the variation around this average moult increments is relatively smaller and the modal structure develops naturally from that. The recruitment dynamics have been chosen to minimize the appearance of these modes because there are none apparent in the size distribution data. Better size distribution data is required (meaning the data collected needs to be representative of more of the catch and more data overall needs to be collected).

The time lag at the end of the fishery, induced by the time it takes new recruits to grow into the fishery is matched at the start of the fishery during which such small catches were taken that no information is available to estimate recruitment across the years and, instead the model lumps all the recruitment necessary to match the early large catches into a single year. In addition, though this may be from the same cause, the average recruitment, except for the single year before the fishery expanded, is greater than most of the fittable recruitment residuals. This has the effect of implying a relatively high average recruitment, which may bias the model outcomes when average recruitment is implied. It is possible that the recruitment dynamics are biased high because of how the model responds to the available data. This would have the effect of exaggerating the productivity of the stock and may lead to recommending unsustainable TACs.

Other weaknesses relate to the available data from the fishery. The length frequency data is based upon samples taken through the year in a haphazard manner, with more data from the west coast than the east coast. The catch rate standardization can at least take into account the different emphasis given to the fishery on the different coasts of Tasmania (the fishery has primarily been prosecuted on the west coast) but there is no way to standardized the size-distribution of catch data.

9.5.4 Future Work

There may be benefits in conducting the assessment by the same methods across all three States but with spatial division on the State or smaller regional level. In particular, there may be value in treating the west and east coasts of Tasmania separately, however, the amount of data available for the east coast may be too sparse to permit a useful assessment to be made. Certainly the catch rate data can be standardized for each coast separately, but there are numerous years where insufficient size distribution data to be representative were collected from the east coast. Whatever the case, an attempt should be made to consider the two coasts separately so that the impact of potential interactions with trawlers on the west coast may be modelled explicitly.

The bycatch catches by trawlers should be included in the model as this will act to reflect a more productive stock. In addition, the impact of some degree of release mortality associated with returning giant crabs to the sea should be investigated.

As more tagging data becomes available the description of growth, especially the intermoult dynamics, should be improved and updated. This is especially critical for the larger sized crabs. Any information relating to them will enable the model uncertainty in relation to the description of growth to be improved upon.

As more and more size distribution of the commercial catch data becomes available this will also enable the elimination of possible problems with the model. If the true size distribution of crabs does not have the modal structure predicted by the model then the model will need modification to eliminate this feature. Possibly this could be removed by including further, smaller size classes into which the new recruits can be pasted.

9.6 Conclusions

- A size-structured stock assessment model has been produced though it has weaknesses relating to details of the description of growth, to the collection of representative data, and the short time series of informative data. As increased quantities of better quality data accumulate then the uncertainty in the assessment from the model should decrease.

- The Tasmanian giant crab stock has declined steadily since the introduction of the targeted commercial fishery; it may have reached as low as 27.87% of the unfished exploitable biomass, which for such an unproductive species appears to be quite heavy depletion.

- If no further negative effects are imposed on the Tasmanian giant crab stock and recruitment is approximately average over the next ten years, then a TAC of 62.1 t appears to have the potential to permit some rebuilding of the stock and hence of the catch rates.

- If a TAC of 62.1 t is sustainable under the present conditions of exploitation in the stock then the catch rates should at least stabilize in the next year or two and ideally would begin to rise. If they do not then the stock would need reassessment under the assumption of lower productivity than currently assumed.

- A TAC of 103.5 t, if it were continued, appears highly likely to continue the depletion of the stock and would not be considered sustainable.

- The model requires further exploratory development but emphasis must be placed on the collection of more and better quality data from the fishery.

9.7 Model Appendix 1. Commercial Length Frequencies across Years

Table 16. Commercial length frequency counts in 10mm size classes for females taken in the Tasmanian giant crab fishery from 1992/1993 until 2002/2003. The bottom line gives the totals for each column. Data is for all Tasmania combined.

Size Class	F93	F94	F95	F96	F97	F98	F99	F00	F01	F02	F03
150	74	356	256	14	0	736	1356	0	194	975	291
160	20	200	180	11	0	676	953	0	115	773	258
170	11	74	95	7	0	503	406	0	29	354	119
180	6	45	60	0	0	294	176	0	12	149	45
190	2	24	24	2	0	169	65	0	3	41	22
200	0	14	9	1	0	41	12	0	0	20	8
210	0	3	1	0	0	2	3	0	0	1	1
220	0	0	1	0	0	0	0	0	0	0	0
230	0	0	0	0	0	0	0	0	0	0	0
240	0	0	0	0	0	0	0	0	0	0	0
250	0	0	0	0	0	0	0	0	0	0	0
10292	113	716	626	35	0	2421	2971	0	353	2313	744

Table 17. Commercial length frequency counts in 10mm size classes for males taken in the Tasmanian giant crab fishery from 1992/1993 until 2002/2003. The bottom line gives the totals for each column. Data is for all Tasmania combined.

Size Class	M93	M94	M95	M96	M97	M98	M99	M00	M01	M02	M03
150	34	42	38	2	0	129	259	0	33	241	139
160	16	35	22	2	0	102	198	0	39	198	93
170	5	31	22	1	0	121	131	0	19	116	52
180	5	33	32	2	0	118	83	0	12	81	30
190	1	20	26	0	0	118	75	0	6	61	30
200	1	10	14	0	0	97	64	0	5	53	34
210	0	13	10	0	0	75	44	0	5	47	28
220	0	5	7	0	0	37	23	0	3	24	14
230	0	1	3	0	0	8	4	0	1	5	4
240	0	0	7	0	0	0	0	0	1	1	1
250	0	0	2	0	0	0	0	0	0	0	0
3504	62	190	183	7	0	805	881	0	124	827	425

10. Model specifications

10.1 Introduction

The commercial fishery for giant crabs in Tasmanian waters began in 1992/1993 after a live export market to Melbourne, Sydney and Asia was established (Gardner, 1998). Giant crab had previously appeared as a small bycatch by those rock lobster fishers operating in deeper waters. Instead of calendar years the fishery for giant crab is considered on the same time-scale as Tasmanian rock lobster with a quota year operating from March 1st to the end of February each year. The current management plan, that introduced quota management, was produced in November 1999 and the first full quota year from 2000/2001 pursued a Total Allowable Commercial Catch of 103.5 tonnes. This was a large reduction from previous catch levels.

Once giant crab became a target species, catches increased dramatically and by the 1994/1995 fishing year, total catch in Tasmanian waters peaked at 291 tonnes. Some of this total may be attributed to misreporting of catch in anticipation of the change in management (the hope of allocating quota on the basis of reported catches often leads to fictitious paper fish being reported). Nevertheless, it was certainly the case that a virgin stock was being fished down. Following the peak in 1994/95 the total catch fell to just 110 tonnes in the 1997/1998 fishing year (Figure 57 and Table 18) and there was concern that the fishery was being over exploited.

Table 18. Reported catch totals, in tonnes, by quota year from before the beginning of the Tasmanian fishery in 1992/1993 until the present. The quota year runs from March 1st to the end of February the following year. East and west are defined as either side of longitude 147° East.

Quota Year	Total	West	East	TAC
1989/1990	0.202	0.097	0.105	
1990/1991	1.706	1.598	0.108	
1991/1992	1.483	1.410	0.073	
1992/1993	118.157	112.794	5.363	
1993/1994	224.233	223.413	0.819	
1994/1995	291.226	217.755	73.471	
1995/1996	224.932	147.904	77.028	
1996/1997	147.380	125.231	22.149	
1997/1998	113.283	77.431	35.852	
1998/1999	75.607	30.410	45.197	
1999/2000	64.212	33.883	30.329	
2000/2001	86.510	60.606	25.904	103.5
2001/2002	96.593	68.640	27.953	103.5
2002/2003	75.242	45.118	30.123	103.5
2003/2004	59.057	39.104	19.953	60.1

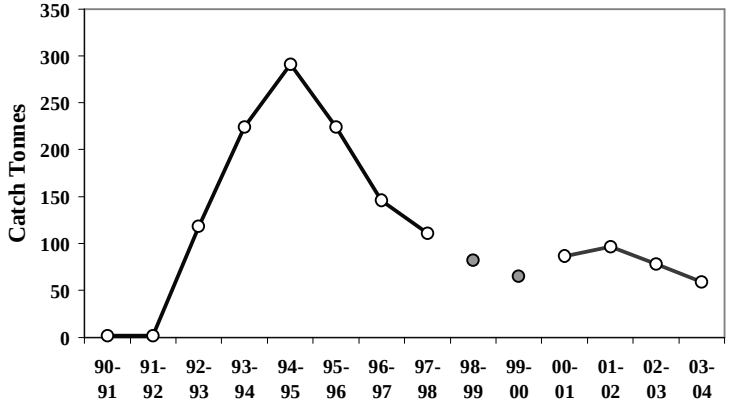


Figure 57. Giant crab catches in Tasmania. The Total Allowable Catch was set at 103.5 tonnes in November 1999. Catches in 98/99 and 99/00 (solid circles) were from partial fishing years due to an extended seasonal closure imposed to allow revision of management arrangements.

All targeted fishing for giant crabs in Tasmanian waters takes place on the edge of the continental shelf on both the east and west coast. Although it is quite probable that there is some larval exchange between coasts, it is unlikely that there is any mixing of the adult populations. Nevertheless, in the first instance it was decided to generate an assessment model dealing with the Tasmanian giant crab population as a single stock.

Catch rates are described separately and, in the first instance, were standardized to provide a unified index of relative abundance through time on the basis of quota years and across the whole Tasmanian fishery. The next step would be to develop the model across the east and west of Tasmania separately.

10.1.1 Management

The original TAC in 2000/01 was 103.5 t, which was made up of 1,035 units each of 100 kg. For the 2004/05, season the TAC has been reduced to 60.1t, which is 60kg per unit, and this will be continued into 2005/06. There is a closed season for females between May 1st and October 31st each year. In addition, ovigerous females must be returned to the water. Size limits have altered through time with currently the minimum legal length being 150mm for both sexes with a maximum length of 215mm (Table 19).

Table 19. Minimum and maximum legal lengths around Tasmania.

	Female		Male	
Quota Year	**Minimum**	**Maximum**	**Minimum**	**Maximum**
1990/1991	150	250	150	250
-	-	-	-	-
1996/1997	150	250	150	250
1997/1998	150	250	150	250
1998/1999	150	250	150	250
1999/2000	150	250	150	250
2000/2001	150	215	150	215
2001/2002	150	215	150	215
2002/2003	150	215	150	215
2003/2004	150	215	150	215

10.2 Biological Data.

10.2.1 Size at Maturity

The maturity-at-size, P_i for females is described by a standard logistic curve relating the proportion of females mature to their size-class L_i, (Figure 58). The two parameters, for Tasmanian giant crabs are Gardner *et al.* (2002): a = -47.3703, and b = 0.43523, which implies (Figure 58) a size at 50% maturity of about 108.8mm ($-a/b$).

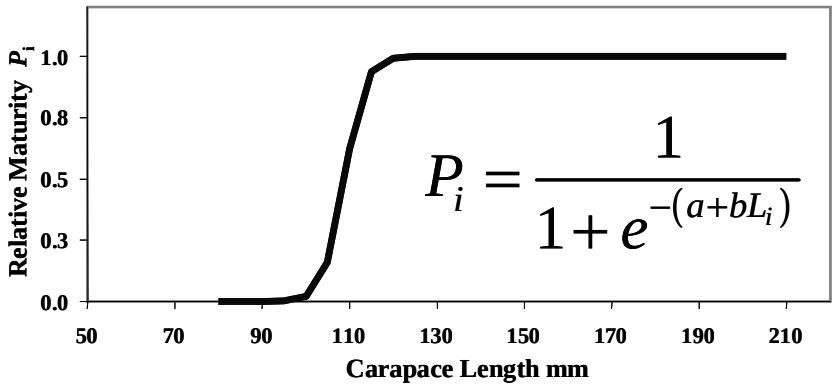


Figure 58. Maturity at size for Tasmanian giant crabs.

10.2.2 Fecundity at Size

A power relationship (Gardner, 1997) is assumed to hold between a female crabs fecundity and its size-class (Figure 59). The two parameters of the relationship were c =

181.673842 and d = 1.754983. The effect of size at maturity would be to reduce the overall contribution made by the smaller animals.

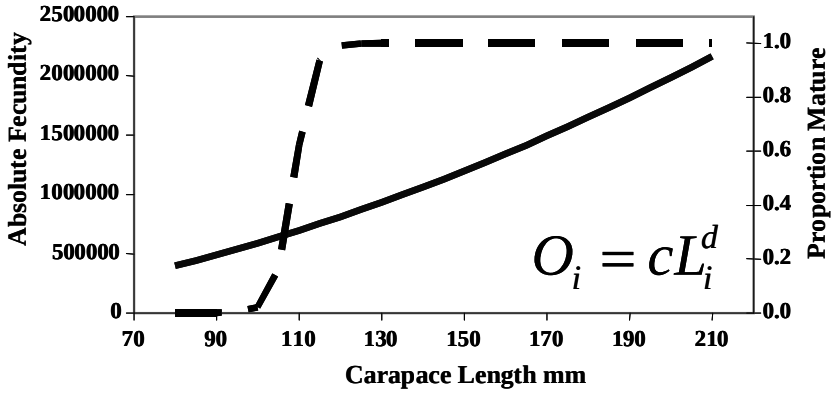


Figure 59. Fecundity relative to size (solid line), the equation relates to the power function describing fecundity. The dashed line indicates the proportion mature (Figure 58) indicating that the egg production of the smaller animals would be reduced relative to larger animals.

Extrusion of eggs tends to occur in May and extends through November into December. This has implications for the fishery because it is illegal to land ovigerous females and the closed season for females only extends to the end of October. All females caught are discarded between May and October, and ovigerous females are discarded at all other times (in practice in November and December). Currently, it is assumed that there is no mortality associated with discarding but this may need to be implemented to investigate the sensitivity of the dynamics to this potential issue. One way of including this discarding of ovigerous females is to alter the selectivity for females to reduce the total retained.

10.2.3 Selectivity

Selectivity of the gear is assumed to match a standard logistic curve. An alternative might be a logistic with a reducing tail for the very large size classes but no information is available to differentiate between these; although both trawl caught specimens and visual observations using benthic cameras do not indicate an abundance of very large crabs, so the second option is less likely. Selectivity is assumed to be described by a logistic curve for both sexes but with independent parameters. A simple logistic is fitted with two parameters, $L50^k$ and $L95^k$, with the k superscript denoting the separate sexes. These parameters represent the carapace lengths at which 50% and 95% are selected. To ensure that the L95 is greater than the L50 it is made up of the L50 term multiplied by a scaling parameter that is constrained to lie between 1.01 and 1.5.

The equation is:

$$V_i^{k,t} = \frac{\pi}{1+e^{-\mathrm{Ln}(19)\left(\frac{i-L50^k}{L95^s-L50^k}\right)}} \qquad LMinL < i < LMaxL$$
$$V_i^{k,t} = 0 \qquad i < LMinL, i > LMaxL \qquad 13.1$$

where $L95^k = L50^k$ x $Scale95^k$. Changes to selectivity that would have followed from the changes that have occurred to the legal size limits are accounted for through the use of the *t* subscript (Table 19) and setting particular sizes to zero selectivity or that calculated through Eq. 13.1 depending on the legal limits. The selectivity for females needs to be modified to account for the closed season for females (May 1 to October 31) and for the average proportion of ovigerous females during the open season. This is implemented by multiplying the selectivity for females by a constant π. For males π is set to 1.0. For females this constant can be estimated by multiplying the proportional monthly catch by the monthly proportion of ovigerous females (or by one during the female closed season) to determine the proportion of the total catch of females that can be expected to be ovigerous (Figure 60, Figure 61 and Table 20).

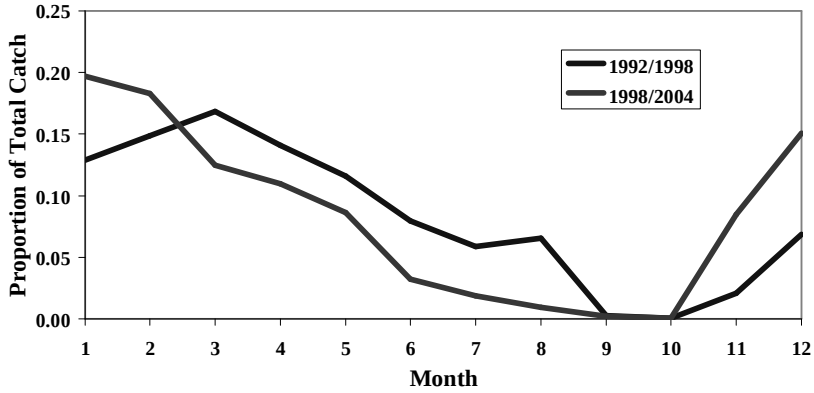


Figure 60. Seasonality of catch in the Tasmanian Giant Crab fishery using data from the 1992/1993 to the 2003/2004 season. Each line represents six years of the fishery, splitting the fishery into two parts.

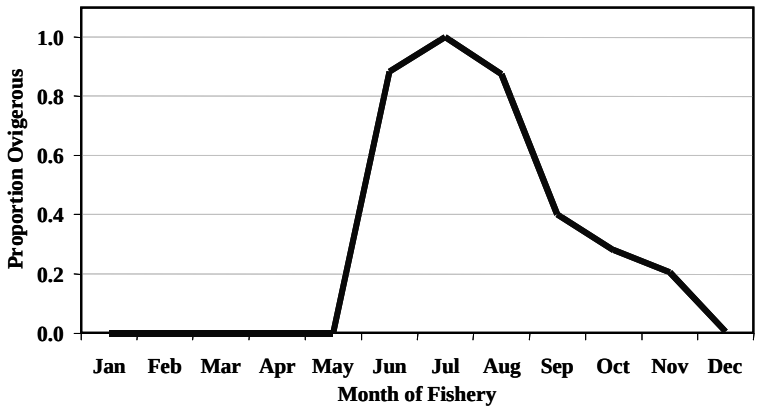


Figure 61. The seasonality of the proportion of female Giant Crabs in the Tasmanian fishery that are ovigerous.

Table 20. Estimation of the proportion of the catch assumed to be female in the closed season for females or ovigerous during the open season. % Berried is the proportion found to carry eggs during catch sampling. % females returned is the proportion of the catch of females returned to the water (includes the closed period from May till October). %Catch 1992/1998 is the proportion of the total catch taken in different months over the period 1992/1993 to 1997/1998; % Catch 1998/2004 is the same for 1998/1999 to 2003/2004. The final two columns relate to the contributions each month makes to the estimation of π in Eq. 13.1.

Month	% Berried	%Females Returned	% Catch 1992/1998	% Catch 1998/2004	1992/1998	1998/2004
1	0.0005	0.0005	0.1286	0.1969	0.0001	0.0001
2	0.0	0.0	0.1486	0.1828	0.0000	0.0000
3	0.0	0.0	0.1683	0.1248	0.0000	0.0000
4	0.0009	0.0009	0.1411	0.1095	0.0001	0.0001
5	0.0	1.0000	0.1161	0.0864	0.1161	0.0864
6	0.8824	1.0000	0.0795	0.0322	0.0795	0.0322
7	1.0000	1.0000	0.0587	0.0189	0.0587	0.0189
8	0.8750	1.0000	0.0657	0.0097	0.0657	0.0097
9	0.4010	1.0000	0.0030	0.0026	0.0030	0.0026
10	0.2813	1.0000	0.0006	0.0006	0.0006	0.0006
11	0.2049	0.2049	0.0212	0.0848	0.0043	0.0174
12	0.0050	0.0050	0.0687	0.1507	0.0003	0.0008
$1-\pi$					0.3284	0.1687

Combining the proportion of total catch by month by the proportion of females that are ovigerous by month and the closed season for females leads to an estimate of the proportion of the catch expected to be ovigerous each month. When this is summed over all months the total was 32.84% for the first half of the fishery and 16.87% for the second half of the fishery. Thus the best estimates of π currently available are 1.0 – 0.3284 = 0.6716 and 1.0 – 0.1687 = 0.8313.

10.2.4 Natural Mortality

Natural mortality is modelled in two ways. The first is the background natural mortality rate across all size-classes each year. This is implemented as a survivorship (e^{-M}) with which the matrix of numbers-at-size by years-to-moult is multiplied. In an effort to model some of the within season dynamics, the background natural mortality is implemented by two applications of half the natural survivorship ($e^{-M/2}$), one before fishing mortality occurs and one after.

The second form of natural mortality was implemented as a natural mortality rate associated with moulting. This was modelled as a linear relationship between the instantaneous moulting mortality and size-class and is described in more detail where growth dynamics are described. When the linear instantaneous moulting mortality rate is converted to a survivorship it becomes a non-linear descending curve (Figure 62).

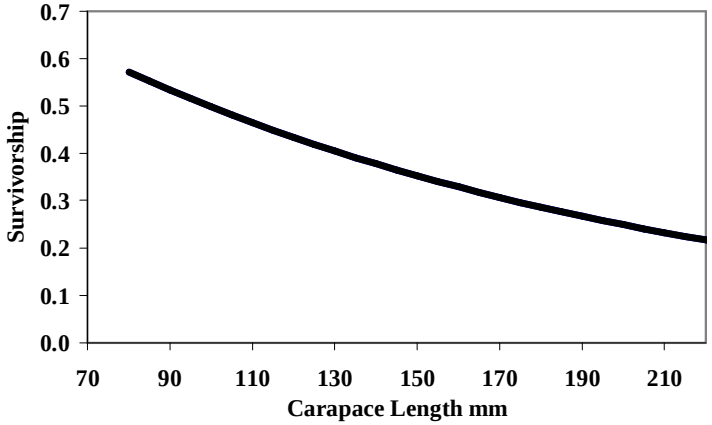


Figure 62. The implied survivorship at moulting relative to premoult carapace length. The extremely long intermoult periods have the effect of increasing the effective survivorship each year. The parameters used in the linear relationship between instantaneous rate of moulting mortality were intercept = 0.005 and gradient = 0.00695.

The vector of survivorships were placed into the diagonal of a square matrix and used to multiply the growth transition matrix for each sex. In this way the moulting mortality was automatically coordinated with growth when it occurs.

10.3 Length-Based Modelling

As with many other invertebrate species, Giant Crabs (*Pseudocarcinus gigas*) cannot be aged with any degree of ease or accuracy. An alternative way of describing the population dynamics of such a species is to use a size-based model (*e.g.* Punt & Kennedy, 1997). The principle behind such models is that a vector of numbers at size ($\mathbf{N}_l$) is projected through time by multiplying it by a square matrix representing the probabilities of growing from one size class into a subsequent set of size classes over the period of time represented by the matrix (**G**). In addition, survivorship following natural and size-selective fishing mortality occurs ($\mathbf{S}_l$) along with new recruitment (**R**), as follows:

$$\mathbf{N}_{l,t+1} = \mathbf{S}_{l,t}\mathbf{G}\mathbf{N}_{l,t} + \mathbf{R} \qquad 13.2$$

The time step and size-class selected in such models tends to be fixed at some convenient period and width over which data is available. Thus, Punt and Kennedy (1997) use a set of four 3-monthly growth transition matrices to describe the growth expressed each year by Tasmanian rock lobsters with 2mm size-classes, and Hobday and Punt (2001) use a single annual growth transition matrix and 5mm size-classes to describe growth in Victorian rock lobsters. Length-based models can be highly

successful at describing population dynamics but some aspects intrinsic to the design of such models can be a source of problems. The two problems of most concern here are

1) the fact that the growth transition matrix is couched in terms of size-classes (*e.g.* 2mm or 5mm), and

2) the fact that the transition matrix summarizes growth data representing a fixed period of time (*e.g.* 3-months or 1-year).

Problems could arise if the maximum growth that occurs for a given size-class within a single time-step is less than the width of the size-class. If that occurs then the animals could become mathematically trapped with no hope of ever growing out of this effectively terminal size-class. In effect this final size-class would be the equivalent of a plus group and this would only be a bad thing if this imposed excessive distortion on the description of numbers at size. If the time-step that the growth transition matrix represents is markedly different from the biological properties of the species concerned there could be a proportion of animals that do not moult in the available time. If the difference between the moulting interval and the time-step of the transition matrix is not too different this lack of growth may be accommodated by including the probability of not growing out of the size-class into the transition probabilities. However, this option would act to obscure the real dynamics of the time-lags in moulting if the moulting interval was very long relative to the time-step of the transition matrix.

Such moulting intervals reach extremes in the Tasmanian Giant Crab, in which large animals can go many years between moults (Gardner *et al.*, 2002; McGarvey *et al.*, 2002). One way of attempting to capture the dynamics involved with such delays in moulting is to model the probability of moulting in a particular year in an explicit way. Thus, the probability of moulting would depend upon both the size of the animals, the sex of the animals and the time since the animals last moulted. The moulting model would be used to determine in each year how many of each size-class were expected to moult. A growth transition matrix with a time-step of one year could then be applied to those animals expected to moult.

In the case of the Tasmanian giant crabs the population dynamics are novel in that the intermoult intervals are modelled explicitly. To do this we have added a new matrix of the numbers of years spent in each size class before moulting. Thus, in each year instead of a single vector of numbers-at-size, $\mathbf{N}_m$, for each sex representing the total population across *m* size-classes, the number-at-size for each sex are distributed within a matrix, $\mathbf{N}_{m,y}$, describing the maximum number of years, *y*, for which the moulting dynamics are followed (Eq. 13.3). Thus, with *m* size classes following *y* years of moulting history for each size class we end with a matrix of the following form to describe numbers-at-size:

$$
\begin{array}{cccccccc}
\mathbf{N}_m & & & \mathbf{N}_{m,y} & & & & \\
N_1 & & N_{1,1} & N_{1,2} & N_{1,3} & . & . . & N_{1,y} \\
N_2 & & N_{2,1} & N_{2,2} & N_{2,3} & . & . . & N_{2,y} \\
N_3 & & N_{3,1} & N_{3,2} & . & . & . . & . \\
. & & . & . & . & N_{4,4} & . . & . \\
. & \Rightarrow & . & . & . & . & . . & . \\
. & & . & . & . & . & . . & . \\
. & & . & . & . & . & . . & . \\
. & & . & . & . & . & . . & . \\
N_m & & N_{m,1} & . & . & . & . . & N_{m,y}
\end{array}
\qquad 13.3
$$

To complement this we need an equivalent order matrix describing the proportion in each size class in each year of the moulting history, that will moult in the given year, $\mathbf{P}_{m,y}$. In short, this all means that instead of following the fate of a vector of numbers-at-size the process follows a matrix of numbers-at-size by years-to-moult.

10.3.1 Model Structure

With size-based models, the order in which the different drivers to the dynamics occur can have a significant influence on the outcomes (Haddon, 2001, p. 219) so the sequence of matrix operations was important. The sequence of operations acting on the matrix of numbers-at-size for each sex to describe the population dynamics in each year can be formally described. The numbers-at-size (*i*) by years-to-moult (*j*) matrix for sex *k* at time *t* can be represented by $N_{i,j}^{k,t}$, or in matrix notation $\mathbf{N^{k,t}}$. The various stages in the algorithm will be represented by incrementing the time superscript *t* by the stage of the operation (*a to m*; stage *n* is the final step and is represented as *t*+1; stage names *i*, *j*, and *k*, are omitted to avoid confusion with subscripts in the equations). The dynamics can be represented by nine steps:

a. Multiply the matrix of numbers-at-size (by years-to-moult) by the survivorship arising from applying half the background natural mortality (*M*/2).

$$N_{i,j}^{k,t+a} = N_{i,j}^{k,t} e^{-M/2} \qquad 13.4$$

b. Multiply the numbers-at-size by years-to-moult matrix by the moulting matrix for each sex *k*, $\mathbf{P^k}$, on a cell by cell basis, to identify $\mathbf{\Gamma}$, those fish in each size-class (*i*) and each year-to-moult (*j*) that are due to moult.

$$\Gamma_{i,j}^{k,t+b} = P_{i,j}^{k} \times N_{i,j}^{k,t+a} \qquad \text{for each } i \text{ and } j \qquad 13.5$$

c. Remove the numbers to moult from each size-class

$$N_{i,j}^{k,t+c} = N_{i,j}^{k,t+a} - \Gamma_{i,j}^{k,t+b} \qquad 13.6$$

d. Project the remainder forward one year along the years-to-moult axis. Setting the maximum number of years used to track the time till moulting as $y_{\max}$. This action empties the first column of the matrix. $Y_{\max}$ acts as a plus group.

$$\begin{aligned} N_{i,y_{\max}}^{k,t+d} &= N_{i,y_{\max}}^{k,t+c} + N_{i,y_{\max}-1}^{k,t+c} \quad && j = y_{\max} - 1 \\ N_{i,j+1}^{k,t+d} &= N_{i,j}^{k,t+c} && 1 \le j \le y_{\max} - 2 \end{aligned} \qquad 13.7$$

e. Generate a vector of numbers-at-size that will moult by summing the numbers to moult from each of the years-to-moult columns of $\mathbf{\Gamma}$.

$$n_i^k = \sum_{j=1}^{y_{\max}} \Gamma_{i,j}^{k,t+b} \qquad \text{For each } i \qquad 13.8$$

f. Fill the first column of the number-at-size matrix by multiplying the vector of crabs due to moult $\mathbf{n^k}$, by the respective growth transition matrix for each sex, $\mathbf{G^k}$, which includes survivorship from moulting mortality (see section on Growth Dynamics). This action refills the first column of the numbers matrix. The effect of moulting mortality, containing in $\mathbf{G^k}$ implies that the sum of $\mathbf{n^k}$ is greater than the sum of the first column of the numbers matrix ($\sum N_{i,1}^{k,t+f}$).

$$N_{i,1}^{k,t+f} = \mathbf{G^k n^k} \qquad 13.9$$

g. Using $L_{\max}$ as the maximum size-class, W_i as the vector of weight at size-class i, and V_i as the selectivity of size-class i, calculate the exploitable biomass for both sexes ($k = M$ and F) and all size-classes.

$$T_i^k = \sum_{j=1}^{y_{\max}} N_{i,j}^{k,t+f} \qquad \text{For each } i \qquad 13.10$$

$$B_E^t = \sum_{k=M}^{F} \sum_{i=1}^{L_{\max}} T_i^k W_i^k V_i^k \qquad 13.11$$

h. Calculate the harvest rate, H^t (conditioned on catch, C^t) and then multiply H^t by the selectivity for each size-class to spread the harvest rate over all size-classes. Use this to calculate the predicted catch by numbers, $X_i^{k,t}$, including weight at size to determine the predicted catch as biomass.

$$H^t = \frac{C^t}{B_E^t} \qquad \mathrm{X}_i^{k,t} = T_i^k V_i^k H^t \qquad 13.12$$

$$\hat{C}^t = \sum_{k=M}^{F} \sum_{i=i}^{L_{\max}} X_i^{k,t} W_i^k \qquad 13.13$$

l. Remove the numbers caught at size from the numbers matrix by multiplying by the survivorship modified by the selectivity curve.

$$N_{i,j}^{k,t+l} = N_{i,j}^{k,t+f}\left(1 - V_i^k H^t\right) \qquad 13.14$$

m. Distribute the recruitment across the first four size classes.

$$N_{i,j}^{k,t+m} = N_{i,j}^{k,t+k} + R_i^t \qquad \text{for i = 1..6} \qquad 13.15$$

n. Remove the final half of natural mortality.

$$N_{i,j}^{k,t+1} = N_{i,j}^{k,t+l} e^{-M/2} \qquad 13.16$$

In reality these operations are not a linear series but rather a branching pathway (Figure 63).

10.3.2 Non-legal Animals

Sub-legal and super-legal sized animals are returned to the sea and, currently, the model assumes zero discard mortality. If it is desired to include a discard mortality this could be implemented by not setting the portions of the selectivity curve (Eq. 13.1) below the legal minimum length and above the legal maximum length to zero but, instead, modify the selectivity beyond the legal sizes by multiplying those selectivity values by the predicted death rate from being discarded. Thus, if there is a 10% discard mortality then the selectivity values above and below the legal lengths are multiplied by 0.1. The summation of catch would still need to exclude animals from above and below the Legal limits as would the estimation of exploitable biomass. Perhaps the best way of implementing this would be to have two selectivity curves for each sex, one with discards the other without. This would enable the removal of discards from the numbers matrix but they would not contribute to the landed catch. This would imply that the harvest rate derived from conditioning the model on catch would be applied above and below the legal sizes modified via the selectivity curve that included discard mortality.

10.3.3 Recruitment

The sex ratio of the annual recruitment is assumed to be 1:1, and recruitment is assumed to occur into the first six size-classes only. Instead of estimating an annual recruitment for each year of the fishery, a mean recruitment level $\bar{\mathbf{R}}$ is assumed for each stock and region and there are log-normal recruitment residuals ε_t around this mean, which are estimated for each year. These constitute the main parameters for the model, the geometric mean recruitment plus a recruitment residual for each year:

$$R_{1..6}^{k,t} = \bar{R}e^{\varepsilon_t}/12.0 \qquad 13.17$$

Because new recruits can take up to five years to become 150mm and enter the fishery the final five years of the recruitment estimates are unlikely to vary from the geometric mean value. This has implications for when the model is projected into the future during risk assessments or harvest strategy evaluation. If the model were allowed to fit to the recruitment residuals in an unconstrained fashion there is the possibility of extremely good fits but unrealistically variable recruitment levels. It is usual to set a coefficient of variation for the recruitment residuals (σ_R) and develop a penalty function designed to constrain recruitment variation that is added to the total log-likelihood:

$$Penalty = \frac{\sum_{k=1}^{years} \left(\varepsilon^k\right)^2}{2\sigma_R^2} \qquad 13.18$$

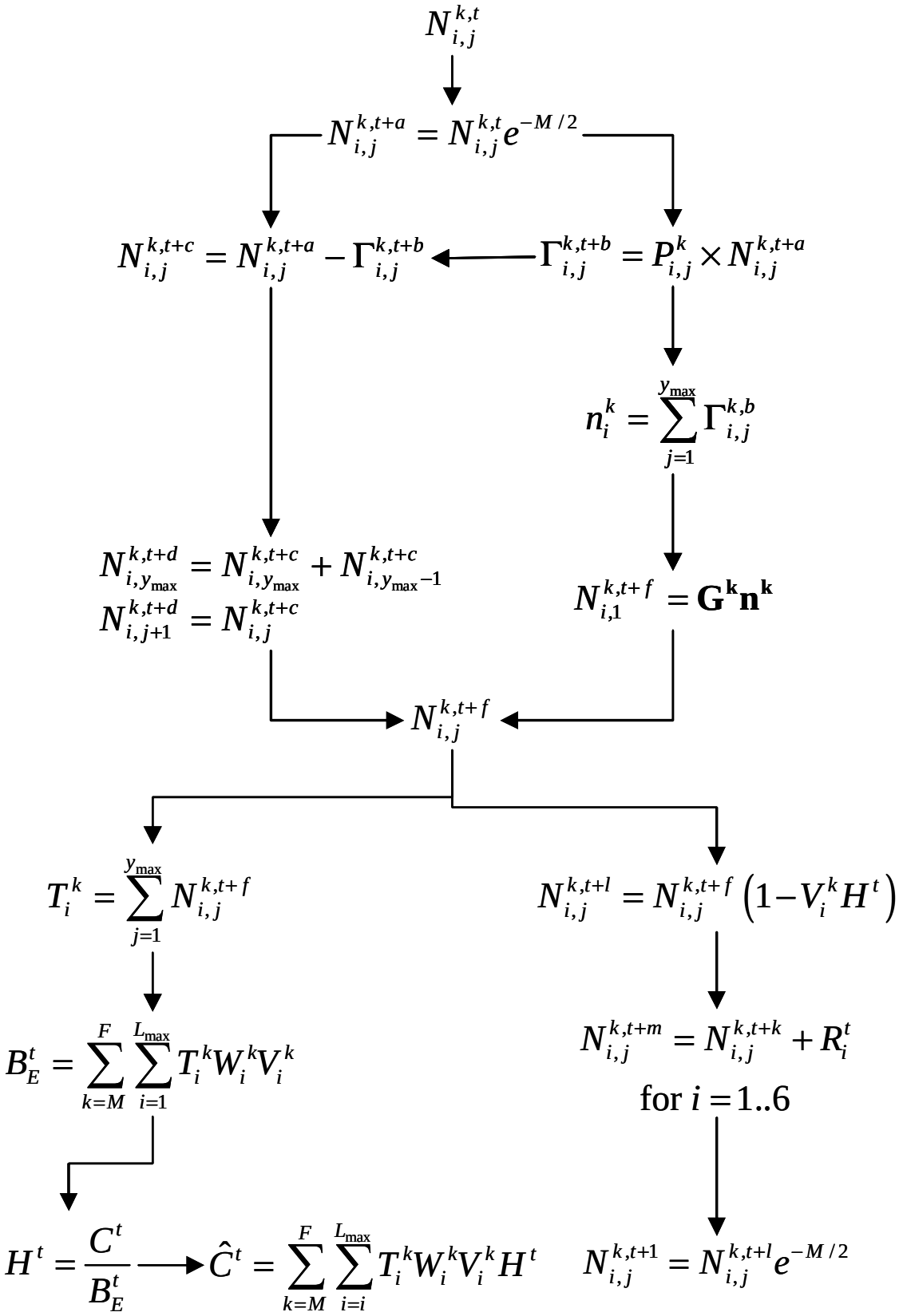


Figure 63. Schematic flow chart of the operations included in the algorithm for one time step of the Tasmanian giant crab model. All symbols are as described in Equations 13.4 to 13.16.

10.3.4 Catches

H^t, the harvest rate, the proportion of available or exploitable biomass taken, calculated by assuming that the total commercial catch (including bycatch), is taken instantaneously in the middle of the season, after half the natural mortality and growth of those animals that are to moult has occurred (Eq. 13.12).

10.3.5 Catchability

This is likely to vary across the season, which may affect such things as sex ratio. However, on a yearly time scale seasonal variations should average out across years. A closed form or analytic estimation method is used to estimate the catchability. This involves comparing the observed catch rates with the exploitable biomass that gave rise to the catch rates (Haddon, 2001). This is described below in the section detailing with the likelihood component relating to catch rates.

10.3.6 Growth Transition Matrix

The growth transition matrix is a square matrix of length equal to the number of size classes, in which only the lower diagonal is populated. The upper diagonal is populated with zeros because negative growth is assumed not to occur. The expected mean growth increment for an animal of length L_i^s (the midpoint of size-class *i*) over a single time period was obtained from the linear regressions of moult increment versus premoult carapace length for both single moults and double moults:

$$\begin{aligned} \bar{\Delta}_i^1 &= a + bL_i^s + \varepsilon && \text{one moult} \\ \bar{\Delta}_i^2 &= 2\left(a + bL_i^s\right) + b(a + bL_i^s) + \varepsilon && \text{two moults} \end{aligned} \qquad 13.19$$

in this case the expected mean length $\bar{L}_i^s$, of an animal of sex *s* and of size-class i (identified by the mid-class-length L_i^s) one moult later is:

$$\bar{L}_i^s = L_i^s + \bar{\Delta}_i \qquad 13.20$$

Equation 13.20 is used to generate the growth transition matrix as described in the section on growth dynamics. Detailed descriptions of the intermoult dynamics, and the moulting mortality are also provided in that section.

10.3.7 Initial Conditions

The history of this fishery in Tasmania is reasonably well known so it may be possible to reconstruct the early development of the stock dynamics. For many years before the giant crab fishery developed there was a minor bycatch by rock lobster fishers predominantly of large males. Very little of this was landed so the stock was essentially

unfished until the target fishery developed. Without independent information with regard the state of the stock it will be necessary to assume that the stock was in equilibrium with its mean recruitment level at the time the fishery began. With a simple growth description that does not require the use of tracking the years-to-moult it is possible to generate the equilibrium numbers-at-size in an analytical fashion. However, the added complexity of the years-to-moult matrix representation means that the equilibrium conditions, in this case, need to be determined iteratively. In practice, the population can be initiated by starting with an empty numbers-at-size by years-to-moult matrix (the numbers matrix) and distributing the total recruitment across the first six size-classes. If there are then 200 passages through a routine for updating the stock dynamics in the absence of fishing, in practice this appears to be more than enough to attain an equilibrium state within the numbers matrix. The stock dynamics routine involves applying half the natural mortality (13.4), identifying those animals that will grow and subtracting them from the numbers matrix (13.5 and 13.6), the numbers matrix is then incremented one year forward (13.7) and the first column of the numbers matrix is filled with the numbers-to-moult multiplied by the respective growth transition matrix (13.8 and 13.9). There is no fishing mortality so the dynamics moves immediately to adding the new recruitment (13.15) and finally removing the last half of natural mortality (13.16).

10.4 Likelihood Functions for Model Fitting

10.4.1 Catch Rate Data

Assuming catch rates are log-normally distributed leads to the following likelihood:

$$L_{CE} = \prod_t \frac{1}{I_t \sqrt{2\pi}\sigma_q} \exp\left(-\frac{\left(\mathrm{Ln} I_t - \mathrm{Ln}\left(q B_t^E \right) \right)^2}{2\sigma_q^2} \right) \qquad 13.21$$

where σ_q is the standard deviation of the residual errors around the expected catch rates, I_t is the catch rate for year t, and B_E^t is the exploitable biomass after half of natural mortality and growth have occurred. Happily, this equation can be greatly simplified as a negative log-likelihood (minimizing this leads to the maximum likelihood estimate):

$$-LL_{CE} = -\frac{n}{2}\left(Ln(2\pi) = 2Ln(\hat{\sigma}) + 1 \right) - \sum_{t=1}^{Years} Ln\left(I_t \right) \qquad 13.22$$

For further simplicity the final summation term of Ln(I) is a constant and can be omitted without affecting the outcome. The value of $\hat{\sigma}$ can be obtained using the maximum likelihood estimate; note the use of n and not n-1 in the denominator:

$$\hat{\sigma} = \sqrt{\frac{\sum_{t=1}^{Years} \left(Ln\left(I_t\right) - Ln\left(\hat{I}_t\right)\right)^2}{n}} \qquad 13.23$$

In addition, the maximum likelihood estimate of q, which optimises Eq. 13.22 can be determined analytically as:

$$\hat{q} = \exp\left(\frac{\sum_t Ln\left(I_t / B_t^E\right)}{n} \right) \qquad 13.24$$

where n is the number of years for which catch rates are available (Haddon, 2001).

10.4.2 Length Frequency Data

It is assumed that the length-frequency data available will be fitted using a multinomial likelihood (Quinn & Deriso, 1999; Haddon, 2001). Thus:

$$L_{LF} = n! \prod_{i=1}^{L_{\max}} \frac{p_i^{n_i}}{n_i!} \qquad 13.25$$

where

$$n = \sum_{i=1}^{L_{\max}} n_i \qquad 13.26$$

when this is converted to a negative log-likelihood we obtain:

$$-LL_{LF} = -\sum_{j=1}^{n} Ln\left(j\right) - \sum_{i=1}^{L_{Max}} \left[n_i Ln\left(p_i\right) - \sum_{j=1}^{n_i} Ln\left(j\right) \right] \qquad 13.27$$

The first and last terms are merely the logarithmic form of calculating the factorial terms. For any particular problem these terms are constant and are usually ignored in the calculation of the negative log-likelihood. For added stability the number of observations in each size-class n_i can be converted to proportion by dividing by the sum of all the observations (Quinn and Deriso, 1999). We are left with:

$$-LL_{LF} = -\sum_{i=1}^{L_{Max}} \frac{n_i}{n} Ln\left(p_i\right) \qquad 13.28$$

When Eq. 13.28 is minimized the match between the observed length frequencies and those predicted by the model is optimised.

10.4.3 Total Likelihood

The model is fitted by combining the various sources of likelihood and the penalty term from the recruitment residuals (Eqs 13.18, 13.22, and 13.28). Each of the likelihood terms can have its own weighting, which can be used to explore the relative contribution of each source of likelihood to the final solution:

$$-LL = -LL_{CE} \,.\, Wt_{CE} + -LL_{LF} \,.\, Wt_{LF} + Penalty \qquad 13.29$$

11. A User Interface for Conducting Model Runs: "Renoware"

11.1 What is Renoware?

Renoware is an interface to automate the process of fisheries resource assessment modelling on Giant Crab (*Pseudocarcinus gigas*) stocks. The interface interacts with a model of the giant crab population to produce predictive data of crab stocks in Tasmanian waters. Initial parameter estimates are entered into the model to start the optimisation process. Raw data from the fishery is also entered into the program. The model interprets the data, the results of which are used to generate predictions and the comparisons between the predicted values and those observed from the fishery, and are presented in the form of analytical data and graphics.

Renoware takes data from input files and the UI (user interface), which interacts with a model (a computer driven simulation of a real world environment) to supply forecasts and projections in creating sustainable, manageable fisheries.

The resource modelling attempts to predict the catch rates and size distributions observed in the fishery. The assessment is an optimisation problem of matching the predicted values to those observed, which is done by modifying an array of model parameters.

The software was developed by Michael Shaw, Eliza Ralph, Chantel Sommerville, Nick Bester and Jason McGuinness from the University of Tasmania's School of Computing.

11.2 Features of Renoware

Renoware is a stand-alone program developed for the Windows XP/Windows 2000 operating environments.

- Renoware provides an easy to use graphical user interface.
- Automation of tedious tasks.
- User-configurable settings for supplying input data.
- Handled data storage and retrieval that allows for easy collaboration between users.
- Fully functional search facility for retrieving stored data.
- A batch based execution system (for performing multiple model runs sequentially.
- A fully featured graphing package with the ability to export graphs.
- Throughput input validity checking.
- In-built help system.

11.3 Renoware's intended audience

The intended audience of the software is for biologists and fisheries managers.
It is required that the user has knowledge of resource modelling. Renoware will serve as a front-end package to be used by fisheries managers and biologists to harness the model for prediction and analytical purposes, allowing comparisons to be made between different management arrangements.

The model was developed by and intended for use of TAFI.

11.4 Conducting model runs

11.4.1 Set-up and configuration

Detailed set-up and configuration information is available through the Renoware User Manual, which is loaded through the auto-install process. This process is similar to most software installation although attention must be paid to the directory structure for saving model results.

11.4.2 Input – Hindcast

This contains data fields and tables that revolve around establishing a mathematical model of various aspects of the giant crab population, based on historical data.

The Input – Hindcast Tab sub tabs are shown below in Figure 64. The sub tabs are Run Settings, Biological Data, Growth Data, Fishery Data and Length Frequency Data.

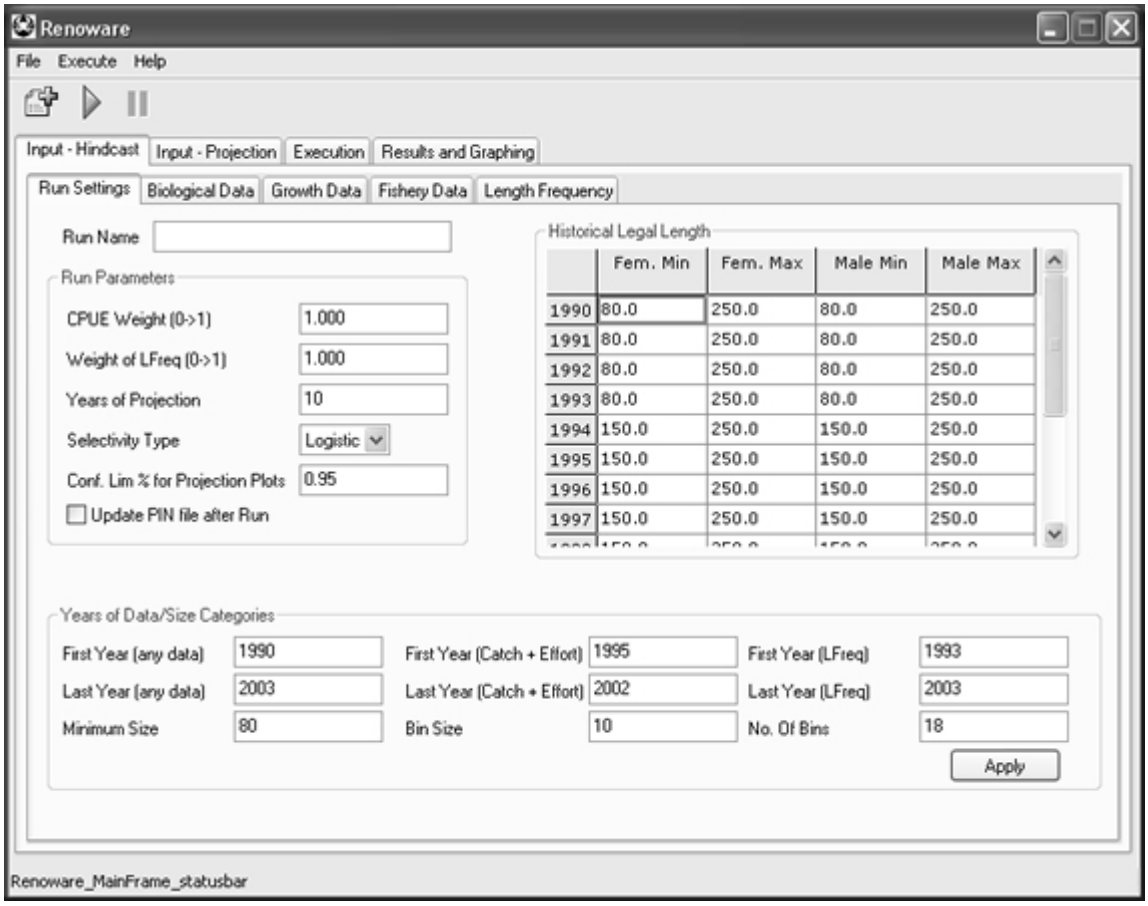


Figure 64. Input - hindcast tab.

11.4.3 Run settings

The Run settings sub tab is shown in Figure 65. The parameters under Run Settings are the most frequently changed when attempting to find an accurate model of past trends.

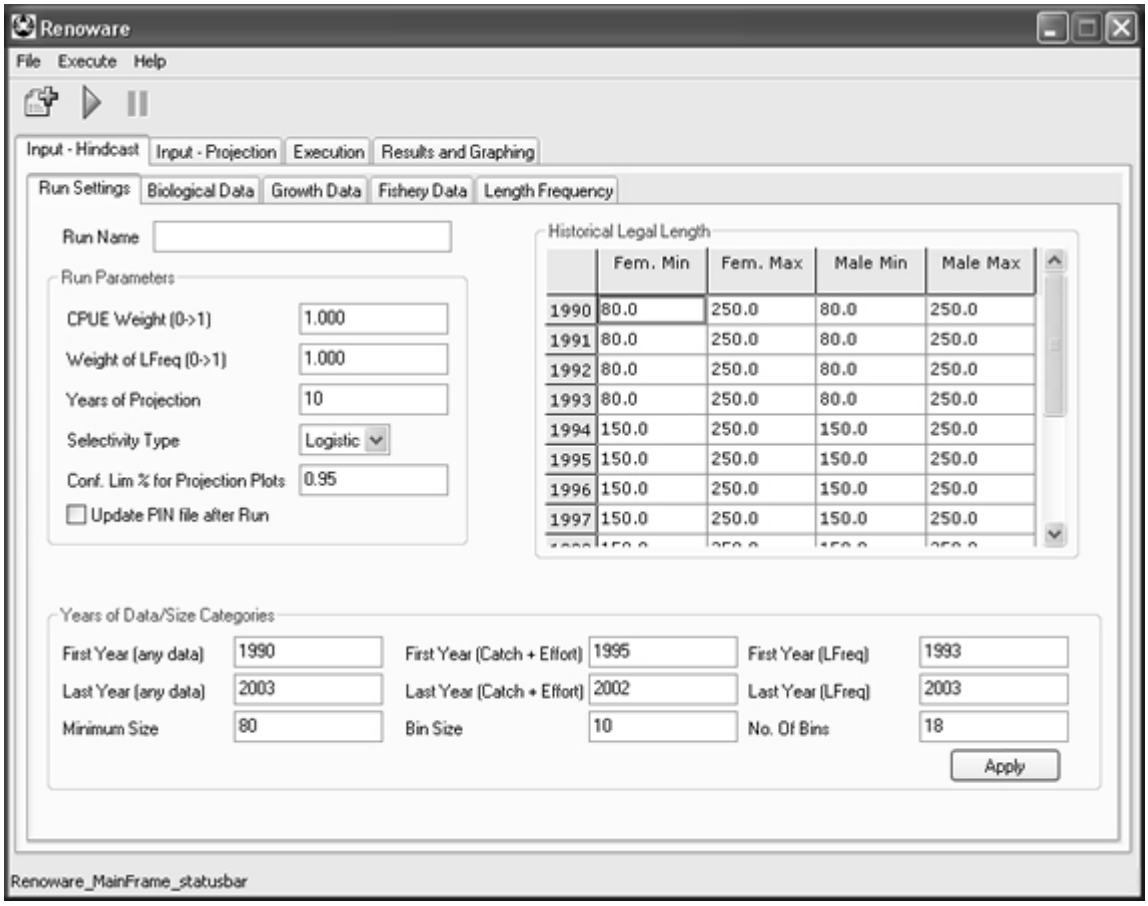


Figure 65. Run settings tab.

The **Run Name** text field stores the name of the model run. Model runs require a unique name whether they are to be executed or have been executed as to identify different model runs. Data stored to the database is filed under the model run name.

Run Parameters is where model run parameters can be set. Parameters include Catch per unit effort factor, Weight of length frequency, Year of projection, Selectivity type, Confidence limit % for projection plots and others.

The CPUE Weight (0>1) text field is where the user can set the weighting for the CPUE (catch per unit effort) factors. A valid input is a floating point number. The default value is 1.00.

The Weight of LFreq (0>1) text field is where the user can set the length frequency weighting. A valid input is a floating point number between 0 and 1.

> **For example** , CPUE weight of "0.5" and weight of LFreq of "1.0" will lead to greater reliance on length frequency data. This particular scenario could be selected where there was less confidence in catch and effort data, such as through known mis-reporting of effort. Ideally, the sources of likelihood should be weighted in proportion to their

relative variability. Thus, if one data source is more uncertain than another, this should receive a lower weighting.

The **Year of Projection** text field is where the number of years to project forwards is entered. A valid input is an integer number. The default value is 10.

Note: Normally this would be 10 years or less as confidence in estimates diminishes with longer periods of projections. The objective of the projections is not so much to predict the future as a reality but rather to compare the implications of different management options.

The **Selectivity Type** drop down box gives two options; Logical or Normal.

Note: Logistic selectivity is the more typical situation for trap fisheries where target species are not captured by gear when small, but their retention increases as their size increases. Logistic selectivity assumes that once animals are fully recruited to the gear then they will remain fully selected with increasing size. Normal selectivity is chosen where animals have a peak of selectivity at a certain size, but lower selectivity when smaller or larger. An example is the selectivity of gill nets, which have low ability to catch very small or large fish. Traps can also have approximately normal selectivity where the neck size excludes large animals.

The **Confidence limit % for projection plots** text field is where a percentage value can be entered to provide confidence limit bounds around the median estimate for projections. A valid input is a floating point number. The default value is 0.95.

Note: A value of 95% is commonly used. Entering a value of 100 will result in display of the extreme upper and lower projection runs. A common alternative is to use the 90th percentiles

Update PIN file on Run check box is deselected by default. Selecting this check box updates the PIN file with the new parameters entered.

> **Note:** This option is here to cover cases where the user can explore options that lead to unstable or pathological results. Under such circumstances, it is convenient not to save the new parameter estimates over the good ones.

Years of Data settings are where first and last year of any data, catch and effort and length frequency are entered. These settings exist because fisheries typically have increasing level of data collection as they develop.

> **Note:** Gaps in any data series should be entered as zeros; these will be ignored when the model is being fitted

First Year (any data) text field is where a numeric value for First Year (any data) can be entered, it is usually the first year that catch data is recorded

First Year (catch + effort) text field is where a numeric value for First Year (catch + effort) can be entered. This field is required to have a value entered.

First Year (LFreq) text field is where a numeric value for First Year (LFreq) can be entered. This field is required to have a value entered.

Last Year (any data) text field is where a numeric value for Last Year (any data) can be entered.

Last Year (catch + effort) text field is where a numeric value for Last Year (catch + effort) can be entered; it is usually the most recent year.

Last Year (LFreq) text field is where a numeric value for Last Year (LFreq) can be entered; it is usually the most recent year.

The **Size Categories** settings contain three text fields which are used to define the size categories used for growth matrices and also for length frequency data.

> **Note:** If for example the following values are used, 80 mm for minimum size, 5 mm for size of categories, and 20 for Number of categories. This then gives 20 cells in 5 mm increments from 80 mm to 180 mm.

Minimum Size text field is where a numeric value (in millimeters) for the minimum size is entered. Usually the minimum size that animals are sampled in surveys collecting length-frequency data.

Size of Categories text field is where a numeric value (in millimeters) for the size of Categories is entered. The Size of Categories value is the size used to increment size categories

Number of Categories text field is where a numeric value for the number of categories is entered. The Number of Categories value is the number of increments of size categories.

Apply button 

allows the user to apply the run settings. Renoware checks the validity of the inputs. A list is presented of invalid fields, if there are any present.

Historical Legal Length table in the Historical Legal Length pane, shows minimum and maximum legal lengths for both females and males for each year of data. The maximum for females are implied in the early years. The **Historical Legal Length** tables row labels are deteminded by two values entered under the **Years of Data/Size Categories** pane, which are **First Year (any data)** and **Last Year (any data)**.

11.4.4 Biological data

The **Biological Data** sub tab is shown below in Figure 66. The Biological Data tab is where the user defines model parameters that simulate real world conditions affecting giant crabs. These parameters will remain largely unchanged, only being changed when scientific data suggests that an aspect of the giant crab population acts differently to what was previously thought. The **Biological Data** tab contains the following panes of grouped parameters:

- Population Parameters
- Female Reproduction
- Length to Weight Ratios
- Selectivity
- Custom Parameters

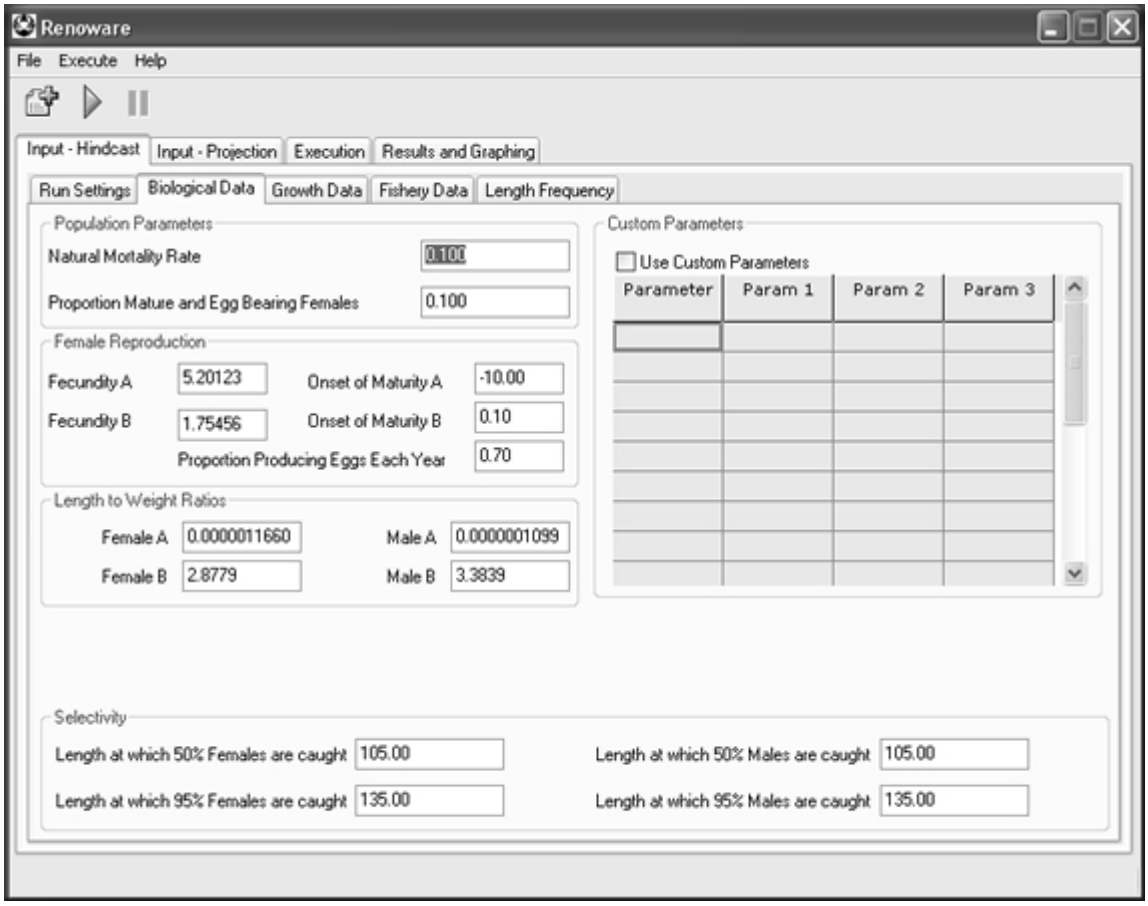


Figure 66. Biological data tab.

Population Parameters is where the user can enter values for the natural mortality of giant crabs and the proportion of females that are ovigerus.

- **Natural Mortality Rate** text field is where a floating-point numeric value for Natural Mortality Rate can be entered. The default value is 0.100.
- **Proportion Egg Bearing Females** text field is where a floating-point numeric value for Proportion Egg Bearing Females can be entered. The default value is 0.100.

> **Note:** Proportion Egg Bearing Females value should exclude females from harvests that are captured during the open season with eggs. If there are no restrictions on the landing of females with eggs then this field should be set to 0.

Female Reproduction pane is where the user can alter the length to fecundity parameter estimates, and the female size at onset of maturity parameter estimates.

- **Fecundity A** text field is where a numeric value is entered for Parameters A of the power function Fecundity = a.Length^b, describing the relationship between length and fecundity of females.

- **Onset of Maturity A** text field is where the parameter A of the logistic function describing the onset of maturity of females is entered. This value is used in combination with the **Proportion Mature + Producing Eggs** value to determine the maximum proportion of females classified as mature in any one year. Maturity = PropEgg/(1+exp(-(a+b.Length))).

- **Fecundity B** text field is where a numeric value is entered for Parameters B of the power function Fecundity = a.Length^b, describing the relationship between length and fecundity of females.

- **Onset of Maturity B** text field is where the parameter B of the logistic function describing the onset of maturity of females is entered. This value is used in combination with the **Proportion Mature + Producing Eggs** value to determine the maximum proportion of females classified as mature in any one year. Maturity = PropEgg/(1+exp(-(a+b.Length))).

- **Proportion Mature + Producing Eggs** text field is where a numeric value for the proportion of Mature females producing eggs can be entered.

> **Note:** In some species, females can have reached maturity, yet not reproduce each year; in these circumstances this text field should be set to a value less than 1. Where all mature females DO produce eggs each year, this text field should be set to 1. Note that this parameter interacts with the size at onset of maturity parameters. –It effectively lowers the upper limit of the logistic curve describing maturity to less than 1.

Length to Weight Ratios is where the user can alter values for the length to weight relationships for both male and female giant crabs.

> **Note:** Length to Weight Ratios is where parameters A and B of the power function Weight = A.Length^B, describing the relationship between length and weight for males and females can be set.

- **Female A** text field is where a numeric value can be entered for the parameter A of the power function Weight = A.Length^B, describing the relationship between length and weight for females.

- **Male A** text field is where a numeric value can be entered for the parameter A of the power function Weight = A.Length^B, describing the relationship between length and weight for males.

- **Female B** text field is where a numeric value can be entered for the parameter B of the power function Weight = A.Length^B, describing the relationship between length and weight for females.

- **Male B** text field is where a numeric value can be entered for the parameter B of the power function Weight = A.Length^B, describing the relationship between length and weight for males.

Selectivity is where the user can alter the fishing equipment selectivity rates for male and female crabs.

Under the **Run Settings** tab for "Selectivity type", if **Logical** is selected then the following equation is used:

Length at which 95% = a* Length at which 50%

Where **a** = the mean value of the expected distribution

Under the **Run Settings** tab for "Selectivity type", if **Normal** is selected then the following equation is used:

Length at which 95% = b* Length at which 50%

Where **b** = the standard deviation of the expected distribution

- **Length at which 50% Females are caught** text field is where a numeric value can be entered for the parameter Length at which 50% Females are caught. This value is used in one of the above equations.
- **Length at which 50% Males are caught** text field is where a numeric value can be entered for the parameter Length at which 50% Males are caught. This value is used in one of the above equations.
- **Length at which 95% Females are caught** text field is where a numeric value can be entered for the parameter Length at which 95% Females are caught. This value is used in one of the above equations.
- **Length at which 95% Males are caught** text field is where a numeric value can be entered for the parameter Length at which 95% Males are caught. This value is used in one of the above equations.

Custom Parameters is where data can be entered to make changes to the underlying model executable without the need for altering Renoware. These settings will not be used by the majority of users and is available to advanced users.

- **Use Custom Parameters** check box is not selected by default. When selected the table becomes active so the user can enter data, then the data in the table is exported into the model run.
- **Custom Parameters table** first column requires a string value. The next three columns take numeric values.

11.4.5 Growth data

The **Growth Data** sub tab is shown below in Figure 67. This tab contains all model parameters pertaining purely to the growth of giant crabs.

The parameters are to describe the transition between size bins through growth, including expected variation. Growth is modelled as a series of normal distributions around the mean expected increment for each size class. The change in the mean expected size increment with size class is described by a simple linear relationship, which is combined with an estimate of variability to generate the normal distribution about the expected.

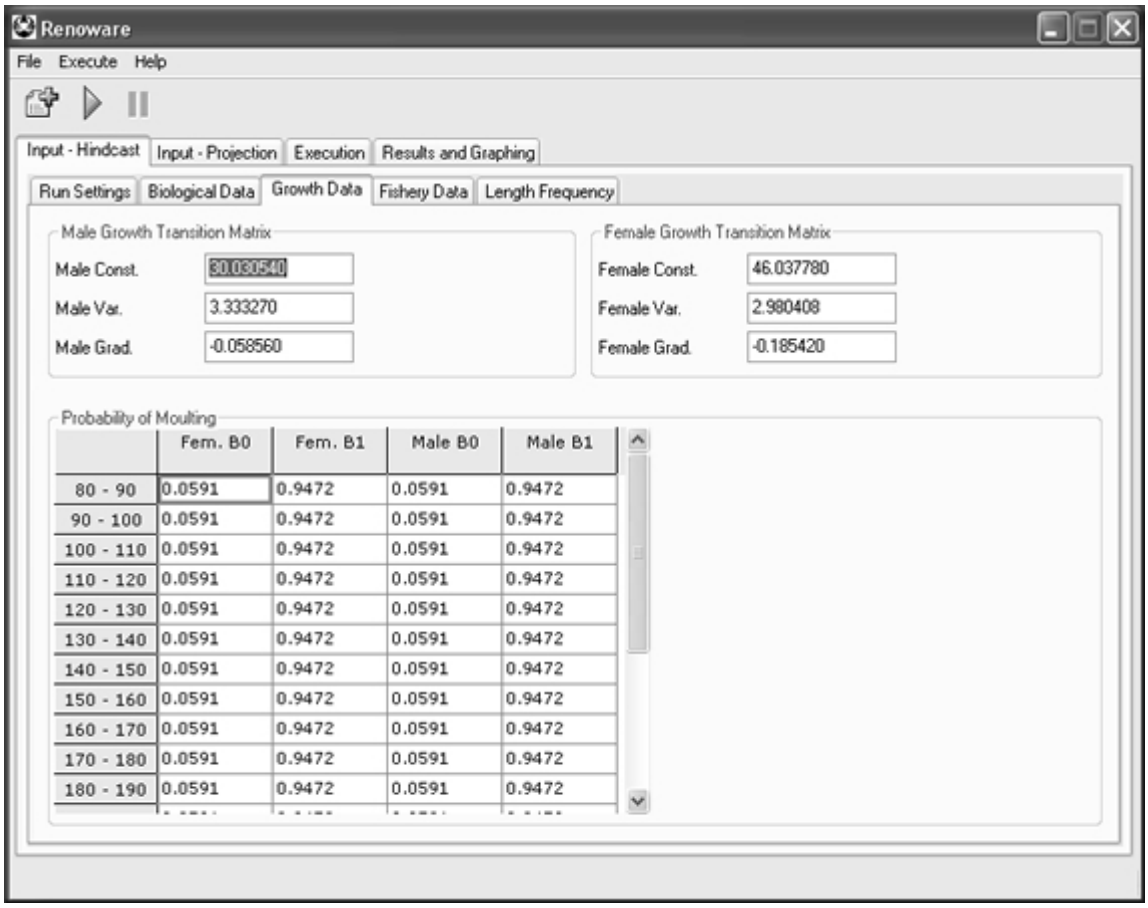


Figure 67. Growth data tab.

The three inputs are the gradient (very low for male giant crabs), the theoretical intercept, and the standard deviation characterizing the spread of growth about mean growth increments.

Male Growth Transition Matrix

- **Male Const.** text field where the Male Constant can be entered.
- **Male Var** text field where the Male Variance can be entered.

- **Male Grad** text field where the Male Gradient can be entered. This is usually very low for male giant crabs.

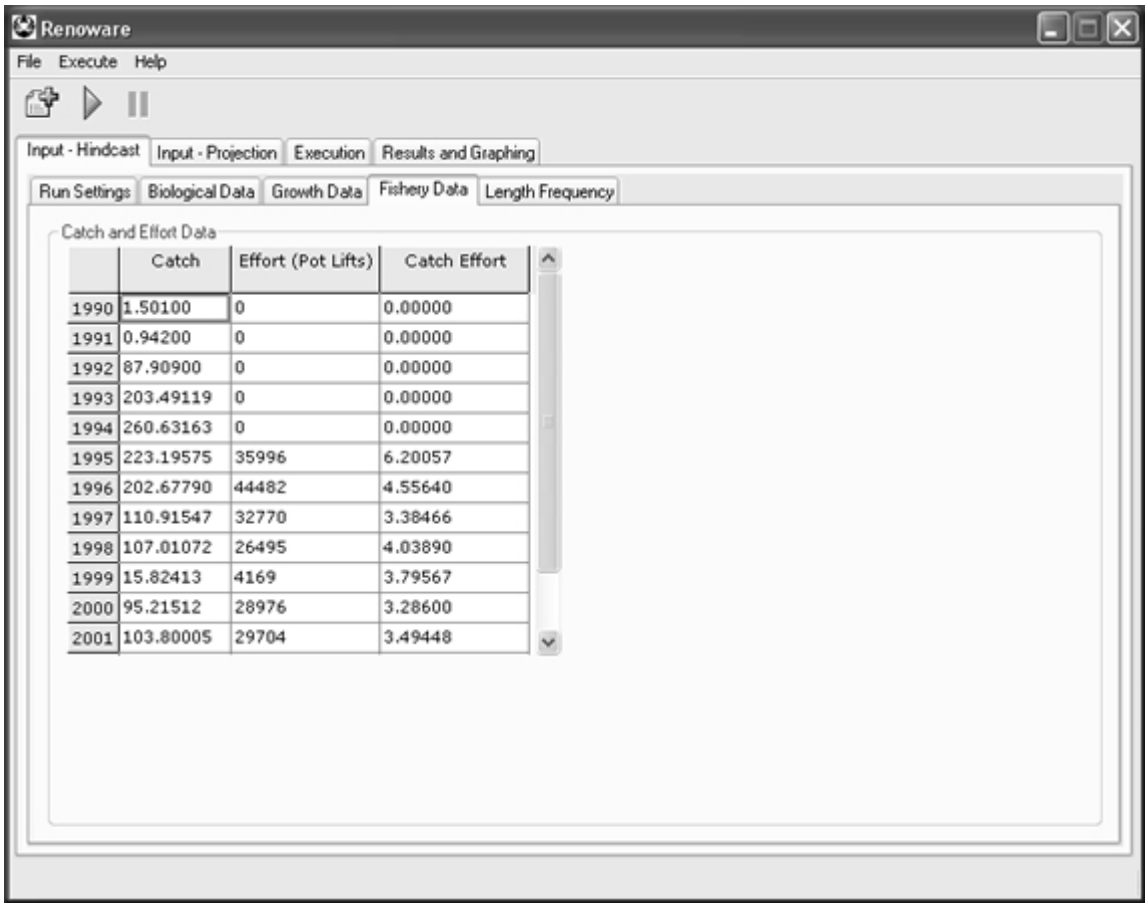
Female Growth Transition Matrix

- **Female Const.** text field where the Female Constant can be entered.
- **Female Var** text field where the Female Variance can be entered.
- **Female Grad** text field where the Female Gradient can be entered

Probability of Moulting table parameters are required where animals do not transit between size categories each time step, such as if they have moult intervals of greater than 12 months, or they grow very little each year. These parameters define the logistic curve that describes the proportion of each size class that moults through the years. The first column in the **Probability of Moulting** table is the size categories, which have been determined under the **Run settings** tab in the **Years of Data/Size Categories** pane.

11.4.6 Fishery data

The Catch and Effort Data table shown in Figure 68, is where data can be entered for catch, effort and catch per unit effort for each year.



	Catch	Effort (Pot Lifts)	Catch Effort
1990	1.50100	0	0.00000
1991	0.94200	0	0.00000
1992	87.90900	0	0.00000
1993	203.49119	0	0.00000
1994	260.63163	0	0.00000
1995	223.19575	35996	6.20057
1996	202.67790	44482	4.55640
1997	110.91547	32770	3.38466
1998	107.01072	26495	4.03890
1999	15.82413	4169	3.79567
2000	95.21512	28976	3.28600
2001	103.80005	29704	3.49448

Figure 68. Fishery data tab.

The columns in the Catch and Effort Data table are Years, Catch, Effort (prot. Lifts) and Catch Effort. The Years column has been determined by the values **First Year (catch + effort)** and the **Last Year (catch + effort)** found under the **Run settings** tab in the **Years of Data/Size Categories** pane.

11.4.7 Length frequency data

The **Length Frequency Data** tab shown in Figure 69 is where the number of animals per size category is entered for each year for both sexes.

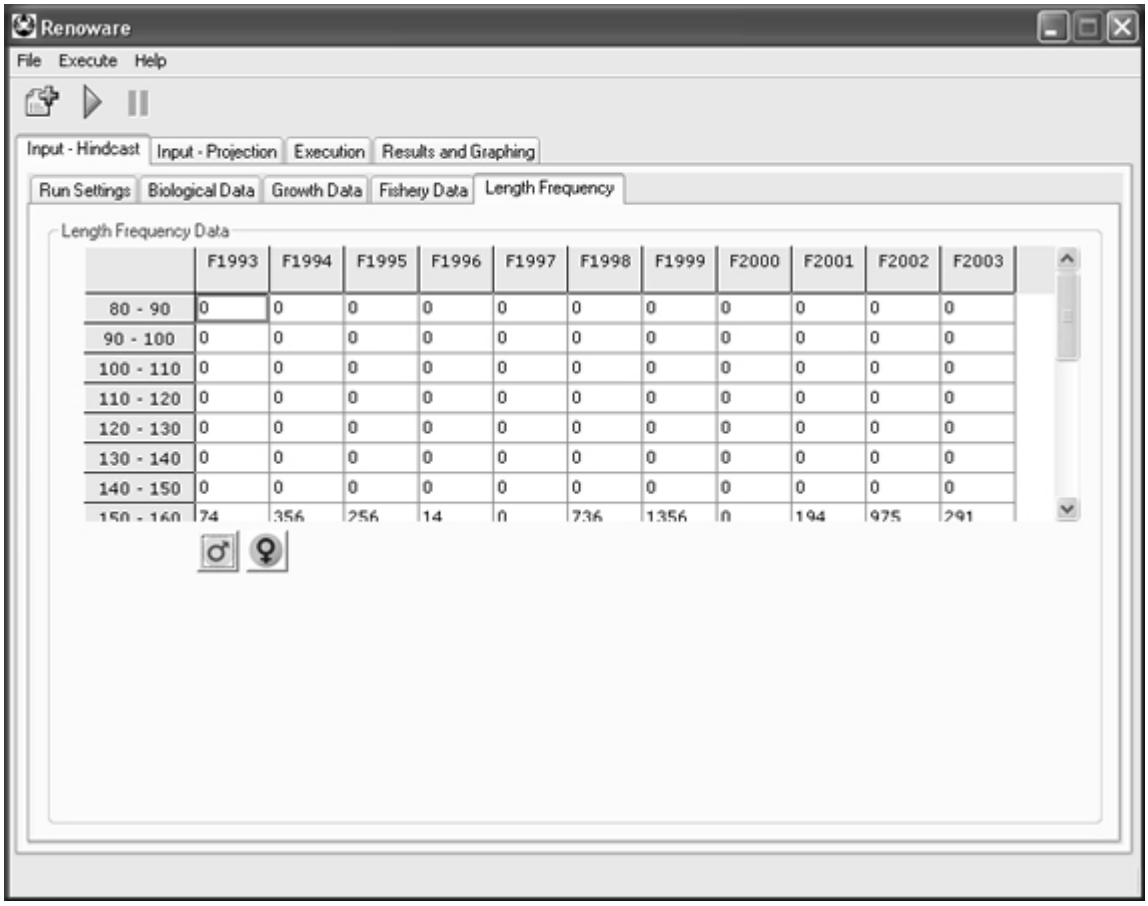


Figure 69. Length frequency tab**.**

The first column under the **Length Frequency Data** table is category size, which have been determined by three values under the **Run settings** tab in the **Years of Data/Size Categories** pane. These values that effect the category size column are; Minimum size, bin size and No. of bins.

The columns after the category size column have been determined by values **First Year (LFreg**) and **Last Year (LFreg)** found in the **Run settings** tab in the **Years of Data/Size Categories** pane.

- The **Male Table** button  - this switches the table under Length Frequency Data is switched to display data for Male Length Frequency. The Male Length Frequency data is displayed in the table by default.

- The **Female Table** button  - this switches the table under Length Frequency Data is switched to display data for Female Length Frequency.

11.4.8 Input- Projections

The *Input – Projection* tab shown in Figure 70, is where specifications for projections are entered: minimum and maximum size limits for each sex for each year and total allowable catch for each year (TAC). These parameters are used to make future projections.

Making useful projections is the goal for using Renoware. Once a good mathematical model of giant crabs is produced, then the functionality of **Input – Projections** tab can be used as a test environment for policy setting. This tab allows the user to play out ideas.

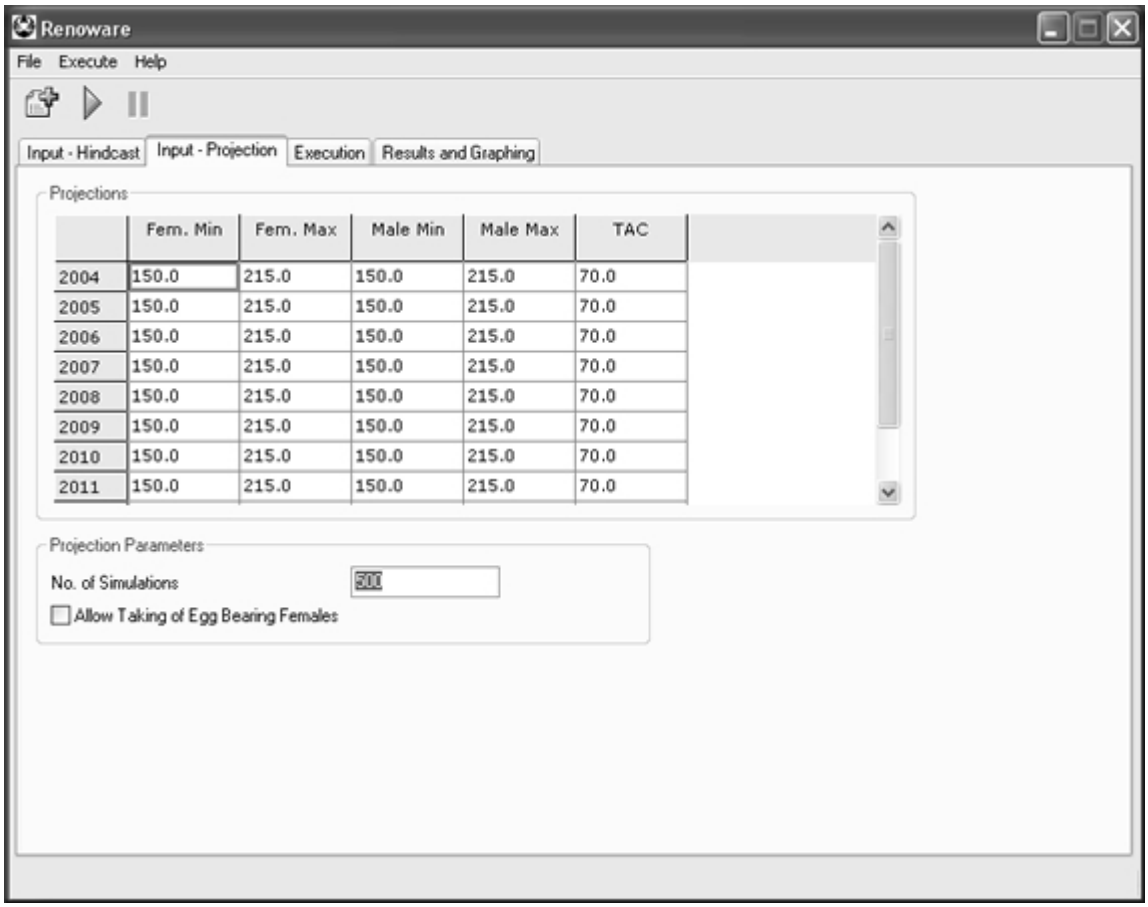


Figure 70. Input - projection tab.

The **Projections** table is where the minimum and maximum legal lengths for male and female giant crabs, TAC (Total Allowable Catch) for the number of years of simulations will be made. The first column is Years and the first value is determined by the current year (handled by Renoware). The years increment acording to the value **Years of Projection,** found in the **Run settings** tab in the **Run Parameters** pane.

Projection Parameters pane is where projection parameters can be set for the number of simulations and whether to allow taking of egg bearing females.

- **No. of Simulations** text field is where a numeric value of the number of desired simulations can be entered.

> **Note:** There is a trade of here between speed of model runs and the quality estimation of confidence limits. 1000 simulations are sufficient as an upper limit for most fisheries (and unlikely to give improved estimates of confidence limits compared to fewer simulations especially when the time series of data is limited).

- **Allow Taking of Egg Bearing Females** check box is deselected by default. If selected, the taking of egg bearing females is allowed.

11.4.9 Execution

The **Execution** tab is where the model run queue can be controlled (Figure 71). Feedback is provided to the user of the run progress.

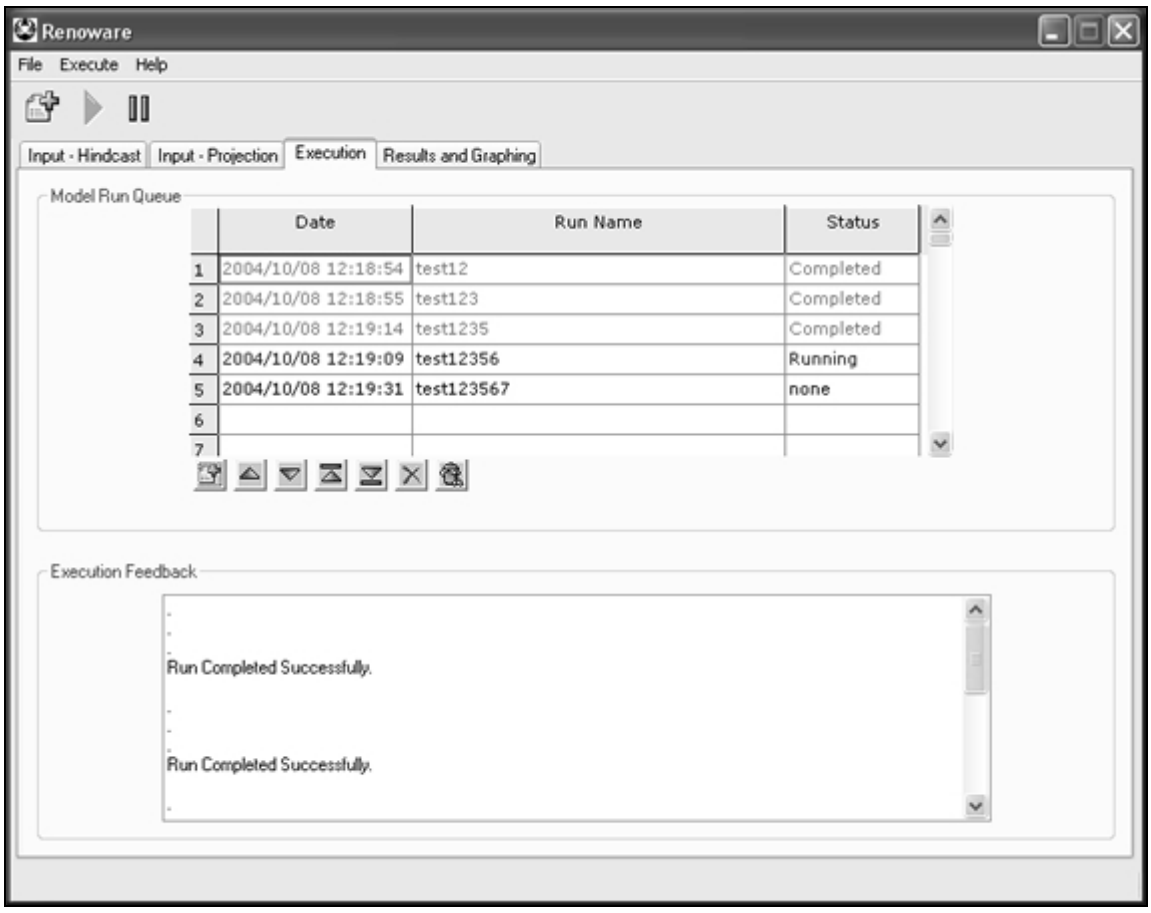


Figure 71. Execution tab.

The **Model Run Queue** pane contains a table of model runs and execution controls.

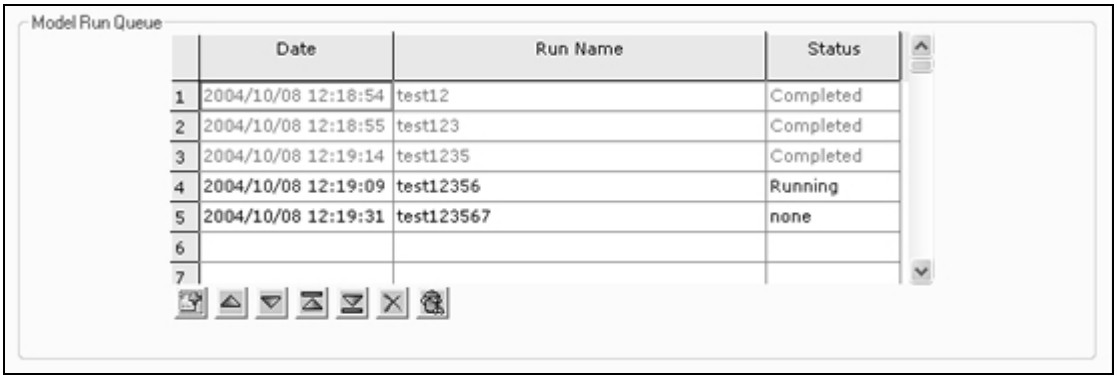


Figure 72. Model run queue pane.

The data in the **model run table** can be selected by clicking on an individual cell, or the corresponding row number. Multiple selections can be made by dragging the mouse over the required cells or by clicking the top left hand corner of the table. The column width can be resized to suit the user by positioning the mouse pointer over the column edge and dragging.

The **model run table** holds from 1 – 100 model run entries. The scroll bar on the right hand side of the table can be used to view all the entries in the table.

The **model run table** consists of three columns, *Date* , *Run Name* and *Status.*

- The **Date** column contains the date and the time the model run was added to the queue. The format of the Date column is YEAR/MM/DD HH:MM:SS.

- The **Run Name** column displays the name of the run as specified by the user at the time of adding the model run to the queue, which is retrieved from the Run Name text field found in *the Input - Hindcast tab, Run Settings sub tab.*

- The **Status** column displays the current status of the model run. The possible status are; *none*, *running* or *completed.* None is the default status for a run that has had no action performed on it. Running denotes that a model run is in progress. Completed denotes that the model run has finished executing.

The **execution controls** are shown in Figure 8 Execution tab, directly below the model run table. The **execution controls** consists of the following:

- **Add to Queue** button – adds a model run to the queue. This is described further in section **Adding a Model Run to the Queue.**

- **Shift Up** Button – moves a model run up the queue. This is described further in section **Control over the Queue.**

- **Shift Down** Button – moves a model run down the queue. This is described further in section **Control over the Queue.**

- **Shift to Top** Button – moves a model run to the top of the queue. This is described further in section **Control over the Queue**

- **Shift to Bottom** Button – moves a model run to the end of the queue. This is described further in section **Control over the Queue.**

- **Delete Selected** Button – deletes model run/s from the queue. This is described further in section **Control over the Queue.**

- **Clear All Completed Runs** Button – clears completed runs from the queue. This is described further in section **Control over the Queue.**

11.4.10 Results and graphing

The **Results & Graphing Tab** is the point where the user can access Renoware's database of completed runs (Figure 73).

Stored results can be viewed, searched by name or date and viewed in graphical form.

> **Note:** Renoware's database is not built on the conventional relational database model. Renoware's collection of completed model runs are stored in a simple filing system in which each run is contained within a directory according to it's unique name. Each run is accompanied by an index file containing data important for searching. This allows users to share data through the simple dragging and dropping of model run directors.

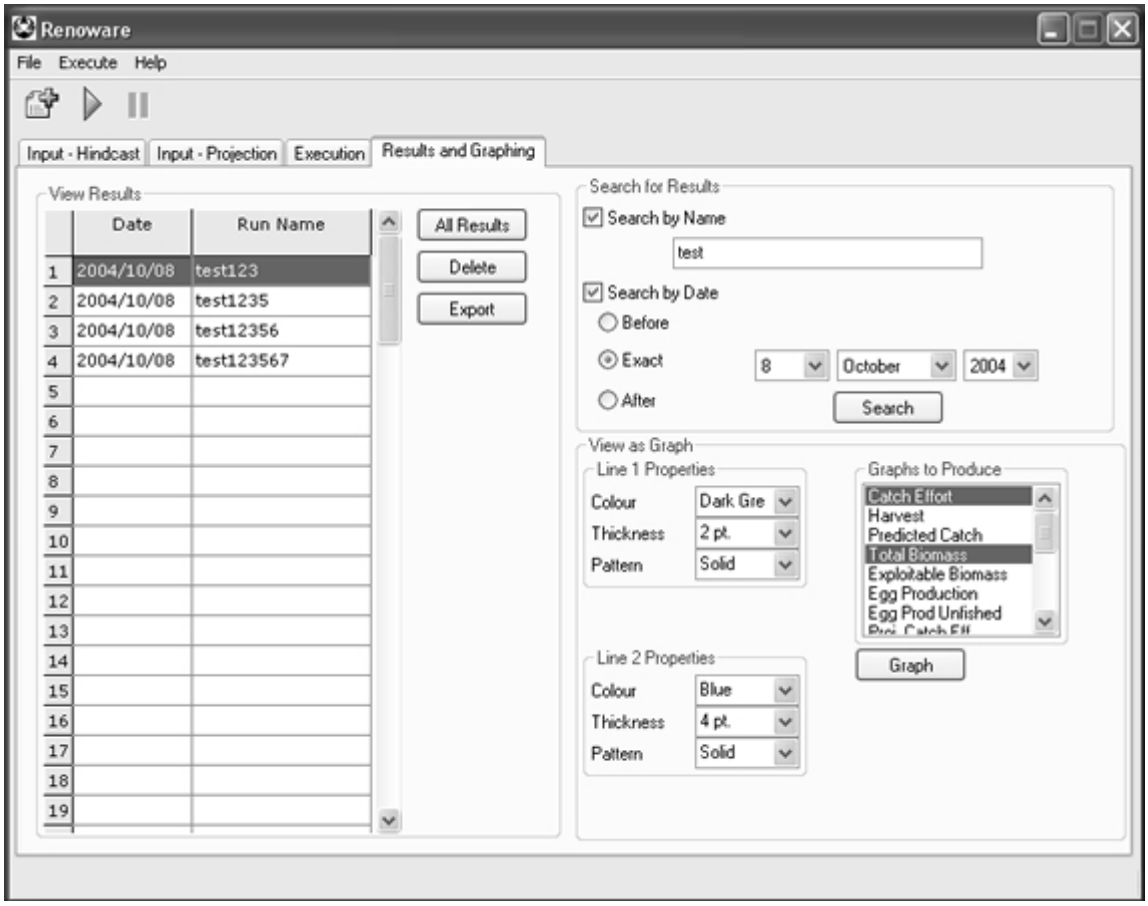


Figure 73. Results and graphing tab.

The '**View Results**' pane provides access to the database and a way to delete unnecessary stored results. It displays either all the records in the database or the results of the last search.

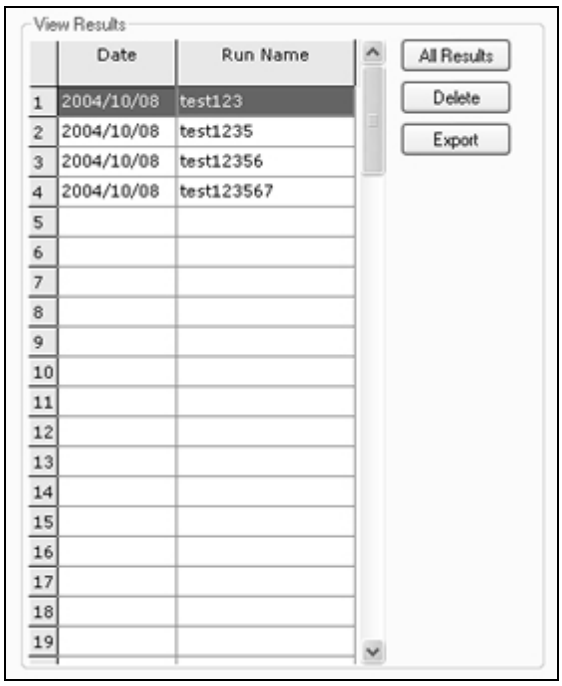
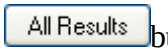


Figure 74. View results pane.

- The **All Results**  button provides a way for all of the stored completed Runs to be listed. This means that no matter what search criteria is used, or how many times the database is searched, all of the results can once again be displayed.

- Upon clicking the **Delete** button  a Confirm dialog box will be displayed. Selecting yes will result in the selected model run being erased from the database. Once this is complete, the run cannot be restored.

- The **Export** button  is used to copy the selected run to a specified location.

11.4.11 Graph viewing

When the **Graph** button is clicked, the requested graphs are generated and the Graph View is displayed on screen (Figure 75). From here, this display may be copied to the clipboard for pasting into a document or the display may be exported to a picture file.

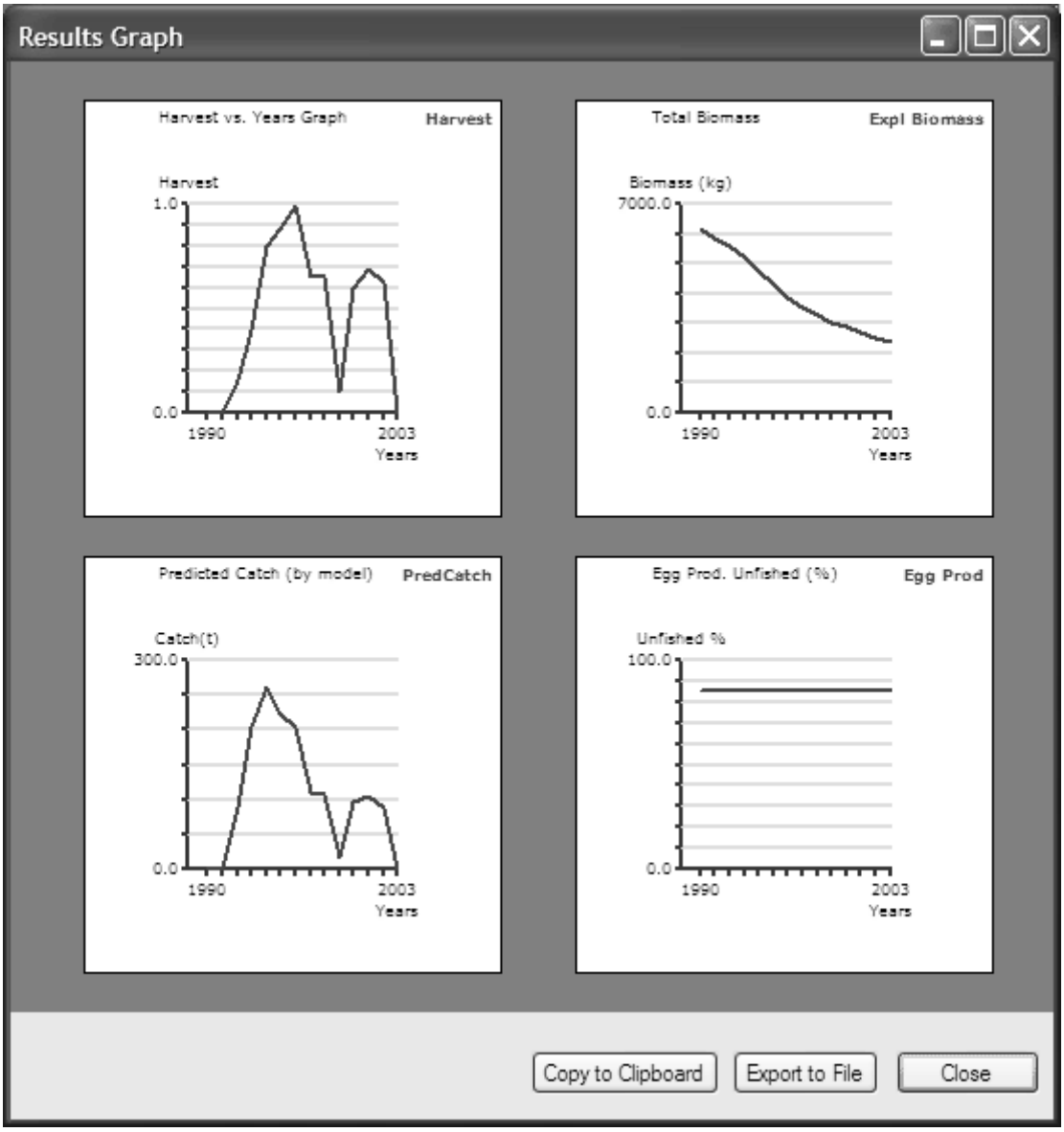


Figure 75. Graph view.

- The **Copy to Clipboard** button Copy to Clipboard - places the displayed graphs onto the system's clipboard as one picture. From here it is available for pasting into any document file.

- The **Export to File** button Export to File - enables the Graph View window to be saved to a specified location as a picture file.

- The Close button Close - closes the graph window down.

11.5 Examples of outputs from Renoware.

The following plots are based on default data inputs for Renoware, which are from the Tasmanian crab fishery up to the end of 2002. They are shown here to demonstrate the capacity of Renoware.

11.5.1 Description of fisheries input data

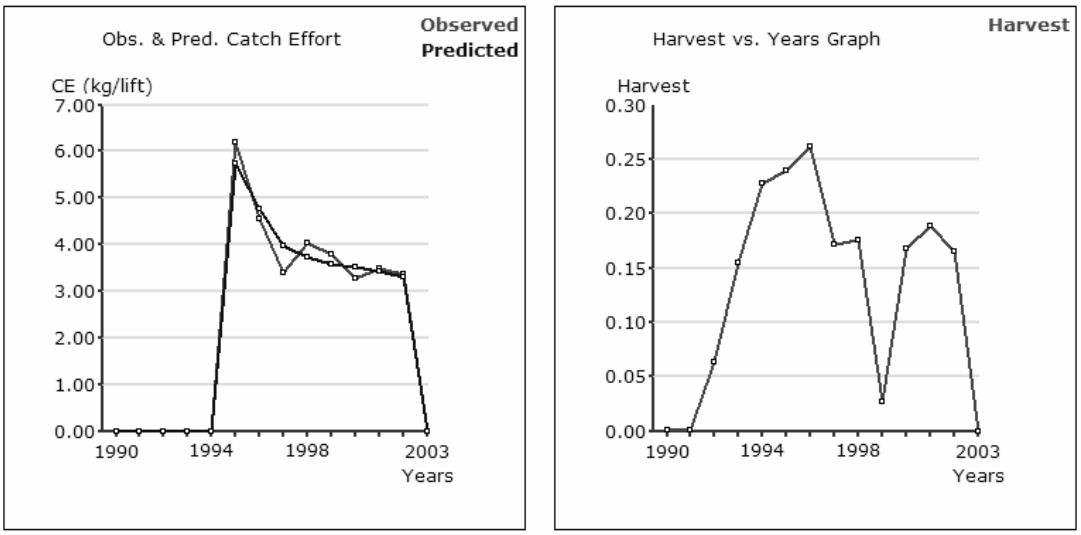


Figure 76. Observed and predicted catch rate (left) and observed harvest rate (right). Values of zero occur in the final year where no data exists.

11.5.2 Hindcast fits of biomass

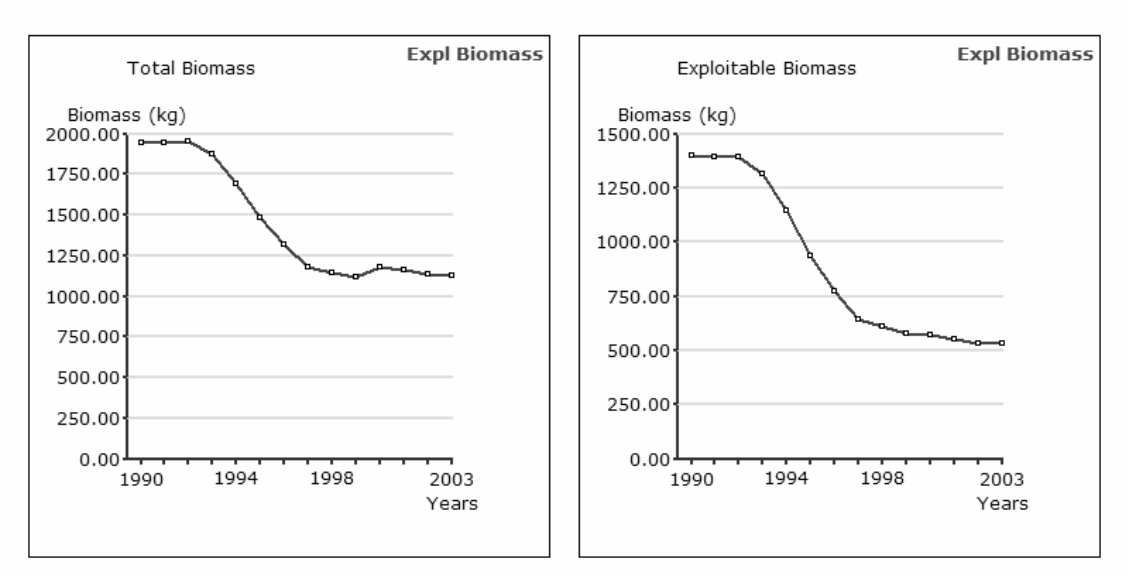
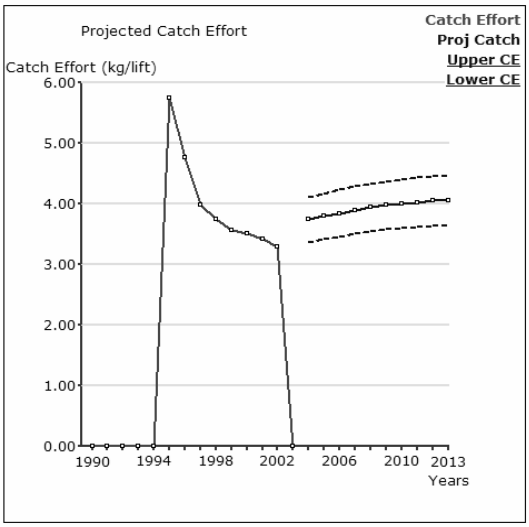
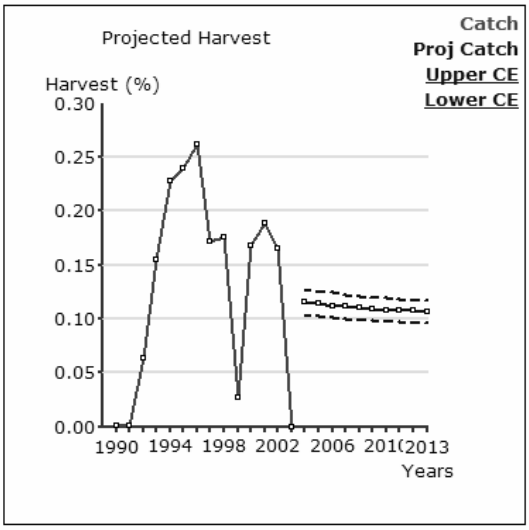


Figure 77. Estimated trends in total biomass (left) and exploitable biomass (right). Exploitable biomass takes account of selectivity and the unavailability of some crabs (such as ovigerous females).

11.5.3 Projections of catch rate, harvest rate and catch





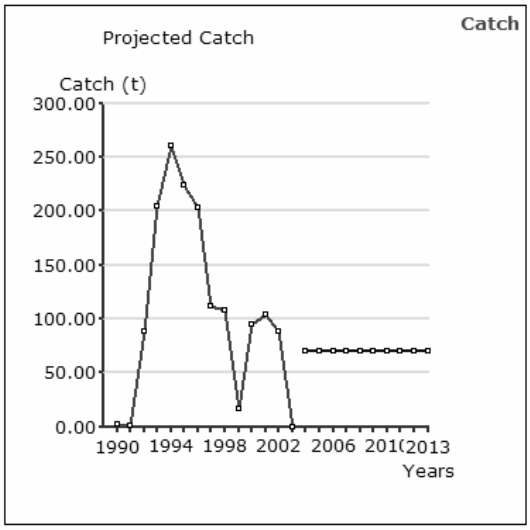


Figure 78. Hindcast data plus projections of catch rate (upper), harvest rate (lower left) and catch (lower right). Projections of catch are a function of the scenario selected for future TACs. Projections for both catch rate and harvest rate show 95% confidence intervals.

11.5.4 Projections of biomass

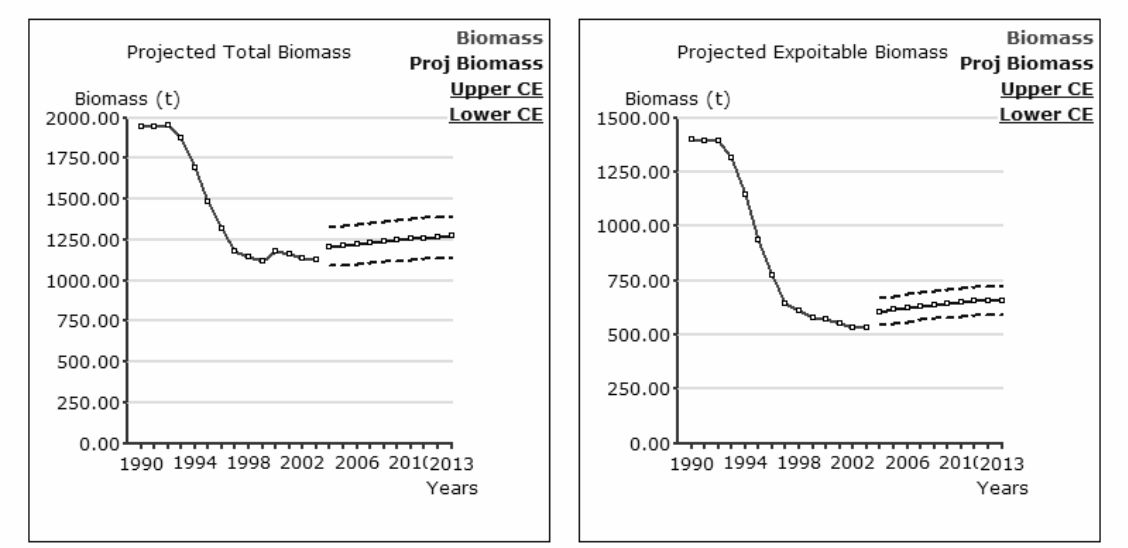


Figure 79. Hindcast data plus projections of total biomass (left) and exploitable biomass (right).

11.5.5 Observed vs predicted length frequency for each sex.

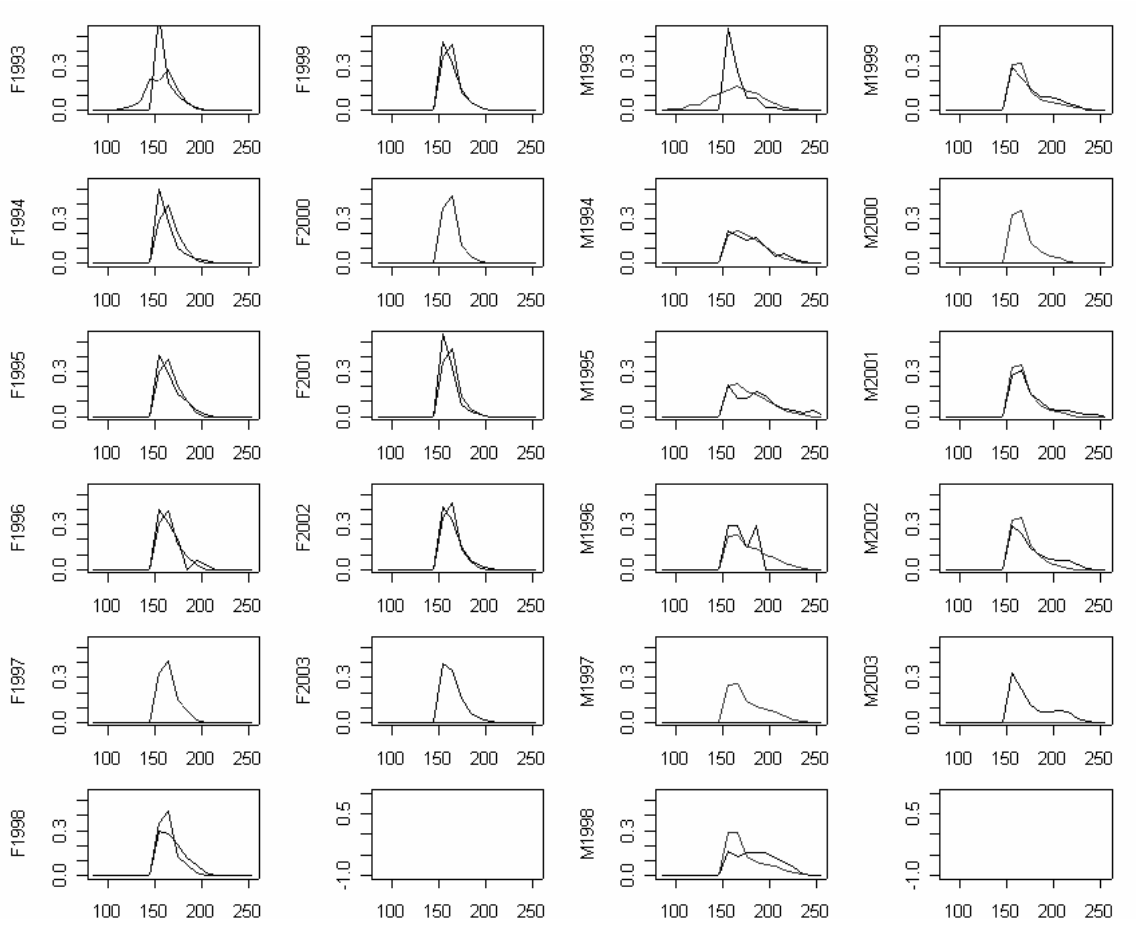


Figure 80. Predicted length-frequency of catches of female (first two columns) and male (rightmost two columns) giant crabs from around Tasmania. The black lines are the length-frequencies observed in the catch while the blue lines represent the predicted female lengths and the red lines the predicted male lengths. The sizes range from 80 mm to 250 mm carapace length, years are from 1993 to 2003.

12. Benefits and adoption

The project has met the objective of providing the tools for low cost assessment of the giant crab resource.

Historical data sets have been "cleaned" and corrected so that they have become more informative about changes in the fishery during the period when the virgin biomass was being fished down. This is an unusual and valuable asset for fisheries management. The presence of known errors in these data sets, such as deliberate under-reporting of effort, had distracted discussion of giant crab management prior to this project. The ability to correct for these types of problems has enabled discussions to move beyond debate about statistics to more constructive discussion of management options.

This project was constructed with the awareness that the resource was small and the fishery would have little ability to fund expensive data collection systems in the future, beyond catch rate data from logbooks. Size structure data from the fishery was one data type that would clearly be valuable for ongoing assessment, but was expensive to collect. Fishers have enthusiastically adopted the solution developed in this project of electronic callipers combined with an electronic logger. This system has dispensed with paper records so that work at sea is easier, and costs for data management (eg data entry) are reduced. This system has now been adopted in all three States.

The capacity for stock assessment modelling has provided a significant benefit for giant crab management. Guidance on alternative management options, especially alternative TACs, has enhanced management. This model has been adopted in Tasmania and South Australia and will be extended to Victorian stocks. A range of analyses including catch rate standardisation and re-analysis of tag-recapture data to estimate growth parameters has underpinned the stock assessment modelling process.

These improvements in stock assessment capability have been important for management decisions on crab stocks and also for obtaining DEH accreditation.

13. Further development

13.1 Low cost length-frequency data collection

Options for extending the value of the electronic calliper system include better integration into databases and better supply of data back to fishers so as maintain their enthusiasm.

Length data is currently joined with location data recorded in logbooks on the basis of fishers name and date of sampling (which are recorded in both data sets). While this process is generally effective, it does introduce risks of errors. A better option may be to record location at the same time as length is recorded. This could be done automatically by incorporating a GPS unit into the data logger. Another advantage of this approach is that it would be easier to eliminate false readings. For example fishers

often tend to demonstrate the units to other people while they're in port; when we recover the data loggers it's not always clear that these measurements were not from crabs. An inbuilt GPS would enable us to be clear whether the fisher was at sea or in port.

Delivery of length data back to fishers could also be improved and is an important consideration in maintaining participation. Length data collected by fishers is currently graphed and then posted back to fishers. This keeps them informed but could be more effective. Ideally the data they collect would be used as part of their business management so that they collect size data for primarily for themselves. A feasible option would be the construction of a website linked back to our database. Fishers could have individual passwords to access the site and view their own length-frequency data. Ideally, they would also be able to access their logbook data and view graphs and maps of their data (perhaps in relation to aggregate data for the fleet). This concept has been submitted to the University of Tasmania School of Computing and may be adopted as a student project.

13.2 Catch rate standardisation

Some aspects of the standardisation process may warrant review as more data becomes available. For example, spatial distribution of effort was accounted for by including statistical block in the Tasmanian analysis, but it may be better to conduct separate assessments for the two coastlines of Tasmania, as each fishery appears to have different characters. Care will need to be taken, as the amount of data available from the East coast is often far less than available for the West coast.

In addition, the annual time step of using quota years may create inconsistent standardisation because the effort permitted has varied greatly through the history of the fishery. Inclusion of Month as a factor in the analysis will have alleviated this problem to some extent, but it would be advantageous to explore the outcomes by using perhaps a two-month time period as the base time step.

13.3 Giant crab growth information

Improving data coverage of legal size crabs would be valuable and should be considered in future research programs. However, this is a difficult exercise due to the cost involved to fishers of releasing a large valuable individual crab. Compounding the problem of obtaining moult data is that legal size crabs are vulnerable to exploitation for many years before a moult occurs. Improving fisher participation and reporting rates will be valuable for improving growth data. Given the large cost involved in deploying tags it is sensible to maximise data returns. One option may be to utilise web-based reporting to provide fishers with instant feedback on their tag-recapture. This could be part of the web-reporting system described for other fisher-based data collection described above (Section 13.1).

13.4 Size based stock assessment modelling

Assumptions and weaknesses of the current assessment model include the description of growth, interaction between growth and recruitment, fitting the final five years of recruitment residuals, and other data problems.

The most obvious weakness in the model is the description of giant crab growth, especially for legal-sized crabs as discussed above (Section 13.3). In addition, part of natural mortality was implemented as a moulting mortality rate, which had a major influence on the potential productivity of the stock. While the description of growth is plausible (though the intermoult periods are very long), this description is nevertheless a major source of uncertainty in the model. This is both model uncertainty (are the dynamics really operating in the way described) and parameter uncertainty (have the parameters been estimated with sufficient precision to provide an accurate description of growth).

A model weakness related to the description of growth is that the current equilibrium size distribution has a modal structure to it that reflects the large moulting increments of the crabs. At the smaller sizes the variation around this average moult increments is relatively smaller and the modal structure develops naturally from that. The recruitment dynamics have been chosen to minimize the appearance of these modes because there are none apparent in the size distribution data. Better size distribution data is required (meaning the data collected needs to be representative of more of the catch and more data overall needs to be collected – addressed above in Section 13.1).

The time lag at the end of the fishery, induced by the time it takes new recruits to grow into the fishery is matched at the start of the fishery during which such small catches were taken that no information is available to estimate recruitment across the years and, instead the model lumps all the recruitment necessary to match the early large catches into a single year. In addition, though this may be from the same cause, the average recruitment, except for the single year before the fishery expanded, is greater than most of the fittable recruitment residuals. This has the effect of implying a relatively high average recruitment, which may bias the model outcomes when average recruitment is implied. It is possible that the recruitment dynamics are biased high because of how the model responds to the available data. This would have the effect of exaggerating the productivity of the stock and may lead to recommending unsustainable TACs.

Ideally, the Tasmanian assessment would treat the two coasts separately, however, the amount of data available for the east coast may be too sparse to permit a useful assessment to be made. Certainly the catch rate data can be standardized for each coast separately, but there are numerous years where insufficient size distribution data to be representative were collected from the east coast. Whatever the case, an attempt should be made to consider the two coasts separately so that the impact of potential interactions with trawlers on the west coast may be modelled explicitly.

The bycatch catches by trawlers should be included in the model as this will act to reflect a more productive stock. In addition, the impact of some degree of release mortality associated with returning giant crabs to the sea should be investigated.

As more tagging data becomes available the description of growth, especially the intermoult dynamics, should be improved and updated. This is especially critical for the larger sized crabs. Any information relating to them will enable the model uncertainty in relation to the description of growth to be improved upon.

As more and more size distribution of the commercial catch data becomes available this will also enable the elimination of possible problems with the model. If the true size distribution of crabs does not have the modal structure predicted by the model then the model will need modification to eliminate this feature. Possibly this could be removed by including further, smaller size classes into which the new recruits can be pasted.

Some potentially valuable fisheries data is currently being collected but is not incorporated into the model. In particular, the number of individual crabs captured of each sex is not currently utilised and may be of value in apportioning harvest rates between males and females, or for providing a measure of average weight.

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15. Appendix 1: Intellectual property

No commercially valuable intellectual property arose from the research. No compelling reason was identified to restrict distribution of results so these have been made publicly available with no protection or confidentiality.

16. Appendix 2: Staff

Project staff were:

Dr Caleb Gardner, Tasmanian Aquaculture and Fisheries Institute, University of Tasmania (Marine Research laboratories).

Assoc. Prof. Malcolm Haddon, Tasmanian Aquaculture and Fisheries Institute, University of Tasmania (Marine Research laboratories).

Dr David Mills, Tasmanian Aquaculture and Fisheries Institute, University of Tasmania (Marine Research laboratories).

Dr Michel Bermudes, Tasmanian Aquaculture and Fisheries Institute, University of Tasmania (Marine Research laboratories).

Dr Rick McGarvey, South Australian Research and Development Institute, Aquatic Sciences.

Mr David Hobday, Marine and Freshwater Systems Department of Primary Industries Victoria.

17. Appendix 3. Giant crab database

The database described here was created in MS Access and was created to store data that was corrected for errors as described in Chapter 3 (page 7).

17.1 Tables

Tables are listed below by State. All fields are named identically across tables and limitations on data availability for each field is given in the next 'Fields' section.

Tasmania GF (records from 01/01/1990 to 30/11/1999)

Tasmania ICE (records from16/11/1999 to 30/06/2002)

Victoria (records from 01/06/1978 to 31/12/2001)

South Australia

17.2 Fields

STATE
In all tables.

DATABASE
In Tasmania GF and ICE only.

RECORD_NO
ID number allocated for the purpose of this work. Run from 1 to 999999 for each dataset (i.e. TAS GF, TAS ICE, VIC and SA). *In all tables.*

VESSEL_MARK
Common to all states. *In all tables.*

SKIPPER_ID_STATE
Corresponds to the Client ID used in each state. *In all tables.*

SKIPPER_ID
Allocated for the purpose of this work according to fisher's name and therefore accounting for fishers fishing in more than one state. *In all tables.*

DATE
Date when the gear was hauled. *In all tables.*

CALENDAR_YEAR
In all tables.

CALENDAR_MONTH
In all tables.

QUOTA_YEAR
Derived field based on haul day and quota management system of jurisdiction. *In all tables.*

QUOTA_MONTH
In Tasmania the quota year runs from March (1) to February (12) with annual closure in October-November, in Victoria from April (1) to March (12) with annual closure in September-November. *In all tables.*

EAST/WEST
Derived field from LATITUDE_DECIMAL and LONGITUDE_DECIMAL (ICE) or BLOCK_HD (GF). E or W. *Only in Tasmania GF and ICE*.

NORTH/SOUTH
Derived field from LATITUDE_DECIMAL and LONGITUDE_DECIMAL (ICE) or BLOCK_HD (GF). N or S. *Only in Tasmania GF and ICE*.

4_CARDINAL
Derived field from LATITUDE_DECIMAL and LONGITUDE_DECIMAL (ICE) or BLOCK_HD (GF). NE, SE, SW or NW. *Only in Tasmania GF and ICE*.

AREA
Derived field from LATITUDE_DECIMAL and LONGITUDE_DECIMAL (ICE) or BLOCK_HD (GF). Fishing areas numbered from 1 to 8 anticlockwise around Tasmania starting from the south-east. *Only in Tasmania GF and ICE*.

BLOCK_D
Degree block. *Only in Tasmania GF and ICE*.

BLOCK_HD
Half-degree block. *Only in Tasmania GF (from 04/01/1995) and ICE.*

LATITUDE_DECIMAL
Only in Tasmania ICE from 01/12/99 onward.

LONGITUDE_DECIMAL
Only in Tasmania ICE from 01/12/99 onward.

MINDEPTH (F)
In Tasmania GF (from 04/01/95).

MAXDEPTH (F)
In Tasmania GF (from 04/01/95).

AVERAGE_DEPTH (M)
In the GF dataset this field was calculated as the average between MINDEPTH (F) and MAXDEPTH (F) and converted to M. In ICE, this field was recorded by fishers in logbooks. *In Tasmania GF (from 04/01/95) and ICE.*

NUM_TRAPS
In Tasmania GF (from 04/01/95) and ICE.

SOAKTIME (DAYS)
Derived field calculated in ICE from SET_DATE, SET_TIME, HAUL_DATE and HAUL_TIME. *In Tasmania GF (from 04/01/95) and ICE.*

POTDAYS
= NUM_TRAPS x SOAKTIME (DAYS). *In Tasmania GF (from 04/01/95) and ICE.*

SHOT_WEIGHT (KG)
In Tasmania GF, SHOT_WEIGHT (KG) is monthly record prior to 04/01/95. *In Tasmania GF (from 04/01/95) and ICE.*

CPUE
= SHOT_WEIGHT (KG) / POTDAYS *In all tables.*

TARGETTING_CRABS
Estimated field in GF and Victorian. Y or N. *In all tables.*

NUM_CRABS
In Tasmania GF (from 04/01/95) and ICE.

NUM_MALES_KEPT
In Tasmania ICE only.

NUM_FEMALES_KEPT
In Tasmania ICE only.

NUM_DISCARD_UNDERSIZE
In Tasmania ICE only.

NUM_DISCARD_OTHER
In Tasmania ICE only.

AVE_WEIGHT_PER_CRAB
Derived field calculated in ICE. *In Tasmania ICE only.*

1ST_EXCLUSION
In all tables.

2ND_EXCLUSION
In all tables.

2ND_EXCLUSION_COMMENTS
Additional comments stating reason for 2ND_EXCLUSION. *In all tables.*

CHECKED
Data has been checked against original (Y/N) if outlier. *In all tables.*

CHANGE
Flags entered according to the field modified:

3 – NUM_TRAPS

4 – TARGETTING_CRABS changed from N to Y

5 – TARGETTING_CRABS changed from Y to N

6 – coordinates

7 – SOAKTIME (DAYS)

8 – SHOT_WEIGHT (KG)

9 – AVERAGE_DEPTH (M)

10 – VESSEL_MARK

11 – DATE

In all tables.

CHANGE_COMMENTS
Usually states the reason for the change (e.g. 'according to original GC record'). *In all tables.*

CHECK
Flags entered according to the field to be checked on the original record:

0 – whole entry against original record

1 – SOAKTIME

2 – NUM_TRAPS

3 – depth unit (for Tasmania only)

4 – DEPTH

5 – S & E marks for trip (for Tasmania only)

6 - AVE_WEIGHT_PER_CRAB (for Tasmania only)

7 – cross check with original rock lobster record (for Tasmania only)

8 – GPS coordinates (for Tasmania only)

9 – skipper or client ID

10 – vessel distinguishing mark

12 – TARGETTING_CRABS

13 – NUM_CRABS

14 – SHOT_WEIGHT (KG)

15 – double entry

In all tables.

CHECK_COMMENTS
Give additional details on the data to be checked. *In all tables.*

OTHER_COMMENTS
In all tables.

17.3 Data exclusion

There are two levels of exclusion each set up as a separate field for record exclusion: 1ST_EXCLUSION and 2ND_EXCLUSION.

1ST_EXCLUSION: select '**N**' to exclude all data that are unsuitable for analysis ('**A**'). These data, unsuitable for any analysis, are detailed in the 2ND_EXCLUSION as:

D: double entry, found in the General Fish (GF) data only, occurred as double entries and as entries split by block when fishers logged more than one block per record (i.e. catch was split in 2 and not n traps);

CC: combined catch, in GF data only, when a record for several days of fishing was not split between days at entry (e.g. a single record on logbook for 500 kg caught with 40 pots over 5 days was split into 5 records, each using 40 pots and each with a catch of 500/5 kg instead of the previous single entry of 500 kg caught with 40 pots);

UN: unsure, doubt over the integrity of the record, only very few instances;

S: entry for species other than GC, usually spider crabs;

I: inappropriate entry, in a few instances catch was entered in GF database when the fisher indicated that the crabs were not kept;

NA: not-(yet)-available data, in ICE, either crabs are in caufs or the fisher is under investigation and SHOT_WEIGHT is not available.

Selecting '**N**' records from the 1ST_EXCLUSION level is suitable only when **working on catch volume**. To **work on effort** the following flags should be excluded from the 2ND_EXCLUSION level:

E: effort is missing (NUM_TRAPS, SOAKTIME or both);

ME: mis-reported (under-reported in most cases) effort;

WM: entry for whole month catch. There were not enough details available in original logbook to split entry in several fishing days;

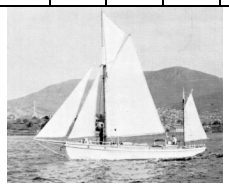
!C!: record yet to be checked.

Additionally when working on effort, all '0' SHOT_WEIGHT entries should be excluded from the ICE data set since fishers did not record no-catch events under the General Fish logbook system.

To **work with coordinates** the '**C**' flag (erroneous coordinates, on land) has to be excluded from the 2ND_EXCLUSION level.

18. Appendix 4. Questionnaire used for interviews

Development of the tools for a low cost, on-going giant crab stock assessment

Section 1: to get an idea of how your crab fishing business developed, and also which years this interview will relate to										
How do you classify yourself now as a crab fisher (main activity/larger player; mid level; low level; bycatch; left the fishery)										
How much quota do you currently fish?										
When did you first start fishing for giant crab (Year?) and how did you enter the fishery ? (applied for permit, bought up quota)										
What year did you put most effort into giant crab										
Compared to your highest year, how much effort were you putting into giant crab in other years:	92	93	94	95	96	97	98	99	00	01
5 star rating or %										
Section 2: To get an indication of the changes in fishing practices that have affected catch rates – so that we can standardise catch records.	  ***(Tas research vessel 1930 and 2000)***									
What changes to your fishing have occurred that you think have changed your catching efficiency. Eg. trap design/ strings/ baiting method/hauling frequency/knowledge on the right depth or location/vessel/plotter										
For each of these could you: 1. Note when this change was made (accuracy here is V. helpful) 2. Estimate improved increased catch rate % 3. Did any of these changes affect where or when you fished? On seasonal changes affecting catch rates: When do catches start to decline? How similar is the timing of this each year? Are there any other seasonal biological events that have a major effect on catch rates? Do you move around the coast in a similar way each season?										
If you fished both before and after the introduction of quota, how have your fishing practices changed? 1. Do you fish at different times? 2. Do you fish at different depths? 3. Do you target different sizes/sexes? 4. Do you fish in different areas?										

5. How do you deal with one-armers? Have you changed your soak times?	
If you fish other species, what controls your decision to switch into or out of giant crab? Do you have any consistent decision process to decide to start or stop fishing for crabs (eg market price = x, or catch rates decline to x)? How has this varied from year to year?	
How has your switching between species changed since the introduction of quota?	
Section 3: On your impression of stability in the fishery- to give an indication of the industry's view on state of the resource.	
Do you think abundance of legal sized crabs has changed since you've been fishing? Do you think the proportion of the catch that is 1) undersize, 2) oversize, 3) one armed - has changed?	
How do you see the long-term future of the industry in terms of sustainable catches?	
Do you think the quality of product has changed through the development of the fishery? (eg more crabs with leg loss, blackened shells, damaged shells, or changes in fouling)	
Do you think export will continue to be allowed under schedule 4 in the future?	
Section 4: On data reporting efficiency and options	
A lot of data is collected through logbooks, do you think these are effective and efficient in describing your operations (eg accuracy in depth and location)? Any ideas on how they could be improved?	
Prior to the introduction of quota and also the permits for 100 pots, many fishers were already using more than 40 or 50 pots, this has an important effect on catch rate data and seems to be responsible for unexpected patterns. Can you recall how many pots you were using in previous years.	92 | 93 | 94 | 95 | 96 | 97 | 98 | 99 | 00 | 01
Section 5: Biological observations	
When do you think moulting of each sex occurs?	
What seasonal patterns have you noticed in depth of crabs? (eg different sizes/sexes)	