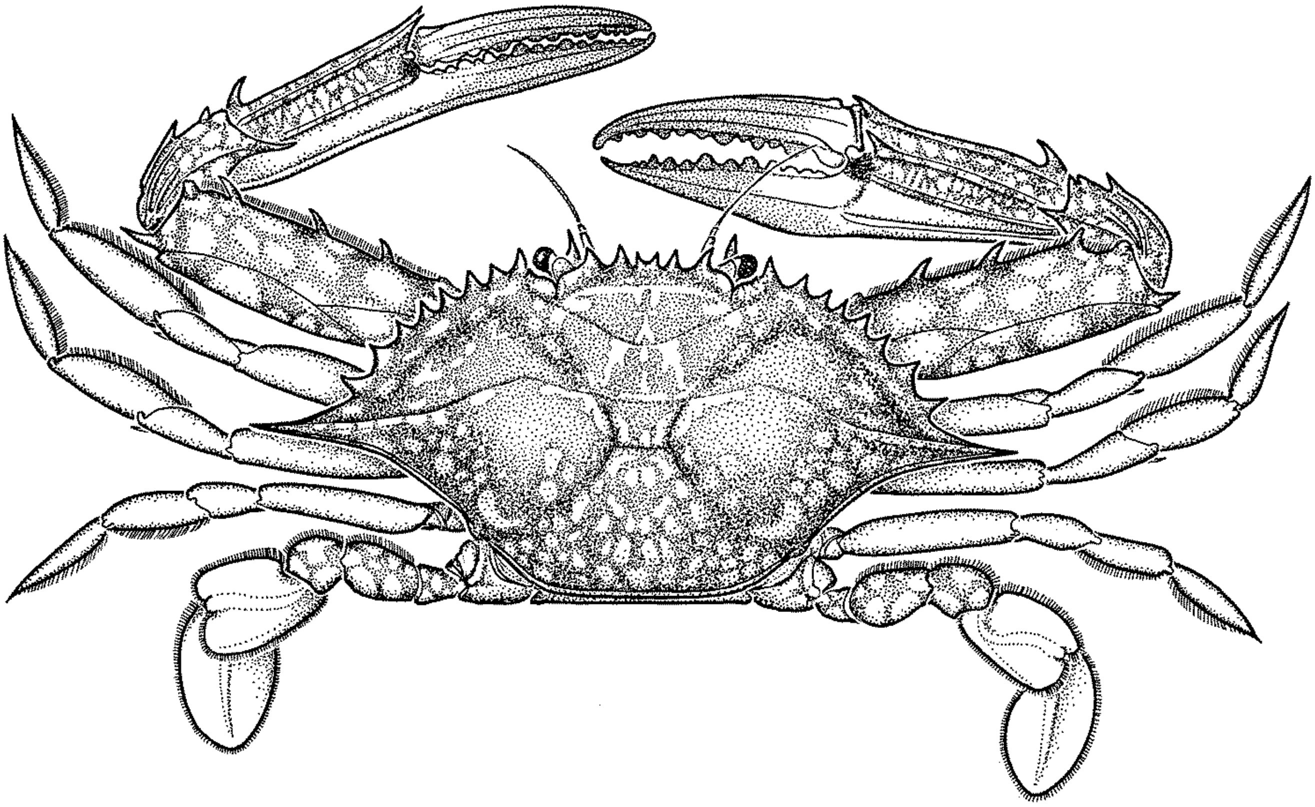
Assessment of the blue swimmer crab (*Portunus armatus*) fishery in Queensland



This publication has been compiled by Wayne Sumpton, Matthew Campbell, Michael O'Neill, Mark McLennan, Alex Campbell and George Leigh of Sustainable Fisheries, Department of Agriculture and Fisheries, and You-Gan Wang and Luke Lloyd-Jones of the University of Queensland.

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Executive Summary

The blue swimmer crab (BSC) fishery in Queensland has undergone considerable change since its development in the middle of the 20th century. In the last 30 years the fishery has progressed to being fully fished with the expansion of crab-pot fisheries to areas outside of Moreton Bay. After the implementation of the Fisheries (East Coast Trawl) Management Plan 1999, the reported harvest from the trawl sector decreased significantly, with the commercial and recreational crab-pot sectors now accounting for the majority of the reported blue swimmer crab harvest. The commercial pot fisheries outside Moreton Bay also developed rapidly in the late 1990s. Concerns have been raised by a number of crab-pot fishers about poor economic viability under current management rules and reduced catch rates from a number of Moreton and Hervey Bay areas. This research and publication was requested by fisheries management to assess reasons for declining catch rates and profits, including evidence associated with overfishing, crab reproduction and disease, and flood events.

The analyses undertaken during the current study suggested that the blue swimmer crab population was not overfished to the point where the spawning biomass was significantly reduced. However, the current levels of population size of male legal crab and fishing effort were not suitable to produce acceptable levels of catch rates for economic profit or angling quality. The reported high commercial harvests experienced in the early 2000's were unsustainable and the validity of this logbook data needs to be examined.

Analysis of the reproductive characters of the blue swimmer crab from fished areas of Moreton Bay has shown no significant changes in key indicators since research was conducted in the mid 1980's. Similarly, the levels of fertilization of immediate post-moult female crabs have remained unchanged in the past 30 years. There was no evidence of declines in fertilization rate as all females assessed had >90% of eggs successfully developing. There was evidence to suggest a decline in the size of females, despite the fact that females are not legally fished. Some fishery independent samples are desirable to fully evaluate the reproductive results spatially.

The levels of parasitism and disease were found to be low and have not changed significantly in the last 30 years. Levels of parasitism by *Sacculina granifera* have declined. There was limited baseline data on which to compare parasitism by *Hematodinium* and *Ameson* species, but available evidence suggests that levels of these parasites have not increased over time. No fishers have recently commented on increasing levels of disease or parasitism of crabs in pots. As noted for the reproductive study, more samples are desirable to spatially confirm the result over wider areas.

Environmental factors have been shown to influence blue swimmer crab fisheries in both Cockburn Sound and Shark Bay in Western Australia, but we found no conclusive evidence to support similar effects in Queensland. The fact that high rainfall in Queensland normally occurs during the summer means that juveniles are particularly adaptable due to their preference for shallower flood-prone inshore areas. Despite this, there was only a weak negative correlation between river flow (a measure of rainfall and flooding) and historic catch rates of blue swimmer crabs. There have been only two extraordinary flood events in Moreton Bay since the collection of logbook catch information in 1988, and too few years of data are available to conclusively determine any environmental links to abundance or recruitment.

Declining catch rates appear to be related to overly competitive fishing, resulting in a smaller population size of male legal crab. Increases in the number of pots used by fishers in all regions is likely a result of escalating costs of fishing, particularly fuel, impacting on profits due to declining beach price relative to inflation. To cure this state, the data and analyses indicate that effort reduction is required in order to significantly improve catch rates and generate economic profits. A range of maximum economic yields were calculated for the Moreton and Hervey Bay regions, so that a meaningful upper limit on license numbers and total allowable fishing effort can be evaluated. Effort reductions of 50% to 70% may be required in order to maximise vessel based profit.

Simple economic break-even points (zero profit-loss) for the average fisher suggest minimum catch rates of 34 kg per boat-day in Moreton Bay (range 15 to 70), but 87 kg per day (range 40 to 150) and 101 kg per day (range 50 to 150) for Hervey Bay and the Sunshine Coast respectively. Such catch rates are very difficult to achieve under current management arrangements. The range of business structures (and wide range in reported catch rates to achieve profitability) indicates that it may be unwise to rely on average conditions of profitable catch rates to represent the economics of the fishery.

The evaluation of raising the minimum legal size (MLS) in order to reduce fishing pressure indicates that this would have a negative impact on fishery economics. Analysis of historic catch rates during the 1980's when the MLS was 15 cm (spine tip-to-tip measure), suggested that profitable catch rates would only be achieved during the peak of the season in March and April.

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Recommendations

- A process of significant effort reduction (model outputs suggest in the order of 50 to 70%) is implemented to improve catch rates and economic returns to fishers.

- Commercial catch and effort data be reviewed and validated to add greater certainty to model outputs and enhance our ability to adequately monitor the performance of the fishery.

- Fisheries Queensland trawl surveys be continued to ensure that fishery independent data are available to monitor the stock.

Further Development

Quantifying the links between the Moreton Bay fishery and the adjacent Sunshine Coast fishery (which are currently considered together in the assessment), as well as links between the Hervey Bay fishery and the Moreton/Sunshine Coast fishery, is an important area of further development.

Economic data are poorly defined for the Hervey Bay fishery in particular. We have divided the Moreton region fishery into Moreton Bay and Sunshine Coast components, and there is justification for doing the same for Hervey Bay, but there was currently insufficient resolution in the available data to accomplish this. The diversity of fishing businesses necessitates that any future economic analysis should be based on individual or representatively grouped data rather than simple regional aggregations, so that the significant variation in business structures can be better accounted for in the fishery models.

The uncertainty in crab growth was highly influential in determining model outputs, and yet there is still considerable uncertainty in growth estimates. Establishing the age of crabs (and in particular the proportion of crabs that are 0+yr, 1+yr or 2+ yr old) that are fished at the height of the fishing season (usually March/April) is critical to the choice of growth scenario and resultant model outputs. Further tag-recapture data (or other novel approaches) are required to estimate blue swimmer crab (BSC) growth by modelling the probability of moulting, together with a distribution for the moult increment. The latter could be gamma distributed and would not depend on the length of the crab. The probability of moulting would depend on length (with larger crabs moulting less often) and would be chosen to make the mean growth increment (including the zeroes) match the postulated growth curve.

The model relies on the fit to the inshore and offshore length data and these were important parameters in the models. It is important that these parameters be further explored. The poor fit of the female length frequency data to the model suggests that further development of the model and data is required to overcome this deficiency. Selectivity and vulnerability of crabs to the fishing gear should be further researched.

The model currently uses the standardised commercial catches of male crabs as an index of abundance. Improved dynamics of the population would be possible if an index of the unfished female abundance could be developed. This would need to be done using fishery independent sampling or by structured surveys using commercial fishers.

Other areas for further development revolve around gaining a better understanding of the recruitment dynamics of blue swimmer crabs and density dependent mortality.

1. Introduction and Background

Historical Development of the Blue Swimmer Crab Fishery in Queensland

In Queensland, the blue swimmer crab fishery dates back to the early 1900s, however, few catch data or information about the fishery in general existed until records began to be kept by the Queensland Fish Board in the 1930s. The annual catch of blue swimmer crabs recorded by the Brisbane Metropolitan Fish Market increased from about 32,000 crabs in 1937 to over 100 000 a decade later. By the early 1960s this number had increased to over 400 000 crabs per year (Figure 1) representing an annual catch of approximately 140 tonnes.

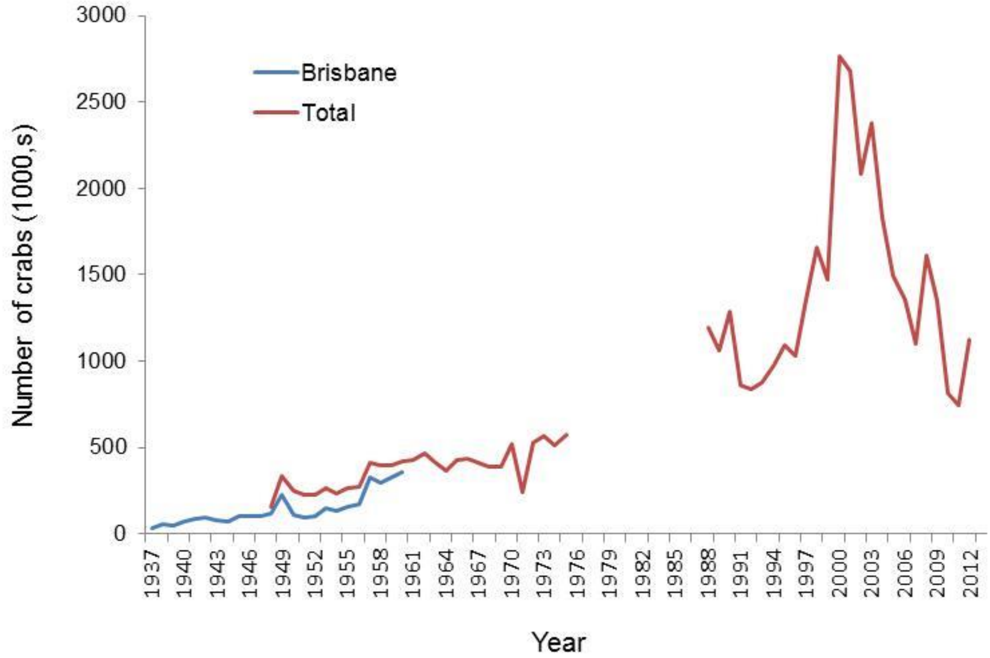

Figure 1: Number of blue swimmer crabs marketed through the Queensland Fish Board from 1937 to 1975 and numbers recorded in CFISH logs (1988 to 2013). The blue line shows the volume marketed through the Brisbane Metropolitan Markets while the upper line is the total marketed from all agencies throughout the state.

Until the 1940s, the majority of the catch was taken using long nets to tangle crabs close to the western shores of Moreton Bay. During the early 1950s, large nets were used in the southern part of Moreton Bay and pots, then technically illegal apparatus, were used in the north. Thomson (1951) noted that during this time most of the catch was still taken from the waters on the western side of Moreton Bay. Authorities ignored the use of pots possibly because of the post-war shortage of cotton for making nets, and the fact that pots apparently did little harm. *The Fisheries Act 1957* allowed the use of pots as a legal apparatus without restrictions on their number; however, pot fishers taking crabs for sale required a license. In December 1976, commercial pot fishermen were restricted to a maximum of 50 pots, and this restriction has remained to this day (despite recent changes in permit conditions), as has a prohibition on the use of mesh nets. Fish Board records also show a highly variable quantity of crabmeat marketed, particularly during the 1970s when up to 11.5 tonnes of blue swimmer crabmeat was marketed each year. It is believed that a large proportion of this meat was from females and undersized crabs.

Until the 1970s, the bulk of the catch was still coming from Moreton Bay. Since the early 1950s, the fishery has developed rapidly as a result of further increases in pot fishery effort, as well as prawn trawling and recreational fishing activity. More recently, pot fishing activities have expanded into offshore waters (outside Moreton Bay) but trawl effort has declined due to industry restructuring. Recreational fishers traditionally used a tangling apparatus known as a “witches hat” or “dilly” to catch blue swimmer crabs, although collapsible pots began to appear in the 1980s and dillies were eventually banned in March 2010. Today, the traditional wire pot is rarely seen in the fishery, gradually replaced by various designs based on a metal/plastic frame covered with polyethylene mesh throughout the 1990s. There is limited information about the contribution of the recreational fishery to the total catch. During 1985/86, Potter et al. (1994) found that over 20% of the tagged crabs that were returned from a research tagging exercise were caught by recreational fishers, confirming the importance of the recreational catch at that time. In some areas the return rate from recreational crabbers exceeded that of the commercial sector. When commercial fishing effort extended into offshore waters, it was noted that crabs were larger and catch rates higher than in Moreton Bay (Sumpton et al. 2003). Earlier research highlighted that large crab size and higher catch rates was typical of what was expected when a previously lightly fished resource was fished more heavily.

In summary, the fishery has experienced the typical pattern where areas closer to port are exploited first, with expansion into more remote locations as catch rates decline and technology improves. The early fishery was restricted to western Moreton Bay. Between the 1960s and the 1980s, effort moved further offshore to the northern banks and Amity Banks area with some exploration in offshore waters outside Moreton Bay and Hervey Bay. At present, effort in offshore waters off the Sunshine Coast, and the more remote regions of Hervey Bay, has reduced to historical levels after significant increases in the late 1990s and peaks in 2003. The trawl by-product component has likewise declined dramatically, although the data on this is more difficult to interpret because it is often a non-target species. There has generally been a declining in blue swimmer crab trawl catch with recent restructuring and effort reductions in the trawl fisheries.

Recent Management History

The previous section has highlighted some of the historical changes in the fishery and its management, but here we concentrate on more recent history, which has seen greater management change coinciding with the development of the fishery in more remote grounds outside of Moreton Bay.

Management of the blue swimmer crab fishery has always been categorised as conservative, largely because of the protection of females, and the fact that the MLS of males has always been larger than in any other Australian state. Despite this “conservative” management, there have been many fisheries management changes that have directly and indirectly affected the fishery. The most notable changes in the last 30 years are highlighted below, and the likely impacts of these changes on the blue swimmer crab fishery (and on the data used to assess the fishery) are presented in brackets for some of the key changes. These management changes were sometimes critical to the data that are used to assess the fishery.

1983 Issue of new non-trawl licences ceased.

1984 Primary/tender boat licence system was introduced which: (i) allocated primary/tender status to all boats licensed at the time; (ii) allocated fishery symbols to all primary licences as nominated by licence holders; (iii) restricted the issue of any new primary and tender boat licences and fishery symbols; and (iv) established a fishing operation around a primary boat, any associated tenders boats, and fishery symbols endorsed on the primary boat licence. Fishery symbols were allocated to all licence holders in 1984 with the C1 symbol allowing the take of crabs including blue swimmer, mud, spanner and other crabs species. At that time, the vast majority of fishers nominated to have C1 endorsements associated with their licences, thus increasing the latent effort that could be associated with the crab fishery. With increasing management change in other fisheries, this enabled many fishers to expend effort in a range of fisheries on an irregular (or regular) basis.

1988 Compulsory commercial logbook reporting commenced.

1996 First total allowable catch (TAC) - Spanner Crab fishery (C1 endorsed fishers were excluded from the spanner crab fishery based on logbook catch history. This resulted in an incentive for fishers to establish history in fisheries in which they were endorsed, but which they had not previously fished).

1997 1 December 1997: A Regulatory Impact Statement (RIS) proposed reduced trawl "in-possession" limits of blue swimmer crabs of 100 for Moreton Bay and 1000 elsewhere.

1999 First Individual Transferable Quota (ITQ) Allocation – Spanner Crab fishery (providing further incentive to establish a catch history).

1999 1 May 1999: Cabinet approved changes to the Regulation (which was subsequently absorbed into the Plan) that enabled limited numbers of blue swimmer crabs to be retained by trawlers until 31 October 2000. The Queensland Fisheries Service had undertaken a review of the arrangement for trawl caught blue swimmer crabs allowing provisional in-possession limit of 100 for Moreton Bay and 600 elsewhere. It was recommended that the provision to allow trawl operators to retain blue swimmer crabs be continued until 1 January 2002. The recreational sector and commercial crab pot fishers were opposed to any retention of blue swimmer crabs by trawl operators. On the other hand, the trawl sector continued to support a proposal to allow increased catches of blue swimmer crabs in the northern Hervey Bay area.

2002 1 January 2002: Trawl in possession limits for blue swimmer crabs reduced to 30 in Moreton Bay and 500 elsewhere.

2003 12 September 2002: East Coast mud crab and blue swimmer crab investment warning.(There were "rumours" of this years before it actually happened further increasing the incentive to establish a catch history in the fishery).

2003 13 December 2003: Blue swimmer crab measurement changed from 15 cm across the spines to 11.5 cm notch to notch (base of spine measurement); effectively a 13 mm lowering of MLS, although an anomaly in the legislation meant that the size limit effectively did not change significantly in some areas, as fishers were able to retain smaller "tipped" crabs prior to this regulatory change.

2008 Removal of latent effort in the line, crab, eel and beam trawl fisheries.

2010 2 April 2004: Dillies prohibited in the blue swimmer crab fishery.

2011 "Crab Review" began.

2012 Entitlement to use an additional 50 to 100 pots under permit.

Management Arrangements in Other Jurisdictions

The management regulations related to blue swimmer crab management across Australia are listed in Table 1. While there are many similarities across the jurisdictions that harvest blue swimmer crabs, there are some significant differences both in management measures and in the gear used to harvest the resource. In general terms, the two other states that have significant blue swimmer crab fisheries are Western Australia and South Australia. The blue swimmer crab fishery in Queensland has around 400 participants in the commercial pot fishery alone which currently lands <400 tonnes of BSC. In contrast, both WA and SA have 32 and 7 license holders, respectively, to catch approximately the same tonnage. In Shark Bay, there are basically two license holders, one that holds entitlements of 600 pots and the other holds a 900 pot entitlement. Trawlers are prohibited from landing blue swimmer crabs in South Australia, while there are catch shares between the trawl and pot sector in Shark Bay and other management areas in Western Australia.

The summary of management regulations shows that the Queensland blue swimmer crab fishery is still the most conservatively managed of all the Australian states having the largest MLS, while also maintaining a total ban on the taking of female crabs. In contrast to other states, there is no recreational bag limit, although the recent banning of dillies or witches hats in 2010 has resulted in reduced recreational fishing effort. In addition, there are trip limits on the take of blue swimmer crabs by the trawl sector, and recent management changes to the trawl industry has resulted in a much reduced trawl catch of blue swimmer crabs.

Table 1: Summary of blue swimmer crab (BSC) management in New South Wales (NSW), South Australia (SA), Western Australia (WA), and Queensland (Qld).

	NSW	SA	WA	Qld
Licensing	157 shareholders in the estuary general trapping fishery 92.3% taken "estuary general fishery" 5.5% by the ocean trawl fishery 1.8% in the estuary prawn trawl fishery	9 licence holders [3] 2 different licence holders in the Spencer Gulf holding 3 and 2 licences respectively 4 licence holders in the Gulf St. Vincent	57 licence holders for BSC Plus retained by West Coast Deep Sea Crustacean fishery (7 licence holders) South West Trawl Managed Fishery (10 licence holders)	430 licence holders (can take blue swimmer and mud crab) of which 126 recorded BSC catch in 2013 Permitted catch in the: Beam trawl fishery Fish trawl fishery Prawn trawl fishery Line fishery Net fishery
	$296 renewal current commercial fishing licence endorsement for fishing activities Renewal of licence for vessel $58 plus $31/m or part thereof in length which exceeds 3m	$2934 base licence fee (per fishery, i.e. lobster, sardine, bsc) $26.90 fee per unit of blue crab quota. **Spencer Gulf** unit value is 57.75kg with 2395 units (2 licences) and 4134 units (3 licences) held by respective licence holders ($64 425 - $111 204 fee) **Gulf St. Vincen**t unit value is 46.2kg with 525 – 1403 units held by respective licence holders ($14 122 - $37 740 fee) Vessel is registered under licence for fishery. Fee to register additional vessels under licence $109	Licence fees vary between bioregions. all commercial fishers are required to hold a: 1) Managed Fishery Licence (MFL) or exemption (if it is a developing fishery), West Coast Estuarine Managed Fishery: Area 1 (Swan-Canning River) - $1525. Area 2 (Peel-Harvey Estuary) - $2370. Cockburn Sound (Line and Pot) Managed Fishery, per licence $1,165 Cockburn Sound (Crab) Managed Fishery, per pot $26.34 Mandurah to Bunbury Developing Crab Fishery one off fee $2335.	Commercial fisher licence $285.50 Crab endorsement fee $331.20 Commercial fishing boat licence $285.50 [5]

	NSW	SA	WA	Qld
			Shark Bay crab fishery $24,234 Warnbro Sound (Crab) Managed Fishery, per licence $1,083 South Coast Estuarine Managed Fishery, per licence $2,667.00 Shark Bay Prawn Managed Fishery, per licence $70,720.00 (licenced to take BSC) South West Trawl Managed Fishery $4,963 (licenced to take bsc) 2) Commercial Fishing Licence (CFL) $87, and 3) Fishing Boat Licence (FBL). Fishing boat licence renewal $87 + Types of boat — (1) a boat 6.5 m or longer $315 (2) a boat shorter than 6.5 m $85	
Management	Regional management (7 regions) But • The commercial estuary general fishery is a regionally endorsement based share managed fishery. Need minimum of 125 shares to qualify for endorsement for trapping No management plan by species	Regional management (2 regions) Spencer Gulf vs. Gulf St Vincent with differing reference points for performance indicators Individual transferable quota system TACC = 626.8 tonnes	Regional management (9 regions) Input control system – regulation of vessel and trap numbers	Managed as a fishery???
Closures	None	Commercial closed season Commercial closed areas	Commercial closed season and daily time restrictions	None

	NSW	SA	WA	Qld
Min Legal size	6 cm carapace length (≈ 12.7 cm carapace width[1]) going to 6.5 cm soon (≈ 13.7 cm carapace width) Berried females prohibited	11 cm notch to notch Berried females prohibited	12.7-13.5 cm carapace width depending on region 12.7 cm carapace width for recreational anglers Berried females prohibited	11.5 cm notch to notch Females prohibited
Catch	Commercial catch has varied from 50.2-201.5 tonnes over the last 8 years 92.3% taken "estuary general fishery" 5.5% by the ocean trawl fishery 1.8% in the estuary prawn trawl fishery Rec catch estimated at 150-310 tonne	510 tonnes 2012/13 Rec catch 07/08 survey 29.8% of total harvest weight or 284 t (Jones 2009)	Usually exceeds 1000 tonnes[2] Rec catch “some hundreds of tonnes” [2]	343 tonnes [6] (2013) Pot 385 tonnes (2013) total Rec catch estimate 2005: 142 tonne
Logbooks	Daily Logbook required	Daily Logbook required	Monthly Logbook required. (Regulation 64)[4]	Daily Logbook required
Recreation	Bag limit of 10 per day and 20 in possession. Gear: 2 pots & 4 “witches hats” or hoop/lift nets Recreational fishing licence $35	Bag limit of 40, daily boat limit of 120. Gulf St. Vincent bag limit of 20 , daily boat limit of 60 Gear: Crab rake, hand net, drop nets (3). If no other fishing gear is being used 10 hoop nets (3 if fishing as well) No recreational licence	Bag limits: West coast bioregion daily bag limit 10 crabs per person and 20 crabs per boat All other bioregions daily bag limit 20 crabs per person and 40 crabs per boat Gear: Catch by hand; wire hook; scoop net; crab rake; drop net (10) Recreational (boat) fishing licence $30	No bag limit Gear: 4 in total pots or hoop nets or mix thereof No recreational licence

See footnotes next page

1. Mehanna, S.F., Khvorov, S., Al-Sinawy, M., Al-Nadabi, Y.S. and Al-Mosharafi, M.N. 2013. Stock Assessment of the Blue Swimmer Crab *Portunus pelagicus* (Linnaeus, 1766). International Journal of Fisheries and Aquatic Sciences 2(1): 1-8, 2013
2 .http://www.fish.wa.gov.au/Species/Blue-Swimmer-Crabs/Pages/Blue-Swimmer-Crab-Management.aspx
3..https://egate.pir.sa.gov.au/fishreg/new/html/register/RegAuth/search?rowCount=8&authorityNo=&submitButton=Search&registrationType=Blue+Crab+Fishery#here
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5 https://www.business.qld.gov.au/industry/fisheries/commercial-fishing/licences-and-fees/commercial-fishing-fees-forms/commercial-fishing-fees
6 .(cube) http://qfish.daff.qld.gov.au/Query/ViewResults?CubeId=7&PredefinedQueryId=f403a64f-df44-4b79-9b0e-9af16fc176e4&ViewKind=Pivot
http://www.fish.gov.au/reports/crustaceans/crabs/Pages/blue_swimmer_crab.aspx

The following WA fisheries target blue swimmer crabs:

- Warnbro Sound Crab Managed Fishery (1 licence)
- Cockburn Sound Crab Managed Fishery (12 licences)
- West Coast Estuarine Managed Fishery (Area 1 – Swan-Canning River) (1 licence)
- West Coast Estuarine Managed Fishery (Area 2 – Peel-Harvey Estuary) (10 licences)
- Mandurah to Bunbury Developing Crab Fishery (Area 1) (1 operator currently fishing under an exemption)
- Mandurah to Bunbury Developing Crab Fishery (Area 2) (1 operator currently fishing under an exemption)
- Shark Bay Crab Fishery (interim management plan) (5 licences)
- Pilbara Developmental Crab Fishery (1 operator currently fishing under an exemption)

NB Several licences are sometimes held by the one individual/company.

Objectives and Scope of the Report

Over the past several years, there has been concern in some sections of the commercial industry about poor economic performance of the blue swimmer crab pot fishery. This has been highlighted by discussions during the recent crab review which began in 2011. Fishers operating in the Sunshine Coast and Hervey Bay regions have stated that profitability has been diminished due to increasing fuel costs and declining catch rates in recent years. Further, some fishers believe that poor economic performance may have been exacerbated by recent flood events in 2010 and 2013, and their detrimental effect on catch rates. Similar declines in catch over a similar time frame have occurred in both Cockburn Sound and Shark Bay in Western Australia. Although these have been linked to temperature effects, they do highlight the possible impact of environmental effects on fishery performance. Likewise, there have been concerns that levels of disease or parasitism may have also impacted on the population of blue swimmer crabs.

Despite the concerns expressed by some fishers, the commercial fishing industry is not united in its views of the current status of the blue swimmer crab resource. Surveys of commercial fishers conducted two years ago as part of the Crab Management Review, along with more recent surveys conducted as part of the current study to gather economic information, have highlighted this lack of consensus.

This report presents an updated assessment of the Queensland blue swimmer crab fishery. Emphasis is placed on the fishery in southern Queensland and, in particular, the Moreton Region fishery (Moreton Bay and adjacent Sunshine Coast area), which represents approximately 70% of the current total catch. We assess the commercial pot, trawl and recreational fishery for BSC but, again, concentrate mainly on the pot fishery being the greatest contributor to the overall commercial catch. The assessment examines a range of indicators of resource health as well as presenting a comprehensive stock model that examines the ecological and economic sustainability of the fishery. Indicators or possible influences on catch rate, including disease, environmental influences and change in recruitment success caused by sperm limitation and impacts of fishing on reproductive potential, are also investigated.

We provide a detailed analysis of the commercial catch and effort data and standardisations used to obtain indices of abundance from these data. The chapter that presents the actual population assessment model includes a more detailed description of all the data that were used, and describes the strengths and limitations of some of these data inputs.

We have not gathered information independent of the logbook data from the trawl sector. The CFISH data shows a much reduced commercial catch of blue swimmer crabs by the trawl fishery as effort has continued to decline with recent trawl industry restructuring. Despite this, the trawl sector is a poorly understood component of this fishery and may have an important impact on the stock in a number of ways (both positive and negative). Wassenberg and Hill (1987), for example, noted that discards from trawlers are an important food source for blue swimmer crabs in Moreton Bay, and likely allow for increased populations within Moreton Bay. As such, although the recent declines in prawn trawl effort have a positive effect on the biomass of blue swimmer crabs in Moreton Bay, the availability of food for the population has decreased in proportion to prawn trawl effort and the increased use of bycatch reduction devices in prawn trawl gear.

Although there is also some uncertainty about the stock structure of blue swimmer crabs on the Queensland east coast, there are certainly regional differences in fleet dynamics. This suggests that management should be based on spatial units associated with the large embayments of Hervey Bay and Moreton Bay. Analysis of commercial catch and effort shows that, for the most part, catch occurs within the big bays or just to the north of these areas. In contrast, very little catch and effort occurs to their east and south. We have chosen to analyse Hervey Bay separate to both Moreton Bay and the Sunshine Coast. There is an argument for further subdividing Hervey Bay into an inshore and an offshore component, but current data resolution does not enable this.

There are also other biological features of the blue swimmer crab that remain poorly understood. These relate mainly to growth rates, density-dependent natural mortality, recruitment dynamics and connectivity of estuarine and offshore populations.

The lack of any reliable estimate of recreational catch is also problematic to the assessment, although there is no reason to assume the recreational catch has increased given recent declines in participation rates. In fact, there is some anecdotal evidence for declining recreational catches as the banning of dillies may have resulted in a dramatic drop in effort. Several commercial fishers have also commented that the banning of dillies was associated with an increasing trend towards loss of pots and theft of crabs from pots.

We further acknowledge previous reports that have assessed the blue swimmer crab fishery and provided management recommendations. The first of these (Potter and Sumpton, 1986) was conducted in 1983 after concern was expressed by some members of the Queensland Commercial Fishermen's Organisation (QCFO) that catches and earnings of commercial pot fishermen were declining. These concerns were supported in an economic survey conducted by Pashen and Quinn (1984). That report provided seven recommendations, three of which have subsequently been implemented. Other recommendations regarding effort control and recreational bag limits remain unimplemented. Other research (Sumpton et al. 2003) highlighted problems with the reporting of catch and effort in commercial logbooks. A feature of the data that is still unresolved today.

2. Analysis of blue swimmer crab catch and effort data

Compulsory commercial logbook data (CFISH data) were obtained from Fisheries Queensland and included daily catches of all crab species from all methods of capture. Species of interest in the current study were blue swimmer crabs, coral crabs (*Charybdis feriatus*), three spot crabs (*Charybdis sanguinolentus*), and hairyback or rock crabs (*Charybdis natator*). Further, catches categorised with the species code “Crab – unspecified” were also obtained, as this category was used by commercial trawl fishers during the 1990s, due to changes in the management of the East Coast Otter Trawl Fishery (ECOTF), as discussed in a previous study by Sumpton et al. (2003). As such, the blue swimmer crab catch from the trawl sector will be the summation of the catches classified as “Crab – blue swimmer” and “Crab – unspecified”. Given the seasonal nature of the blue swimmer crab fishery, with higher catches occurring in the months October to April, blue swimmer crab catches will be analysed in this report on a financial year basis, termed a “fishing year” throughout this report.

Table 2: Total commercial catch, in tonnes, of all crab species, excluding mud crabs (*Scylla serrata*), by all fishing methods from commercial logbook data (1 January 1988 to 30 June 2014). Zeroes represent catches that were present but were less than 100 kilograms.

Species	Prawn Trawl	Beam Trawl	Fish Trawl	Line	Net	Pot
Blue swimmer	2,294.0	14.1	0.8	7.8	28.8	13852.5
Coral	0.3	0	-	-	-	7.7
Hairyback	-	-	-	-	-	12.0
Three-spot	359.3	0	0	0.2	0	221.5
Unspecified	1,787.2	3.7	2	0.8	0.7	122.3

In excess of 18,700 t of crabs were landed by all methods for the period 30 June 1988 to 30 June 2014, of which 16,198 t (~86.5%) were blue swimmer crabs and 1,916 t (~10.2%) were classified as “Unspecified” (Table 2). A total of 13,852 t (~77.1%) of blue swimmer crabs were landed by pot fishers, while the trawl fishery landed approximately 4,081 t (~22.5%). Approximately 581 t of three-spot crabs were landed, predominantly (61.8%) by the trawl fishery, while catches of coral crabs and rock crabs were low by comparison.

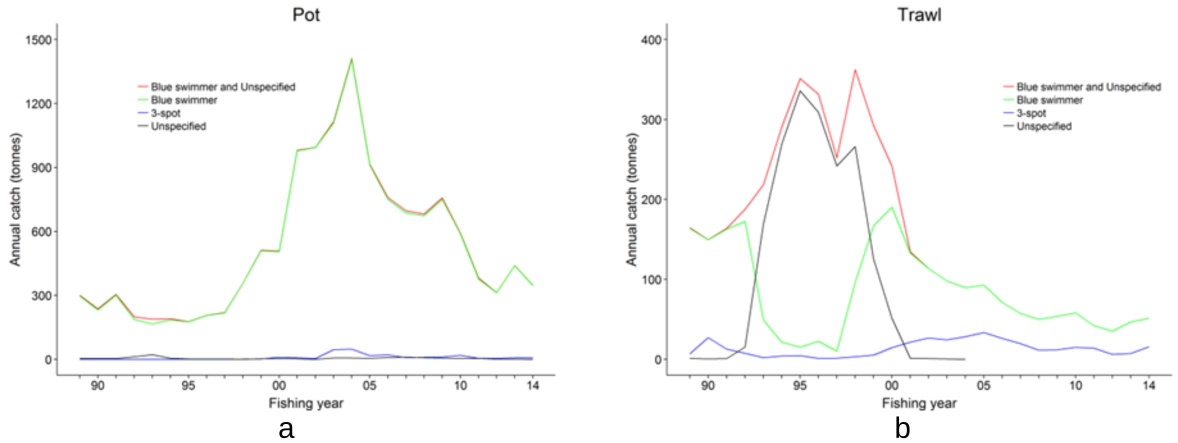


Figure 2: Annual blue swimmer crab catch, in tonnes, for the a) pot and b) trawl fisheries.

In the pot fishery, the annual blue swimmer crab catch was approximately 200 t until 1998 when catch increased to 356 t before peaking at 1,412 t in 2004 (Figure 2a). After 2004, pot catch decreased to 682 t in 2008, before increasing to 757 t the following year. However, since this time, it has decreased significantly ($t = –5.7$, $P < 0.01$)[1] by approximately 84 t pa, reaching just 346 t in 2014. Generally, pot

[1] Based on linear regression over the relevant time period

fishers reported only blue swimmer crab catch, although approximately 21 t of “Unspecified” crabs were reported in 1993 which represented ~11% of the catch of blue swimmer crabs at that time.

Blue swimmer crab trawl catch peaked at 362 t in 1998 (Figure 2b) before a rapid decline to 113 t in 2001, coinciding with the introduction of the *Fisheries (East Coast Trawl) Management Plan 1999*, when significant management changes resulted in effort reduction in the trawl fishery. In 2002, trawl fishers were restricted to 30 blue swimmer crabs per trip in Moreton Bay and 500 elsewhere. Since 2007, mean blue swimmer crab catch in the trawl sector has been ~49 t. The incidence of the reportage of “Unspecified” crabs as a proxy for blue swimmer crabs was highest in the trawl fishery during the 1990s, and decreased to zero in the 2004 financial year.

For the purposes of the current study, the spatial extent of the blue swimmer crab fishery will be restricted to the area south of 23°S (Figure 3) in order to be consistent with Sumpton et al. (2003). Of the 16 146 t of blue swimmer crabs landed by the commercial pot and trawl fisheries in Queensland during the period of compulsory logbooks, 15 368 t (~95.2%) were landed in the Moreton Bay, Sunshine Coast and Hervey Bay geographical regions defined in Figure 3.

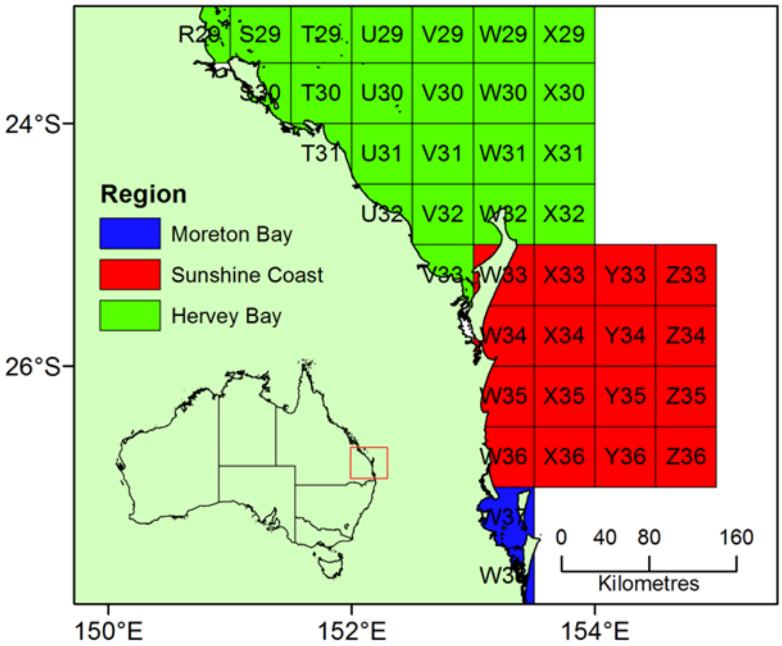


Figure 3: Extent of geographic regions and relevant CFISH reporting grid used in commercial logbooks for both trawl and pot fisheries. Taken from Sumpton et al. (2003), page 10.

Catch

Prior to 2000, pot-caught blue swimmer crab was primarily taken from the Moreton Bay region (Figure 4a). Peak catch occurred in the Moreton Bay region at 542 t in 2001 with decreases in catch evident in subsequent years. A secondary peak of 381 t occurred in 2009 before catch decreased to 165 t in 2011, coinciding with the significant flooding event that occurred in January 2011. The pot catch in the Moreton Bay region decreased significantly (t = –4.4, P < 0.01) by 19.8 t pa after 2001 to 257 t in 2014.

The catch of blue swimmer crabs from the Sunshine Coast region (Figure 3) increased from ~27 t in 1997 to ~341 t in 2002, an increase of approximately 1162%. Since this time, however, catch in the Sunshine Coast region has decreased significantly (t = –6.5, P < 0.01) by 24.7 t pa to 52.8 t in 2014. In the Hervey Bay region, pot catch increased from an average of 13.8 t between 1989 and 1996 to 640 t in 2004. Since 2004, catch has decreased significantly (t = –6.7, P < 0.01) by 46.5 t pa to 30 t in 2014.

The landings from the Moreton Bay region were dominated by catches from the W37 CFISH grid (Figure 3), while landings from W36 and V32 were responsible for the highest proportion of the catch from the Sunshine Coast and Hervey Bay regions, respectively.

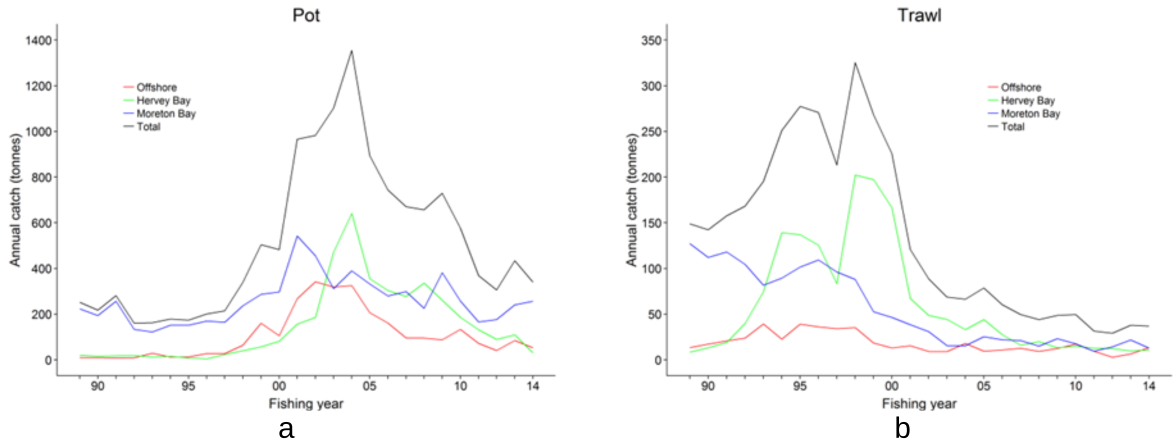


Figure 4: Annual blue swimmer crab catch, in tonnes, for the a) pot and b) trawl fisheries as a function of spatial region in southern Queensland.

The trawl catch of blue swimmer crabs in Moreton Bay has decreased since the implementation of compulsory logbooks (Figure 4b) in 2001. Trawl catch in 1988 was 127 t, the peak annual catch in this region. The introduction of the *Fisheries (East Coast Trawl) Management Plan 1999*, which mandated the use of Turtle Excluder Devices and a trip limit of 30 crabs, had a significant impact on the catch of blue swimmer crabs. Since 2003, mean annual blue swimmer crab catch in Moreton Bay was 17.7 t, 85 t pa less than the mean annual catch during the first 10 years of the compulsory logbook period.

In the Hervey Bay region, annual catch increased to 202 t in 1998 before decreasing to 44 t in 2003. Mean annual catch in the Hervey Bay region since 2003 is 18 t, with the majority of this catch taken from the V32 CFISH grid. Annual catch in the Sunshine Coast region peaked in 1993 at 39 t. Annual catch decreased to 9 t in 2002 and has remained at approximately 10.8 t pa since this time, with landings primarily coming from the W36 CFISH grid.

Effort

In the pot fishery, blue swimmer crab effort in southern Queensland was driven primarily by fishers operating in the Moreton Bay region until 1997 (Figure 5a). After this time, effort in all regions increased at approximately the same rate – 550, 577 and 443 boat–days pa for Moreton Bay, Hervey Bay and Sunshine Coast respectively, with peak effort levels occurring in 2004 in all regions (coinciding with the crab investment warning). Since 2004, effort in the pot fishery has decreased significantly in all regions – 238 boat–days pa ($t = -2.8$, $P = 0.02$) in Moreton Bay, 393 boat–days pa ($t = -10.7$, $P < 0.01$) in Hervey Bay and 257 boat–days pa ($t = -4.8$, $P < 0.01$) in the Sunshine Coast region. Since 2011, approximately 80% of overall effort in southern Queensland has been recorded by fishers operating in the Moreton Bay region.

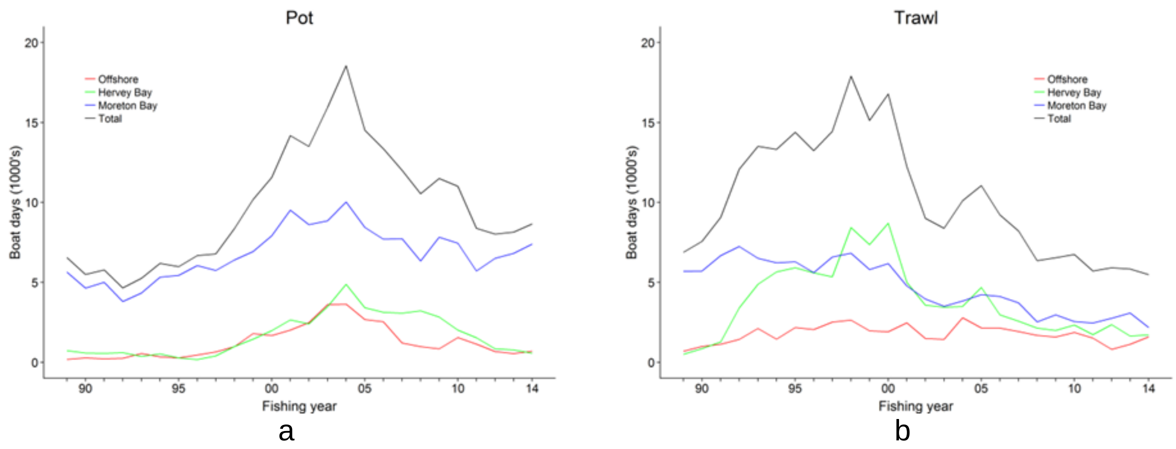


Figure 5: Annual blue swimmer crab effort for the a) pot and b) trawl fisheries as a function of spatial region in southern Queensland.

Trawl effort in the Moreton Bay region reached a peak of 7 241 boat–days in 1992 (Figure 5b) before decreasing significantly (t = –12.4, P < 0.01) at a rate of approximately 229 boat–days pa to 2,168 boat–days in 2014. After a peak of 8,695 boat–days in 1990, trawl effort in the Hervey Bay region decreased to 3,443 boat–days in 2003 after the implementation of the *Fisheries (East Coast Trawl) Management Plan 1999*. Since this time, trawl effort has declined significantly (t = –4.9, P < 0.01) in the Hervey Bay region at a rate of approximately 195 boat-days pa to 1,715 boat–days in 2014. Effort in the Sunshine Coast trawl fishery increased by 1.7 boat-days pa, although this increase was not significant (t = 0.11, P = 0.91). Trawl effort in this fishery has also been problematic. Much of the trawl effort in areas outside of Moreton Bay is in areas where catch rates of blue swimmer crabs are very low (or even zero), yet this effort can be included in the analysis because of the problem of spatially segregating the data. Most trawl shots in Moreton Bay have the potential to catch crabs so this problem is not as great in this area. Fishery-independent beam trawl surveys collected by Fisheries Queensland using much smaller and less efficient gear than that used by the commercial fleet, caught blue swimmer crabs at most sites in Moreton Bay. In contrast to this, many of the Fisheries Queensland Survey trawl shots outside the Bay failed to catch any blue swimmer crabs.

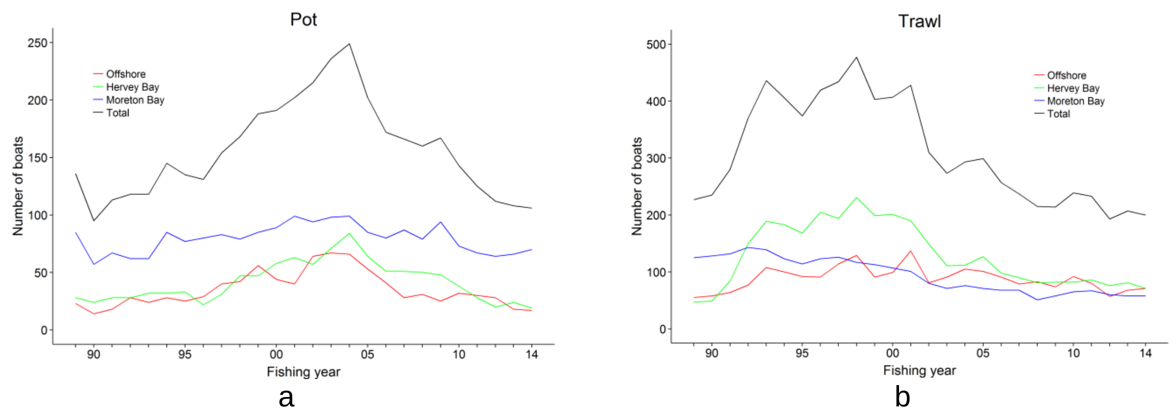


Figure 6: Annual number of boats reporting blue swimmer crab catches for the a) pot and b) trawl fisheries in various regions in southern Queensland

The number of vessels accessing the Moreton Bay pot fishery has been relatively stable since 1988 (Figure 6) while the development of the offshore and Hervey Bay fisheries is clearly seen in the increase in participation rate from the late 1990s.

Catch per unit effort

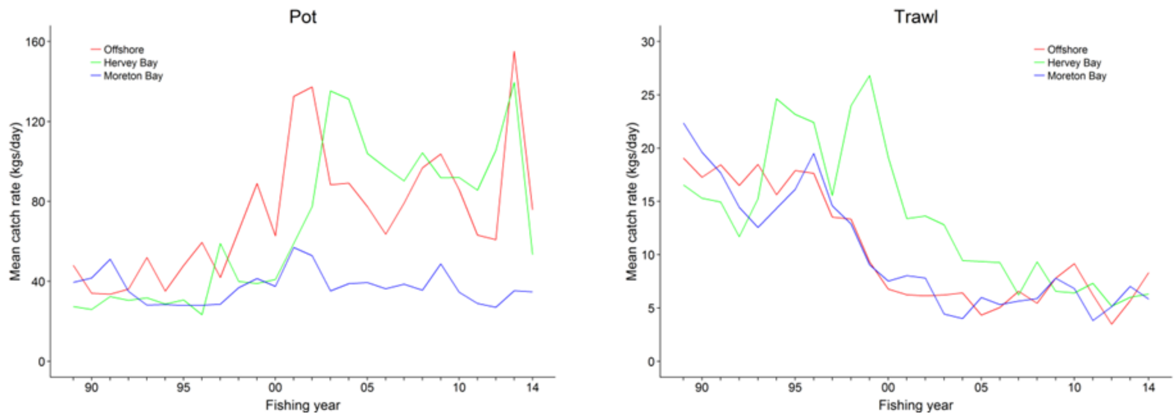
Observed catch rates – i.e. total catch divided by number of boat–days – in the Moreton Bay pot fishery remained stable over the logbook period (Figure 7a) and averaged 37.2 kg per boat–day.

Catch rates were highest in 2001 at 57 kg per boat–day before decreasing in subsequent years. In 2009, catch rates increased to 49 kg per boat–day before decreasing to 29 kg per boat–day in 2011 and 27 kg per boat–day the following year, coinciding with significant flooding events that occurred in those years.

Prior to 1997, mean catch rate in the Sunshine Coast pot fishery was 43 kg per boat–day before catch rates increased to 137 kg per boat–day in 2002. Further peaks of 103 kg per boat–day and 155 kg per boat–day occurred in 2009 and 2013 respectively.

Catch rates in the Hervey Bay pot fishery averaged 29 kg per boat–day until 1996, after which catch rates increased to approximately 47 kg per boat–day until 2001 before reaching a peak of 135 kg per boat–day in 2003. Catch rates then decreased, reaching 85 kg per boat–day in 2011, before again increasing to 139 kg per boat–day in 2013. Catch rates in the Hervey Bay region were 53 kg per boat–day in 2014.

Observed blue swimmer crab catch rates in the trawl fishery were low compared to the pot fishery (Figure 7b). After the imposition of more stringent trip limits in 2001, mean catch rates were 5.8, 6.2 and 8.3 kilograms per boat–day in the Moreton Bay, Sunshine Coast and Hervey Bay regions, respectively.



a b

Figure 7: Observed catch rate, in kilograms per day, for the a) pot and b) trawl fisheries calculated by dividing the total catch by the number of days fished as a function of financial year.

Pot data issues

Sumpton et al*.* (2003) described various issues related to the reportage of commercial crab catch in Queensland. When dealing with the commercial pot fishery, these authors formulated a set of decision rules in order to “clean” the commercial catch data and exclude erroneous or suspicious records. These decision rules were also used in the present study to ensure the CFISH data were of a high standard, so that indices of abundance could be generated for use in the stock assessment model (see page 59).

The CFISH data for the commercial blue swimmer crab pot fishery contains 272 385 individual records for the period 1 July 1988 and 30 June 2014. Of these, the following exclusions were applied based on the decision rules discussed by Sumpton et al. (2003):

- 174 records contained catches from multiple days
- 10 records contained either null or zero retained catch
- 3853 records contained no information regarding the number of pots used or the number of potlifts
- 96 records included a catch of more than 2000 crabs
- 2661 records had no CFISH grid (Figure 3)
- 69 391 records were catches of blue swimmer crabs deemed to be bycatch in the mud crab fishery. That is, blue swimmer crabs made up less than 90% of the catch in each of these records.
- 9981 records occurred outside of the Moreton Bay, Hervey Bay and Sunshine Coast regions.

After the decision rules were applied, 186 219 daily catch records were used to analyse blue swimmer crab catch rates in the Queensland pot fishery.

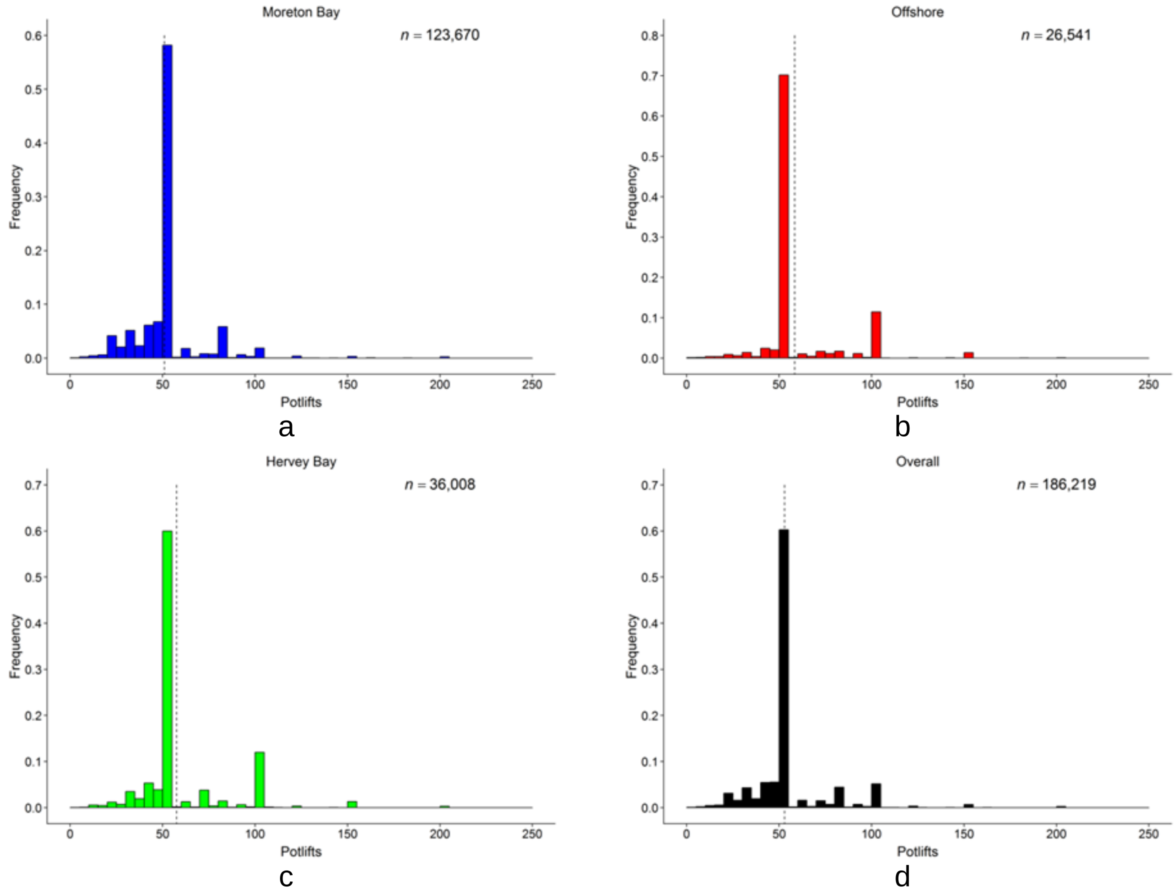


Figure 8: Frequency histograms of the number of potlifts recorded by commercial blue swimmer crab fishers operating in the a) Moreton Bay, b) Sunshine Coast, c) Hervey Bay regions (see Figure 3) and d) overall during the period July 1988 to June 2014 . Potlifts were calculated using methods described by Sumpton et al. (2003). The dashed lines represent the mean number of potlifts reported for each region.

However, the reportage of the number of potlifts is compromised by legislation requiring the use of a maximum of 50 pots. This is reflected in the logbook data, with most fishers most likely to report the use of 50 pots/potlifts (Figure 8). In recent years, fishers have reported the use of more pots after the introduction of policy provisions allowing fishers to use two licences (i.e. 100 pots) on a single vessel. As such, fishers in the Sunshine Coast and Hervey Bay regions in particular, reported significantly more pots in recent years than fishers operating in Moreton Bay (Figure 9).

Data collected during observer-based field work in the pot fishery in southern Queensland reveals that fishers use more pots than is reported in the logbooks (Figure 9). Sunshine Coast fishers, for example, were reporting 50-60 potlifts during the period 1999 to 2001 in logbooks, while the observer data suggests that at least some fishers were using closer to 100 pots. At this time, however, fishers in Moreton Bay and Hervey Bay were reporting the number of pots used relatively accurately. The most recent observer data shows that the number of potlifts per day in the Sunshine Coast region has increased to around 150. The logbook data shows an increase in the number of potlifts per day to approximately 90 in the same period. Observations on commercial vessels in the past two years have shown that commercial fishers working individually floated pots in Moreton Bay, are able to service approximately 20 pots per hour of fishing, so servicing in excess of 150 pots per day is clearly possible, although available evidence suggests that this is not a widespread occurrence. In offshore areas where gear can be run on trot lines (10 pots on a single line), it is possible to work an even greater number of pots.

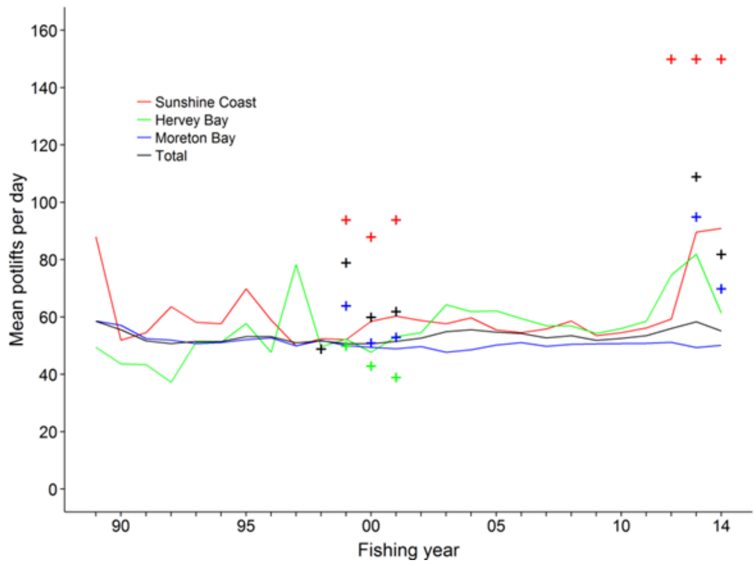


Figure 9: Mean number of potlifts per day as a function of financial year and geographical region (see Figure 3). The mean number of potlifts recorded during fishery-dependent research sampling in the Moreton Bay (+), Sunshine Coast (+) and Hervey Bay (+) regions are also shown.

These inconsistencies in effort reporting were also noted by Sumpton et al. (2003), who reported similar trends in the number of potlifts reported in logbooks compared to those observed during fishery-dependent research sampling. The misreporting of the number of potlifts represents a significant impediment to deriving accurate measures of catch rates and the resultant index of abundance for use in the stock assessment model. For example, it is spurious to equate a boat-day from 1988 to a boat-day from 2014 given that fishers are potentially using three times as many pots as they did historically. This progressive increase in under-reporting of fishing effort (potlifts) will also mask any declines in catch rate over time.

In order to address this important aspect of fishing effort, it was necessary to develop an offset for the number of pots used by fishers operating in the commercial blue swimmer crab pot fishery. During previous fishery-dependent biological sampling undertaken during the periods 1984-1986, 1999-2001 and 2011-2014, observers recorded information on a pot-by-pot basis during normal commercial fishing operations. As such, the number of potlifts was recorded accurately and was found to vary considerably, both inter-regionally and intra-regionally (Figure 10a). For example, in 2014 the number of potlifts recorded in Moreton Bay varied between 9 and 128 per day, with a mean of 70.

To develop an appropriate offset for pot numbers, the observed pot numbers from the fishery-dependent sampling were adjusted using generalised linear modelling (GLM). Both region (Sunshine Coast and Moreton Bay) and financial year were used as factors in a GLM with a Poisson distribution and a logarithm link function. This model provided the mean number of pots used by fishers operating in each region in each year (Figure 10a). However, it was clear from the logbook data that the fishery in the Sunshine Coast region (Figure 4) developed after the 1998 fishing year. Prior to this time, most fishers accessing the Sunshine Coast region were likely to be Moreton Bay fishers using ~50 pots. As such, three scenarios were developed to describe the increasing number of pots used by fishers operating in the Sunshine Coast region (Figure 10b). The three scenarios were developed to describe the increasing catches observed in all regions from around 1998 through to 2003. Further, the increasing numbers of fishers using excess pots in the Hervey Bay region after 1998 necessitated the use of a similar offset for the number of pots used in this region. An offset was then calculated by dividing the number of pots by 50, resulting in a variable describing the change in the number of pots over time as a proportion of the permitted number of pots. This offset allows for catch rates to be corrected for increasing levels of pot effort per boat-day between fishing years.

Hervey Bay data were excluded from this process due to a lack of data points in the most recent sampling period, but the number of pots in this region was assumed to be similar to that used in the Sunshine Coast region over the logbook period.

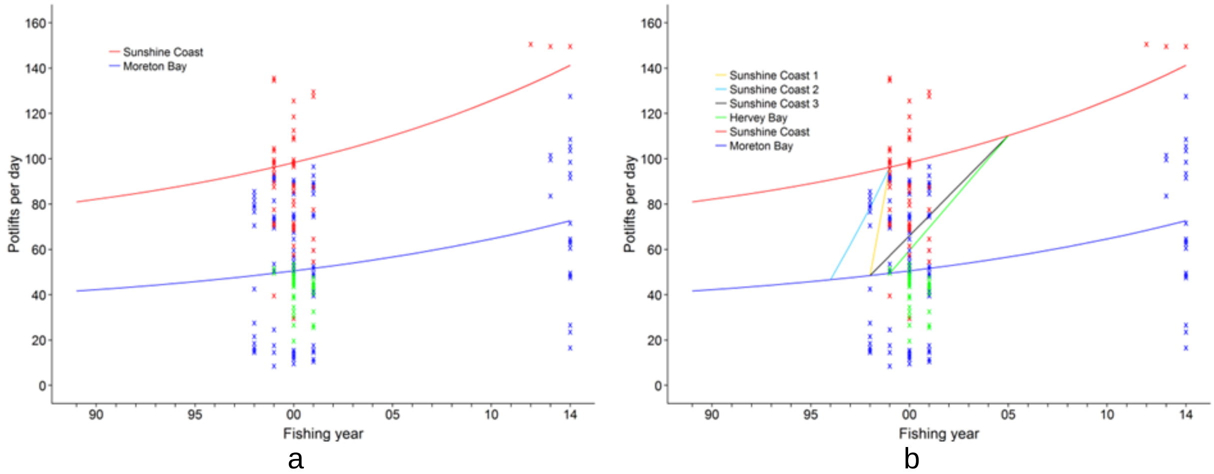


Figure 10: a) the two initial and b) four further possible scenarios generated to account for inaccurate reportage of the number of pots/potlifts in the blue swimmer crab fishery in southern Queensland. The pot numbers recorded during fishery-dependent, observer-based field work in the Moreton Bay (x), Sunshine Coast (x) and Hervey Bay (x) regions are also shown.

Catch rate standardisation

Catch rates were standardised using two residual (or restricted) maximum likelihood (REML) models using GenStat statistical software (VSN International, 2013). The methods for this procedure follow those reported by O'Neill and Leigh (2006) and the reader is directed to this publication for a thorough description of the procedure. The first model analysed the catch rates from the Moreton Bay and Sunshine Coast regions, while the second model analysed the catch rates from the Hervey Bay region only. This was due to the fact that the Sunshine Coast and Moreton Bay regions are geographically adjacent, with crabs within the Sunshine Coast region likely to come from, and/or contribute to, the Moreton Bay population, although the link between these two regions is not well understood. The Hervey Bay region is a large geographical area and contains both inshore and offshore components, however, these components were not differentiated in the model due to a paucity of data.

The daily catch for each vessel for the period 1 July 1988 to 30 June 2014 was log-transformed and analysed using a REML where a three-way interaction term of financial year x month x region and lunar terms were added as fixed effects. Further, CFISH grid and a boat identifier (individual boat mark) were added as random terms. The same model was applied for the Hervey Bay region with the three-way interaction reduced to a two-way interaction between financial year and month.

From the boat identifier term, parameter estimates for each vessel were estimated by the REML, from which changes in fishing power of the vessels accessing the fishery were calculated as a function of financial year and region. This allowed catch rates from each region to be adjusted for the changes in fishing power (Bishop et al. 2008) including advancements in GPS, sonar and crab pot technologies and changes in vessel size or engine power. Annual fishing power p was calculated as follows:

$$p_{y,r} = e^{(\mu_{y,r} - \bar{x}_r)}$$

where $\mu_{y,r}$ is the mean vessel parameter estimate from the REML, on the log scale, for region r and fishing year y and $\bar{x}_r$ is the mean vessel parameter estimate for each region r. Further, the relative fishing power P was calculated by:

$$P_{y,r} = \frac{p_{y,r}}{p_{1991,r}}$$

Where $p_{1990,r}$ is the fishing power estimate for the fishing year 1991 for region r. In order to account for the changes in fishing power, the level of fishing power was set in the `VPREDICT` command in GenStat to the maximum value of $p_{y,r}$ described above. This effectively adjusts catch rates for a standardised vessel throughout the time series in each region.

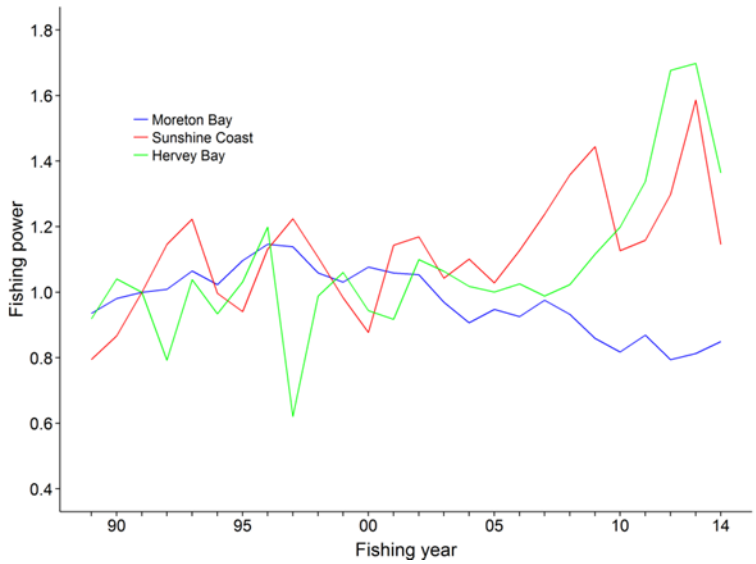


Figure 11: Annual fishing power changes in each region relative to the fishing power in 1990.

The results from this process are shown in Figure 11, with peak relative fishing power for Moreton Bay occurring in 1996 and 2013 for both the Sunshine Coast and Hervey Bay regions. The highly variable relative fishing power in both the Sunshine Coast and Hervey Bay regions reflect the relatively low number of vessels accessing these regions. For example, up until 1996, the mean number of vessels operating in the Sunshine Coast region was 23 (S.E. 1.9) and 28 (S.E. 1.4) in the Hervey Bay region compared to 72 (S.E. 4.0) vessels in the Moreton Bay region. This has also been the case in the last five years, with an average of 25 (S.E. 2.2) vessels accessing the Hervey Bay and Sunshine Coast regions, compared to 68 (S.E. 1.6) in the Moreton Bay region.

Decreasing relative fishing power in the Moreton Bay region suggests that, proportionally, more vessels with lower fishing power have accessed this region since 1995/96. This is likely a result of the fact that a high proportion of Moreton Bay fishers diversify to other fisheries, particularly net fisheries. The number of fishers that specialise in catching blue swimmer crabs is likely to be proportionally fewer in this region, with non-specialists accessing the fishery at periods of high catch. In contrast, the increase in relative fishing power in the other two regions since 2006 is a result of efficient fishers accessing these regions in larger specialised vessels. The decrease in relative fishing power in Moreton Bay is also likely a result of efficient fishers in relatively large vessels accessing the more lucrative Sunshine Coast region on a more regular basis, resulting in the increases in relative fishing power observed in this region. As with the Moreton Bay fishery, there appears to be a number of specialist crab fishers (~5-10) operating in the Sunshine Coast region, with less efficient fishers accessing the fishery on an irregular basis, adversely affecting relative fishing power in years when their access is proportionally high.

Relative fishing power in the Hervey Bay region remained low until 2007, before increasing beyond this point. The increase was driven by a small number of large vessels operating in the more remote areas within the Hervey Bay region, particularly in the V32 CFISH grid (Figure 3). After the introduction of the rotating closures associated with Scallop Replenishment Areas in 2001, access to V32 increased significantly with pot fishers able to access these areas without losing gear to trawlers.

Model outputs

Moreton Bay

Most obvious from the standardised catch rate time series for Moreton Bay is the monthly pattern of catch (Figure 12). Catch rates are lowest in July and August, before increasing to a peak in October/November. Catch rates then decrease in December before an increase to a second peak occurring in March/April.

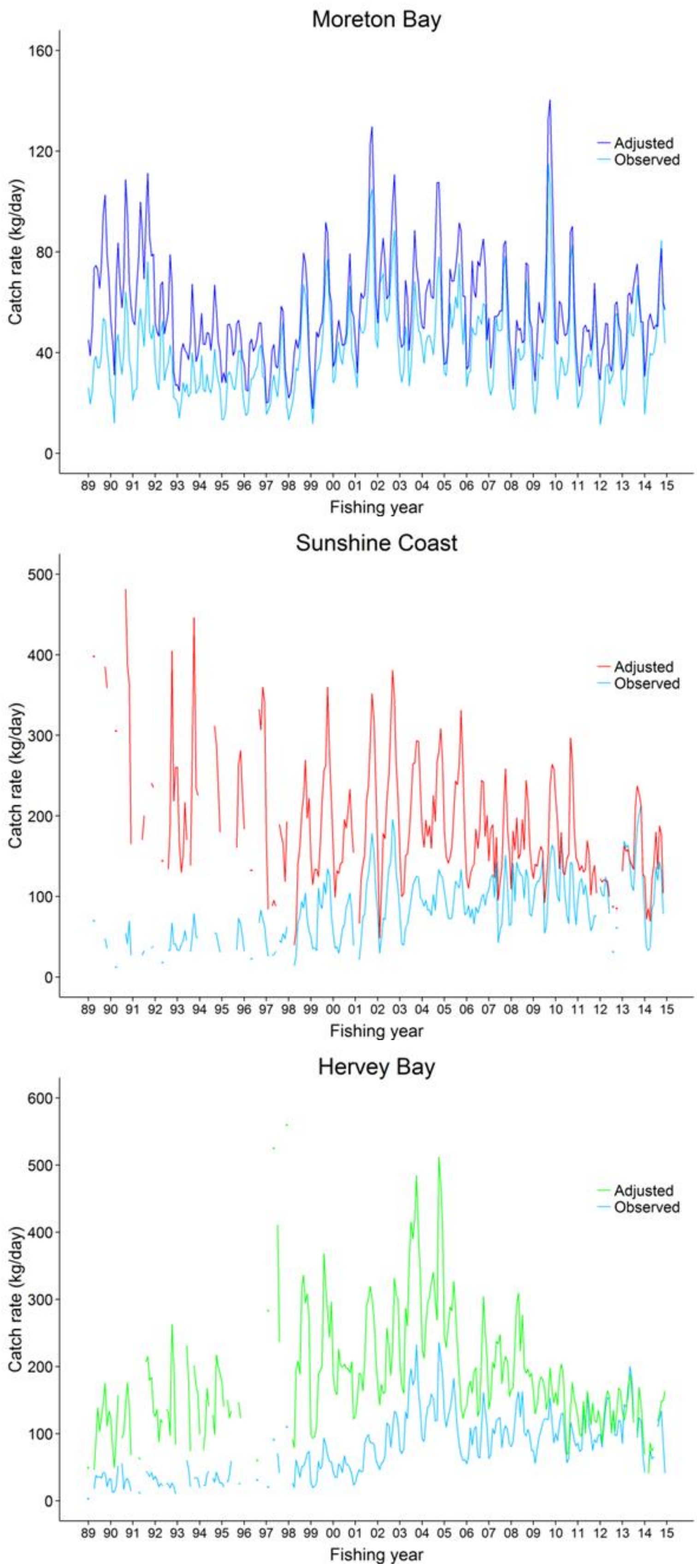


Figure 12: Standardised and observed catch rates as a function of fishing year and month for the Moreton Bay, Sunshine Coast and Hervey Bay regions. Missing data represents months where less than 20 boat-days of effort were reported.

The low catch rates in the winter period, particularly in Moreton Bay, suggest that either catchability is reduced, or that high fishing mortality and lack of moulting has resulted in most marketable crabs being caught by this time, or that they have migrated outside the Bay. At the onset of spring, feeding increases and those crabs that over-wintered in Moreton Bay at a size close to the minimum legal size are able to moult and recruit to the fishery, resulting in high catch rates in October/November. As this cohort is fished down through December, the next cohort recruits to the fishery and catch rates increase through to March/April/May. Blue swimmer crab numbers are also likely enhanced at this time by fast growing 0+ animals that were spawned in the previous spring.

Initially, catch rates were relatively high – 102.6 kg per boat-day in April 1989, 108.7 kg per boat-day in March 1990 and 111.2 kg per boat-day in March 1991 – before a period of low catch rates throughout the mid-1990s. This period coincides with the discovery of the offshore spanner crab fishery, which saw blue swimmer crab fishers diversify into the lucrative spanner crab fishery. It appears, from the estimates of relative fishing power shown in Figure 11, that proportionally more vessels that remained in the blue swimmer crab fishery were efficient blue swimmer crab vessels, with relative fishing power reaching a peak at this time. This reaffirms the hypothesis that a large proportion of fishers operating in Moreton Bay are more likely to be sporadic in accessing the blue swimmer crab pot fishery, diversifying to other sectors when necessary.

After the 1997 fishing year, catch rates increased to a peak of 129.7 kg per boat-day in April 2001. These increases are likely to have occurred for several reasons. Firstly, the rumoured implementation of a quota system for blue swimmer crabs, such as the one introduced for spanner crabs, may have prompted fishers to inflate their reported catch. It was thought that quota would be allocated according to catch history in the fishery and, as such, contrived catch may have been reported by some fishers as a way of demonstrating their historical access to the fishery. Secondly, during the period 1996 to 2003, the trawl catch of blue swimmer crabs decreased from 109 t to 15 t (Figure 4b), while trawl effort decreased significantly during the same period (Figure 5b). Given a probable low post-release mortality of trawl-caught crabs, reductions in trawl catch and effort would likely have resulted in a larger available biomass for pot fishers.

Lastly, from the early 1990s and onwards, the use of collapsible, trawl mesh crab pots increased. Although fishers primarily use the trawl mesh pots due to their durability, the trawl mesh pots also increase catch. Some fishers report that the trawl mesh pots allow more crabs to enter the pots due to their hourglass shape, while the smaller mesh allows for easier ingress of crabs into pots. The effect of using collapsible trawl mesh pots, to some extent, is accounted for by the fishing power adjustment in the REML. However, it would be appropriate to test the effects of using the contemporary pot designs and adjusting for this in future modelling of this fishery.

After the 2001 fishing year, catch rates decreased until the 2004 fishing year when an increase in catch rates occurred. This may have been a result of the change of minimum legal size (MLS) that occurred in December 2003. At this time, the MLS decreased from 15 cm tip-to-tip to 11.5 cm base-to-base, which equates to approximately 13.7 cm tip-to-tip. It was thought that this decrease would have increased catch by approximately 12% (Sumpton et al. 2003). For example, in the March prior to the increase in MLS, adjusted catch rates were 88.46 kg per boat-day, compared to 107 kg per boat-day in March 2004. As such, the decrease in MLS may have had the desired effect on catch. This change is, however, confounded by the practise of “tipping”. When the MLS was 15 cm tip-to-tip, an underbody measurement (Williams and Lee, 1980; Potter and Sumpton, 1986) of 37 mm was applied for crabs, where one or both lateral carapace spines had been damaged. The underbody measurement was very conservative and effectively allowed fishers to retain all blue swimmer crabs above 14 cm tip-to-tip. As such, the reduction in the MLS in 2003 was less likely to impact catches in the following years.

However, after 2004, catch rates decreased until 2009. At this point, catch rates increased significantly reaching 133, 140 and 109 kg per boat-day in March, April and May, respectively. This likely represents the result of a significant recruitment event that occurred the previous spring. Fisheries Queensland’s recruitment survey conducted in November and December 2008 showed significant numbers of juvenile blue swimmer crabs in Moreton Bay, some of which recruited to the fishery in early 2009, along with the 1+ yr old animals from the previous season, to produce the catch rates recorded in the 2009 fishing year. Catch rates in the 2010 fishing year showed signs of benefitting from the recruitment event of the previous season before significant decreases in catch rates in 2011 and 2012, coinciding with flood events in the Moreton Bay region including a once-in-100-year event in 2011 (Figure 30).

Apart from the significant catch rate increases observed in 2009, there has been a general decrease in catch rates since 2001. This may be an artefact of the increasing levels of effort reported by infrequent blue swimmer crab fishers. That is, proportionally more unspecialised crab fishers accessing the fishery, as evidenced by the reduction in the relative fishing power of vessels in the fishery (Figure 11), is likely to result in reductions in catch rates over time. For example, according to the logbook data, only 17 of the 333 vessels reporting blue swimmer crab catch reported 70 boat-days of effort per year for 10 years or more, while 25 boat-days of effort or less was reported for 261 vessels in the years they fished.

The lack of significant beach price increases for blue swimmer crabs, combined with increasing running costs – most notably fuel - has led to the previously-discussed over-potting required to ensure at least small levels of profitability in Moreton Bay (see Economic Chapter). Despite nominal fishing effort decreasing since 1996 (Figure 5), the total number of potlifts has likely increased in that time, resulting in only small changes in effective effort. This has resulted in the decreases in catch rates observed in Moreton Bay since 2001 (Figure 12), derived by the REML at a level of pots equal to that which fishers currently use.

Further, although speculative and difficult to quantify, the over-potting may be having a detrimental effect on catch rates with one fisher’s pots placed in close proximity to another fisher’s pots resulting in gear saturation. This is especially the case during periods of high crab abundance. Although Moreton Bay is large geographically, blue swimmer crabs are targeted in specific areas known to sustain numbers of legal-sized male crabs at certain times of the season. Specialised crab fishers have a tendency to move pots from an area once the number of legal crabs declines. Crab fishers that access the fishery on an infrequent basis are less likely to know what areas are fishing well and are, therefore, more likely to fish their pots adjacent to the pots of a more specialised fisher.

Lastly, it has been hypothesised that declines in the catch rate of blue swimmer crabs may be attributable to a significant reduction in trawl effort, and the resultant decreases in discarded catch from trawlers inside Moreton Bay. Wassenberg and Hill (1987) reported that trawl discards comprised approximately 33% of the blue swimmer crab diet. However, reductions in trawl effort in the Moreton Bay region from 13 177 boat-days in the 2000 to 4004 boat-days (~70%) in the 2013[2] represent a significant decrease in food availability for the blue swimmer crab population in Moreton Bay. As such, the interaction between the trawl fleet and the blue swimmer crab population in Moreton Bay is a complicated issue. That is, reductions in the retention and trawl-induced mortality of crabs resulting from reduced trawl effort have likely led to increasing biomass of blue swimmer crabs in Moreton Bay, while also reducing the availability of food for the population. These interactions should be the subject of further research in order to quantify the effect of trawl effort on the population of blue swimmer crabs in Moreton Bay.

Sunshine Coast and Hervey Bay

The Sunshine Coast and Hervey Bay fisheries are very similar. Initially, catches in these two regions were reported by fishers using relatively small vessels working close to the coast. However, towards the end of the 1990s in both regions, pot fishers began exploiting blue swimmer crab populations further offshore. In the case of the Sunshine Coast, these populations were virtually unfished by pot and subject to only low levels of fishing mortality from the trawl fishery (Figure 4b). As such, the decline in standardised catch rates in the Sunshine Coast region is likely to be the result of the exploitation of a virtually unfished population.

In contrast, the offshore component of the blue swimmer crab in the Hervey Bay region had been subjected to significant fishing mortality by trawl operations, with in excess of 200 tonnes landed by this sector in 1997. The blue swimmer crabs were landed as bycatch by trawl vessels targeting scallops in the area to the north-west of Fraser Island. After 2000, the introduction of the *Fisheries (East Coast Trawl) Management Plan 1999*, led to reductions in blue swimmer crab catch. At this

[2] http://qfish.daff.qld.gov.au/Query/ViewResults?CubeId=7&PredefinedQueryId=f0b3aae4-8411-4ef1-ba2c-4d04949afbba&ViewKind=Pivot

time, trawl fishers were restricted to a maximum of 500 individual crabs and, further, the smaller scallop vessels most likely to retain blue swimmer crabs left the fishery as part of the effort reduction objective of the plan. Also, the legislation requiring the mandatory use of turtle excluder devices (TEDs) in the scallop fishery likely led to decreases in trawl-caught blue swimmer crabs in the Hervey Bay region.

Catch rates in the Hervey Bay region were driven primarily by access to the V32 and V33 CFISH grids (Figure 3). The increased access to V32, after the introduction of the *Fisheries (East Coast Trawl) Management Plan 1999* explains the increasing standardised catch rates in this region between 1998 and 2004, where the effort in this grid, as a percentage of effort in the entire Hervey Bay region, increased from 14.3% to 72.2%. In subsequent years, catch rate declined relative to the amount of effort in the V32 CFISH grid. In recent years, effort in V32 has decreased significantly, with 426 boat-days recorded in 2013 compared to 2843 in 2004.

In both the Hervey Bay and Sunshine Coast regions, a high proportion of the catch reported since 2000 was caught by efficient offshore vessels with the ability to use 100 to 150 pots (or more). These vessels also used larger offshore pots with increasing frequency from the late 1990s. In areas of high crab abundance, smaller pots exhibit gear saturation, limiting the number of legal-sized male crabs entering these pots. In contrast, large pots can hold more crabs, prolonging their ability to catch crabs resulting in higher catches. Further, large vessels attached pots to long lines, called “strings”. Ten pots are placed on each string approximately 50 m apart. This facilitates the use of 150 pots as using this many individually buoyed pots in the depths fished in the Sunshine Coast and Hervey Bay regions would be not be possible, given the length of time it would take to service the pots each day.

In conclusion, the addition of the offset, combined with the use of the fishing power estimates described above, has produced a more realistic index of abundance. This is particularly the case for the Sunshine Coast region, where very little pot-caught blue swimmer crabs were landed, suggesting that this population received very low levels of fishing mortality. However, it should be noted that the veracity of these analyses is contingent on the accuracy of the logbook data supplied to Fisheries Queensland. Clearly, it is very important to ensure that available data are of the highest possible quality when those data are used to manage a fishery. We recommend, therefore, that Fisheries Queensland take steps to validate logbook data where possible and that prior reporting be established for the blue swimmer crab fishery.

Fisheries Queensland Independent Trawl Surveys

Fisheries Queensland have been undertaking fisheries independent trawl surveys of eastern king prawns, blue swimmer crabs and snapper since 2006 and, although the objectives and logistics of the sampling have changed over time, there has been a relatively consistent sampling in November and December each year, using beam trawl apparatus. (For a detailed description of methods see DPI&F (2006), DPI&F (2007 a-d) and DPI&F (2008).)

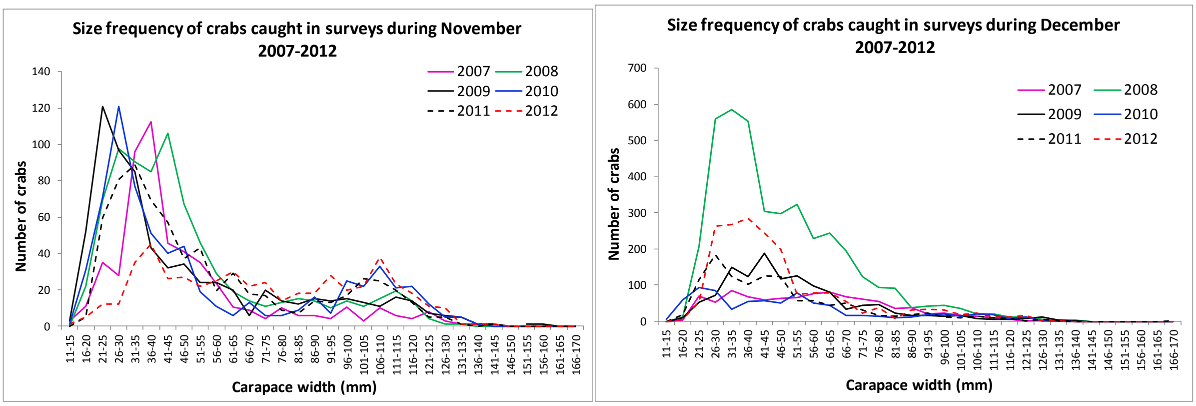


Figure 13: Size frequency of all crabs caught (carapace width) during the Fisheries Queensland trawl surveys in Moreton Bay during November and December from 2007 to 2012.

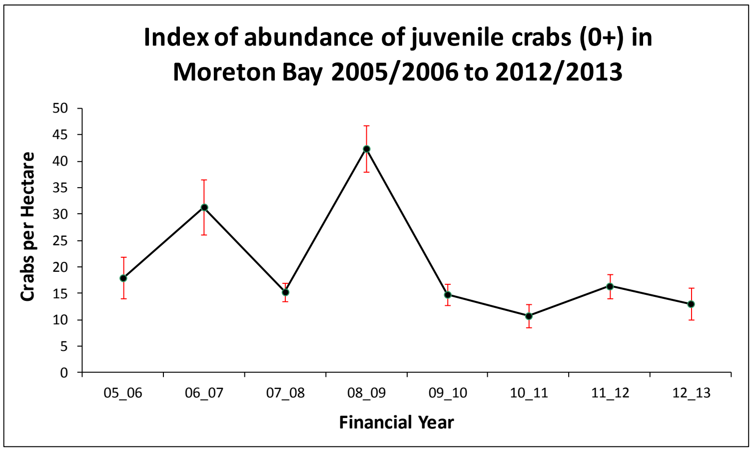


Figure 14: Index of abundance of juvenile crabs (0+) in Moreton Bay between 2005/2006 and 2012/2013 as predicted from the two-part conditional generalised linear modeling.

Figure 13 shows that the surveys consistently sample the 0+ year cohort of juvenile crabs. Given the problems associated with the CFISH data, it is important that these fishery independent trawl surveys are continued as they were used in the current model, and their worth will continue to increase over time as more data are added to the time series. It is vital that some form of index of relative abundance is available for this fishery, and this has been recognised in both South Australia and Western Australia, as the management of blue swimmer crabs relies on the use of similar independent trawl surveys. Already, the pulse of recruits seen in the 2008/09 survey (Figure 14) was reflected in high catches the following year, so the predictive value of the survey is already established. Careful consideration should be given to the timing of surveys if the program needs to be altered in the future. Surveys before November or after March would miss the pulse of juveniles resulting from the spring spawning event and compromise results for reasons discussed. All available evidence suggests that the optimal period for sampling recruits in Moreton Bay would be December to February, capturing the peak in recruitment while minimising the effects of dispersal, reduced catchability and effects of harvest by fishers.

3. Changes in Fisheries Biology and Population Biology

Introduction

There is extensive literature describing blue swimmer crab fisheries biology based on research in most Australian states that support blue swimmer crab fisheries. In Queensland the earliest fisheries research into the fishery was conducted by Thomson (1951) who examined the composition of the commercial Moreton Bay catch but described little of the crabs' growth, reproductive biology or other population processes. In the 1980s research in Moreton Bay, (Potter and Sumpton (1986); Sumpton et al. (1994)) described the fisheries biology of the blue swimmer crabs in Moreton Bay, and a subsequent study (Sumpton et al. 2003) extended the fisheries information into areas of the fishery that had only relatively recently been developed (e.g. Sunshine Coast and offshore areas of Hervey Bay). In earlier analyses, key biological parameters were shown generally not to differ between the regions, although crabs were generally significantly larger in offshore areas outside of Moreton Bay. These three datasets form the basis of comparisons with the conditions at present in the fishery.

With the expansion of the blue swimmer crab fishery, there are still important unknowns including the connectivity of embayment and offshore fisheries, recruitment dynamics and growth. This chapter examines some of the spatial and temporal changes in biological features of the blue swimmer crab concentrating on research conducted during three time periods - 1984 to 1986, 1998 to 2001 and 2013 to 2014. Readers are referred to earlier reports and publications (Potter and Sumpton 1986, Sumpton et al. 1994 and Sumpton et al. 2003) where methods are described in detail.

Materials and Methods

During 1984-1986 and 1997-2001, samples of *Portunus armatus* were taken opportunistically from commercial pot and trawl catches in northern and southern Moreton Bay, Hervey Bay and the Sunshine Coast offshore waters. The most recent samples collected during 2013 and 2014 were limited to the waters of Moreton Bay and the Sunshine Coast, and sampling during 1984 to 1986 was limited largely to Moreton Bay as the offshore fisheries were yet to be fully developed.

We use methods that are well described in previous reports and publications (Sumpton et al*.* 2003) but note that the previous assessment of the maturity stage of male crabs based on abdominal morphology has been shown to be flawed, and future assessment *of* male reproductive maturity should be made on the basis of gonad development. We also assessed egg fertilization success by taking 5 to 10 subsamples of approximately 200 eggs from grey egg masses and counted eggs that were successfully developing.

Growth of blue swimmer crabs

One of the key parameters affecting a species' resilience to the effects of fishing is its growth rate. Growth rate is one of the key features that affect the model outputs (see later), but it is also very difficult to assess the growth rate of crabs, given the stepwise pattern of crustacean growth caused by moulting. We have a good understanding of the first few months of growth from modal progression analysis of trawl samples. However, once crabs approach sexual maturity the selectivity of fishing gear means that larger individuals are poorly represented in trawl samples, as they are able to swim fast enough to escape net capture. Further, there is considerable overlap of the 0+ and 1+ size modes resulting in difficulties in identifying modes in length frequencies.

This feature is not uncommon, as growth rate of many larger crustaceans is known with poor accuracy and precision. In the case of the blue swimmer crab, several techniques have been trialed including modal progression analysis (Sumpton et al. 1994) and tagging studies (Potter et al. 1996), while lipofuscin and telomeres have been unsuccessfully trialed to age spanner crabs and other crustaceans.

As part of the current assessment, mixture modelling of historic catch data (Potter and Sumpton 1986) from both trawl and pot catches was undertaken in order to improve previous estimates of growth (See Appendix 1 for details of methods and results of this analysis).

Tagging studies of blue swimmer crabs have been unsuccessful due to poor tag retention, particularly following moulting. Tagging-induced mortality can also be high, and in a study conducted in 1985/86, there was limited growth of recaptured crabs recorded and Fabens' models used to estimate growth fitted poorly to the data (Potter et al. 1996).

In the assessment model we have trialed a series of different growth transition matrices that cover three different growth scenarios (see Appendix 2 for a discussion of growth scenarios used in the assessment model). This wide variation in parameter space reflects the uncertainty and likely variation in growth of this species. In aquaculture studies, blue swimmer crabs have been known to reach 150 mm carapace width in nine months. As such, rapid growth and recruitment to the fishery within 12 months is possible for a proportion of the population.

Ageing Crustaceans using sections of body parts retained during the molt.

A key unknown in the growth of blue swimmer crabs is whether they can reach the current MLS (115 mm BW) within 9-12 months of hatching, or whether they have to overwinter before they reach the MLS. Currently, the length frequency modal progression is difficult to interpret once crabs reach maturity due to the overlapping nature of the 0+ and 1+ years length frequencies.

Traditionally, hard parts (such as otoliths spines and vertebrae) of fish have been used to age fish, but as crustaceans have few skeletal components that are retained during their life (due to periodic shedding of the exoskeleton), it has been difficult to use similar methods to age crustaceans. Recently a number of laboratories have investigated using the gastric mill, as well as eyestalks, to assist in crustacean age determination. The technique is similar to that used on fish hard parts and involves sectioning of various body parts. The most promising area has involved using parts of the gastric mill and, in particular, the mesocardium and the urocardium which are retained during the moulting process. Eyestalks have also been trialed after transverse sectioning, similar to preparations needed to assess the urocardium and mesocardium.

As part of the current research we examined the eyestalks, gastric mill and skeleton of blue swimmer crabs for features that could represent possible growth banding (Figure 15). At this stage, we were unable to validate any estimate of growth given visual assessment of these structures. We presented images and data of sectioned BSC at a workshop in Darwin in July 2014, and discussed recent advances in crustacean ageing technologies with international and local researchers, but were unable to get any clarity about the use of these structures for ageing blue swimmer crabs. However, research is continuing in other laboratories, and with further development the technique may eventually prove useful for estimating crab growth.

Despite the lack of banding in either the eyestalk or gastric mill, there was some evidence that the carapace of crabs had banding (Figure 16) but, at this stage, the techniques for ageing blue swimmer crabs await further investigation and development. It is further unlikely that the carapace will be useful, as the visible bands only represent a short period in the crab's life cycle, as the carapace is definitely shed at the moult.

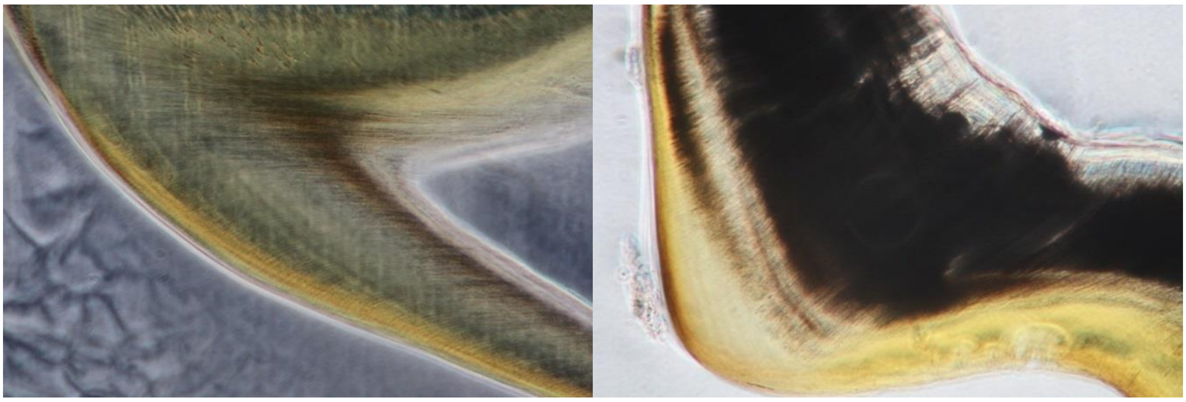


Figure 15: Sections of blue swimmer crab gastric mills showing lack of structures that could be interpreted as growth bands.

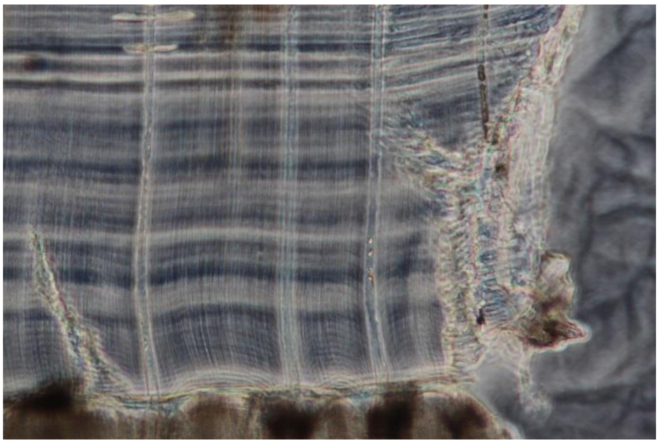


Figure 16: The sectioned carapace of a blue swimmer crab showing lines possibly representing periods of growth.

Results

A range of key biological features (mainly related to reproduction) that may have been affected by fishing were analysed, but the statistical analysis was often compromised by using fishery dependent sampling of commercial fishers who changed throughout the time series. They also fished in different areas even though they were fishing in the same broader regions of Moreton Bay, Hervey Bay and Sunshine Coast. The effect of fisher was always highly significant in statistical models used to test many of the biological features investigated. Aliasing was a significant problem across the 30 year time series investigated, as there was only a single fisher who was represented in all sampled years. In the case of average crab size, model predicted estimates sometimes differed by more than 30 mm between fishers. Such variation that cannot be accounted for across the time series has a major impact on testing the statistical significance of features across years. In most cases, GLMs and other models could not predict when fisher was included as a factor in the models, and not being able to account for the effect of fisher in the models, would have biased results. These differences relate partly to the size selectivity of fishing gear, but also to differences in the areas and targeting preferences of individual fishers.

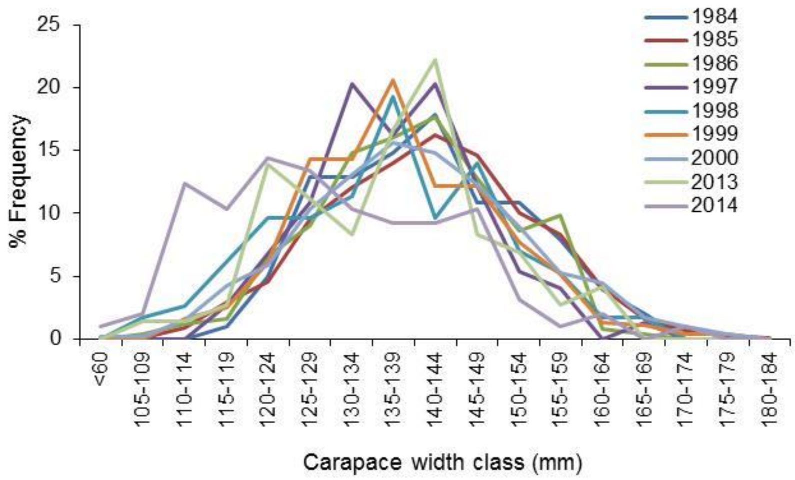


Figure 17: Size frequency of ovigerous female blue swimmer crabs sampled during each of the 4 decades of sampling.

Historic data has shown ovigerous females were present during all months of the year in all regions sampled, but were still at their lowest frequency during May and June (the main mating period) and peaked during August and September. We were unable to confirm that August and September were still the months when the majority of mature females were ovigerous, but females with eggs were sampled in all regions during all sampling months in 2013 and 2014. There were no consistent spatial or temporal trends in the incidence of the various stages of eggs, with both recently extruded eggs and eggs that were close to hatching observed throughout most of the year, both inside Moreton Bay and in offshore waters. Figure 18 shows the change in the proportion of mature females that were ovigerous across the 30 year period when samples were obtained. We have standardised the figure to only include months from January to June as not all months were sampled in all years and regions, and we have already noted a strong seasonal component to reproductive biology. There was no consistent trend in declining frequency of ovigerous females over time in any region. The 2001 year was anomalous in Moreton Bay and the Sunshine Coast largely due to the smaller sample size probably not being representative of the entire population. Sample sizes were over 500 for all years except 2001 when fewer than 200 females were sampled.

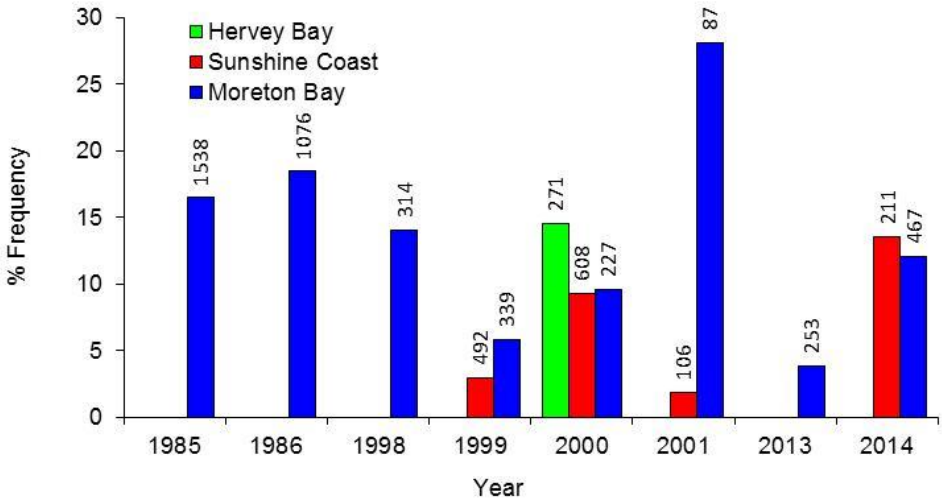


Figure 18: Change in the percentage of mature females that were ovigerous during January to June. Data from commercial pot catches. Sample size is shown above each bar.

Mating activity, as assessed by the presence of recently implanted spermatophores, was mainly taking place during May and June with relatively little mating activity during the spring. Sampling during 2013 and 2014 was not as temporally or spatially exhaustive as previous studies, and we were unable to determine recent changes in the seasonality of mating. However, Figure 19 shows little difference in the proportion of females in pots that had full spermathecae, indicating recent mating.

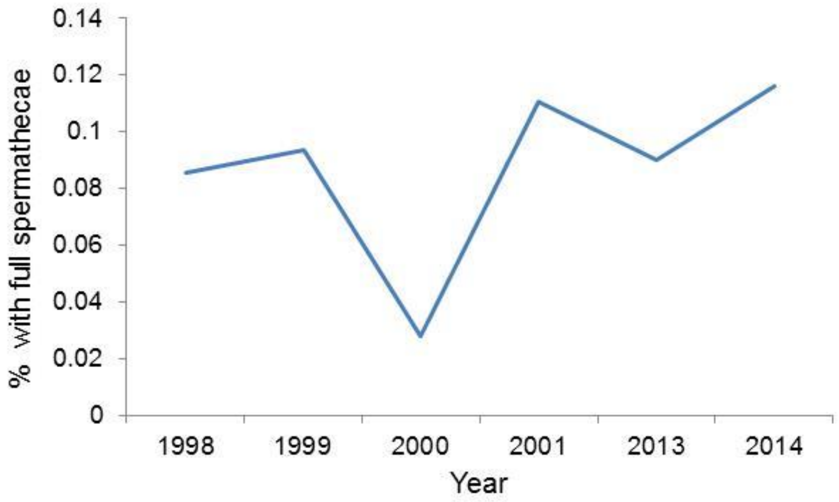


Figure 19: The percentage of mature females sampled in Moreton Bay and Sunshine Coast that had full spermathecae indicating recent mating.

Size frequencies of pot caught crabs in all areas had very few juvenile male crabs (<120 mm CW) and it was uncommon to catch many sexually immature crabs in many of the pot designs despite variable mesh sizes of the different pots.

The average size of females sampled from all areas showed similar trends to males with few immature females and broadly consistent sizes among regions and times. Small sample size was mainly responsible for the lack of numbers at the extreme ends of the size distributions in some cases. The main sexual difference in the size frequency data was the similarity in maximum size of females sampled in the different regions, when the larger size classes of males were virtually absent from Moreton Bay samples.

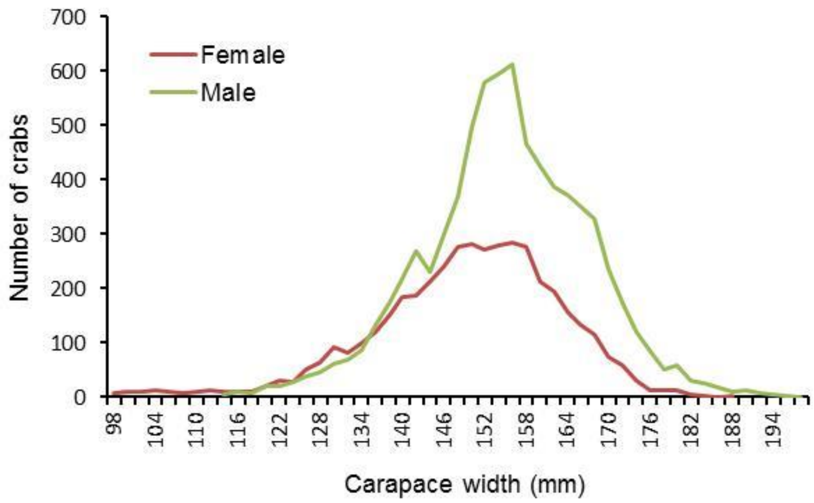


Figure 20: Size frequency of male and female blue swimmer crabs sampled in commercial pots and nets from western Moreton Bay during the late 1940s. Data adapted from Thomson (1951).

Size frequency data collected in Moreton Bay during the 1940s show that the size structure of both females and males differed markedly from the current size structure with a higher proportion of larger individuals represented in the samples. It needs to be acknowledged that during this time, both nets and pots were used, and the selectivity of both these apparatus remains historically unknown and, thus, it is not valid to statistically compare the size structure of males in particular with current size structures.

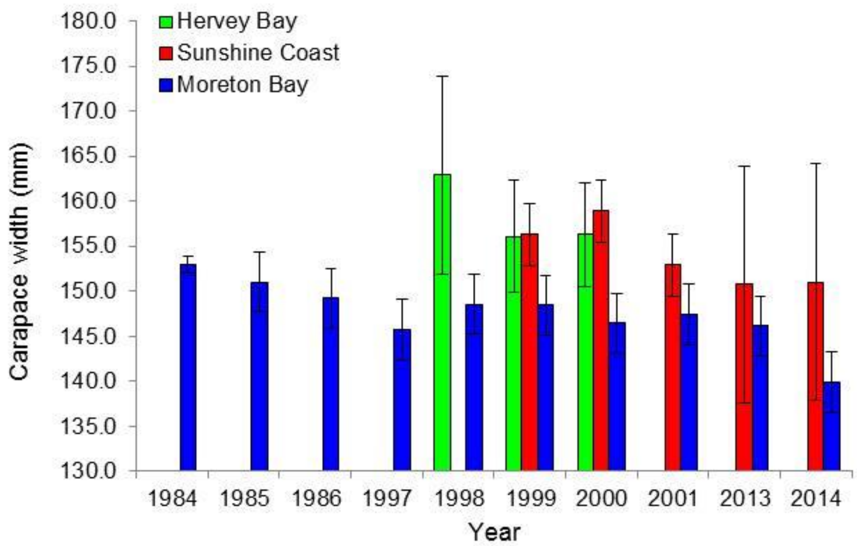


Figure 21: Predicted average size of male blue swimmer crabs in the catches of commercial crab fishers (Based on REML with region and year as fixed effects and date as a random effect). Bars represent 95% confidence intervals.

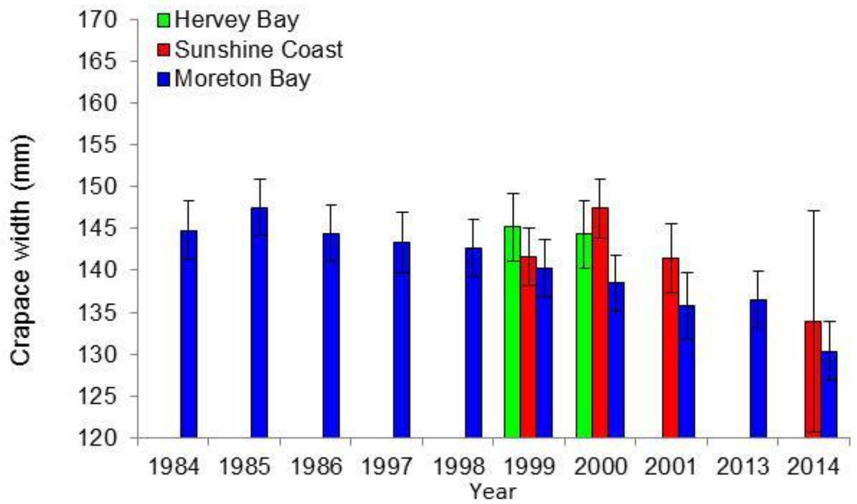


Figure 22: Predicted average size of female blue swimmer crabs in the catches of commercial crab fishers (Based on REML with region and year as fixed effects and date as a random effect). Bars represent 95%

The average size of the retained male catch differed more spatially than temporally (Figure 21) with the offshore regions having significantly larger male crabs than Moreton Bay, although this trend was not as obvious in the 2013/14 samples. We were unable to sample Hervey Bay in the most recent assessment so we are unable to comment on changes in that fishery in terms of size of crabs. As mentioned earlier, the 2001 Hervey Bay sample of males was anomalous due to the fact that it came from the catch of only two crabbers. The difference in size of females among regions was not as large as that of marketable males with few significant differences evident (Figure 22). During 2000, when sampling was most intense, females sampled from the offshore regions were significantly larger than Moreton Bay samples, but the pattern was not repeated in any other year. There was a declining trend in the average size of females sampled in Moreton Bay.

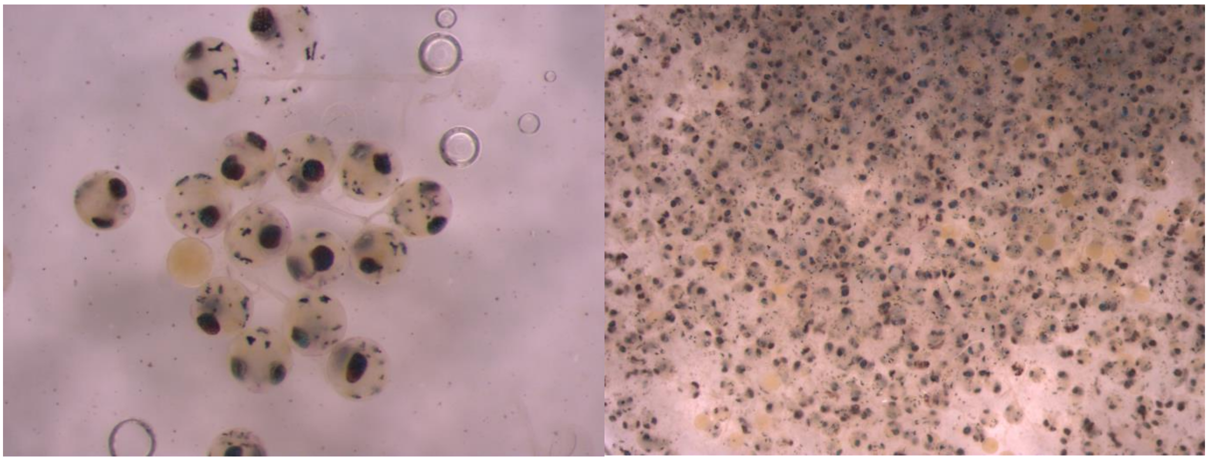


Figure 23: (A) Developing embryos in fertilised blue swimmer crabs eggs. Note the single non-developed egg highlighted by the arrow. (B) Sample of eggs showing numerous non-developing eggs.

In all eggmasses examined, over 90% of eggs were fertilised and developing successfully (Figure 23). Non-developing eggs were found in sub-samples of all eggmasses examined (Figure 24) although the percentage of eggs that were not developing was generally less than 4% and there was no size-related trend in the fertilisation rate.

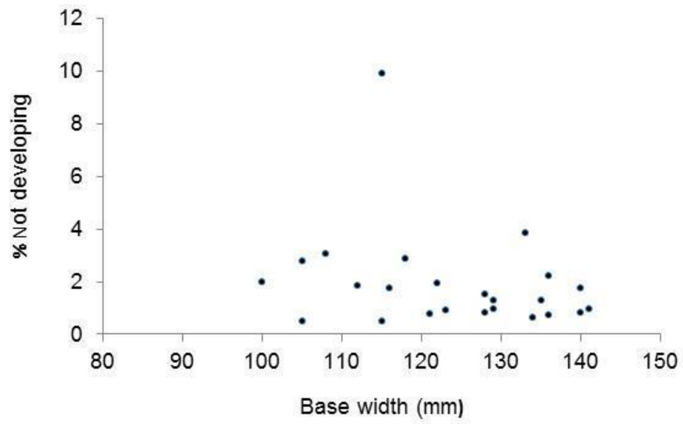


Figure 24: The percentage of eggs in “grey” eggmasses (most advanced stage) that were not developing for a range of sizes of ovigerous female blue swimmer crabs.

Figure 25: Dissected female blue swimmer crabs showing (A) a stage 2 gonad and full spermathecae (arrowed) and (B) Orange gonad (stage 5) covering most of the thorax and hepatic region.

The presence of recently implanted spermatophores was easily visible in dissected female crabs (Figure 25) and, apart from a single post moult female crab that had not apparently been mated, all females post moult crabs caught in pots had been recently mated. Males were often found in a copulatory hold of late-premoult and early-postmoult females.

Discussion

The main biological parameters, which have been derived for blue swimmer crabs previously (Sumpton et al*.* 1994 and Sumpton et al. 2003), are still broadly consistent for the recently collected samples in Moreton Bay and the Sunshine Coast. We were unable to adequately assess any changes in Hervey Bay for a range of logistic and other reasons. Moreton Bay, with its longer history of exploitation, still has significantly smaller sized male crabs than the Sunshine Coast. Whether this is due to heavy exploitation pressure or differences in population structure and gear selectivity is still unclear as insufficient, sampling was conducted offshore.

Thomson (1951) investigated the blue swimmer crab fishery in Moreton Bay over 60 years ago when the exploitation pressure on the resource was not as great as the present day, and found size structures that contain a higher proportion of larger crabs (of both sexes) than those found in the present day fishery. Fish Board records presented by Thomson show a fishery with a catch less than 20% of what it currently is in Moreton Bay today. During this period there was also little recreational fishing effort, and trawling in Moreton Bay did not really begin until the 1950s. The fact that in Thomson's study, the relative difference in the size structures of males and females was similar to the present day, suggests that selectivity of the gear may have been a contributing factor. The data collected during the 1940s was also partially collected by mesh net with the relative contribution of each method to the overall sample not being discernable from Thomson's data.

The use of pots as a sampling method for determining biological features of crab populations may cause biases, not only because of the selective nature of the apparatus, but also due to the targeting practice of the individual fishers that set the traps. Thomson (1951) noted that there was considerable selectivity of the gear and it is unwise to interpret differences as being caused solely by fishing. Blue swimmer crabs are known to segregate by size and sex at times, and fishers can effectively target particular sizes by avoiding areas where there are large numbers of females and undersized crabs (unless there is a high proportion of marketable crabs in the area as well). The fact that fisher was always a highly significant factor affecting the various biological parameters being assessed by fishery dependent sampling is also an issue.

It is possible that male crabs in the offshore areas of the Sunshine Coast and Hervey Bay undergo an additional moult causing a higher proportion of larger animals to be available in these areas. These larger crabs may be either crabs from the embayments moving out into deeper water once they reach a certain size or particular moult stage (probably the terminal moult).

We note again that the growth data obtained for blue swimmer crabs appears accurate for the first years growth, but separation of modes for the faster growing 0+ year old crabs and the 1+ year old crabs is difficult, particularly during the winter and early spring when the smaller size classes are not as common in trawl samples (Sumpton et al. 1994). The recent assessment of growth using mixture modelling techniques (Appendix 1) has not been successful in resolving this issue. The lack of good growth information for the second (and possibly subsequent) year(s) of life probably results in an underestimation of $L\infty$ because crabs up to 220 mm have been found and it is common to catch crabs in excess of 180 mm, particularly in offshore waters. The discrepancy in $L\infty$ in particular has a significant impact on the derivation of many fisheries parameters including mortality, and is relevant to the sensitivity analysis of growth in the population model presented in the stock modelling chapter.

One of the important areas for future research relates to accurately determining the longevity and moulting frequency of crabs once maturity is reached. There are good data available now from a number of sources that provide growth estimates of crabs up to about 120 cm carapace width. Despite this, growth of crabs greater than this size remains poorly understood due to blurring of size frequency modes and insufficient tagging growth data. Based on the size of crabs in the offshore fishery (which can reach over 220 mm CW), it is likely that growth parameters derived from modal length frequency information are biased. Indeed, the recent analysis using innovative mixture modeling techniques (Appendix 1) had considerable uncertainty around modelled parameters.

The fisheries with the longest history of exploitation are also the ones that have the more abbreviated size structures, but they may also be the main nursery areas contributing crabs to the previously less heavily exploited offshore areas. It is not possible to say with certainty that the offshore areas are solely fed by recruits from the inshore fishery, but there are several lines of evidence that support this view including: (1) the lack of juveniles in trawl catches in offshore waters; (2) size frequency data which show an abundance of pre-recruits from inshore waters with a general increase in average size of blue swimmer crabs with increasing depth (Sumpton et al. 1994).

The most recent sampling showed that almost all immediate post-moult females had been recently mated suggesting that, despite high levels of fishing mortality, there are still sufficient reproductively capable males in the population to mate with the available females. This is identical to the results of research in Moreton Bay conducted during 1984-1986 (Sumpton et al. 1994) and 1999 to 2001 (Sumpton et al. 2003), which showed that all reproductively capable females had been mated. It is a well-established fact that, of a copulating pair, the male is always larger (and usually considerably larger) than the females. Copulatory pairs that have been measured have the male on average 13% larger (in terms of carapace width) than the female. Indeed, most of the pairs observed in this and previous research have been males in attendance of females in their first maturity moult, and few pairs have been observed where the females exceed 150 mm CW. Despite this, ovigerous females were found throughout the size range and, in fact, the two largest crabs sampled were carrying eggs. The trend was for a higher proportion of large females to be carrying eggs than for smaller females. One of the hypotheses that may explain this observation is that females in their final moult may suffer higher levels of natural mortality once they have extruded all their eggs than females in the first maturity moult.

We addressed the issue of sperm limitation by assessing the proportion of the mature female population that was ovigerous based on samples obtained from the commercial pot fishery. Imprecision in the determination of egg batch size was so great and imprecision in egg counting so high, we were unable to gain sufficient power to detect differences. While there is no real consensus about the likelihood of infertile eggs attaching to the pleopods following extrusion, we chose to examine subsamples of mature eggmasses in an effort to quantify fertilisation rates in these particular clutches of eggs, as previous research has shown that a proportion of these eggs were infertile. Quantification of the volume of sperm in the spermathecae and the development of methods to determine sperm limitation in this fishery were not progressed during this current research. It is a simple matter to determine immediate post moult females and measure the volume of sperm prior to any egg extrusion, but the subsequent batches extruded during a moult are more difficult to determine. Nevertheless the volume of sperm in the spermathecae immediately after mating is probably a better indication of sperm limitation, should such be occurring. The number of females that a male can mate with and the volume of sperm inseminated is still not fully understood, but this can be best assessed by experimental holding of crabs, which was outside the scope of the present study. Given the variation in gonosomatic index (GSI) determined from earlier research, there was little chance in delineating a statistically significant change in sperm volume based on field sampling alone. Unlike mud crabs, where it is possible to determine if a male has mated with a female based on the presence of mating scars, there is currently no simple way of determining whether a male has previously mated with a female based on the analysis of fishery dependent samples from the population.

We have not modelled the effect of discard mortality on the blue swimmer crab resource, but current evidence suggests that significant discard mortality is not a major problem in either the trawl or pot fisheries, providing best practice handling procedures are applied. Likewise, the recent prohibition on the use of suicide dillies has greatly lowered the discard mortality inflicted by the recreational sector. Of the two main methods of capture (potting and trawling), the latter poses the greatest risk as higher proportion of smaller individuals are incidentally caught, and trawling inherently causes more damage to the crabs. Exposure times can also be longer than pot caught crabs, but as most trawling is usually conducted at night, this may not be as problematic. Sorting practices of some pot crabbers can also be more damaging than those of some trawl operators, particularly if crabs are sorted and discarded after the lifting of several pots, rather than on a per pot basis. Poor sorting practice can result in crabs being exposed during the day for 30 minutes or more before they are returned to the water. On the other hand, best practice handling procedures of some pot fishers can result in undersized and female crabs being returned to the water in less than 30 seconds.

There is also evidence from both tagging studies (Potter et al*.* 1994) and mortality trials in Western Australia (Melville-Smith et al. 2001), which further supports low mortality of trawled and pot discarded blue swimmer crabs is comparatively low. Over the years there have been informal arrangements to ensure the survival of discarded blue swimmer crabs. These have involved the use of mist sprays on sorting trays as well as practices, to ensure that crabs are sorted within a "reasonable" time after being removed from the pot. As is the case with most fisheries, the practices employed by various fishers vary dramatically from sorting each pot immediately it is lifted to sorting the entire catch at the end of the day. Certainly the latter practice results in unnecessary mortalities of discarded crabs since few would survive being kept out of water for more than an hour. There are also difficulties in being too prescriptive with sorting practice regulations, and there is a need to ensure that whatever regulation is in place, is also enforceable by compliance officers. If crabs are sorted immediately after each pot, unnecessary damage may also be caused to both the marketable and discarded portions of the catch. This is because crabs can remain active for several minutes after being placed in a sorting tray, tending to grab at everything with their claws. During this time they may lose claws and legs if they are moved around and sorted as they will continue to inflict damage as they are pried apart. Normally after a few minutes the crabs have settled down enough to make sorting easy and less likely to damage crabs.

The practice of placing crabs in an ice slurry prior to sorting (as is commonly used in Western Australia) reduces the damage to crabs, but there is the additional problems of mortalities related to cooling discarded crabs as well as the additional cost pressures that such a process places on fishers. The mortality rates caused by this sorting practice are described in Melville Smith et al. (2001) but it is doubtful whether it would be warranted in most areas in Queensland.

4. Parasitism and Diseases

Introduction

Disease and parasitism have been linked to the collapse of crustacean fisheries around the world (Stentiford and Shields 2005). The three main pathogens that have potential to impact on Queensland stocks of blue swimmer crabs are the rhizocephalan barnacle *Sacculina granifera,* the parasitic dinoflagellate *Hematodinium* and the microsporidian *Ameson sp*.

Research on *S. granifera* in Australia has been generally limited to the waters of Moreton Bay where the prevalence can be as high as 30% in some areas (Thomson, 1951; Sumpton et al*.* 1994). This parasite, in the later stages of its infection, eventually causes sterilisation and there have been concerns about the impact of the parasite on egg production given the high prevalence of *Sacculina* in some areas. Despite this, there has been no evidence of any increase in prevalence and it has always been a feature of the population. The most recent study (Sumpton et al. 2003) found no evidence of an increase in prevalence in Moreton Bay.

Microsporidians have been known to cause mortalities of the portunid crab *Callinecthes sapidus* in North America (Overstreet, 1978), and have been recorded in relatively low prevalence in *Portunus armatus* in Moreton Bay (Shields 1992, Sumpton 1994, Sumpton et al. 2003). Severe microsporidian infection can make crabs unmarketable as cooked, infected crabs have very dry and fibrous flesh due to degeneration of muscle tissue. Although this “mushiness” has been linked to poor cooking and handling practices, it is clear that microsporidian infection may also contribute to this.

Another pathogen, Hematodinium has been identified as one of the most economically significant diseases/parasites of crustaceans, and has had detrimental effects on fisheries for both lobsters and crabs in other parts of the world (Stentiford and Shields 2005).

Any increase in the prevalence of these parasites could pose a significant risk both to the viability of the blue swimmer crab population, and to the continued successful marketing of the product. This chapter examines changes in the prevalence of these parasites in blue swimmer crabs and assesses risks to the population. We have chosen to examine the prevalence in terms of the most advanced stages of infection only, as other historical datasets have only examined the population in this level of detail. We acknowledge that cryptic mortality of juveniles could not be detected by the sampling methods undertaken in this study, as samples were limited to the sexually mature component of the population, and we were relying on collecting samples from a fishery which strongly selects for the mature population.

Materials and Methods

Male and female crabs were collected on observer trips with commercial pot fishers during the years 1984 to 1986, 1998 to 2001 and 2013 to 2014. These were examined for externae of *Sacculina granifera*, which were defined as immature sacs (sacs < 25 mm breadth, mantle opening not fully developed) or mature sacs (sacs > 25 mm breadth, mantle opening well developed) as described in Sumpton et al. 1994. Male crabs with a modified abdominal flap indicating the presence of an interna as well as individuals with abdominal scars (i.e. from a dislodged externa) were also recorded (see Figure 26 for photos showing parasitised and non-parasitised crabs).

Thoracic muscle tissue and internal organs of each sampled crab were also examined macroscopically for evidence of microsporidian infection by *Ameson* and infection by the dinoflagellate, *Hematodinium*. Crabs infected with either of these parasites often displayed no external signs of infection, but internal examination of infected crabs showed that muscle tissue lost its normal translucent appearance and took on a white grainy texture. Infection by *Hematodinium* in its later stages of development within the host often caused the haemolymph to take on a milky appearance and lightened the colour of the hepatopancreas. During the recent research, no histological sampling was undertaken to determine the prevalence of early stages of infection. In the past, gross pathology of *Ameson* and *Hematodinium* have been confused and this may have caused problems with historical comparisons of prevalence. We also examined the gills of crabs for the presence of *Octolasmis spp*., stalked barnacles known to infest blue swimmer crabs.

Results

The prevalence of *Sacculina granifera* infection of male crabs caught by commercial pot fishers varied among areas and years (Figure 27). The prevalence of *Sacculina granifera* in male crabs that were retained by commercial pot fishers was significantly less (t = 2.45 P < 0.01) than for females with rates approximately half those of females. The analysis included all mature female crabs (Figure 28) that were caught in pots and demonstrated that, at times, the rates of infection among females could be high (over 20%). Due to the fact that individual fishers targeted different areas of varying parasite prevalence, it was not statistically valid to compare historical samples temporally for statistical significance, and we only report here on trends which only highlight any possible major differences over the time series. There was no significant difference (P>0.05) in the prevalence of the parasite in Hervey Bay and Moreton Bay, but the offshore areas of Bribie to Fraser Island had a significantly lower prevalence of the parasite than either of the embayment fisheries for both sexes. During 1985 and 1986, *Sacculina* was present in up to 3% of crabs in the Bribie to Fraser area but in none of the sampling since then did the prevalence exceed 1% in the broader Sunshine Coast area.

Figure 26: *Sacculina granifera* infected female (on bottom left) and male (on bottom right) blue swimmer crabs with externa clearly visible beneath the abdominal flap. Unparastised ovigerous female and normal male crabs are shown above.

We noted in the previous chapter that only one fisher was constant throughout the time series of 30 years. The prevalence of *Sacculina* in his catch is shown as a reference line in Figure 27 and Figure 28.

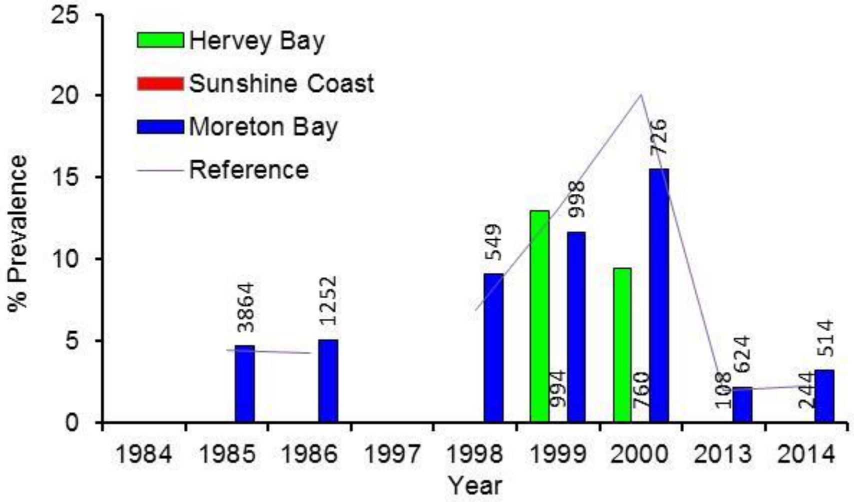


Figure 27: Change in the prevalence of *Sacculina granifera* in male blue swimmer crabs caught in pots from various areas in Southern Queensland

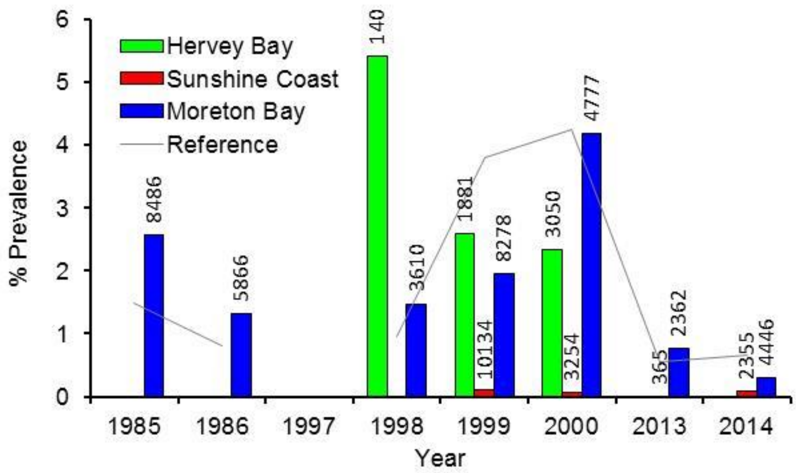


Figure 28: Change in the prevalence of *Sacculina granifera* in female blue swimmer crabs caught in pots from various areas in Southern Queensland. Sample sizes are shown above each bar.

(a) (b)

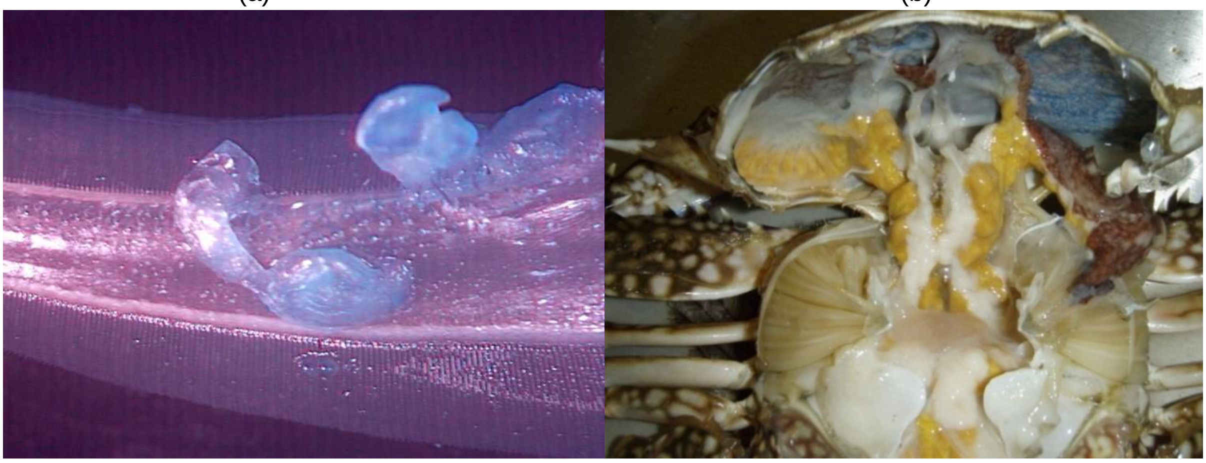


Figure 29: (a) Goose neck barnacle on the gill of a blue swimmer crab. (b) Ameson infection of a blue swimmer crab (Note change in color of muscle tissue).

Goose neck barnacles were still common on the gills of blue swimmer crabs (Figure 29a) in all sample areas with no apparent long term temporal trend. Advanced stages of infection by *Ameson* and *Hematodinium* were not common in sampled blue swimmer crabs from either Moreton Bay or the Sunshine Coast, with the prevalence of advanced stages of infection less than 1% in pot caught samples in any year.

Discussion

There is currently no evidence to support parasitism or disease as being responsible for lower catch rates reported in some areas post the 2011 flood, although we have no current information to update the Hervey Bay data which was last collected 14 years ago in 2000.

The similarity in female prevalence rates for pot caught and trawl caught crabs noted in earlier studies (Sumpton et al. 2003) suggests that an infected female crab will have the same probability of capture in pots as an uninfected crab. This is important as it validates the use of pots as a sampling tool for representative sampling of diseased crabs (at least within the size range sampled). The rates determined during the most recent period of sampling (2013 and 2014) are similar to historic rates, although sample sizes were lower and, again, there is considerable spatial and temporal variation among the studies.

As mentioned earlier, the sampling of different areas within regions during the three different times that research has been conducted on blue swimmer crabs, complicates the detection of long-term temporal changes in infection rates. The samples collected outside Moreton Bay during the 1980s were taken from areas just east of Bribie Island because the fishery had not expanded into more remote offshore waters further to the north and east. During the 1990s, fishing effort spread further outside Moreton Bay to greater depths and more oceanic conditions. Temporal differences in prevalence rates may also be a reflection of small-scale spatial variations in sampling intensity. *Sacculina* prevalence in blue swimmer crabs is known to vary dramatically over both small temporal and spatial scales (Sumpton et al. 1994). Some fishers tend to avoid areas that have high rates of infection as some pots positioned in areas of only a few hundred square metres had a very high proportion of parasitised crabs in the catch where they were absent from areas immediately adjacent.

One interpretation of the low prevalence of *Sacculina granifera* infection in oceanic waters from recent samples is that the offshore areas are not heavily reliant on recruits from the embayment areas. However, it is also possible that parasitised crabs may remain inside Moreton Bay due to behavioral modification. Such a mechanism has been described for *Carcinus maenas* by Rasmussen (1959) who found that parasitised individuals remained within the bays.

Parasitism by *Hematodinium* has been known to cause significant mortalities in crab fisheries in other areas of the world, particularly the USA. While dead blue swimmer crabs were often seen in pots, these mortalities were caused by a range of factors including predation by octopus, sea lice and other marine predators, or from antagonistic interactions with other crabs. The present study showed no evidence for an increase in this mortality, and industry have generally not highlighted any increase in cryptic mortality of blue swimmer crabs in their pots.

Gannon and Wheatly (1992) found that high infestation rates by *Hematodinium* caused physiological stress on the closely related blue crab (*Callinectes sapidus*) in the USA. Crabs with massive infestation did not survive the stress of experimental handling, and displayed a higher incidence of experimental mortality when subjected to aerial exposure and elevated temperatures (Gannon and Wheatly, 1988). The present study used larger experimental crabs than previous studies and the high barnacle load on *Portunus armatus* may potentially cause high mortality for crabs that are stressed in other ways. This could be particularly relevant for commercially caught crabs harboring heavy barnacle loads. Such crabs that are stressed during handling may suffer high rates of post discard mortality, thereby adversely impacting on the fishery. Recent sampling, and the generally low infestation rates, suggests this is highly unlikely to be the case.

5. Environmental Influences on the Fishery

Introduction and Methods

The blue swimmer crab fishery exhibits strong seasonal variations in catch that are broadly consistent from year to year. Typically in Moreton Bay, catch rates increase during the spring from a winter low, declining again in summer before reaching the usual autumn peak (March/April). Trends offshore do not follow the same strong pattern, although there does tend to be a seasonal component to catch. This relatively consistent annual cycle is certainly related to patterns of recruitment and growth, but may also be affected by environmental factors such as temperature and rainfall, since catch rates within the fishery are generally lowest during winter. The relatively rapid growth rate and relatively short life cycle of blue swimmer crabs means that a single year class (or at most two year classes), the strength of which could be influenced by environmental factors during the spawning season and early juvenile development stages, is responsible for the bulk of the catch. The success of the annual recruitment, as well as subsequent growth of the 0+ year cohort (in particular), may thus be influenced by environmental conditions at critical times of the life cycle. The fact that there is a trend for juveniles to have a higher relative abundance in the western side of Moreton Bay (Sumpton et al. 1994) also makes them vulnerable to the effects of river flow and flooding events that can dramatically reduce salinities, particularly in the southern and western parts of Moreton Bay and parts of western and southern Hervey Bay.

We collated river flow data from both the Mary River and Brisbane River and these are presented in Figure 30.

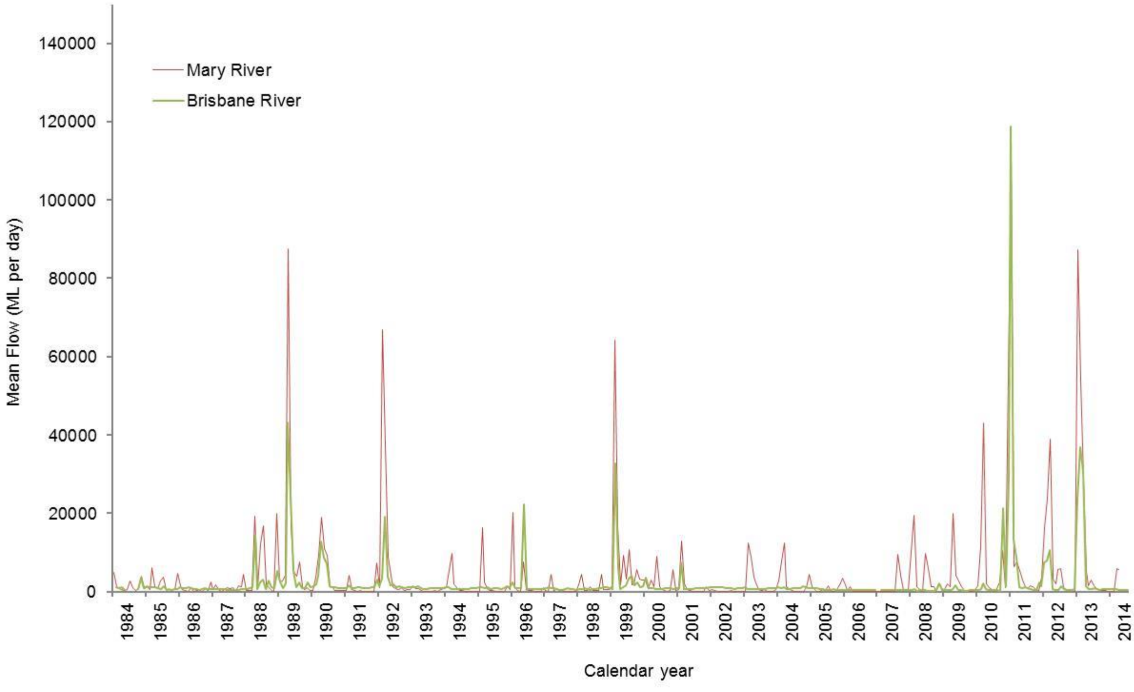


Figure 30: Relative mean daily flow of Mary River and Brisbane River based on recorded flows of upstream reference stations from 1984 to 2014.

It is important to note that these flow figures do not represent the actual flow into the two embayments but are more of a reference to provide an indication of the broad scale temporal variation in relative flows.

In addition to the broader seasonal cycles in catch rates described earlier, there are small-scale daily variations where catches can vary by more than 50% from day to day (commercial fisher observations and CFISH data). These finer scale changes are believed by fishers to be due to the effects of tide, wind, temperature and other factors. Research conducted on other crab species has confirmed the importance of all these factors in determining both recruitment success and the growth of the individual crabs. While the small-scale variations are interesting, it is the large-scale annual variations that are the most relevant to both the fishers and managers since it may be possible to link year class strength and catches with environmental factors.

In this chapter we discuss the possible influences of the environment on blue swimmer crabs relying on earlier work where temperature and the Southern Oscillation Index were investigated as influences on blue swimmer crab catch. We also discuss recent flood events and possible impact of river flow on blue swimmer crabs.

Results/Discussion

Previous research has found little variation in temperature between sites within Moreton Bay with much of the variation associated with water depth, rather than actual spatial effects (at least on a fine scale (Sumpton et al*.* 2003)). In the earlier study catch per unit effort (CPUE), data from 1996 to 2000 were compared against variables such as sea surface temperature taken from a wave rider buoy situated off Point Lookout, North Stradbroke Island (just outside Moreton Bay) and monthly Southern Oscillation Index (SOI) values.

Of the variables tested, fishing effort was the main factor influencing catch, and temperature was only a relatively minor explanatory variable (at least on a small scale). The lack of a tight relationship between catch rates and temperature suggests that other factors were also contributing to the daily variations in catch rates so there may be a lag in the effect of temperature. Broadly speaking, there is a seasonal pattern to moulting with little moulting activity during the winter months when crabs tend to be less active. Once temperatures increase in spring, over-wintered crabs resume moulting, but there are no specific times when moulting takes place since moulting activity (as evidenced by the proportion of “soft” crabs in both fishery dependent samples and research samples) occurs throughout the year. Lunar trends may also play a role in determining environmental influences, as periods of elevated temperature during the warmer months of the year were also associated with tidal influences, causing higher temperatures in shallow areas (Sumpton et al 2003). This could be exacerbated by using baited traps as a sampling method. The movement of the “bait odour plume” influences the attraction of crabs to baited traps. Fishers have noted that there are optimal tidal currents for maximising catch. Too little tidal run and there is insufficient dispersion of the bait plume, while too much run results in bait plumes dissipating too rapidly.

The lack of small-scale spatial resolution in the logbook data may be problematic for any analysis of environmental impacts within Moreton Bay. This is caused by the practice of some fishers recording daily catches as averages over a week. A greater problem is recording practice of fishers to record daily catch averages over a week. These practices would “smooth out” the small scale daily variations in catch and significantly impacts on the ability to determine the impact of various environmental parameters, which may change over quite small spatial and temporal scales. Similarly, rainfall affects the western bay far more than the eastern bay.

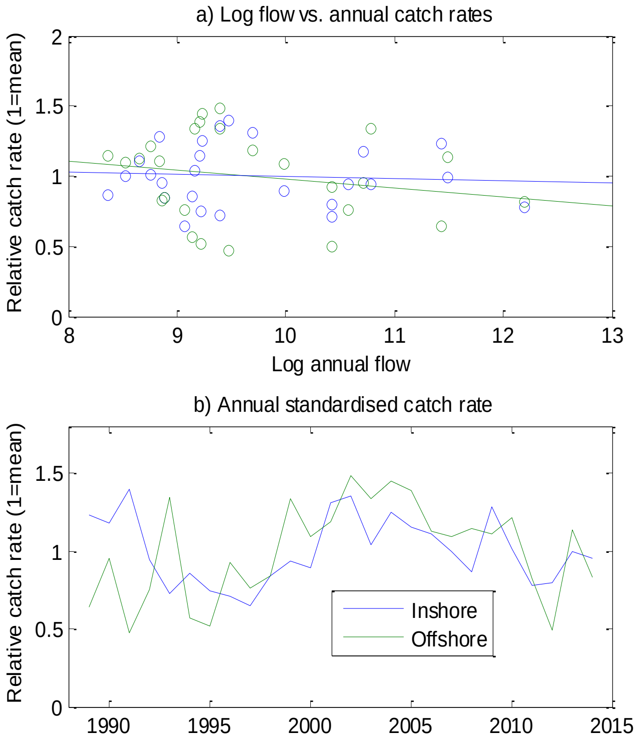


Figure 31: (a) Catch rates in inshore and offshore blue swimmer crab fisheries relative to river flows and (b) Annual change in standardised relative catch rate of inshore and offshore blue swimmer crab fishery.

Unlike the small-scale environmental effects, a major seasonal shift in temperature or rainfall may impact spawning, recruitment or even survival of either juveniles or adults. Figure 31 shows that there is only a very weak correlation between blue swimmer crab catch rate and river flow, and virtually no difference between the effects for the Moreton Bay fishery (inshore) and the Sunshine Coast fishery (offshore), despite the expectation that flow would most likely impact on areas closer to the rivers and estuaries where the effects of freshwater runoff would be greatest.

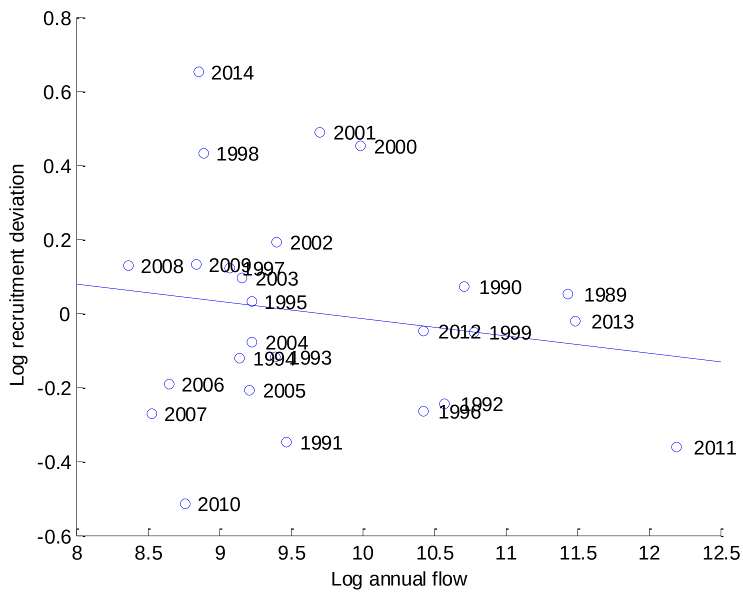


Figure 32: Correlation between river flow and recruitment deviation for blue swimmer crab Moreton region population.

Similarly, recruitment was only weakly correlated with flow (Figure 32), although the 2011 flood was noticeable in terms of low predicted recruitment. Ocean warming events, such as those experienced in Western Australia, have had dramatic effects on fisheries resources but it appears unlikely that temperature has a dramatic impact on small-scale daily variations in catch rate. Fishers have often speculated about environmental influences affecting their catch. Many fishers note that too much or too little rain during the summer months can impact on the fishery. This was possibly evident during the last four years when major flooding events may impact negatively on the blue swimmer crab fishery. Although this cannot be categorically proven as there was only a weak correlation between flow and recruitment as described earlier.

There has always been much debate on the effects of wind on catch rates. Traditionally, fishers have noted an increase in catch rates in the northern bay after a period of SE winds and, conversely, those in the south have suggested that their catch rates are improved after a period of northerly winds. The influence of wind is also supported by data presented in Campbell and Sumpton (2004) which showed elevated catch rates in ghost fishing experiments after a period of strong southerly winds. Linking wind with catch rates recorded in the logbooks is possible, but the spatial and temporal data resolution difficulties described previously for the temperature data also impact on the analysis of the effect of wind. There were also difficulties in determining an appropriate lag period to apply, as well as determining an appropriate way of treating different duration and strengths of wind conditions. Wind effects are complicated to model because of colinearity of some of the factors. The fact that wind has been found to be important in a range of crustacean fisheries that rely on inshore recruitment of larvae and juvenile life history stages, suggests that it is also an important factor affecting the blue swimmer crab fishery. The linkage of BSC catch and environmental effects is still an important area for ongoing research.

6. Commercial Fishery Economics

Introduction and Methods

The blue swimmer crab pot fishery in South East Queensland operates in inshore and offshore waters with a wide range of different business structure operating in the fishery. These range from a minority of fishers that rely on blue swimmer crabs for their sole income to fishers who only rely on the incidental catch of blue swimmer crabs for a negligible part of their fishing related income. In this chapter we describe some of the economic detail relevant to the blue swimmer crab pot fishery. These data are used later in the chapter that presents the population model and overall stock assessment to investigate potential economic yields in the fishery. We only investigate the commercial pot fishery in this analysis as the trawl fishery largely takes blue swimmer crabs as an incidental by-product, and it is more difficult to attribute costs to a relatively minor part of a trawl operator's income.

Table 3: Questionnaire used to gather information from commercial pot fishers. Fixed costs were scaled up or down depending on the proportion of their fishing income that was derived from blue swimmer crab fishing.

Units/ Measure	Description (related to BSC only)
Metres	Vessel size
Horsepower	Vessel engine/motor power
Days	Number of days BSC crabbing last calendar year
	Proportion of income derived from BSC crabbing
1, 2 or 3	Number of pots <50 (1), 50 - 100 (2), 101 to 150 (3)
MB, SC, HB, Other	Region usually fished
Small, Medium, Large	Self-categorization (size of operation)
Main fishing season	Months usually fished
(% per year or description)	How much has your fishing effort increased over time
Profitable catch kg/day	What level of catch do you consider profitable
Variable Costs	
$ per boat-fishing day	Deckhand (proportion of catch)
$ per boat-fishing day	Boat repairs/maintenance
$ per boat-fishing day	Fuel cost
$ per boat-fishing day	Bait cost
$ per boat-fishing day	Gear replacement (and loss) and maintenance
$ per boat-fishing day	Cooking and processing (gas, chlorine, chemicals)
$ per boat-fishing day	Motor vehicle (registration/maintenance/fuel)
$ per boat-fishing day	Other variable cost 1 (describe in a cell comment)
$ per boat-fishing day	Other variable cost 2 (describe in a cell comment)
Fixed Costs	
$ per boat-yr	Licensing and permit fees (fishing and processing)
$ per boat-yr	Insurance costs
$ per boat-yr	Electricity costs for freezers etc
$ per boat-yr	Mooring/slippage
$ per boat-yr	Other fixed cost 1 (describe in a cell comment)
$ per boat-yr	Other fixed cost 2 (describe in a cell comment)
$	Selling price of your boat and crabbing gear

A survey was conducted via face to face interviews and over the telephone. The questionnaire (Table 3) examined the fishery at the three broad regions used in the later modelling (Moreton Bay, Sunshine Coast and Hervey Bay) and gathered information on general fishing operations (size of vessel, engine horsepower, days fished, etc.), variable costs (fuel, bait, gear loss etc.) and fixed costs (licence fees, insurance, registration etc.). In the case of fishermen who were involved in other fishing activities, the proportion of the costs attributed to the blue swimmer crab fishery were recorded, as were fishers assessment of daily catch rates required to achieve profitability.

Table 4: Number of questionnaires completed by various subsets of commercial pot fishers in SE Queensland.

Number	Description
70	Contacts from a total of 85. The extra 15 were “double-ups” of the same crabber i.e. duplications due to business names, or use of wife’s name
3	Numbers incorrect or cancelled
13	No answer
5	Refused interview
10	Leased out licences and no longer crabbing
5	Not currently crabbing (2 had sold endorsement)
4	Mud crabbers with incidental blue swimmer crab catch
6	Contacts provided by leasers
36	Total number of completed interviews
24	Interviews Moreton Bay
6	Interviews Sunshine Coast
6	Interviews Hervey Bay

The responses were drawn from an initial contact list of 85 fishing businesses that had recorded landings of more than 250 kg of blue swimmer crab in the last calendar year (Table 4). Of the 85 contacts listed, 15 were duplications due to use of a partners name or business names, 3 of the contact’s numbers were incorrect or cancelled; and 13 contacts never answered repeated phone calls. Of the 67 fishermen successfully contacted 5 declined to be interviewed, 4 were mud crabbers with incidental catch, 2 had sold their licence or endorsement, 3 were not currently working in the industry and 10 were not crabbing but had leased out their licence or endorsement. The remaining 30 fishermen completed the survey with an additional 6 surveys completed from contacts supplied by fishers who were leasing out their licences.

Results/Discussion

The largest number of respondents was drawn from Moreton Bay while there were only 6 interviews each conducted in both the Sunshine Coast fishery and Hervey Bay fishery. The average number of days fished was higher in Moreton Bay compared to the other two regions (Figure 33). Income from the fishery differed both within and between regions with some fishermen earning as little as 5% of their incomes from blue swimmer crabs, whilst very few relied on the fishery for 100% of their income. In Moreton Bay, 50% of the fishermen interviewed made ≤ 30% of their income from blue swimmer crabs, whilst 24% (6) of the fishermen relied on blue swimmers for ≥80% of their income. Reasons for this included some of the Moreton Bay fishermen targeted blue swimmer crabs only during the peak season, seasonality of other fisheries and some ran additional non-fishing businesses. In contrast, the Sunshine Coast fishery had most fishermen fishing both in the spanner crab fishery and in the blue swimmer crab fishery, with an average 58% of income derived from the blue swimmer crab fishery. In Hervey Bay, the average income from blue swimmers crabs was only 23%. However, for the majority of the fishermen in this region, blue swimmers were either an incidental catch or fished during the peak season only.

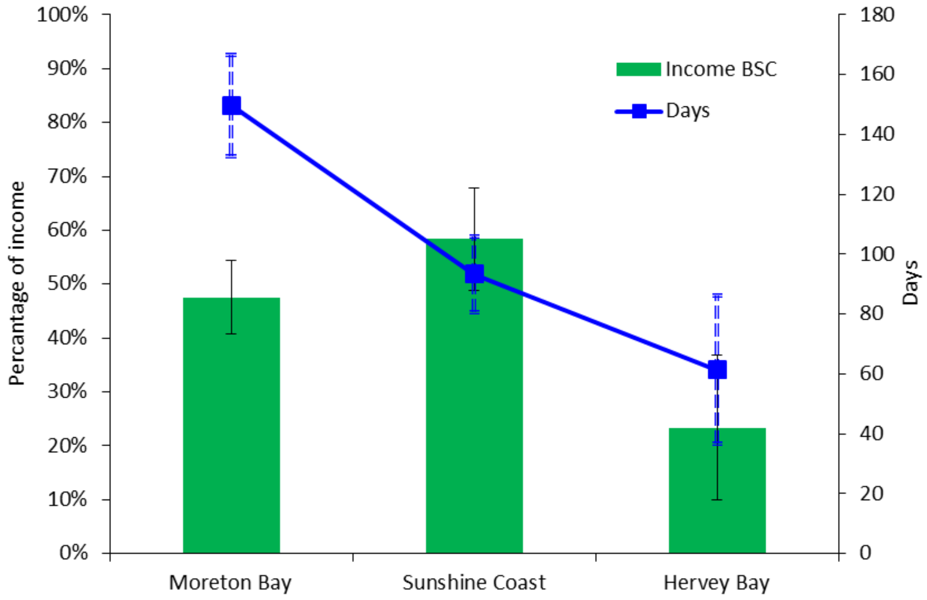


Figure 33: Income from blue swimmer crabs and days fished per year in each region. Bars are standard error.

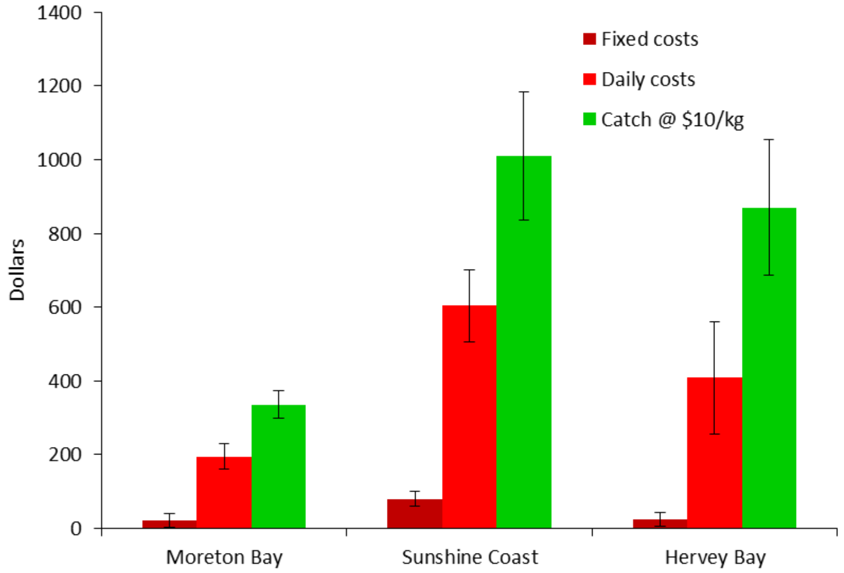


Figure 34: Daily costs, fixed costs per day and catch required to be profitable at $10/kg

Variable and fixed costs across the different regions reflected differences in the logistics of operating in sheltered embayment conditions close to port (e.g. Moreton Bay), compared with more remote offshore environments (e.g. Sunshine Coast and parts of Hervey Bay). Daily variable costs were lower on average in Moreton Bay (Figure 34) due to the smaller relative vessel size and reduced fuel costs due to shorter distances travelled. The Hervey Bay fishery, in reality, includes both inshore and offshore components, and this is reflected in the high variance in costs and vessel characteristics. For example, in Moreton Bay the average vessel size is 5.7 m. In contrast, the Sunshine Coast fishery operates in offshore waters and, therefore, larger vessels are used (average 9.5 m), whilst the average vessel size in Hervey Bay is intermediate at 7.9 m. With the use of larger vessels, fixed and daily costs are higher than those of Moreton Bay fishers (Figure 35).

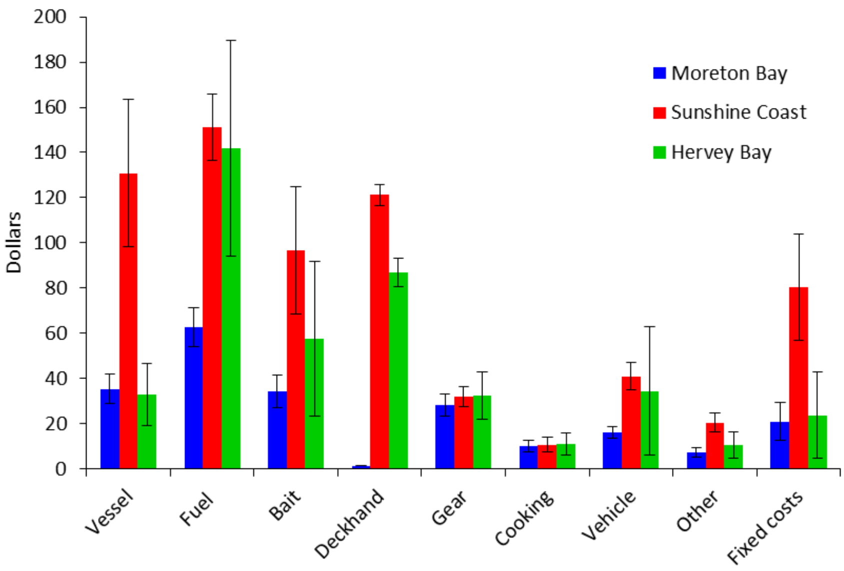


Figure 35: Average variable daily costs ($) and fixed daily costs attributed to the blue swimmer crab fishery within each fishing region.

Cost of vessel maintenance is higher in the Sunshine Coast fishery due to insurance costs and increased costs associated with mooring the generally larger vessels. Fuel costs are obviously higher for both the Sunshine Coast and Hervey Bay regions due to the greater distances covered in the course of a day's fishing. Another cost that the Moreton Bay fishery doesn't have in common with the offshore fisheries is the cost of deckhands. Fishers in the Sunshine Coast and Hervey Bay fishery tend to run more pots resulting in higher costs than for those fishing in Moreton Bay. With the need to purchase and store more bait comes associated costs such as electricity to run freezers.

Of note is that on a daily basis, the gear costs are nearly the same across all three fisheries. However, most Moreton Bay fishers run less gear (pots), and the reason the gear costs are the same across the fisheries is the substantially higher costs, due to higher levels of pot loss experienced by Moreton Bay fishers, presumably due to greater levels of fishing effort and increased likelihood of theft.

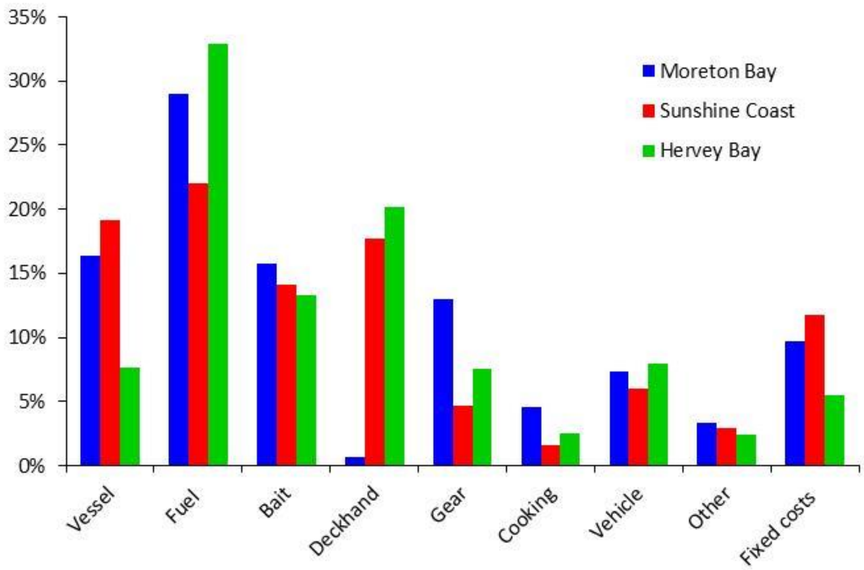


Figure 36: Average daily costs as a percentage of the total daily costs in the three fishing regions.

Gear loss makes up a larger component of the daily costs of Moreton Bay fishermen when compared to fisheries in the other two regions (Figure 36). Whilst the vessel and fuel proportional daily costs are similar in the Moreton Bay and Sunshine Coast fisheries, the overall costs to fishermen in Moreton Bay are lower.

Questionnaire respondents in Moreton Bay required an average of 33.5 kg/day (range 10 to 80 kg) to record a profit. This equates to a catch of approximately two crabs per pot when using 50 pots. Historical catch rates show that in the years 1984-1986 (when the MLS was 150 mm), equivalent catch rates were only obtained, at most, for two months (March and April) each year (Sumpton *et. al*. 1989). Given that the current MLS is approximately 10 mm smaller than this, any increase in the legal size could result in lower catch rates with a concomitant reduction in profitability.

Catch rates reported to achieve profitable catches for the average fisher crabbing in Hervey Bay and the Sunshine Coast were 87 kg per day (range 40 to 150) and 101 kg per day (range 50 to 150) respectively. Such catch rates are virtually impossible to achieve under current pot restrictions (50 pots) in these areas for most of the year and, clearly, the current permit system allowing the use of additional pots is the only reason that allows this fishery to continue to operate. The challenge is to improve returns to fishers for economic efficiency while achieving overall goals of effort reduction. In addition, the range of business structures (and wide range in reported catch rates to achieve profitability) indicates that it may be unwise to rely on average conditions of profitable catch rates to represent the fishery.

We have already noted that there is diversity in catch rates that are considered to be profitable, but there are few fishers who would nowadays consider catch rates of fewer than two crabs per pot profitable.

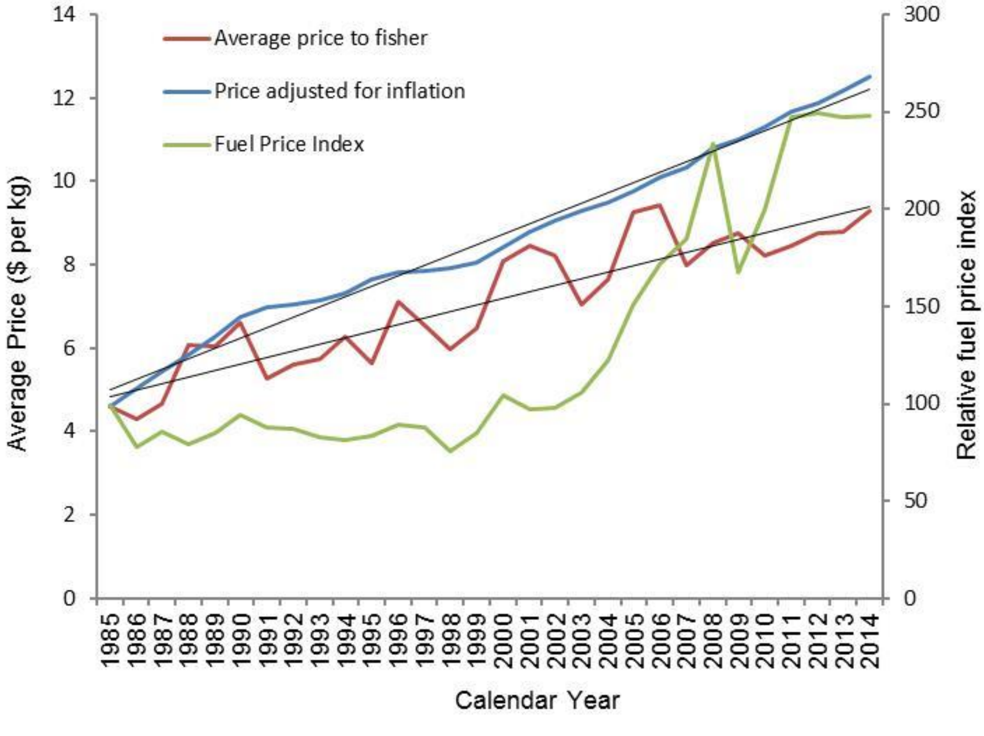


Figure 37: Fuel price index and average annual price of blue swimmer crabs to commercial fishers and price adjusted for the compound effects of inflation from 1985. Trend lines are shown as thin black lines.

Financial conditions in the blue swimmer crab fishery have been challenging for commercial pot fishers during the last 10 years in particular. Trends in price received for their product has not kept up with inflation (see trend lines in Figure 37). Despite this, recent trends (last three years) in fuel costs have been more favorable. We have not fully quantified other variable costs, the most significant relates to the manufacture of crabs pots which has been impacted by the rising price of steel in recent years.

In conclusion the economic analysis highlighted the great diversity of business structures and the difficulty in categorizing a typical fishing business, particularly in inshore areas where fishers tend to be “mixed fishers” relying on a range of different fisheries for their income. The variable cost structures result in widely different perceptions on what is considered to be profitable.

7. Population Modelling and Stock Assessment

Introduction

There has not been any previous attempt to construct a population model of the blue swimmer crab fishery in Queensland. Simple yield per recruit modelling has been conducted in several Australian states and several models were reported by Sumpton et al. (2003). Sumpton et al. (2003) reported the yield-per-recruit supported a minimum legal size (MLS) of under 12 cm base width assuming: a) deterministic equilibrium conditions, b) constant recruitment that prevented overfishing, c) full vulnerability to fishing across all sizes >= MLS, and d) the objective was to maximise number of crabs harvested rather than yield in weight. Simple biomass dynamics models (Schaefer) were also presented, but these generally failed to fit the time series of available catch and effort data that were available at the time (up to 2002) (Sumpton et al. 2003). Since that report, there are now an additional 12 years of commercial data and considerable advancement in our ability to model the dynamics and economic conditions of our fisheries. In this chapter we present a blue swimmer crab population model that estimates both maximum sustainable yield (MSY) as well as an economic reference point for maximising economic yield (MEY) from the fishery. Analyses were conducted for the Moreton (Moreton Bay and Sunshine Coast areas) and Hervey Bay fishing regions separately due to the different characteristics of these fisheries and the possibility of separate stocks.

Materials and Methods

Population Model and Parameters

The blue swimmer crab population model had a monthly time step and tracked numbers (N) and biomass (B) of crab by their sex (s) and length (*l*) (Table 7), and included the processes of mortality, growth and recruitment in every month (t). The model was run for the Moreton Region (Moreton Bay and Sunshine Coast) and Hervey Bay crab stocks separately, with different estimated parameters. For Moreton Bay, three competing sources of fishing mortality were considered: (1) Moreton Bay commercial sector for pot and trawl fishing (size vulnerability assumed equal); (2) Moreton Bay recreational pot sector (size vulnerability assumed equal to commercial fishing in (1)); and (3) Sunshine Coast (outside) Moreton Bay commercial pot sector and trawl (different size vulnerability to (1) and (2) with larger crab harvested). For Hervey Bay, only two competing sources of fishing mortality were modelled assuming equal size vulnerability: (1) Commercial pot and trawl sector, and (2) Recreational pot sector.

Historical simulations were conducted of the blue swimmer crab stocks for the fishing years 1989 to 2014. Due to limited historic catch reporting prior to 1989, it was unfeasible to start the model from earlier years or at an unexploited state (virgin population). The model, therefore, assumed the population was at equilibrium at the start of the 1989 fishing year with respect to each sectors' average monthly harvest or effort 1989–1991. This same method to initialise population conditions was used to model Southern Rock Lobster (McGarvey et al. 2014). We recognise that this assumption may not mimic the long term pattern of expansion of Queensland crab fisheries (Figure 1), but the lack of a species-specific time series necessitated a compromise to initialise suitable model conditions.

Model parameters were estimated by calibrating the model using negative log-likelihood functions for standardised catch rate and size-composition indices (Table 8). Additional likelihood functions were also evaluated to estimate recruitment compensation (r_{max}), natural mortality (M) and annual recruitment variation (Table 9). The estimation process was conducted in Matlab® (MathWorks, 2014), and consisted of maximum likelihood fitting for all analyses followed by Markov Chain Monte Carlo sampling (MCMC) for Moreton scenarios 1 and 3, and Hervey Bay. The MCMC used parameter by parameter jumping following the Metropolis-Hastings algorithm described by Gelman et al. (2004). The MCMC was run in two stages: (1) first to estimate the parameter covariance matrix and to customise the jumping of parameter samples, then (2) simulate posterior parameter distributions with fixed covariance. Final parameter distributions were based on 1000 posterior samples (with thinning rate = 100), which were analyzed using "coda" package of the software R to document MCMC performance (Plummer et a. 2006).

Model simulations of posterior samples were used to estimate uncertainty in equilibrium management reference points for Moreton scenarios 1 and 3 (Table 5) and Hervey Bay. Equilibrium reference points for maximum sustainable yield (MSY tonnes) and maximum economic yield (MEY tonnes) were calculated by optimising the population and economic models (O'Neill et al. 2014) through mean monthly fishing mortality. The population dynamics were propagated to equilibrium using the estimated mean monthly fishing mortality rate, adjusted according to each sectors' monthly average fishing patterns and harvest fractions calculated from the last five years.

A total of 10 different model scenario runs are presented here with the base fit being described by the parameter set shown in Table 5. Detailed descriptions of the parameters for each scenario are presented in Appendix 2 as are various model diagnostic and goodness of fit plots.

Table 5: Specifications of each Scenario used to analyse the model sensitivity to parameters or data for the Moreton region. See Appendix 2 for detailed description of the respective parameters. Growth for each scenario is described in Table 19.

Variable/ parameter	Scenario									
	1	2	3	4	5	6	7	8	9	10
M	0.1	0.15	est.	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Price by CW	Uniform	Uniform	Uniform	High	Low	Uniform	Uniform	Uniform	Uniform	Uniform
Growth	a	a	a	a	a	a	a	b	c	a
Catch rate offset	yes	yes	yes	yes	yes	yes	no	yes	yes	yes
Rec. harvest	decline	decline	decline	decline	decline	constant	decline	decline	decline	decline
Vulnerability	est.	est.	est.	est.	est.	est.	est.	est.	est.	fixed

We examined the sensitivity of the modelled outputs to natural mortality (*M*), growth rate, offsets to fishing effort (allowing for increases in effective fishing effort based on increasing pot numbers), price and recreational harvest (Table 5). We allowed the model to estimate the rate of natural mortality and also included two runs when monthly instantaneous mortality was 0.1 (base case) and 0.15 with all other parameters, as described in the base case. Three different growth scenarios were modelled and three price schedules. We also allowed for a constant recreational effort, as well as a declining time series of effort, based on the participation rates of recreational fishing obtained from Taylor et al. (2012).

Table 6: Equations used for simulating blue swimmer crab population dynamics. **Equations**

Number of crabs:

$$N_{l,t,s} = \exp\left(-Z_{l,t-1,s}\right)\sum_{l'}\Xi_{l,l',t-1,s}N_{l',t-1,s} + 0.5R_{l,t} \quad (1)$$

Recruitment numbers — Beverton-Holt formulation:

$$R_{l,t} = \frac{\tilde{E}_{y-1}}{\alpha + \beta\,\tilde{E}_{y-1}}\exp\left(\iota\log\left(\text{env}_{y-1}\right)\right)\phi_t\Lambda_l\exp\left(\eta_y\right), \quad (2)$$

where y indicated the fishing year, env the environmental variable for river flow into the Bay areas.

Spawning index — effective annual spawning biomass:

$$\tilde{E}_y = \sum_s\sum_t\sum_l N_{l,t,s}m_{l,s}w_{l,s}\theta_t \times 10^{-3} \quad (3)$$

Recruitment pattern — normalised monthly proportion:

$$\phi_t = \exp\left[\kappa\cos\left\{2\pi(t-\mu)/12\right\}\right] \Big/ \sum_{t'=1}^{12}\exp\left[\kappa\cos\left\{2\pi(t'-\mu)/12\right\}\right], \quad (4)$$

where t indicated time-of-year months 1…12. A further mixing parameter π was tested to explore a bimodal recruitment pattern, with μ_1 and μ_2, and common κ.

Mid-month exploitable biomasses—forms 1 and 2:

$$B^1_{t,\text{f}} = \sum_l\sum_s N_{l,t,s}w_{l,s}v_{l,\text{f}}\exp\left(-M/2\right), \text{ and}$$

$$B^2_{t,\text{f}} = \sum_l\sum_s N_{l,t,s}w_{l,s}v_{l,\text{f}}\exp\left(-M/2\right)\prod_{\text{f}}\left(1-u_{t,\text{f}}/2\right), \quad (5)$$

where f indicated the sectors.

Survival:

$$\exp\left(-Z_{l,t,s}\right) = \exp\left(-M\right)\prod_{\text{f}}1-v_{l,\text{f}}u_{t,\text{f}},$$

where commercial $u_{t,\text{f}}$ was calculated iteratively allowing for competing harvest rates on male crabs between fishing sectors:

$$u_{t,\text{f}} = \frac{C_{t,\text{f}}}{\exp\left(-M/2\right)B^1_{t,\text{f}}\prod_{\text{f}'\neq\text{f}}\sqrt{1-v_{l,\text{f}'}u_{t,\text{f}'}}}, \quad (6)$$

$u_{t,\text{f}=\text{rec}} = 1-e^{-q_{\text{rec}}E_{t,\text{rec}}}$ was the recreational harvest rate, and C was a fishing sectors monthly harvest kgs. As harvest of female crabs are prohibited, $u_{\text{female}} = 0$.

Crab vulnerability to fishing:

$$v_{l,\text{f}} = \frac{1}{1+\exp\left(\delta\left(l^{50}_{\text{f}}-l\right)\right)}, \quad (7)$$

where required, the schedule accounted for minimum legal size of male crab. Note minimum legal size changed from 15cm total carapace width (spine tip-to-tip) to 11.5cm base-spine carapace width in December 2003.

Population indicators—catch rates by indicator:

$$c^{\text{f}}_t = q^{\text{f}}(t)B^2_t\exp\left(\varepsilon^{\text{f}}_t\right), \text{ Commercial (f; kg boat-day}^{-1}\text{):}$$

$$c^{\text{s}}_y = q^{\text{s}}\bar{R}_{y(4,5)}\exp\left(\varepsilon^{\text{s}}_y\right) \text{ Survey (s; number trawl-shot}^{-1}\text{):}$$

$$c^o_t = q^o\sum_l B^2_{l,t}\Big/w_{l,s}\exp\left(\varepsilon^o_t\right) \text{ for fishing months = Oct(4) and Nov(5) Observer (o; No. pot-lift}^{-1}\text{):} \quad (8)$$

Recreational harvests:

$$C_{t,rec} = \frac{F_{t,rec}}{Z_t}B^2_{t,rec}1-\exp\left(-Z_t\right) \quad (9)$$

Table 7: Definitions and values for the population model parameters.

Model parameters	Equations, values and errors	Notes
Assumed		The values and errors were calculated from published research or data. Length = carapace width measured across large spin tip-to-tip.
Ξ	$l_{\infty,s} = [19.5, 22.5]$ $k = 1.830$ $\theta = [1.640, 0.949]$ $z(t) = k + \theta_1 \cos(2\pi t) + \theta_2 \sin(2\pi t)/12$ $\alpha_{l,t,s} = E(l_{l,t,s})/\beta$	Growth transition matrix allocated a proportion of crabs in carapace length-class l' at time *t*-1 to grow into a new length l over one time-month *t*. The transitions varied with crab sex *s* and month *t*, and assumed a gamma probability density function (Haddon, 2001; Quinn and Deriso, 1999a). The growth model was based on the seasonal and non-seasonal estimates of crab growth. Their annual growth rate z(t) was integrated per time-month *z(t)*. The gamma distribution β parameter was derived from tagging data which defined the variance of the mean monthly growth increment $\bar{\Delta}_{l,s}$, in cm. (See Appendix 1 and 2)
Λ	Summary percentiles [2.5 25 50 75 97.5] = [2.35, 3.30, 3.94, 4.70, 6.60] cm.	Proportion of crab recruitment in length class l (0.5…23 cm). The proportions were calculated from a lognormal distribution for length at recruitment, based on trawl monitoring data in fishing years 1984 and 1985. The frequencies were approximately equal for male and female crab.
w	$w_{l,s} = a_s l^{b_s}/1000$, $a_{\text{male}} = 0.00000855, b_{\text{male}} = 3.466$, $a_{\text{female}} = 0.0000931, b_{\text{female}} = 2.984$	Average crab weight (kg) at length l mm for sex *s*.
f	$f_l = al^b$ $a = 31.605; b = 0.0144$	Batch fecundity (egg production) at length per female crab
m		Logistic maturity schedule by length (mm). The schedule was estimated using binomial regression and logit link, with parameters $\beta_0 = [-23.57965, -13.51291]; \beta_1 = [0.216872, 0.139929]$ for female and male crab.
θ	θ =[0,1,1,1,0,0,0,0,0,0,0,0]	Crab spawning by fishing month (Sumpton et al. 2003).

Table 7 continued

Model parameters	Equations, values and errors	Notes
Estimated	N≈11–13 (+ 26 with recruitment residuals)	The values and their variances and covariance's were estimated.
ξ, Υ and ι	$\alpha = E_0(1-h)/(4hR_0)$ $\beta = (5h-1)/(4hR_0)$ $R_0 = \exp(\Upsilon)\times 10^8$ $h = r_{\max}/(4+r_{\max})$ $r_{\max} = 1+\exp(\xi)$	Two parameters for the Beverton-Holt spawner-recruitment equation 2 (Table 6), that defined α and β (Haddon, 2001). Virgin recruitment (R_0) was estimated on the log scale. $\tilde{E}_0$ was the virgin effective egg production from equation 3. ι was the estimated environmental effect.
μ and κ		Two parameters for the estimated mode (μ) and concentration (κ) of the monthly recruitment pattern, equation 4; according to a von Mises directional distribution (Mardia and Jupp, 2000).
l_f^{50} and δ	l_1^{50} for fishing in the Bays. l_2^{50} for fishing offshore.	Three parameters for the estimated logistic vulnerability, equation 7 (Table 6). δ governed the initial steepness of the curve and l^{50} was the length at 50% selection by fishing sector.
M	$N(0.1, 0.05)$	One parameter for instantaneous natural mortality month^{-1}, according to log-likelihood equation 13). The prior distribution allowed for 3–4 years maximum longevity (reference?).

ζ	$\boldsymbol{\eta} = \boldsymbol{\zeta}\mathbf{e}$
	e = zeros (nparRresid, nparRresid+1);
	for i = 1:nparRresid
	  hh = sqrt(0.5 * i ./ (i + 1));
	  e(i, 1:i) = -hh ./ i; e(i, i + 1) = hh;
	end; e= e ./ hh;
		Recruitment parameters to ensure log deviations sum to zero with standard deviation σ, equation 14). If estimated, ζ were the 26 estimated parameters known as barycentric or simplex coordinates, distributed $NID(0,\sigma)$ with number nparRresid = number of recruitment years – 1 (Möbius, 1827; Sklyarenko, 2011). $\mathbf{e}$ was the coordinate basis matrix to scale the distance of residuals (vertices of the simplex) from zero (O'Neill et al. 2011; O'Neill et al. 2014).

$q^f(t)$, q^s, and q^o	$q_f(t) = \exp\left(\log(q_f) + \varsigma\cos(t_{seq}) + \vartheta\sin(t_{seq})\right)$ $t_{seq} = 2\pi\,\text{seqmonth}/12$	Fishery catchability by sector was based on a sinusoidal function to model monthly patterns using the variable 'seqmonth'. As the maximum water temperature was in February, (2 parameters seqmonth = 1 in March and = 12 in February. The equation was defined through the amplitude (ς) and peak timing of catchability (ϑ). Each sectors overall catchability q_f was calculated as closed-form geometric mean of standardised catch rates divided by the mid-month biomass form 2 (Haddon, 2001). Survey and observer catchabilities were also calculated as a single closed-form geometric mean.

Table 8: Negative log-likelihood functions for calibrating population dynamics (O'Neill et al. 2014).

-LL functions for:	Theory description	Equations
Log standardized catch rates and recreational harvest (c): $\frac{n}{2}\left(\log(2\pi)+2\log(\hat{\sigma})+1\right)$, or simplified as $n\log(\hat{\sigma})$, where $\hat{\sigma}=\sqrt{\sum\left(\left(\log(c)-\log(\hat{c})\right)^2\right)/n}$ and n was the number of months or years with catch rate or harvest data (monthly for commercial and observer catch rates; yearly for survey catch rates and recreational harvests).	Normal distribution (Haddon, 2001)	(10)
Length (l) size-composition data: $-\sum\left(\log\left(\nu^{(\tilde{n}-1)/2}\right)-\left(\frac{1}{2}(\tilde{n}-1)\frac{\nu}{\hat{\nu}}\right)\right)$, or simplified as $-\sum\frac{1}{2}(\tilde{n}-1)(\log\nu-\nu/\hat{\nu})$, where $\tilde{n}$ was the total number of size categories (l) with proportion-frequency > 0, $\hat{\nu}=(\tilde{n}-1)/2\sum\hat{p}\log(\hat{p}/p)$, $\nu=\max(2,\hat{\nu})$ specified sample size bounds, $\hat{p}$ were the observed proportions > 0 and p were predicted.	Effective sample size (ν) in multinomial likelihoods (Leigh, 2011; O'Neill et al. 2011)	(11)

Table 9: Negative log-likelihood functions for parameter bounds and distributions.

-LL functions for:	Equation
Recruitment compensation ratio r_{max}: $0.5\left(\frac{\xi-\log(4-1)}{\sigma}\right)^2\times\left(\xi>\log(19)\right)$, where $\sigma=0.005$ defined the *–LL* penalty.	(12)
Instantaneous natural mortality M month^{-1}: $0.5\left(\frac{M-0.1}{\sigma}\right)^2$, where $\sigma=0.05$ defined the prior distribution.	(13)
Annual log recruitment deviates η_y: $\frac{n}{2}\left(\log(2\pi)+2\log(\sigma)+(\hat{\sigma}/\sigma)^2\right)$, or simplified as $n\left(\log\sigma+\frac{1}{2}(\hat{\sigma}/\sigma)^2\right)$, where $\sigma=\min\left(\max(\hat{\sigma},\sigma_{\min}),\sigma_{\max}\right)$, $\sigma_{\min}=0.1$ and $\sigma_{\max}=0.4$ specified bounds, $\hat{\sigma}=\sqrt{\sum\eta_y^2/n}$ and n was the number of recruitment years y.	(14)

Economic Model and Parameters

The economic model calculated net present value (NPV) based on total discounted profit theory (Ross, 1995). The NPV objective function used geometric discounting that summed profits over future model projections:

$$\mathrm{NPV} = \sum_{y=1}^{\infty} a^y \pi_y$$

where $a = (1+i)^{-1}$, *i* was the annual interest (discount) rate and π_y was the profit during year *y*. To avoid model projections over many years, the NPV was truncated to a terminal year *T* and equilibrium was assumed thereafter (O'Neill et al. 2014):

$$\mathrm{NPV} = \sum_{y=1}^{T-1} a^y \pi_y + a^{T-1} i^{-1} \pi_T \, .$$

Annual profit was calculated as the harvest value minus the variable and fixed costs:

$$\pi_y = \sum_t \left(\sum_l v_{t,l} C_{t,l} - \Omega_t^{\mathrm{V}} \right) - \left(\Omega_y^{\mathrm{F}} \frac{E_y}{\bar{d}} \rho \right),$$

where $v_{l,t}$ was the average price received by fishers for crab in fishing month *t* and length class *l* (Table 20) $C_{t,l}$ was the crab harvest weight, Ω_t^{V} was the total variable costs, c_L was the share of the catch paid to crew members (a labour cost), E_y was the total annual boat days fished, Ω_y^{F} the average annual fixed costs, $\bar{d}$ was the mean number of days fished per boat year and ρ was the fraction of fixed costs allocated to the blue swimmer crab fishery (Table 10). The division by $\bar{d}$ allowed the annual number of vessels to change based on profitability.

Variable costs Ω_t^{V} were calculated by fishing month *t*. This included the proportional labour cost (c_L), cost of repairs and maintenance per boat-day (c_K), fuel cost per boat-day (c_F), bait cost per boat-day (c_B), and other incidental minor costs per boat-day (c_O) such as for cooking, processing and motor vehicle (Table 10):

$$\Omega_t^{\mathrm{V}} = \sum_l c_L v_{t,l} C_{r,t,l} + \left(c_K + c_F + c_B + c_O \right) E_t \, .$$

Average annual fixed costs Ω_y^{F} were calculated using vessel costs (*W*), and opportunity (*o*) and depreciation (*d*) rates on average total investment value per vessel (K_y) (Table 10):

$$\Omega_y^{\mathrm{F}} = \left(W + (o+d) K_y \right).$$

Annual vessel costs (*W*) were not related to fishing effort. They were the sum of costs needed to support a vessel before fishing. The average total investment value per vessel includes the current vessel value and fishing gear.

Coefficient of variation (10%) was allocated to simulate uncertainty in total variable and fixed costs.

Table 10: Input parameter values used in the economic component of the assessment model.

Parameters	Moreton Bay	Sunshine Coast	Hervey Bay
Variable costs:			
Labour (c_L: proportion of catch $)	0.06	0.13	0.10
Repairs (c_K: $ boat-day^{-1})	40.96	137.5	33.00
Fuel (c_F: $ boat-day^{-1})	80.79	173	141.90
Bait (c_B: $ boat-day^{-1})	46.00	128.70	57.67
Incidentals (c_O: $ boat-day^{-1})	64.26	86.87	78.60
Annual fixed costs:			
Vessel costs (W_y: $ boat^{-1})	2322.05	8069.30	4620
Total investment (K_y: $ boat^{-1})	50 000	120 000	131 500
Proportion allocated to BSC (ρ)	0.55	0.80	0.23
Annual fishing effort:			
Mean number of days boat-year^{-1} $\left(\bar{d}\right)$	66	34	61
Annual economic rates:			
Interest rate (i)	0.05	0.05	0.05
Opportunity cost (o) = i	0.05	0.05	0.05
Depreciation rate (d)*	0.037	0.037	0.037

Results/Discussion

Figures and tables showing the goodness of fit of the model are shown in Appendix 2. These generally show that the Moreton Bay/Sunshine Coast model performed well and fitted the available data better than the Hervey Bay model. In general, the model was able to fit the length frequency data (MB male LF, MB female LF, SC male LF and SC female LF) with all of the log-likelihoods for these parameters being below zero. In contrast, the log-likelihood vales for the catch rate parameters were positive. Scenario 8, with the growth parameters being derived using mixture modelling (Chapter 7), consistently performed poorly in comparison to the other models. Scenarios 1, 2, 3, 6 and 7 appeared to perform best. Fits to survey recreational harvest were varied and marginal.

Moreton Region Model

Biomass predictions from the Moreton Region model peaked in the early 2000s, reflecting the high catch rates reported during that time in the Sunshine Coast component (Figure 38).

Sensitivity analysis showed that growth and vulnerability were two of the most important parameters affecting model outputs. Faster growth scenarios clearly favored lower sizes at first capture while setting the vulnerability parameters was also highly influential. It is important to acknowledge that the sensitivities around the base case (Scenario 1) do not infer this as the “most likely” scenario. Likewise, the figures do not cover the full range of possible outcomes given likely variations in some of the parameters. There are many more combinations of parameters that could be tested, but we have chosen to show the sensitivities to key parameters.

Median MSY estimates ranged between approximately 375 and 750 tonnes depending on the scenario, but when uncertainty is included, the distribution of possible MSY estimates is pushed even wider. Uncertainty around modelled outputs was high (as shown by the relative size of the error bar) reflecting the high sensitivity to key parameters (Figure 39). Variations in growth had a dramatic effect on the estimates of MSY and optimum MLS to achieve MSY, obviously reflecting the higher productivity of the stock under assumptions of relatively fast growth. The most scientifically rigorous estimate of growth (Scenario 8) supported the current MLS, but at an “unrealistically” low level of productivity of the stock (reflected in a relatively low MSY) and overall poorest fit to the model (Table 22). The model outputs suggest that, in order to maximise MSY, the current MLS could be increased but economic efficiency is promoted by quite significant reductions in fishing morality (Figure 41). Levels of fishing mortality were assessed as very high under all scenarios, particularly during the middle of the time series between 1996 and 2007 (Figure 40) when biomass was high. Figure 41 shows that significant reductions in fishing effort are required to ensure optimum economic yield, as scenarios show that fishing mortality is around twice the optimum level. The analysis of the CFISH data and data from comparable fisheries in Western Australia and South Australia suggests that levels of effort are high compared with blue swimmer crab fisheries in other states. The fact that currently approximately 80 fishers report blue swimmer crab catch in Moreton Bay suggests a conservative potential effort of at least 4000 pots (80 fishers x 50 pots). As a comparison, the Shark Bay fishery in Western Australia has about 1500 pot entitlements to land more than the current Moreton Bay catch. Similarly the levels of allowable effort in South Australia are far less than in comparable areas of Queensland.

The economic model indicated that these increases in MLS would be detrimental to the economics of the fishery, and that the current MLS (or even a smaller MLS) was more appropriate for improving profitability. This is driven largely by increases in MLS causing reductions in catch rates as fewer crabs would be landed.

Model outputs suggest that of the management measures available, the preferred option in terms of economics, is a reduction in fishing mortality. While this can be achieved by reducing the quantity of gear used by fishers, this would further force businesses into uneconomically viable conditions. Any increases to the minimum legal size would also cause a short-term reduction in catch rates, but may improve future total catch rate as the fewer crabs caught will be of a larger average size. The arguments for maintaining an MLS of 11.5 cm BW are provided in Sumpton et al. (2003), and we will not explore these in detail further in this report. Smaller MLS will always be favored for strategies where maximising numbers of crabs in the catch is the objective, but there is the trade-off in causing a reduction in the total weight, and this is affected by growth and natural mortality in particular. The preferred strategy is clearly one of reducing effort. While other output controls, such as a TAC (total allowable catch), could be used to reduce overall fishing mortality, they are generally not recommended in fisheries that have strong annual variations in recruitment (such as prawn, crabs and other relatively short lived crustaceans). In these fisheries, TACs may limit catches in years of strong recruitment when higher catches could be attained to improve profitability.

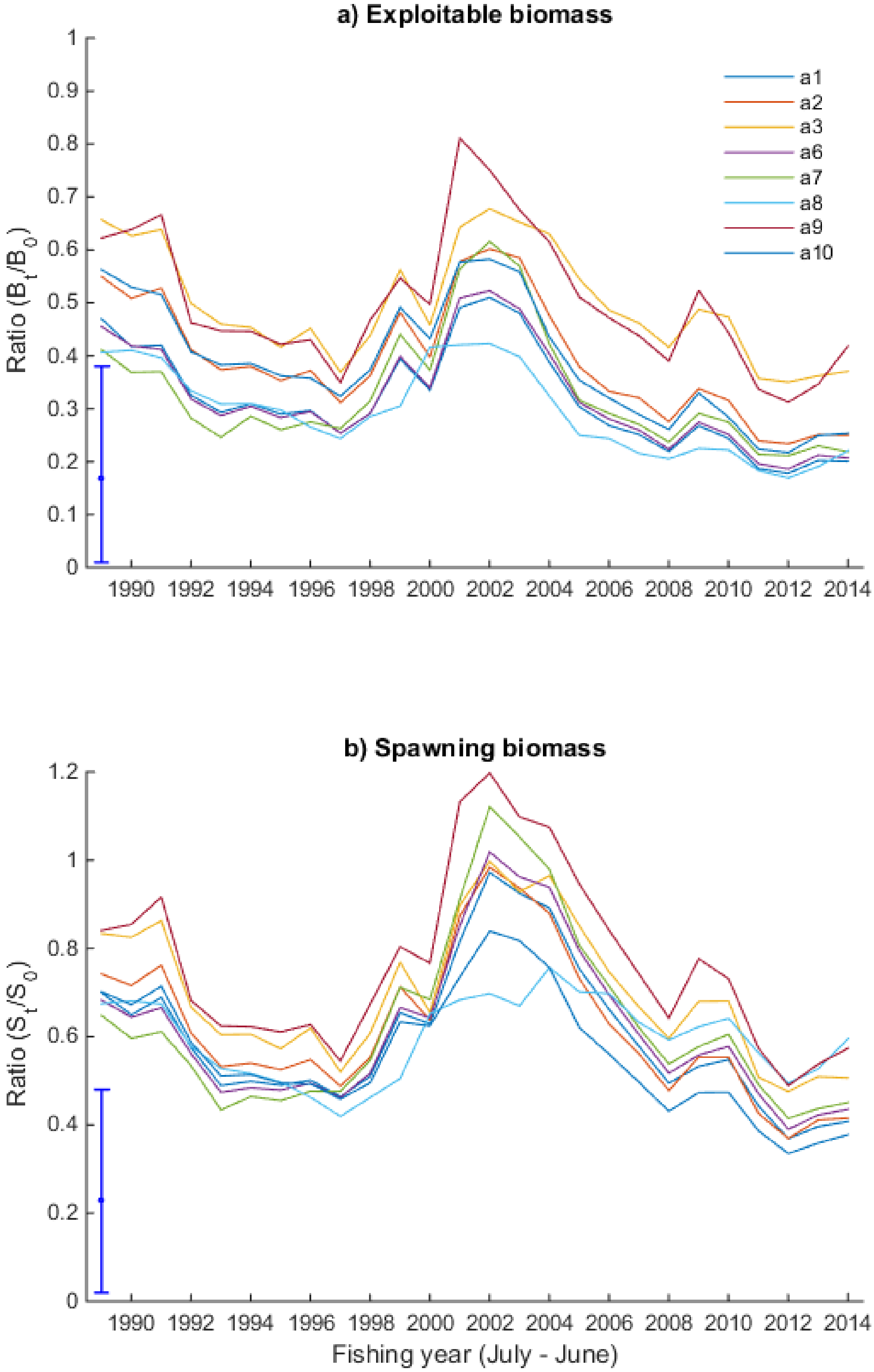


Figure 38: Model predicted exploitable biomass (male legal crab) and spawning biomass (mature male and female crab) ratios for Moreton Bay and Sunshine Coast waters and the 10 different uncertainty scenarios; NB. Scenarios presented cover only analysis outlined in Table 5 and do not represent all possibilities. The 90% confidence error bar shown adjacent to the y axis was calculated from a3, and is used to illustrate approximate uncertainty on all estimates.

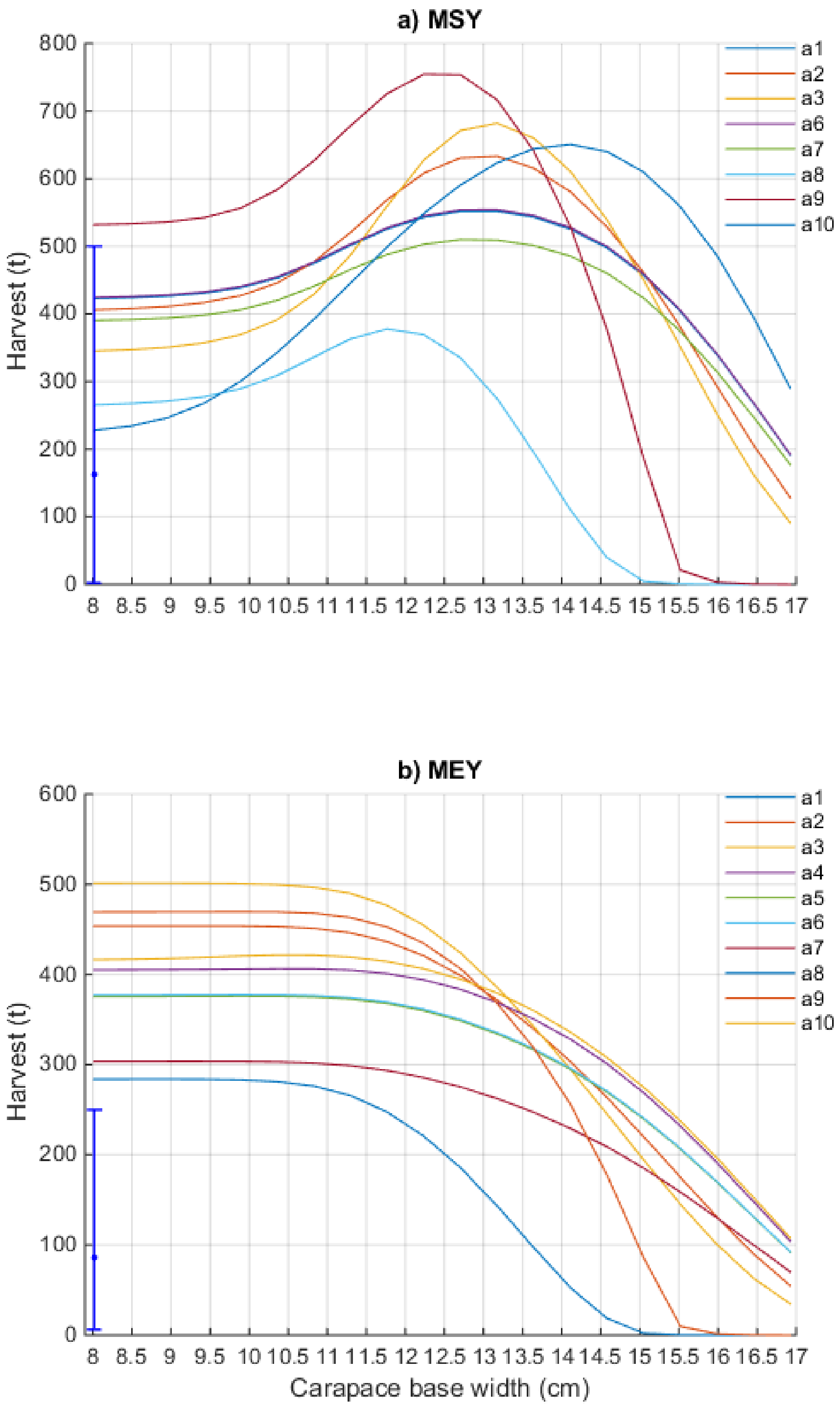


Figure 39: Sensitivity of maximum sustainable (MSY) and maximum economic (MEY) yields of blue swimmer crabs from Moreton Bay and Sunshine Coast waters; NB. Scenarios presented cover only those analyses outlined in Table 5, and not all possible outcomes. The 90% confidence error bar shown adjacent to the y axis was calculated from a3, and is used to illustrate approximate uncertainty on all estimates.

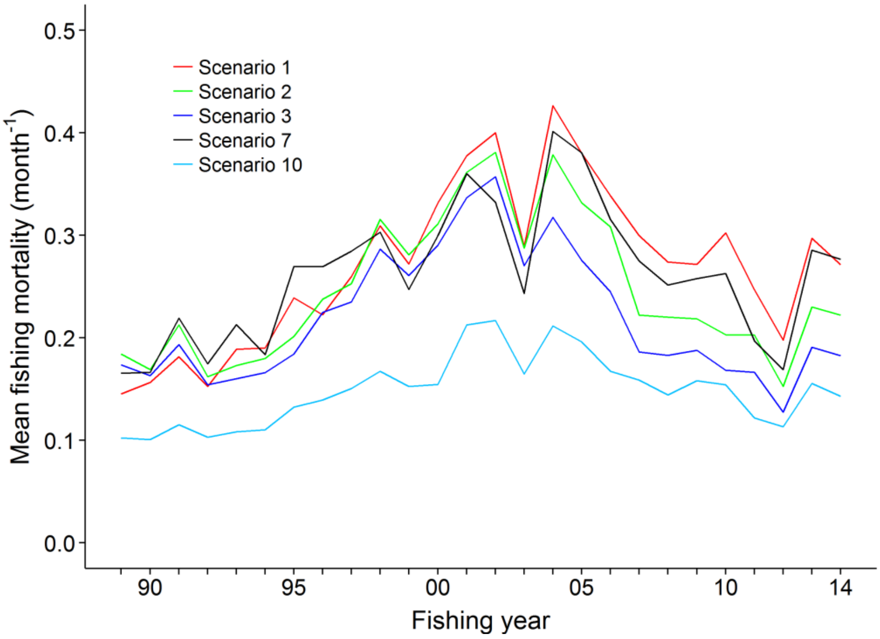


Figure 40: Change in mean monthly fishing mortality in the Moreton region predicted by the model for scenarios 1,2,3,7 and 10. Standard deviation = 0.076.

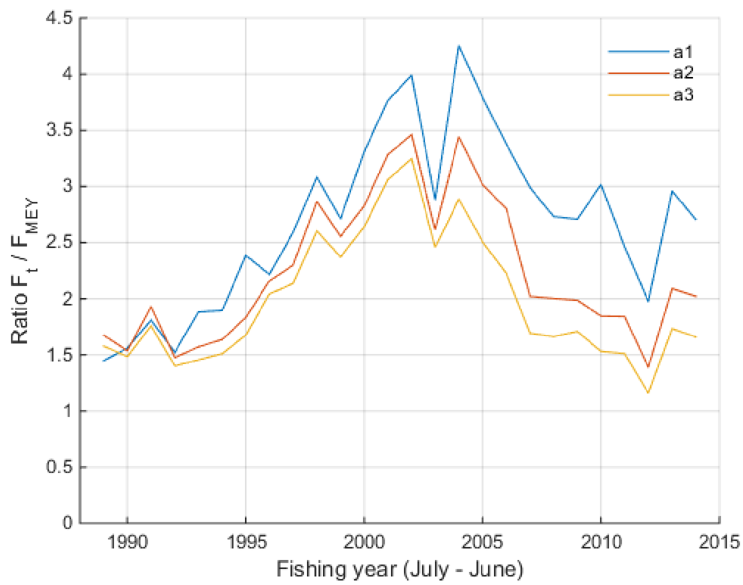


Figure 41: Derived mean monthly fishing mortality in the Moreton Region for scenarios 1, 2 and 3 as a proportion of the mean monthly fishing mortality required to achieve maximum economic yield (MEY) for each scenario.

Hervey Bay Model

The Hervey Bay model did not perform as well as the Moreton Region model, and we do not present sensitivity analysis for this model as most scenarios failed to converge to realistic solutions. Biomass trajectories for Hervey Bay are shown in Figure 42 and indicate a similar trend to those of the Moreton Region model. The base fit, with similar parameter specifications to the Moreton Region (Figure 43), suggest similar conclusions to those indicated by the Moreton Region model. Specifically, effort reductions in order to maximise economic efficiency are highly desirable. The fishery is still assessed as ecologically sustainable under current management arrangements, but MSY for Hervey Bay is about half that of the Moreton Region.

Figure 42: Model predicted exploitable biomass (male legal crab) and spawning biomass (mature male and female crab) ratios for the Hervey Bay base case scenario. 90% confidence intervals are shown as dashed lines.

High catches during the middle of the time series when the pot fishery clearly expanded into previously lightly fished areas were difficult to fit to the modelled dynamics of the population. The lack of a reliable time series of length frequency data from this region also did not aid in modelling the dynamics of the population. Economic data were also more variable with average economic conditions used in the model being unrepresentative of the fishery given the diversity of business structure in this region. There is an argument for further subdividing the Hervey Bay fishery into an inshore and an offshore component similar to the Moreton Region. This would better reflect the different business structures with larger vessels with higher costs generally fishing the more remote areas around Hervey Bay further from port. Given the current spatial resolution of the data, this subdivision would not be possible.

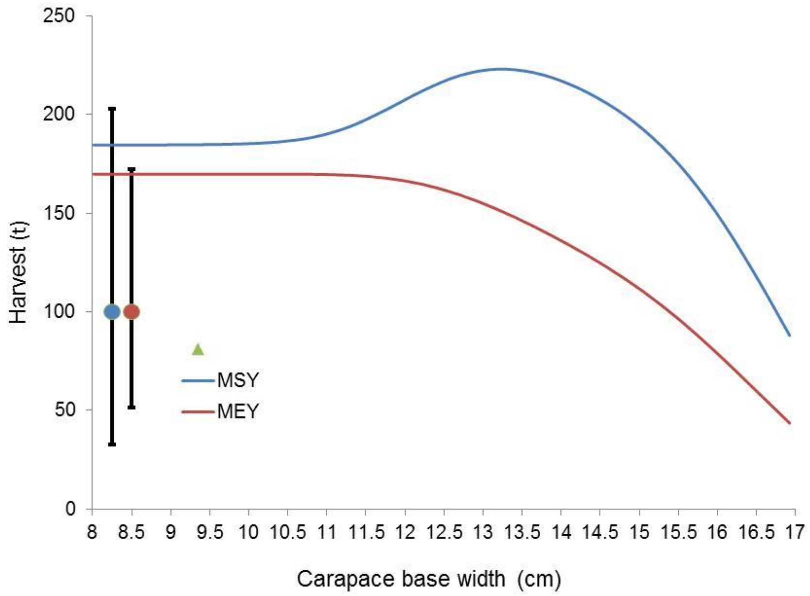


Figure 43: Model predictions of maximum sustainable (MSY) and maximum economic (MEY) yields for the Hervey Bay blue swimmer crab fishery. The 90% confidence error bars shown adjacent to the y axis were calculated from scenario a3, and are used to illustrated approximate uncertainty on all estimates.

General Discussion

The analyses presented here were the most comprehensive evaluation of the blue swimmer crab population and economic condition of the fishery to date. They were based on monthly data that captured the seasonal patterns in biology, fishing and economics. The population model was designed to explore policy options for MLS and profitable levels of harvest and catch rates, over simpler and less informative methodology (Walters and Martell 2004). The model was optimally complex to examine these questions and account for historical changes in management. Current data on BSC are of mixed quality. The analyses attempted to make the most of the data and knowledge to address important management questions highlighted above. Historically we know the biology and management relatively well. We also know the timing of various events that may have impacted on the fishery such as floods, which will not necessarily play nicely with an annual time step. Therefore, we have used a relatively sophisticated structure, making the most of the current state of knowledge. The analyses are, in essence, simulations with structural realism over simpler statistical parameterisations. Although the best available data and analyses were used given time resources, the uncertainties of some model inputs and outputs should be noted. We have already presented some of these uncertainties in previous discussion as they apply to some of the data inputs, but there are a number of other uncertainties that should be recognised.

The primary structure in the modelling was that the BSC standardised catch rates were assumed proportional to the legal-male-crab abundance. The catch rate offsets for increased potting provided crucial contrast to model change in abundance between 1989 and 2014. Without this contrast (adjustment to catch rates), model outputs would be less certain. However, the stock model results do question the fidelity of the 2001–2005 peaks in harvest and catch rates; which may confound/bias population signal. The high harvest tonnages can only be explained by overly strong positive recruitment. Quality control analyses and harvest verification with fishers are required to verify logbook data. The time series of unstandardised catch rates were clearly not solely reflective of changes in biomass because they are impacted by fishery management changes and inconsistent reporting practices (such as the possible inflating/misreporting of catches to establish catch history in anticipation of changes in fisheries management).

Not all variations in parameters were explored in the current assessment and we relied on modelling what was considered by the steering group to be the key parameters and likely ranges of those parameters. The spread of results and confidence intervals indicate considerable uncertainty. Despite these uncertainties, the main message of high levels of fishing mortality and the need to reduce effort in order to maximize economic efficiency is clear.

The model predictions in the late 1990s to early 2000s in both Hervey Bay and the Moreton Bay/ Sunshine Coast models result from the high reported harvests and catch rates. The high spawning biomass and exploitable biomass ratios during this period partially reflects spatial movement of fishing to previously lightly-exploited offshore areas, and suggests that finer spatial scales may be required in the catch rate standardisation process, in order to increase precision. During these years, the model must predict high levels of recruitment in order to best describe the high harvests and catch rates. Model inferences also suggest that the magnitude of harvests may represent unrealistic over-reporting, as suggested by some parts of industry.

The final models used to assess the fishery were simplified from those that are possible to run given the structure of the assessment model developed for this fishery. For example, we have chosen to model spawning as if it occurs only during the period August to October when, in fact, ovigerous females are found throughout the year (Sumpton et al. 2003). We used this spawning pattern because other evidence supports a single large cohort of crabs seen in trawl samples (Sumpton et al. 1994, Sumpton et al. 2003). Also, we have assumed constant catchability, whereas there is clearly a seasonal component to catchability with lower catchability during the winter months (Sumpton and Smith, 1989).

The modelling process also highlighted that recording, maintenance and verification of catch and effort data through fishery logbooks were inadequate. Enforcement of logbook compliance, data management and modernisation of collection methods are required, and should be considered a high priority. If this is not undertaken, there is a risk that future stock assessments will provide biased and unrealistic advice. The current method of collecting logbook data – paper logbooks completed by fishers and sent to Fisheries Queensland within three months – could be improved. It is important that this process be refined so that logbook data are improved and made more reliable. Electronic reporting systems (eLogs) currently being trialed for some fisheries in Queensland, would enhance the collection of logbook information and provide a more cost-effective method of gathering these important data, although they may not improve accuracy if the incentives to falsify records remain. Further, verification of logbook data would ensure the accuracy of the catch and effort data reported by commercial fishers. The misreporting of catch is a common issue among all commercial fisheries which, unfortunately, is difficult to avoid unless comprehensive and cost-efficient fishery-independent indices of abundance can be generated and used as an alternative index of abundance, in models used to assess the fishery. As such, the data generated by Fisheries Queensland's recruitment surveys will likely become an increasingly important input to models into the future and, for this reason, the current survey should be maintained.

The spatial resolution reported by commercial crab fishers could be improved. At present, fishers are only required to report at CFISH grid with a scale of 30 minutes by 30 minutes, although it would be preferable if vessels were fitted with VMS or some other GPS-enabled recording system. Such systems are available and can be facilitated by current smart phone or tablet technologies. They would allow for more precise spatial stratification in the population model.

Recreational blue swimmer crab catch and effort data are also currently imprecise, and yet historically recreational catch has been an important component of the overall catch, particularly in Moreton Bay where, at times, it has been listed as one of the top three target species (Sumpton et al. 2003). In the most recent recreational fishing survey (Taylor et al. 2012), the errors around blue swimmer crab catch estimates resulted in them being considered “unreliable” but “low”. The population model in the current study inferred monthly recreational CPUE from five separate recreational fishing surveys and commercial pot effort as a proxy for relative recreational fishing effort. In order to improve precision of recreational catch and effort, it would be necessary to target blue swimmer crab fishers in the phone diary portion of the current recreational fishing surveys undertaken by Fisheries Queensland. Alternatively, it is hoped that better methods of collecting recreational blue swimmer crab catch and effort data will be established at the conclusion of current FRDC-funded research (What data how? Empowering and engaging industry to ensure the needs of contemporary fisheries data are achieved – FRDC Project number 2014/200). However, changing fishing practices, notably the removal of dillies as a permitted apparatus, may have resulted in decreased targeting of blue swimmer crabs by recreational fishers, although this is not universally acknowledged.

The inshore and offshore length frequency data were influential in the model fit and this is reflected in the negative log likelihood profiles which limited fits to the standardised catch rates. The development of a better female catch index possibly using fishery independent techniques, would improve the ability of the model to explain the population dynamics.

The MEY predictions relied heavily on the economic data which were ultimately aggregated over quite broad scales of fishing business structure and size. The economic data used in the models were regarded as representative of the fleet, but we acknowledge that the Moreton Bay economic data, in particular, is complicated by the diversity of business structures in that region and possible biases due to lack of total fishery coverage. Future economic evaluations will require time-series of economic data, and currently these data are not readily available. The economic data were important for model projections and monitoring catch rate “profitability”, yet only averaged conditions were used which clearly advantage/disadvantage subsets of fishing businesses at the margin of these distributions. The cost structures and catch rates required to achieve a profitable outcome from the blue swimmer crab fishing activities may change over time and also vary among fishers. Interviews used to gather economic data clearly showed that widely different daily variable costs and fixed costs were still considered profitable to individual operators. Dichmont et al. (2010) noted that the list of economic variables to collect and include in assessments may change in future assessments of the fishery, depending on their accuracy, variability and MEY.

In conclusion, this assessment has described a population assessment model and profitable management procedures for the blue swimmer crab fishery. The most prudent interpretation of results is that significant reductions in effort are required in order to maximise economic efficiency. The estimates of profitability are a function of individual business structure and, at present, the different business models affect what is perceived to be a profitable fishery by many industry participants.

8. References

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9. Appendices

Appendix 1 Growth estimation via mixture models and the MM algorithm

Introduction

Fisheries are often spatially partitioned into separate management units, particularly if there is little movement of the species from one management unit to another. These management units are called stocks, and each stock of sufficient importance will be the subject of a stock assessment. Understanding how aquatic species grow is fundamental in fisheries because stock assessment relies on growth dependent statistical models. The statistical method used to make inference about growth depends on the data available; the three most common data types are (i) fish length and time at liberty data from tag-recapture experiments; (ii) length-frequency data gathered from fishers and/or research surveys; and (iii) length data with direct age via otoliths readings. It is common to use tag-recapture data to estimate the parameters of a potential growth model, but tagging studies can be costly and ineffective for some species (especially crustaceans). Length-frequency based methods become important when tag-recapture data or direct ageing of the species are either not possible, or very expensive. Length frequency data are recordings of individual lengths at a time point and are often visualised as size-frequency distributions. This visualisation often presents separate modes, which may be interpreted as different age cohorts. Following the modes of these cohorts through time gives a natural way to model growth of a species. These plots can also be interpreted as a mixture distribution, where each cohort has a distribution of lengths. To model growth using these data one must first decide on a growth model.

The von Bertalanffy growth model (VBGM) is common in fisheries research, and can be used to predict the length of an individual at time t. The VBGM has a biological basis, and empirical studies have shown it to be statistically sound. The VBGM describes the relationship between time t and length L by:

$$\mathrm{L(t) = L_\infty\{1 - exp[-K(t - T_0)]\}}$$

where $\mathrm{L_\infty}$ represents the asymptotic length, K controls the curvature, and $\mathrm{T_0}$ is defined to be the time when an individual would have had length 0, if its post juvenile growth stage is projected backwards (in keeping with standard probability notation, all random variables in this document will be represented with a capital letter; lower case letters will denote realisations of the respective random variable). Therefore, $\mathrm{L_\infty}$ represents the random asymptotic length with expectation μ_∞ and variance σ^2_∞. When individual variability is modelled (as apposed to a population growth curve), the variable $\mathrm{T_0}$ takes on different values from organism to organism and thus is represented with a capital letter. When individual variability is taken into consideration, it is debatable whether both $\mathrm{L_\infty}$ and K should be considered random, because there are problems with over -parameterisation. In this document, we treat K as a common population parameter denoted k; and outline the principal reasons for doing so.

To estimate the VBGM parameters, tag-recapture data are often used. Individuals are tagged at time $\mathrm{T_1}$ and the length $\mathrm{L_1}$ is recorded. They are then released and at each subsequent recapture time $\mathrm{T_j}$, where the length $\mathrm{L_j}$ and $\mathrm{T_j}$ are recorded. The relative age at first capture $\mathrm{A = T_1 - T_0}$ of the individuals sampled in the wild is difficult to estimate, but inference regarding A can be drawn from $\mathrm{L_1}$. Historically, the advantage of tag-recapture studies is that the age need not be known. The increment $\mathrm{L_2 - L_1}$ can be modelled via the Fabens increment expression:

$$\mathrm{I = (L_\infty - L_1)[1 - exp(-k\delta T)]},$$

where $\mathrm{\delta T = T_2 - T_1}$ (with realised value $\mathrm{\delta t}$). The relative age at capture is not present in this expression, which is mathematically advantageous. This expression circumvents the problem of working with age directly. It also allows for the VBGM to be used in a length frequency context because the function is only dependent on time, length and estimable parameters.

This work was motivated by the former Department of Agriculture, Fisheries, and Forestry, Queensland, Australia, who were concerned about the sudden decline in catch of the blue swimmer crab (BSC) (*Portunus pelagicus*) off the east coast of Queensland. Tag-recapture data are difficult to gather for crustaceans because exoskeleton moulting leads to loss of tags. Additionally, tagged crustaceans are often re-caught quickly by the fishery before moulting can occur, leading to large measurement errors in the data because the next measurement is being taken close to the previous measurement. Although desirable, the resultant tag-recapture data is unreliable. As crustaceans cannot be directly aged, the only data source left was length frequency data. These data are easy to collect, but fewer models have been developed for growth estimation that can incorporate individual variability and time dependent covariates, such as seasonality; the BSC has a known seasonal growth pattern with hibernation in the winter where no growth is likely. To make use of more advanced statistical models in the larger stock assessment, we set out to use length frequency data to make inference about individual variability and seasonality of BSC growth, with a fast and robust estimation procedure using length frequency data. Approaches that incorporate the estimation of a parametric growth curve into the length-frequency analysis have been developed (eg MULTIFAN). MULTIFAN is a likelihood-based method that estimates, from length-frequency data, a sum of normals mixture; one distribution for each age class, which represents the length distribution for that age class. Each normal distribution is calculated from three parameters: the mean length; the standard deviation of the lengths about the mean length; and the proportion that that age comprises of the total length-frequency data set. The parameters are estimated to make the predicted length-frequencies most consistent with the observations, as quantified by the likelihood function. The mean length-at-age is often represented by the von Bertalanffy growth curve and the standard deviation of length-at-age by a linear relationship with mean length. In MULTIFAN, the proportions for each age class are estimated as free parameters. The estimated catches-at-age, which are represented by age proportions, can then be used in a catch-at-age analysis. To our knowledge, however, few methods have incorporated individual variability and time dependent covariates (seasonality) into the modelling process. We sought to develop a novel technique that models individual variability and time dependent growth covariates, such as seasonality, with length frequency data. The model was designed to solve the specific problem at hand (i.e. growth estimation of the blue swimmer crab) but has wider applicability.

In our study, we develop a new framework for estimating growth from length-frequency data. We use a generalised von Bertalanffy growth framework to estimate the parameters of the von Bertalanffy growth model (VBGM) and a seasonal growth curve that models the change in growth through the year. The seasonal model is further constrained such that a hibernation period can be modelled. We use an MM algorithm with a Nelder-Mead step to optimise the likelihood and estimate the parameters of the mean constrained mixture of normal distributions for each of the length frequency sub-samples. The variances are constrained to be a function of the mean length for each cohort, which allows for an estimate of the distribution of L_{∞}, and the variance of the normal distribution at any length. This method gives a detailed picture of growth and is generalisable across species and for more than the number of cohorts used in our analysis. We test the method with and a simulation study and then apply it the blue swimmer crab. The resultant estimates will greatly assist the stock assessment team in their investigation of the causes of the apparent stock decline.

Materials and methods

Data

The data available for this fishery was scarce, therefore, the final data set was a combined length frequency data set from trawl and pot fishing gear. In our analysis, both males and females data sets are used even though the fishery only harvests males. There were 12 023 individuals (male and female) used in the analysis across two separate data sets.

Data set 1
The first data set was gathered using trawling methods described in Sumpton et al. (1994)
Data set 2
The second data set was gathered using pots and includes all females measured that are caught in pots but only the male crabs greater than 150 mm, as these males are the ones that are targeted by fishers. There are huge selectivity issues with using male crabs smaller than this size as fishers tend to avoid areas that have large numbers of smaller crabs (some can do this more successfully than others). Temporal changes in the right hand end of the size structure of the targeted male catch is more representative of the population trends for this size range of the population.

Growth model estimation for the blue swimmer crab

Our objective is to use length frequency data to estimate the parameters of the von Bertalanffy growth model (VBGM) and a seasonal growth curve that models the change in growth through the year. We are also interested in estimating the distribution of the random variable L_∞ and the dynamics of the cohorts (juveniles and yearly adult cohorts) by modelling how the proportions of each cohort changes through time.

To model the length frequency data, we derive a mixture model approach where the means are constrained so they follow a VBGM. Recruitment is defined to be the entering of juveniles to the fishery i.e. when juveniles reach a length susceptible to being caught by the fishery. Months that contain new recruitment are deemed ineligible for use in modelling because the change in the mode is not driven by growth, but by smaller individuals entering the fishery. Therefore, differences between these months will not follow a VBGM. The decision rule for when recruitment has stopped was taken to be when the scaled density height of the juvenile population peaks, i.e. the next month's scaled peak is smaller than the previous month. This is quite a subjective notion and will need to be defined by the modeler based on experience and prior knowledge of a species' population dynamics. The month when the density peaks is used as the first month to model. The following derivation outlines the growth model used and how it is incorporated in the mixture modelling process.

The traditional VBGM assumes that the growth rate can be modelled by

$L'(t) = k[L_\infty - L(t)]$,

$$L'(t) = k[L_\infty - L(t)],$$

where (k, L_∞) are growth parameters, L_∞ is the asymptotic length, while k determines the shape of the curve. We use the following generalised von Bertalanffy model proposed by the model time dependent covariates. The change in length with respect to time can be modelled as:

$$L'(t)=[L_\infty - L(t)]g(\theta, x\_t) + \sigma(t)\ \varepsilon(t), \qquad \text{Equation 1}$$

with $\varepsilon(t)$ being a zero mean error term representing the environmental perturbation and $\sigma(t)$ accounting for the heteroscedasticty of the error process. The latitudinal and seasonal effects are incorporated into the model via a link function denoted $g({ \theta},{\bf x}_t)$, where θ can be a vector or a scalar. The solution to the differential equation with initial conditions $L(b_0) = l_0$ has the form

$$L(t) = l_0 + [L_\infty - l_0]\{1 - \exp[-z(b_0, t)]\} + w(b_0, t). \qquad \text{Equation 2}$$

In Equation 2

$$z(b_0, t) = \int_{b_0}^{t} g(\theta, x_u)\, du \qquad \text{Equation 3}$$

and

$$w(b_0, t) = \int_{b_0}^{t} \{\exp[\int_{t}^{u} g(\theta, x_s)\, ds\,]\, \sigma(u)\varepsilon(u)\} du. \qquad \text{Equation 4}$$

This model allows for time dependent covariates to be incorporated into the VBGM. The growth rate of the blue swimmer crab is known to be seasonal with a hibernation period during the winter months. The crabs are hypothesised to cease growth during this period. Modelling the potential no-growth period is achieved by restraining the growth link function to be positive during the integration step of the model derivation. Therefore, for blue swimmer crabs we model seasonality over a year as:

$$g(\theta, t) = k + \theta_1 \cos(2\pi t) + \theta_2 \sin(2\pi t),$$

where $\theta = (k, \theta_1, \theta_2)$. To ensure negative growth is not modelled we let

$$z(b_0, t) = \int_{b_0}^{t} \max\,[g(\theta, t), 0]\ dt.$$

Depending on the choice of link function, this integral has varying difficulty. The difficulty rests on whether the roots of the polynomial formed by the trigonometric functions can be solved. Given the model, the roots for the trigonometric functions can be found and incorporated into the algorithm by letting the integral equal 0 between the two roots.

Firstly, we visualised the BSC length frequency data using histograms and concluded that many frequency distributions could be represented well as a mixture of three populations. We hypothesised that these three populations represented the juvenile, adult, and close to asymptotic length cohorts. As a preliminary investigation, we fitted a mixture of three normal distributions to each cohort for each time step and hypothesised that the adult cohort is one year older than the juvenile cohort, and that the asymptotic cohort is 2 years older than the juvenile cohort. Prior knowledge of the biology of the BSC contributed to this decision, with BSC being a short-lived species, and thus reaches its asymptotic length within 2-3 years.

The following derivation outlines how we modelled the three cohorts through the years of 1985 and 1986 and the model constraints imposed by the data. The means of these cohorts are hypothesised to follow a VBGM curve. Therefore, let t_i (in fraction of a year) be the time caught from January 1 ($t_1 = 0$) for the ith individual, and let L_i be the length of the ith individual that was caught in month $m \in (1, \ldots, M)$, where M is the number of months since the first month, and year $y \in (1, \ldots, Y)$, where Y is the number of years modelled. For each year we reset the mean of the first modelled month (μ_{0y}) and estimate another parameter so that the growth during each year is not dependent on the previous year. This allows peak recruitment in the juveniles to have a different mean each year. Let μ_{Jmy} be the juvenile mean length at month m in year y, which can be paramaterised using the Fabens increment equation as:

$$\mu_{Jm}(t) = \mu_{0y} + (l_\infty - \mu_{0y})(1 - \exp[-z(t_0, t)]),$$

where μ_{0y} is the juvenile mean of the first month considered in year y, which will be estimated from the data, and t_0 is the time from January 1 for the first group of juveniles. For example, if the first group of juveniles were caught in mid-February, then $t_0 = 0.125$. We hypothesise that the adult group is just the juvenile group from the previous year and thus one year older than the juveniles. This same principle applies to the hypothesised two year old group. Therefore, we let μ_{Amy} be the mean of the adult individuals at month m in year y, which can be paramaterised as:

$$\mu_{Am}(t) = \mu_{0y} + (l_\infty - \mu_{0y})(1 - \exp[-z(t_0 + 1, t + 1)]).$$

The close to L_∞ group can be modelled as:

$$\mu_{L_\infty m}(t) = \mu_{0y} + (l_\infty - \mu_{0y})(1 - \exp[-z(t_0 + t_\infty, t + t_\infty)]),$$

where $t_\infty = 2$ is large enough such that most individuals are close to L_∞. To save further indexing over the year, the years are incorporated into the method by letting the months be the number of months from the first month incorporated in the model. At each month, let the distribution of individuals at each month m be given as:

$$f(l_i) = \pi_{Am}\phi(l_i; \mu_{Am}, \sigma^2_{Am}) + \pi_{Jm}\phi(l_i; \mu_{Jm}, \sigma^2_{Jm}) + [1 - (\pi_{Jm} + \pi_{Am})]\phi(l_i; \mu_{L_\infty m}, \sigma^2_{L_\infty m}).$$

The likelihood function can be written as:

$$L(\theta) = \prod_{i=1}^{n}\prod_{m=0}^{M}[\,\pi_{Am}\phi(l_i; \mu_{Am}, \sigma^2_{Am}) + \pi_{Jm}\phi(l_i; \mu_{Jm}, \sigma^2_{Jm}) + [1 - (\pi_{Jm} + \pi_{Am})]\phi(l_i; \mu_{L_\infty m}, \sigma^2_{L_\infty m})]^{\mathbb{I}(m_i = m)}.$$

The log-likelihood can be written as:

$$\log L(\theta) = \sum_{i=1}^{n}\sum_{m=0}^{M}\mathbb{I}\,(m_i = m)\log\sum_{j=A,J,L_\infty}\pi_{jm}\,\phi(l_i; \mu_{jm}, \sigma^2_{jm}). \qquad \text{Equation 5}$$

The variances for each cohort in each month are constrained to be functions of the mean length of the cohort. The variances are constrained such that $a\mu_{jm}\exp(-b\mu_{jm}) + \exp(c(1 - \exp(-d\mu_{jm}))$; this is done to reduce the number of parameters and allow for the variance to be known at any mean length. The function used is a combination of a Ricker function and an always positive asymptotic function. This function has the desired properties of always being positive (a necessary property of the variance), unimodal, and asymptotes to some positive value, which we hypothesise to be the variance of the individuals as time goes to infinity. Most importantly we can calculate the variance at L_∞. To estimate $\theta = (k, l_\infty, \mu_0, \theta_1, \theta_2, \pi_J, \pi_A, \pi_{L_\infty}, a, b, c, d)$, $\mu_0 = (\mu_{01}, \ldots, \mu_{0Y})$, $\pi_J = (\pi_{J1}, \ldots, \pi_{JM}), \pi_A = (\pi_{A1}, \ldots, \pi_{AM})$, $\pi_{L_\infty} = (\pi_{L_\infty 1}, \ldots, \pi_{L_\infty M})$, we employ the MM algorithm paradigm . There are $M - R$ (where R represents the number of months that contain recruitment) parameters for the mixing proportions, and $Y = 1, \ldots, y$ starting means. Using the MM algorithm allows for a scheme to be devised without the constraints of the probabilistic setup of the EM algorithm.

To optimise the objective function, consider that the natural logarithm is a strictly concave function and thus $logL(\theta)$can be minorized by

$$Q(\theta) = \sum_{i=1}^{n}\sum_{m=0}^{M} I\,(m_i = m) \sum_{j=A,J,L_\infty} \tau_{ijm}^{(k)} \log[\pi_{jm}\phi(l_i;\mu_{jm},\sigma_{jm}^2)] + C$$

$$= \sum_{i=1}^{n}\sum_{m=0}^{M} \mathbb{I}\,(m_i = m) \sum_{j=A,J,L_\infty} \tau_{ijm}^{(k)} \log\pi_{jm} + \sum_{i=1}^{n}\sum_{m=0}^{M} \mathbb{I}\,(m_i = m) \sum_{j=A,J,L_\infty} \tau_{ijm}^{(k)} \log\phi(l_i;\mu_{jm},\sigma_{jm}^2) + C$$

$$= \sum_{i=1}^{n}\sum_{m=0}^{M} \mathbb{I}\,(m_i = m) \sum_{j=A,J,L_\infty} \tau_{ijm}^{(k)} \log\pi_{jm} - \frac{1}{2}\sum_{i=1}^{n}\sum_{m=0}^{M} \mathbb{I}\,(m_i = m) \sum_{j=A,J,L_\infty} \tau_{ijm}^{(k)} \log(\sigma_{jm}^2)$$

$$-\frac{1}{2}\sum_{i=1}^{n}\sum_{m=0}^{M} \mathbb{I}\,(m_i = m) \sum_{j=A,J,L_\infty} \tau_{ijm}^{(k)} \frac{(l_i - \mu_{jm})^2}{\sigma_{jm}^2} + C$$

Here,

$$\tau_{ijm}^{(k)} = \frac{\pi_{jm}^{(k)}\phi(l_i;\mu_{jm}^{(k)},\sigma_{jm}^{(k)2})}{\pi_{Am}^{(k)}\phi(l_i;\mu_{Am}^{(k)},\sigma_{Am}^{(k)2}) + (1-\pi_{Am}^{(k)})\phi(l_i;\mu_{Jm}^{(k)},\sigma_{Jm}^{(k)2})},$$

which are the canonical membership probabilities in the EM algorithm and can be derived from the MM paradigm as well . Thus, in each step, we update:

$$\pi_{jm}^{(k+1)} = \frac{\sum_{i=1}^{n}\mathbb{I}\,(m_i = m)\tau_{ijm}^{(k)}}{\sum_{i=1}^{n}\mathbb{I}\,(m_i = m)}.$$

In the algorithm the updates for $\mu_{jm}^{(k+1)}$ are obtained via *optim* in the R programming language (www.r-project.org/), which is a general-purpose optimization function based on the Nelder–Mead algorithm. In each of the Nelder-Mead steps $\log L(\theta)$ is used as the objective function. Convergence is reached when the difference in the likelihood is less than 10^{-7}.

Constraining the maximum of the seasonal curve

Once the model is fitted to the combined male and female data sets, we hypothesise that both males and females experience the same seasonal growth pattern. From experience, the seasonal component is the most variable and heavily data dependent with male and female estimates differing from each other, and parting from reasonable biological sense if the seasonal parameters are left free to be fitted by the data. To account for this variability, we constrain the maximum value of the seasonal curve for the independent male and female runs to be the same as that of the combined run. This allows k to change and for compression or magnification of the periodic curve but no lateral shifts. This is implemented by forcing:

$$\theta_2 = \theta_1\frac{\sqrt{1-\cos^2(2\pi M)}}{\cos(2\pi M)},$$

where

$$M = \frac{1}{2\pi}\arccos(\frac{\theta_1}{\theta_2\sqrt{1+(\theta_1/\theta_2)^2}})$$

and the θs are estimated from the combined model run.

Algorithm summary

Initialise $\theta = (k, l_\infty, \mu_0, \theta_1, \theta_2, \pi_J, \pi_A, \pi_{L_\infty}, a, b, c, d)$

Iterate following until convergence:

Calculate $\tau_{ijm}^{(k)}$ for each individual

Calculate $\pi_{jm}^{(k)}$ for each month and class

Given $\tau_{ijm}^{(k)}$ and $\pi_{jm}^{(k)}$ optimise $\theta_{\mu_{jm}}^{(k)} = (k, l_\infty, \mu_0, \theta_1, \theta_2)$ via Nelder-Mead and log-likelihood (Eq.)

Update the $\mu_{jm}^{(k+1)}$ given the estimate of $\theta_{\mu_{jm}}^{(k)} = (k, l_\infty, \mu_0, \theta_1, \theta_2)$

Optimise via Nelder-Mead and the log-likelihood (Equation 5) over $\theta_{\sigma_{jm}^2}^{(k)} = (a, b, c, d)$

Update the log-likelihood (Equation 5) based on all new parameter estimates and assess convergence.

Simulation

To assess the method, a simulation study was setup. The simulation was designed to mimic the data observed for the blue swimmer crab. We simulated three cohorts that included a juvenile cohort, a one year old adult cohort, and a four year old cohort that had mean length close to asymptotic length. The mean of each of the cohorts followed a von Bertalanffy growth curve with a seasonal curve $g(\theta, t) = 1 + 2\cos(2\pi t) + 2\sin(2\pi t)$. The seasonal curve is constrained to have a no-growth period between mid-May and mid-September. We set mean asymptotic length $\mu_\infty = 170$, initial length $\mu_{01} = 60$, and the variance quadratic terms $a = 0, b = 1, c = -0.005$. This gives maximum variance at $\mu = 100$ and a $\sigma_\infty^2 = 35.5$. The inclusion of the a parameter is debatable as the variance at length 0 should be theoretically 0, but we included it to add extra flexibility. Given the parameters, we drew 200 samples from each of the cohorts from $N(\mu_{jm}, \sigma_{jm}^2)$ for each of $j \in \{J, A, L_\infty\}$ and $m \in \{1, \ldots, 12\}$. The means were constrained to follow the VBGM and the variances, a function of the means determined by the quadratic parameters. Sampling 200 from each normal distribution imposes mixing proportions of $1/3$ for each of the classes. Modelling 12 months allows estimation of the dynamics of a population over a year. The total data set comprised 7200 simulated individuals. Standard errors were generated by running the simulation 200 times.

Application to blue swimmer crab

To understand how the BSC population changes from month to month, preliminary investigation into the data using an unconstrained mixture of three normal distributions was fitted to the length frequency data for each month. This allowed diagnosis of those months to include and exclude from the model depending on whether they contained significant recruitment or not. The raw data included information from October 1984 to June 1986, but only the months of February 1985 to August 1985 were included from the first year, and February 1986 to May 1986 from the second year. All other months were deemed ineligible due to a recruitment pattern observed in the mixture model fits. In total, there were 11 months modelled over two years.

In the development of the method, we settled upon the use of two length frequency data sets, one gathered via trawling and the other gathered using pots. Although only males are taken from the BSC fishery, both female and male growth was estimated for a comparison, and to understand how females may be affected if future changes were made to the management of the fishery. The pot data set do not contain recruitment and just contain larger females and males. The pot data provide an upper limit distribution on larger BSCs, as these were caught in the deeper offshore areas where BSCs are known to migrate after full maturity. In each month, data were gathered from different dates. However, when modelled, the data are considered to be from the same month with the middle of each month set to t in the model. Therefore, the integration step in each mean calculation is integrated from mid January 1985.

Results/Discussion

Simulation

The method was coded in the R programming language and applied to the simulated data set. The primary reasons for running the simulation were to diagnose any misconceptions in the method and in its implementation. It was also done to confirm that if data were generated from the model that we proposed, then the method could estimate the original parameters.

The parameter estimates from the simulation study agree well with the true values (Table 11). We see that estimates for k, μ_∞, μ_{01}, θ_1, θ_2, b, c are unbiased and have small standard errors. The parameters σ_∞^2 and a are more biased with a having relatively large standard errors. The π and μ estimates are precise and have low bias.

The fitted mixtures match well with the original data (Figure 44). The mean model (average estimates over the 200 simulations) was visualised, showing that by the end of the year, the one year old adults approach the asymptotic adults. The fit for the variance function shows the greatest variability, which reflects the estimated values. Confidence intervals (95 %) show tight banding on the seasonal and variance curves (Figure 44). Overall the method performs well under data simulated under the model.

Blue swimmer crab

The method was applied to the combined length frequency data set from trawl-caught blue swimmer crab. The combined results show that $\mu_\infty \approx 180$ mm and a seasonal curve that peaks in January and is lowest in June (Table 13 and Figure 45). The primary reason for doing the combined run is to reduce variability in the seasonal curve estimates for the individual male and female runs. Given the estimates from the combined run, we constrain the maximum of the seasonal curve to be the first day of January, which is the day that the combined curved reaches its maximum.

For the male run, we see a mean asymptotic length $\mu_\infty \approx 182$ mm and variance $\sigma_\infty^2 = 40.2$, which gives a 0.001 probability of male individuals being greater than 202 mm at asymptotic length (Table 14), if we considered the asymptotic lengths to come from a normal distribution. No male individuals were recorded at lengths greater than 200 mm in this data set. However, males have been observed at a maximum carapace width of 220 mm in the BSC fishery. The estimates of the means of the initial months coincide well with the true data for the 1986 year, but less well for the year of 1985 (Figure 46). The seasonal parameters impose a curve that has a small, no-growth period between the end of April and beginning of July. It is noted that this run of the males was allowed to have negative growth in the seasonal curve because the added maximum constraint from the combined curve led to poor convergence without this extra flexibility. However, in further analysis, this period is considered to have zero growth rather than negative growth.

For the female run, we see that females are much smaller than males with a $\mu_\infty \approx 165.5$ mm and a higher k estimate (Table 17). Females exhibit much more variability in L_∞ than males giving a similar probability of being greater than 200 mm carapace width (Table 17). The seasonal curve exhibits no period of negative growth for females and has a smaller amplitude when compared with the males. The estimates of the means of the initial months fit well with the data with juveniles being included in the asymptotic adult group by August 1985.

Table 11: Summary of von Bertalanffy parameter estimates from simulation study.

Parameter	k	μ_∞	μ_{01}	θ_1	θ_2	σ^2_∞	a	b	c
True values	1	170	60	2	2	35.5	0	1	0.005
Estimates	1.05	170.3	59.7	2.02	1.93	28.4	-0.813	0.995	0.0048
Standard errors	0.0556	0.0722	0.121	1.60	0.581	6.81	14.8	0.261	0.0012

Table 12: Summary of μ estimates from simulation study.

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul	Aug.	Sep.	Oct.	Nov.	Dec.
True value L_∞ adult	169.3	169.5	169.6	169.7	169.8	169.8	169.7	169.7	169.7	169.6	169.6	169.7
Estimate L_∞ adult	170.2	170.3	170.4	170.4	170.4	170.4	170.4	170.4	170.4	170.4	170.4	170.4
S.E. L_∞ adults	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66
True values 1 yr old	144.8	151.5	156.4	159.4	160.8	161.1	161.1	161.1	161.1	161.1	161.3	162.5
Estimate 1 yr old	144.5	151.2	156.0	159.0	160.4	160.7	160.7	160.7	160.7	160.7	161.0	162.2
S.E. 1 yr old	3.53	2.99	2.52	2.21	2.07	2.06	2.07	2.07	2.07	2.09	2.21	2.19
True values juv.	60.0	89.2	110.6	123.7	129.9	131.0	131.0	131.0	131.0	131.0	132.1	137.2
Estimates juvenile	59.8	90.0	111.6	124.6	130.8	132.0	132.0	132.0	132.0	132.1	133.8	139.3
S.E. juvenile	0.72	1.89	2.37	2.53	2.75	3.15	3.19	3.19	3.19	3.28	3.78	3.88

Table 13: Summary of von Bertalanffy growth parameter estimates for combined male and female blue swimmer crab length frequency data with a subset of months chosen to exclude recruitment.

Parameters	k	μ_∞	μ_{01}	μ_{02}	θ_1	θ_2	σ^2_∞	a	b	c	d
Estimates	0.714	179.5	65.3	80.8	0.299	0.0172	63.0	29.5	0.0247	-16.1	805.0

Table 14: Summary of von Bertalanffy growth parameter estimates for male blue swimmer crab length frequency data with a subset of months chosen to exclude recruitment.

Parameters	k	μ_∞	μ_{01}	μ_{02}	θ_1	θ_2	σ^2_∞	a	b	c	d
Estimates	0.692	182.2	71.5	79.2	0.867	0.0436	40.2	71.6	0.0317	-13.6	945.6

Table 15: Summary of von Bertalanffy growth parameter estimates for female blue swimmer crab length frequency data with a subset of months chosen to exclude recruitment.

Parameters	k	μ_∞	μ_{01}	μ_{02}	θ_1	θ_2	σ^2_∞	a	b	c	d
Estimates	0.748	165.5	59.6	81.0	0.377	.0190	138.6	10.6	0.0153	-6.78	1470

Table 16: Summary of mean *k* estimates per month for male blue swimmer crabs

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Estimates	1.53	1.33	0.955	0.512	0.116	0.000	0.000	0.055	0.429	0.872	1.27	1.51

Table 17: Summary of mean *k* estimates per month for female blue swimmer crabs

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Estimates	1.11	1.03	0.863	0.670	0.498	0.393	0.383	0.471	0.633	0.826	0.998	1.10

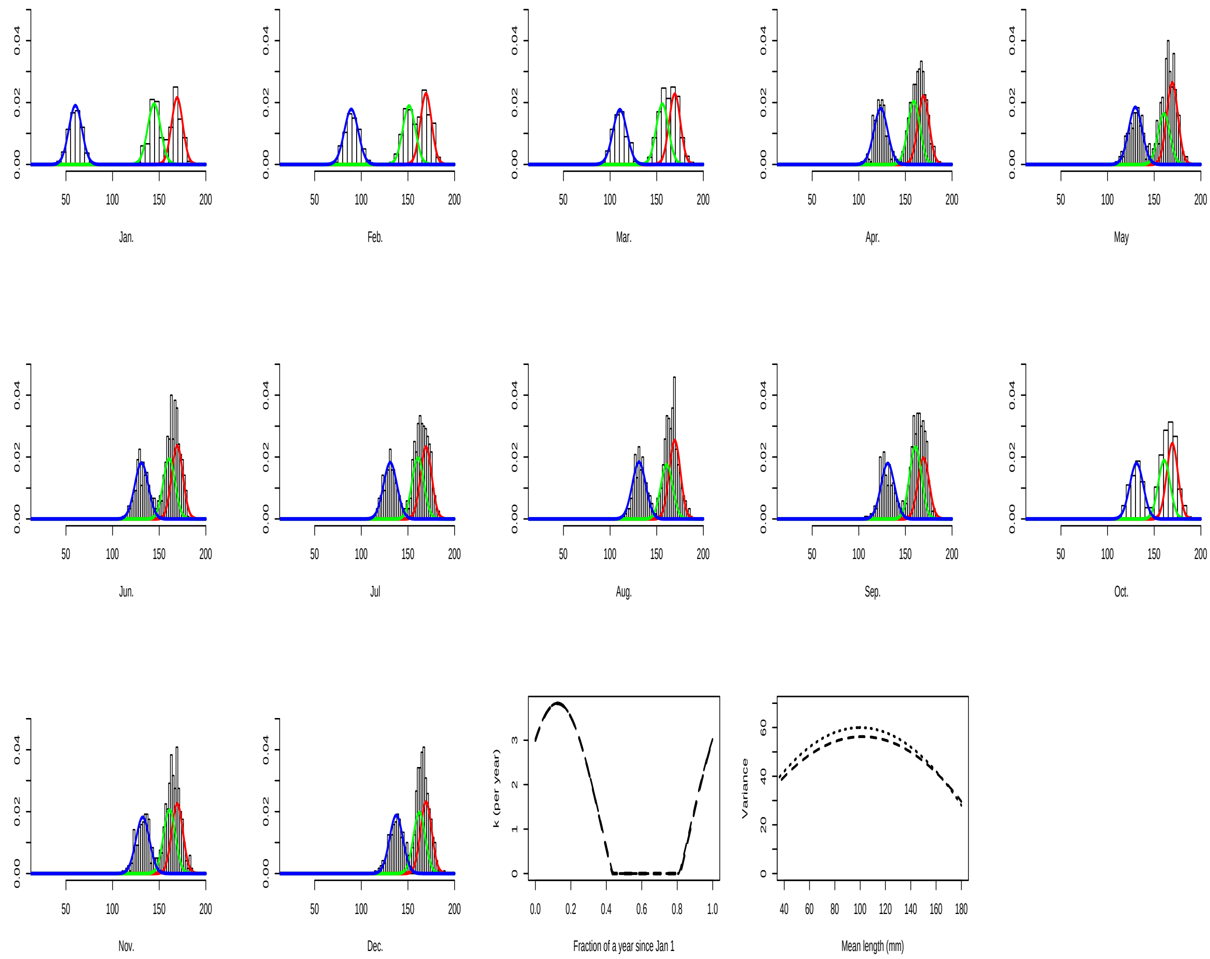

Figure 44: Windows 1-11 are the mixture fits to the simulated data from January to December. The blue curve represents the juvenile cohort, green curve the 1 year group, and the red curve the adults at asymptotic length. Window 12 contains the seasonal curve as a function of fraction of a year with the true and estimated curves plotted. Window 13 contains the variance as a function of the mean length with the short dashed curve being the estimated curve and the long dashed the true curve.

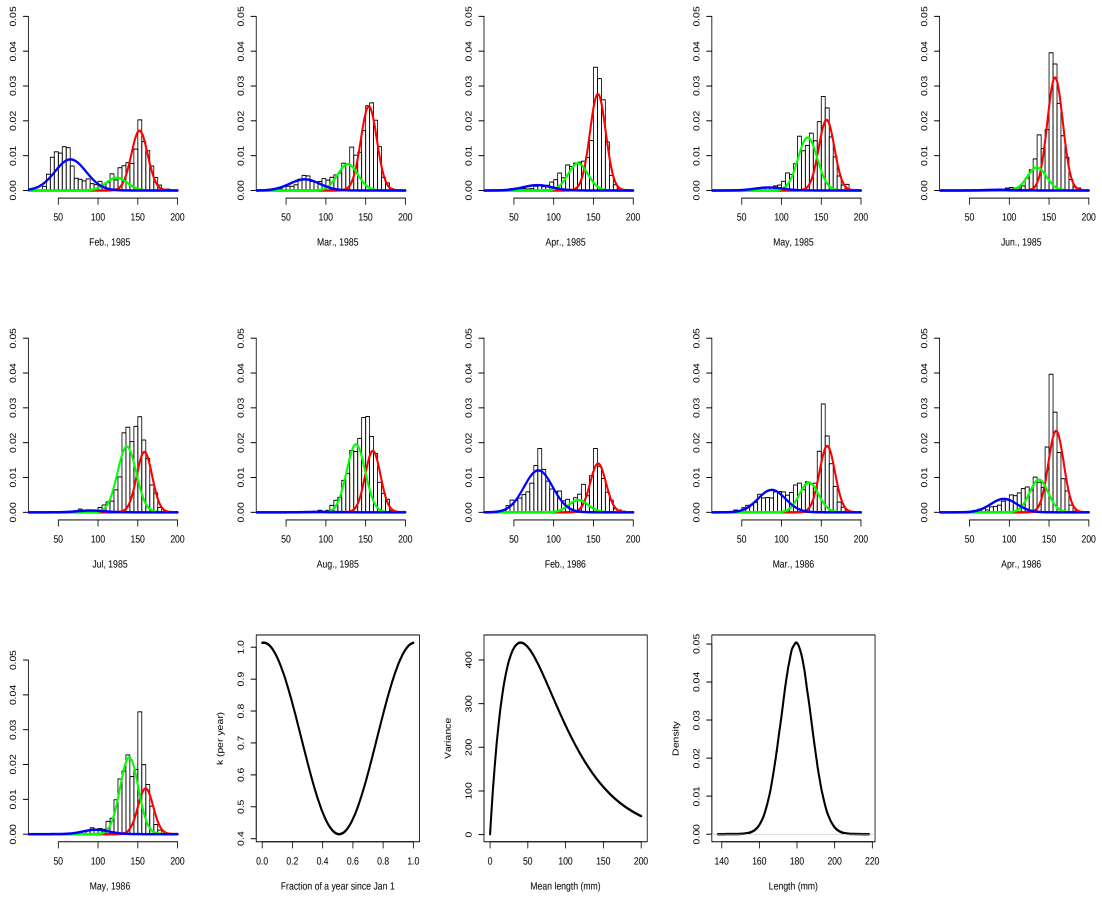

Figure 45: Windows 1-11 are the mixture fits to the combined female and male length frequency data (mm) with a subset of months excluding recruitment from 1985 and 1986, where the blue curve represents the juvenile cohort, green curve the 1 year group, and the red curve the adults at asymptotic length. Window 12 is the seasonal curve as a function of fraction of a year. Window 13 is the length variance as a function of the mean curve. Window 14 displays the distribution of the random variable L_∞ assuming a normal distribution.

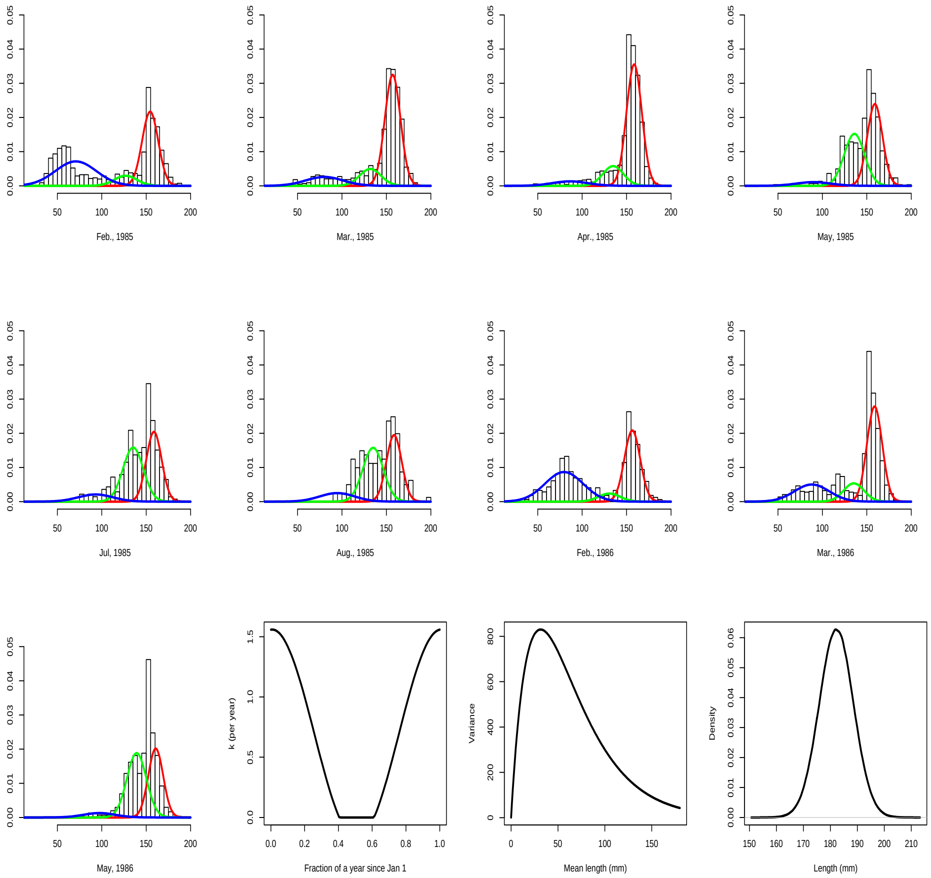

Figure 46: Windows 1-11 are the mixture fits to the male length frequency data (mm) with a subset of months excluding recruitment from 1985 and 1986, where the blue curve represents the juvenile cohort, green curve the 1 year group, and the red curve the adults at asymptotic group. Window 12 is the seasonal curve as a function of fraction of a year. Window 13 is the length variance as a function of the mean curve. Window 14 displays the distributions of the random variable L_∞ assuming a normal distribution.

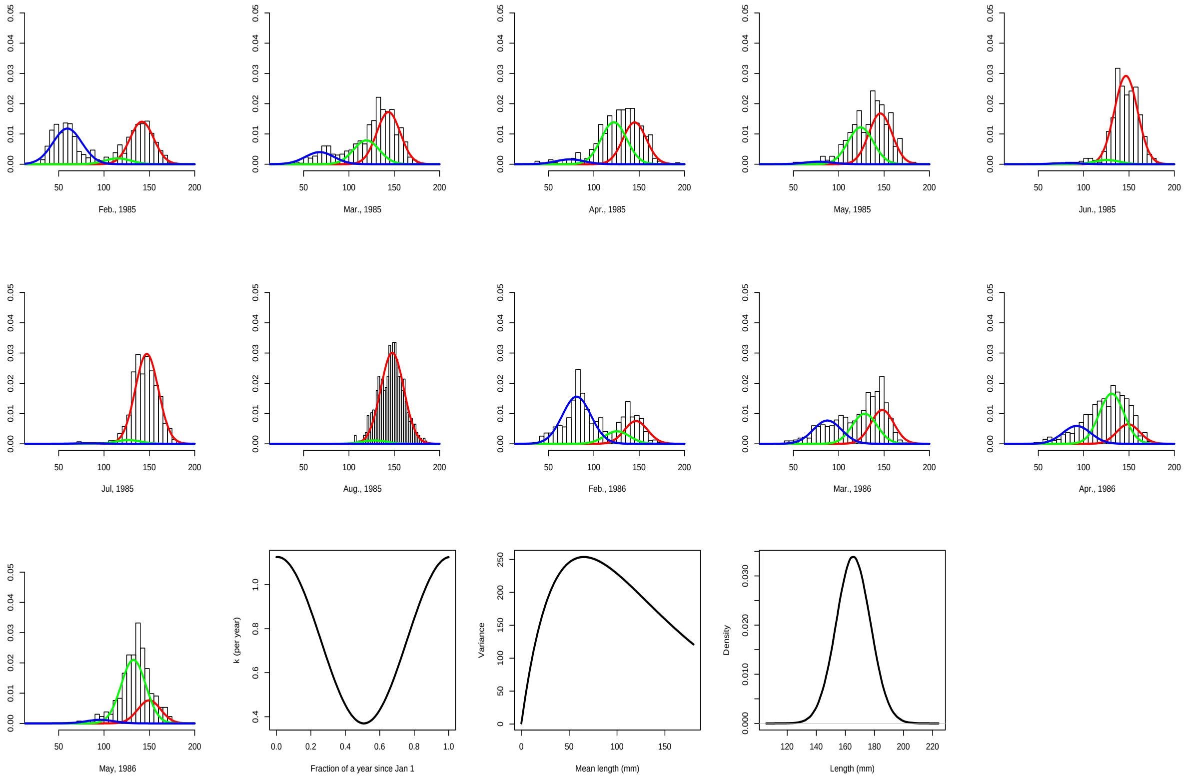

Figure 47: Windows 1-11 are the mixture fits to the female length frequency data (mm) with a subset of months excluding recruitment from 1985 and 1986, where the blue curve represents the juvenile cohort, green curve the 1 year group, and the red curve the adults at asymptotic length. Window 12 is the seasonal curve as a function of fraction of a year. Window 13 is the length variance as a function of the mean curve. Window 14 displays the distributions of the random variable L_∞ assuming a normal distribution.

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Appendix 2: Model Inputs

The data used in the stock assessment models were derived from both the CFISH data discussed in Chapter 6, along with data collected as part of fishery-dependent and fishery-independent sampling conducted at various times since 1984.

Scenarios

Table 18 shows the Scenarios used to analyse the sensitivity of the population model, where Scenario 1 represents the base model. The instantaneous rate of natural mortality was fixed at M = 0.1month^{-1} for all scenarios, apart from Scenario 2, where it was fixed at M = 0.15month^{-1}, and Scenario 3, where M was estimated by the model. The beach price varied seasonally and was uniform for all sizes of crab. However, in the case of Scenario 4, the beach price was uniformly high for all sizes and didn't vary by month, while, for Scenario 5, the price was uniformly low and did not vary by month.

The male von Bertalanffy growth parameter L_∞ was 17 cm for Scenario 8 in accord with estimates discussed in Appendix 1, while growth was not seasonal in Scenario 9. Catch rate standardisations used by the model were derived using the offsets derived in Chapter 6 for all scenarios apart from Scenario 7 where no offset was used in these calculations. Recreational effort was forced to decline, in proportion to the participation rates reported by recreational fishing surveys conducted in Queensland (McInnes, 2008; Taylor et al. 2012), in all scenarios apart from Scenario 6 where recreational effort was constant. The length of first capture for blue swimmer crabs caught in each of the Moreton Bay and Sunshine Coast regions was estimated by the model in all scenarios apart from Scenario 10, where these values were set at L_{50} = 11.75cm and L_{50} = 13.25cm, respectively.

Table 18: Specifications of each Scenario used to analyse the sensitivity of the population model. See text for description of the respective parameters.

Variable/ parameter	Scenario 1	2	3	4	5	6	7	8	9	10
M	0.1	0.15	est.	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Price by CW	Uniform	Uniform	Uniform	High	Low	Uniform	Uniform	Uniform	Uniform	Uniform
Growth	a	a	a	a	a	a	a	b	c	a
Catch rate offset	yes	yes	yes	yes	yes	yes	no	yes	yes	yes
Rec. harvest	decline	decline	decline	decline	decline	constant	decline	decline	decline	decline
Vulnerability	est.	est.	est.	est.	est.	est.	est.	est.	est.	fixed

Growth

For the purposes of the current study, growth of blue swimmer crabs was modelled using a size transition matrix. Essentially, this method allows a crab to grow each month according to a given distribution which, in this case, was based on increment data derived from a tagging study conducted by Potter et al. (1991). Quinn and Deriso (1999) reported that the expected length $E(x)$ with a size l^* one time unit later is $E(x) = l^* + \overline{\Delta_l}$. The expected carapace width at the next time interval is modelled using a gamma distribution with a scalar parameter, α, and a shape parameter, β. The mean and variance of the gamma distribution is given by Quinn and Deriso (1999b) as $E(x) = \alpha\beta$ and $Var(x) = \alpha\beta^2$. Both $E(x)$ and $Var(x)$ were calculated from growth increments recorded during the study by Potter et al. (1991), before the shape parameter, β, was calculated by dividing the variance by the expected value, i.e.:

$$\frac{Var(x)}{E(x)} = \frac{\alpha\beta^2}{\alpha\beta} = \beta$$

This shape parameter was calculated to be 0.28 and was used to determine seasonal growth in Appendix 1 and resulted in the three growth conditions depicted in Figure 48.

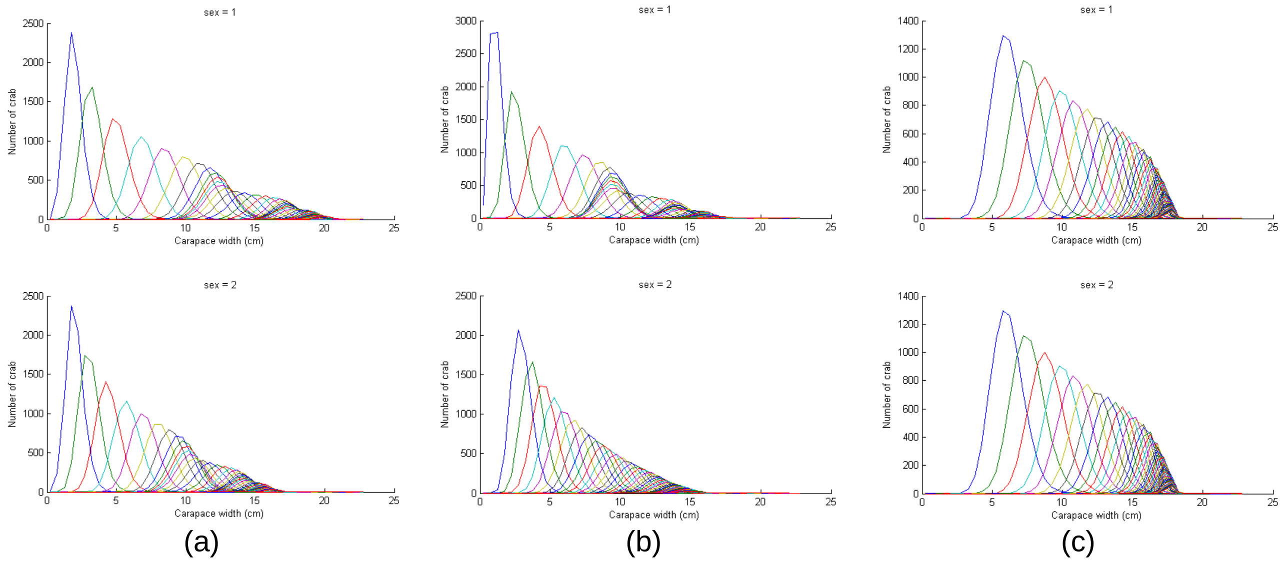

Figure 48: Illustration of monthly male (sex = 1) and female (sex = 2) blue swimmer crab abundance as a function of carapace width, and natural mortality. Distributions are based on gamma distributions with distribution parameters (α and β) derived using methods described by Quinn and Deriso (1999) from tagging data reported by Potter et al. (1991). Method 'a' was used in Scenarios 1, 2, 3, 4, 5, 6, 7 and 10; Method 'b' was used in Scenario 8; and Method 'c' was used in Scenario 9.

Table 19: Parameters used to derive the crab abundance figures shown in Figure 48.

Parameter	a	b	c
Male L_∞	21.0	18.2	17.7
Female L_∞	17.1	16.6	17.7
Male k (yr^{-1})	0.882	0.692	1.62
Female k (yr^{-1})	0.882	0.748	1.62
Male θ_1	0.49	0.867	0
Female θ_1	0.49	0.377	0
Male θ_2	0.40	0.044	0
Female θ_2	0.40	0.019	0
β	0.28	0.28	0.28

Price to fishers was modelled as a seasonally varying price paid by the Sydney Fish Market during the 2014 fishing year (Table 20). Other pricing scenarios included a fixed average monthly price of $8 per kg and $14 per kg, representing the lower and upper limits of price respectively.

Table 20: Average price paid by the Sydney Fish Market to commercial fishers for cooked blue swimmer crabs during the 2014 fishing season.

Month	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
Price ($/kg)	8.54	8.33	8.49	9.55	7.85	10.47	11.09	9.26	8.06	7.01	7.36	8.49

Moreton Bay and Sunshine Coast

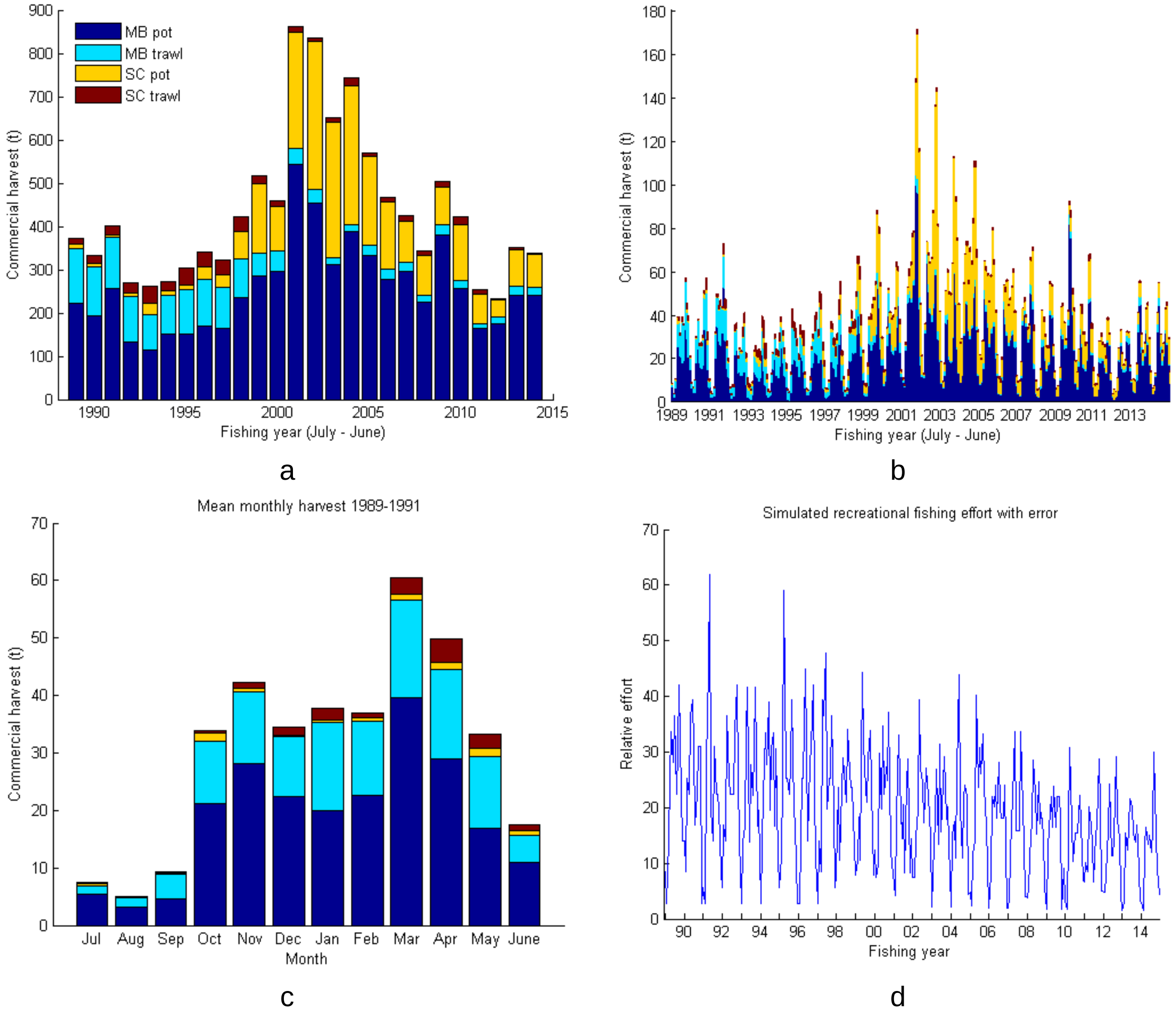

Figure 49: Model inputs for all scenarios – a) annual and b) monthly catch by sector for the Moreton Bay (MB) and Sunshine Coast (SC) regions; c) mean monthly catch by sector for the fishing years 1989 – 1991 by sector; and d) monthly recreational fishing effort.

Total catch by fishing year (Figure 49a) and fishing year/month (Figure 49b) as a function of fishing sector were calculated from CFISH data. The equilibrium point – the point at which catch rates stabilise after initial levels of exploitation – was calculated from the mean monthly harvest for the years 1989 to 1991 from CFISH data (Figure 49c). Relative recreational fishing effort (Figure 49d) was estimated from recreational fishing survey estimates (e.g. McInnes, 2008 and Taylor, et al. 2012) and standardised with the levels of fishing effort in the commercial pot fishery, assuming recreational and commercial fishing effort are correlated.

Male and female carapace width-weight relationships (Figure 50a), female fecundity as a function of carapace width (Figure 50b), and maturity at carapace width (Figure 50c) were derived using parameters estimated from data collected during fishery-independent trawl surveys, and fishery-dependent biological sampling conducted during the period 1999 – 2001.

The carapace width (mm) - weight (g) relationships for males and females are represented by the equations:

$$\text{Male:} g = 8.55 \times 10^{-6} mm^{3.466}$$
$$\text{Female: } g = 9.31 \times 10^{-6} mm^{2.984}$$

Female fecundity f as a function of carapace width (mm) is represented by the equation:

$$f = 31.605 \times mm^{0.0144}$$

Maturity ogives were generated with the following equations, where m is the proportion of mature animals as a function of carapace width (mm):

$$\text{Male: } m = \frac{e^{-13.5129+(0.139929 \times mm)}}{1+e^{-13.5129+(0.139929 \times mm)}}$$

$$\text{Female: } m = \frac{e^{-23.57965+(0.216872 \times mm)}}{1+e^{-23.57965+(0.216872 \times mm)}}$$

The length at recruitment was derived by modelling the length frequency distribution of juvenile (<10cm carapace width) male and female blue swimmer crabs on the log scale (Figure 50d). These animals were caught during fishery-independent trawl surveys conducted by Sumpton et al. (2003).

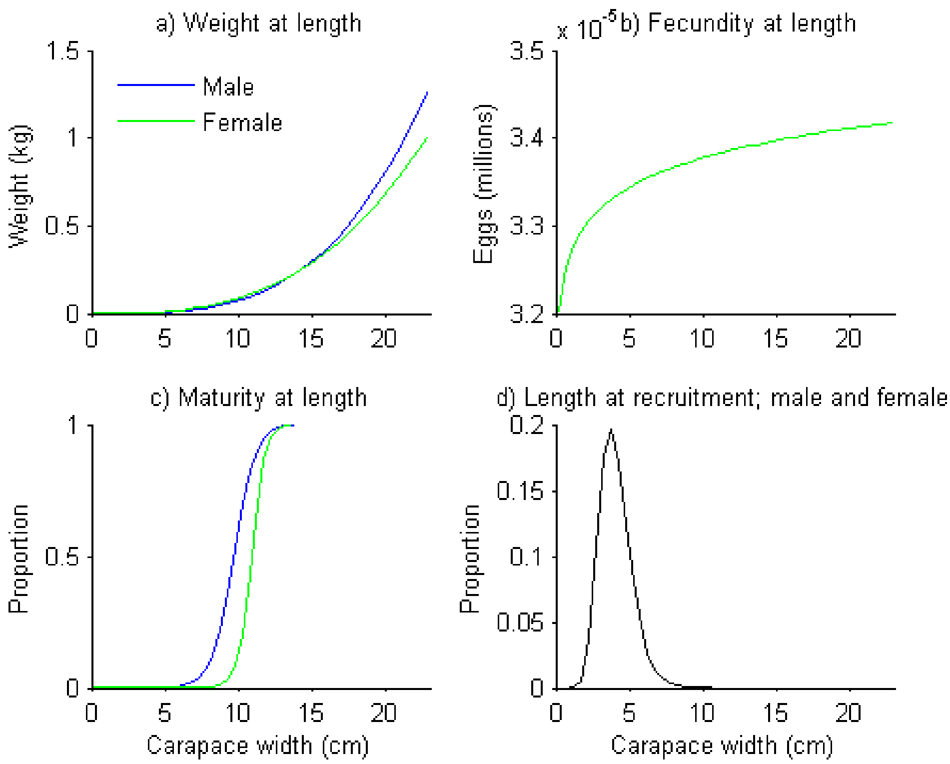

Figure 50: Biological parameters used in the stock assessment model – a) length-weight relationships; b) female fecundity; c) maturity ogives and; d) recruitment for males and/or females all as a function of carapace width in centimetres. See text for methods used to derive the parameters.

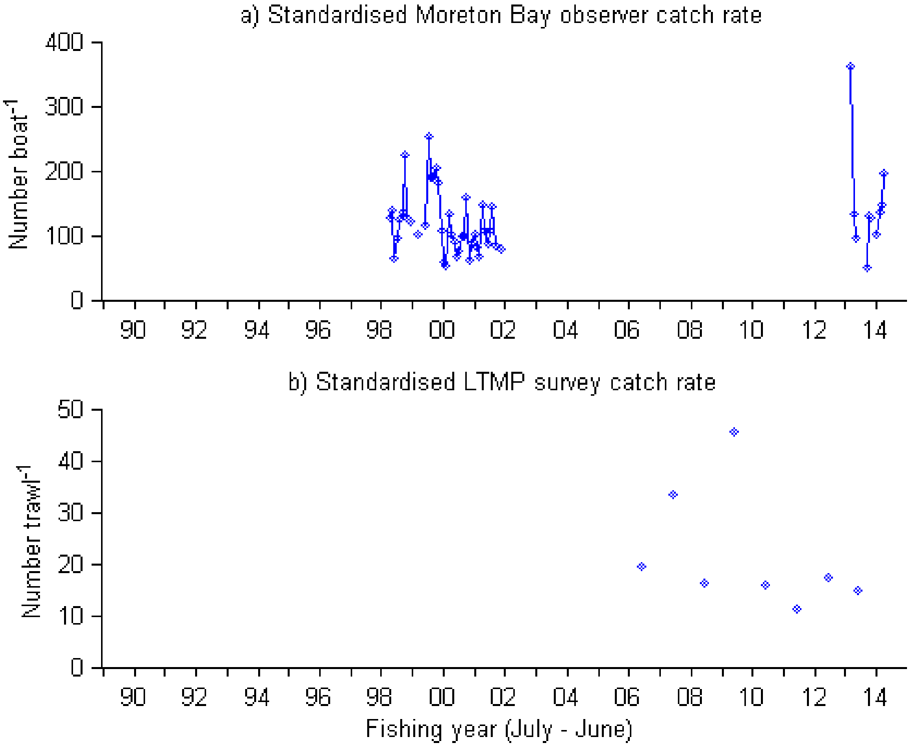

Figure 51: a) standardised catch rate for fishery-dependent sampling of commercial blue swimmer crab pot fishers operating in the Moreton Bay region; and b) standardised catch rate of juvenile blue swimmer crab reported from Fisheries Queensland's annual recruitment surveys conducted as part of its' Long Term Monitoring Program.

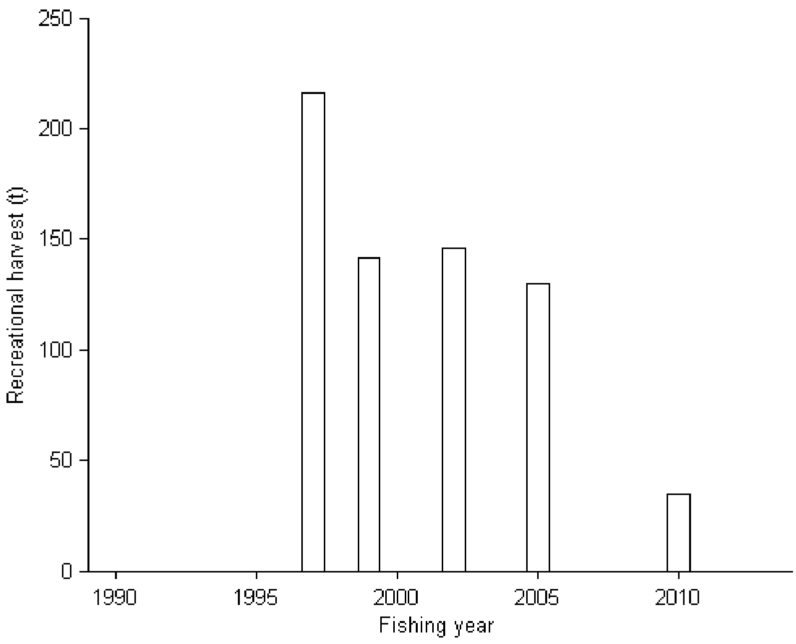

Figure 52: Estimated recreational harvest, in tonnes, of blue swimmer crab from relevant recreational fishing surveys such as those reported by McInnes (2008) and Taylor et al. (2012).

Hervey Bay

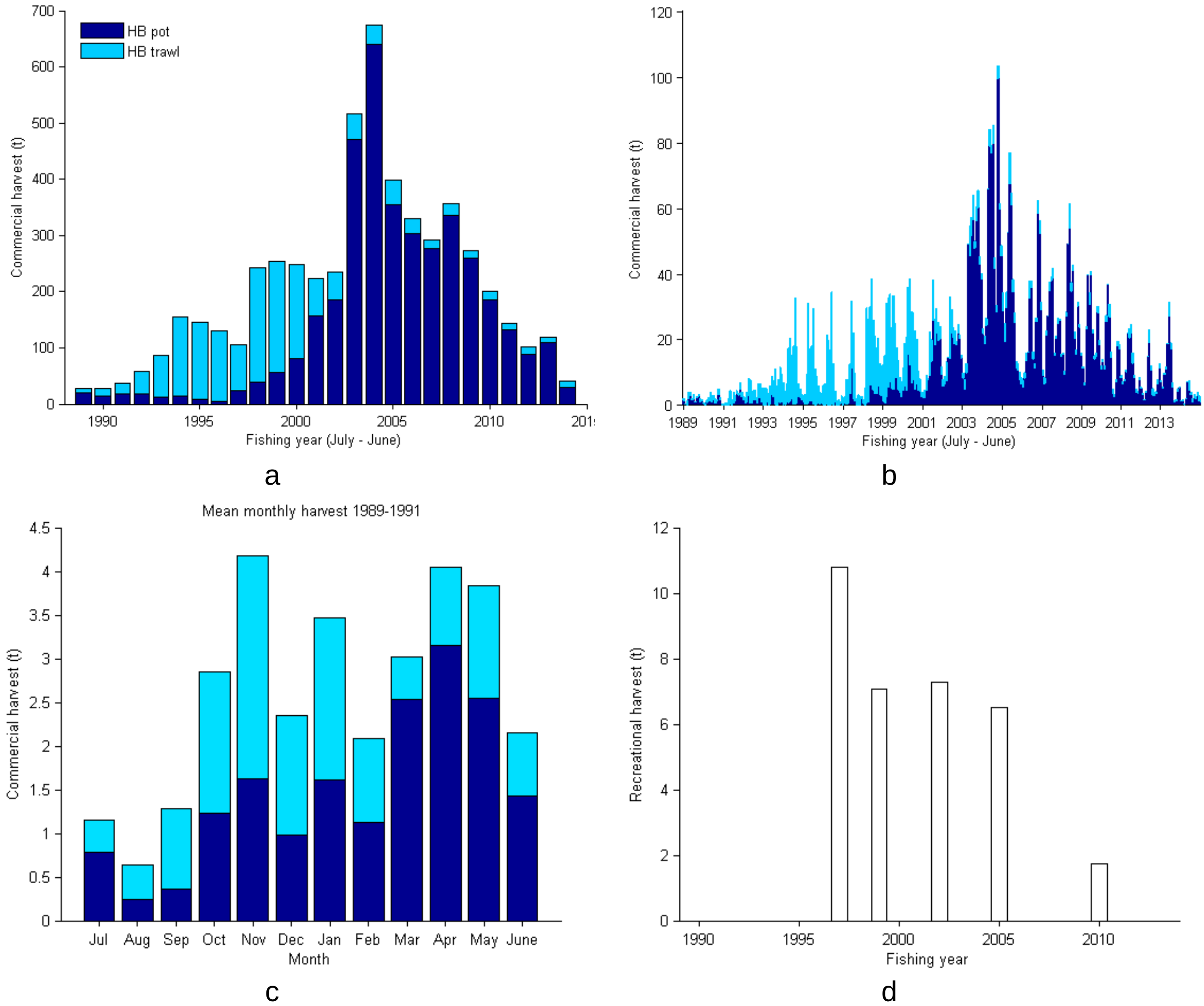

Figure 53: Model inputs for all scenarios for Hervey Bay – a) annual and b) monthly catch by the pot and trawl sector; c) mean monthly catch by sector for the fishing years 1989 – 1991 by sector; and d) recreational pot catch.

Model input catch data for the Hervey Bay fishery model is shown in Figure 53. Other Hervey Bay model input data (particularly biological and growth data) were identical to those used in the Moreton Region models (Figure 50). The fishery Independent data (Figure 51) were not used in the Hervey Bay models as the surveys were only conducted in Moreton Bay, and no comparable data were available for the Hervey Bay fishery.

Model Outputs

Moreton Bay and Sunshine Coast

Table 21: Maximum likelihood parameter estimates for each Scenario. The parameters are: 1) $\log(R_{max} - 1)$ = Recruitment compensation ratio for Beverton-Holt stock-recruitment curve; 2) $\log(R_0)$ = virgin recruitment; 3) μ = recruitment peak; 4) κ = recruitment spread; 5) L_{50} IS = Moreton Bay carapace width at first capture; 6) δ = Moreton Bay carapace width at first capture slope; 7) L_{50} OS = Sunshine Coast width at first capture; and 8) q_{rec} = recreational catchability.

Parameter	Scenario							
	1	2	3	6	7	8	9	10
$\log(R_{max} - 1)$	2.944	0.612	-0.246	2.944	2.944	0.064	2.944	0.719
$\log(R_0)$	-1.950	-0.772	0.098	-1.946	-2.028	-1.204	-1.867	-1.509
μ	9.433	9.433	9.267	9.418	9.877	7.461	7.689	7.539
κ	0.429	0.318	0.222	0.416	0.450	3.849	0.749	0.565
L_{50} IS	13.250	13.524	13.738	13.250	13.209	13.040	12.818	11.750
δ	1.652	1.647	1.664	1.652	1.673	1.502	1.699	1.652
L_{50} OS	14.684	14.837	14.948	14.683	14.591	13.938	14.158	13.250
q_{rec}	0.00082	0.00214	0.00241	0.00091	0.00019	0.08839	0.00061	0.00169
M	0.1	0.15	0.192	0.1	0.1	0.1	0.1	0.1

Table 22: Negative log-likelihood values for a range of parameters estimated as part of each modelling scenario. The model calculated log-likelihood values for each parameter, with lower values representing better fits. MB CPUE = standardised catch rate in the Moreton Bay region; SC CPUE = standardised catch rates from the Sunshine Coast region; LTMP CPUE = standardised catch rate (numbers trawl^{-1}) from Fisheries Queensland's recruitment survey; Observer CPUE = standardised catch rate from fishery dependent sampling in Moreton Bay; MB male LF = male length frequencies from the Moreton Bay region; MB female LF = female length frequencies from the Moreton Bay region; SC Male LF = male length frequencies from the Sunshine Coast region; SC Female LF = female length frequencies from the Sunshine Coast region; Rec. harvest = recreational harvest; M = natural mortality (month^{-1}); and Small population = penalty parameter to prevent small population.

Component	Scenario							
	1	2	3	6	7	8	9	10
MB CPUE	67.6	83.3	96.2	67.4	41.5	207.7	52.1	54.0
SC CPUE	48.8	42.9	40.2	49.0	34.7	217.9	116.8	41.6
LTMP CPUE	4.9	4.2	3.7	4.9	5.2	4.6	4.0	4.6
Observer CPUE	29.1	29.6	30.3	29.3	29.0	53.9	28.9	29.0
MB Male LF	-905.4	-923.8	-937.1	-905.2	-890.3	-275.6	-901.2	-597.7
MB Female LF	-519.6	-581.1	-594.5	-519.9	-523.5	-549.5	-366.6	-532.9
SC Male LF	-585.6	-573.0	-564.8	-585.6	-584.8	7.8	-423.2	-445.3
SC Female LF	-144.3	-172.1	-186.0	-144.3	-148.2	-198.7	-103.3	-212.0
Rec. harvest	9.5	4.9	4.4	9.5	12.6	9.9	8.2	3.3
M	0.0	0.0	10.5	0.0	0.0	0.0	0.0	0.0
Recruitment deviates	10.4	5.9	3.9	10.3	11.4	-3.0	18.3	3.7
Small population	0.0	0.0	0.0	0.0	0.0	5.6	0.0	0.0
Total	-1984.5	-2079.1	-2093.3	-1984.7	-2012.4	-519.4	-1565.9	-1651.8

The following figures represent outputs from the stock assessment model for Scenario 1. Similar outputs were generated for each scenario tested. For the sake of brevity, only relevant outputs are reported.

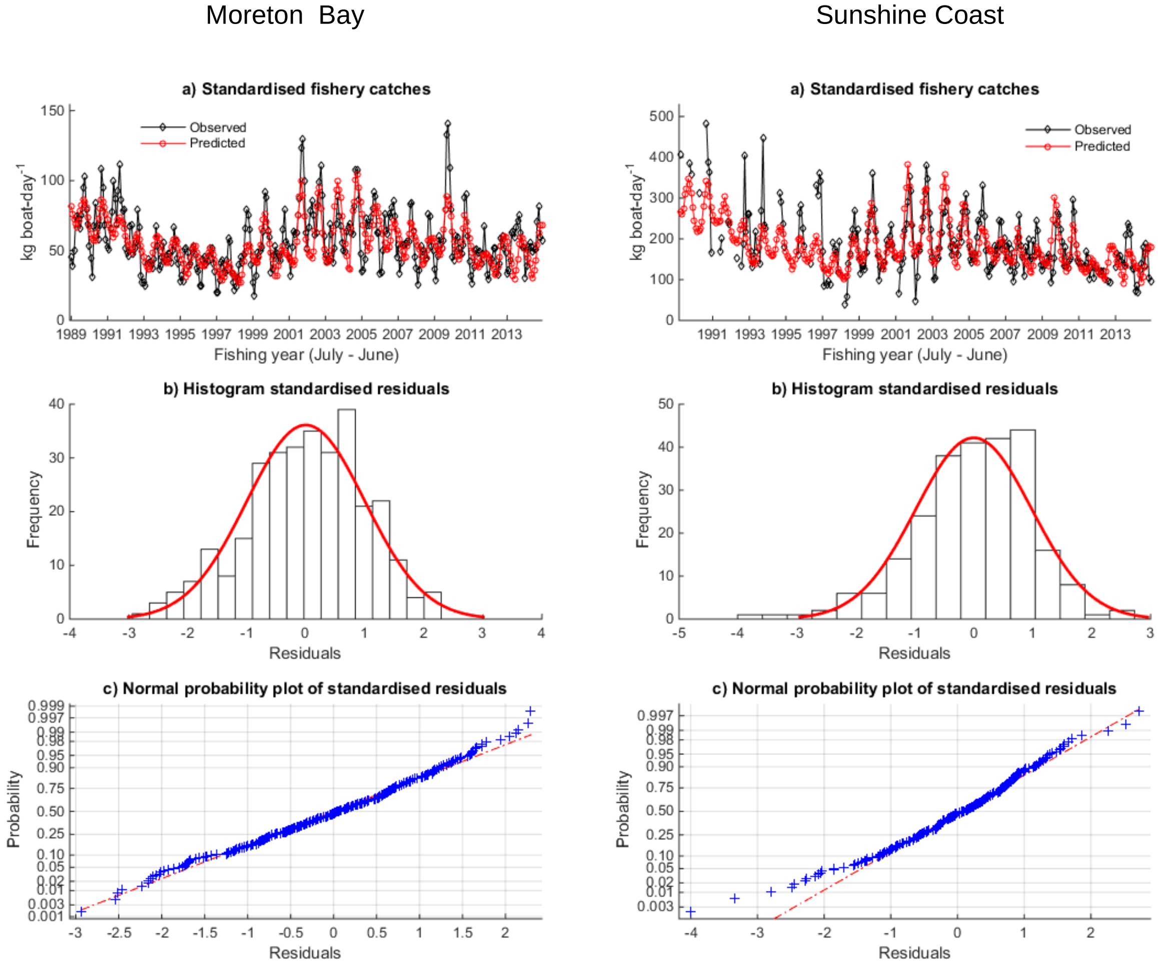

Figure 54: Moreton Region scenario 1 diagnostic plots for a) comparing estimated and observed catch rates (from the catch rate standardisation process described in Chapter 6), b) comparing the density of log standardised residuals against normal distribution, and c) linear normality plot of log standardised residuals.

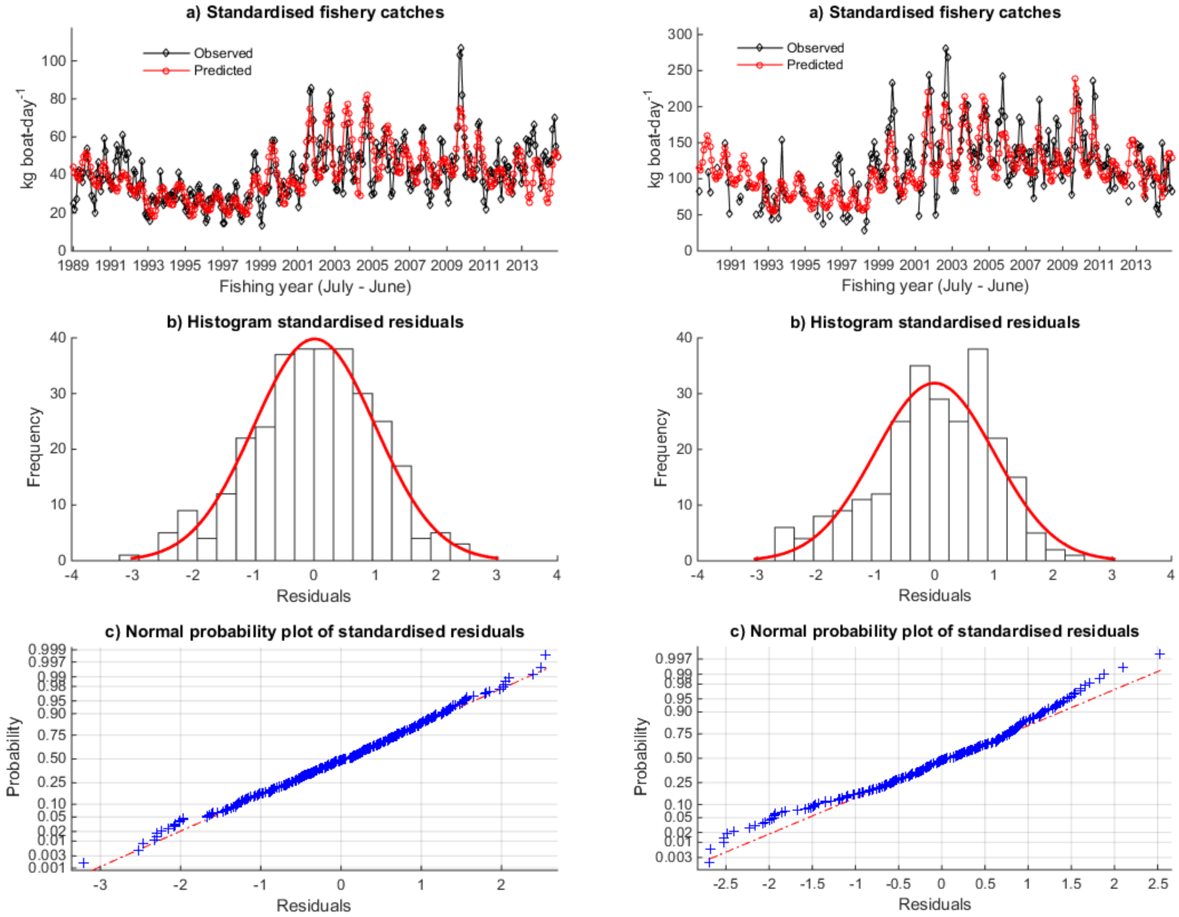

Figure 55: Moreton Region scenario 7 diagnostic plots for a) comparing estimated and observed catch rates (from the catch rate standardisation process described in Chapter 6), b) comparing the density of log standardised residuals against normal distribution, and c) linear normality plot of log standardised residuals.

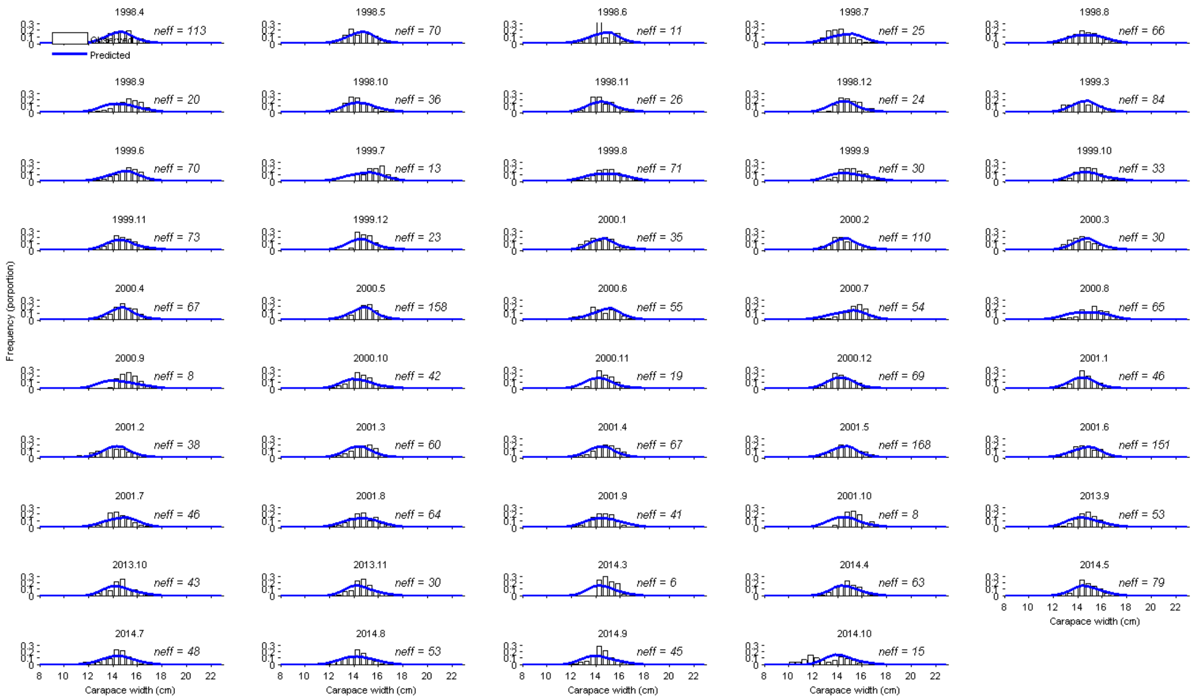

Figure 56: Predicted and observed length frequency distributions for male blue swimmer crabs from the Moreton Bay region for Scenario 1.

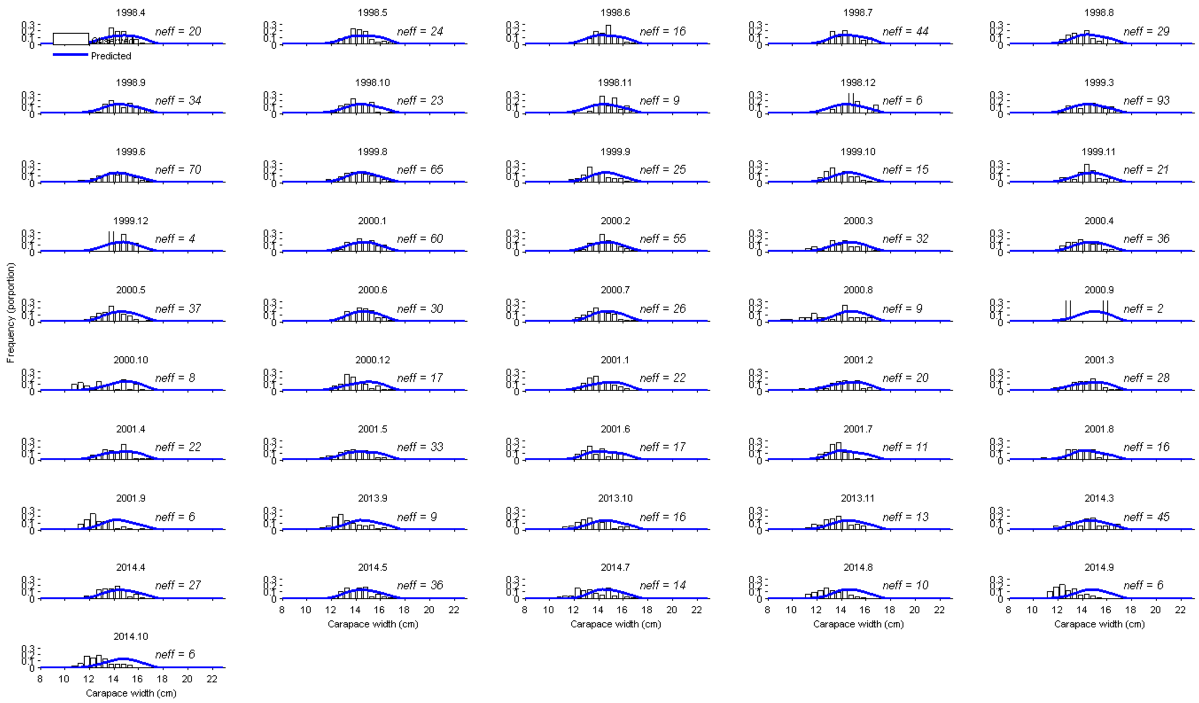

Figure 57: Predicted and observed length frequency distributions for female blue swimmer crabs from the Moreton Bay region for Scenario 1.

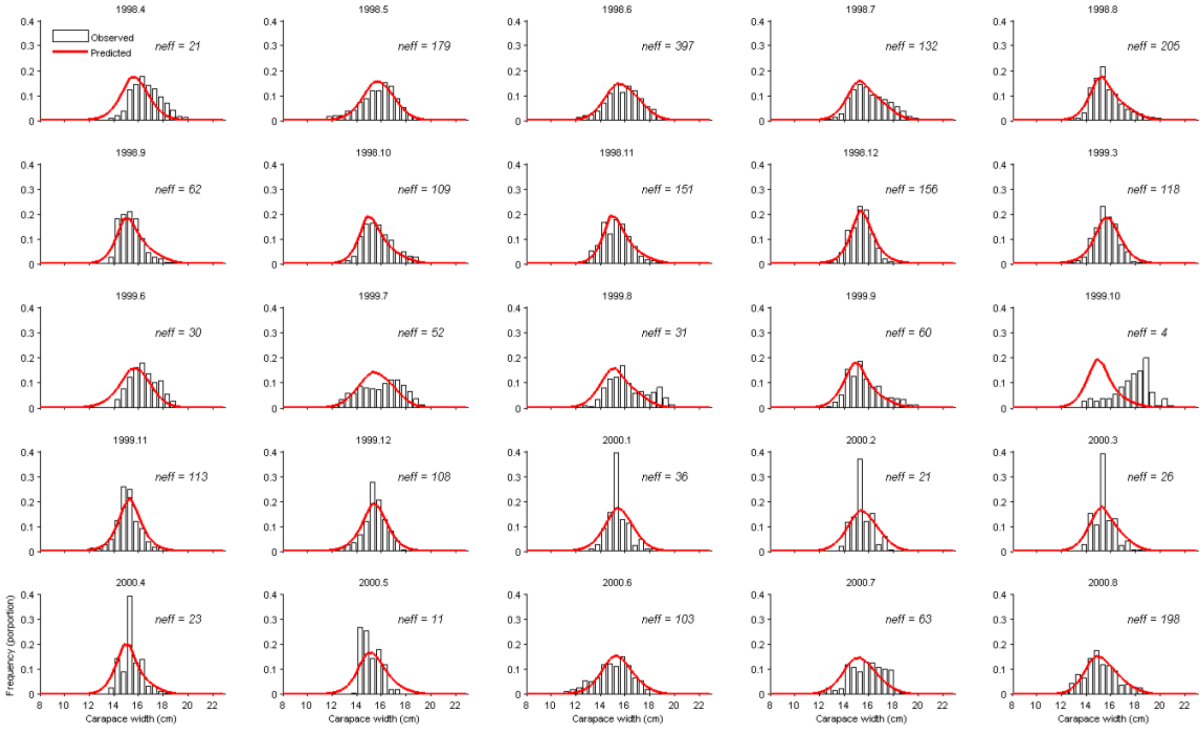

Figure 58: Predicted and observed length frequency distributions for male blue swimmer crabs from the Sunshine Coast region for Scenario 1.

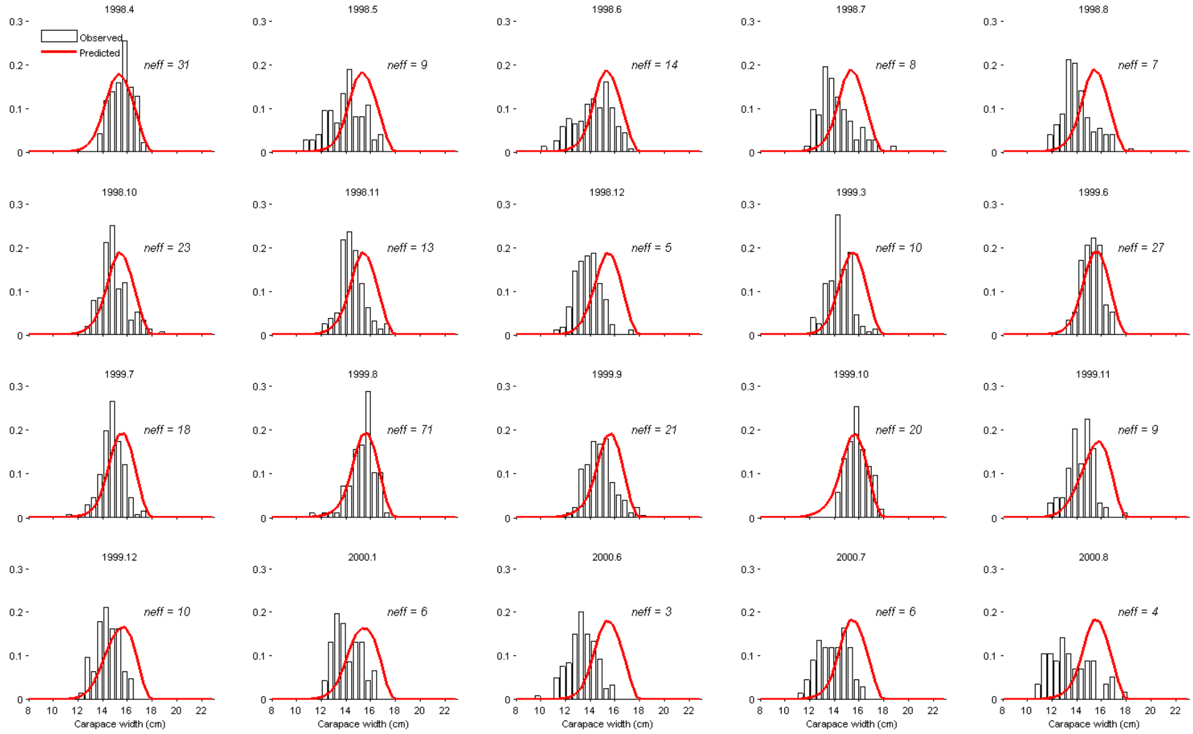

Figure 59: Predicted and observed length frequency distributions for female blue swimmer crabs from the Sunshine Coast region for Scenario 1.

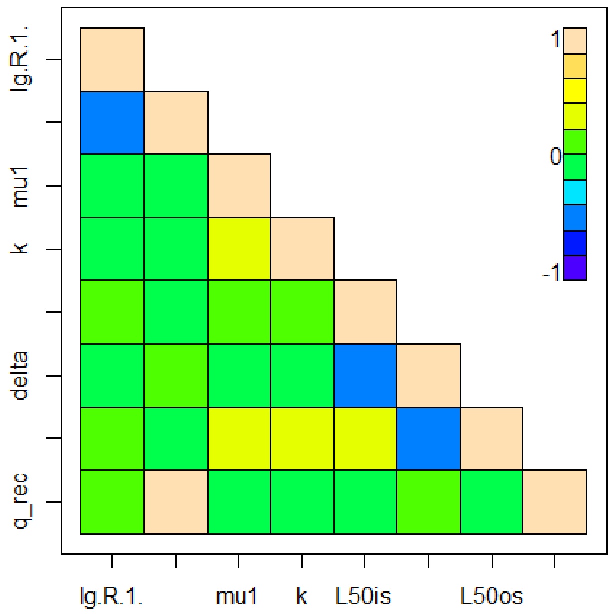

Figure 60: Correlation matrix of estimated parameters for Scenario 1. Parameters, in order, on the y-axis are: 1) Recruitment compensation ratio for the Beverton-Holt stock-recruitment curve; 2) virgin recruitment; 3) recruitment peak; 4) recruitment spread; 5) Moreton Bay carapace width at first capture; 6) Moreton Bay carapace width at first capture slope; 7) Sunshine Coast width at first capture; and 8) recreational catchability.

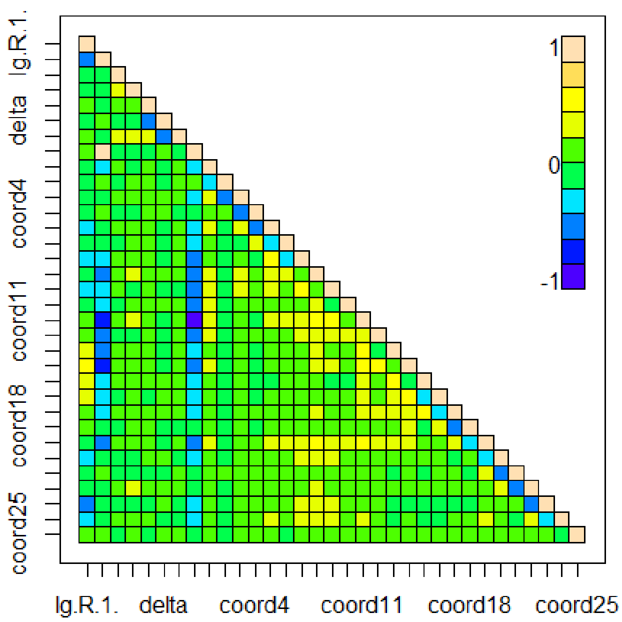

Figure 61: Correlation matrix of estimated parameters for Scenario 1. Parameters, in order, on the y-axis are: 1) Recruitment compensation ratio for the Beverton-Holt stock-recruitment curve; 2) virgin recruitment; 3) recruitment peak; 4) recruitment spread; 5) Moreton Bay carapace width at first capture; 6) Moreton Bay carapace width at first capture slope; 7) Sunshine Coast width at first capture; and 8) recreational catchability. Remaining 25 parameters are recruitment co-ordinate parameters.

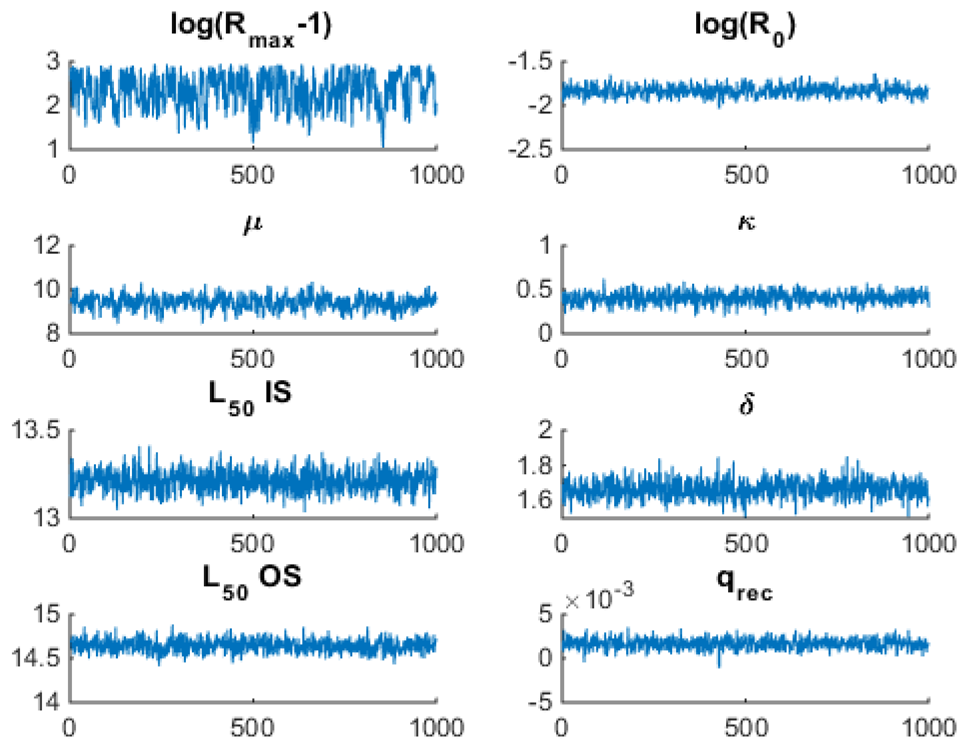

Figure 62: Parameter traces for estimated parameters from 1000 Markov Chain Monte Carlo (MCMC) iterations for Scenario 1. The parameters are: 1) $\log(R_{max} - 1)$ = Recruitment compensation ratio for Beverton-Holt stock-recruitment curve; 2) $\log(R_0)$ = virgin recruitment; 3) μ = recruitment peak; 4) κ = recruitment spread; 5) L_{50} IS = Moreton Bay carapace width at first capture; 6) δ = Moreton Bay carapace width at first capture slope; 7) L_{50} OS = Sunshine Coast width at first capture; and 8) q_{rec} = recreational catchability.

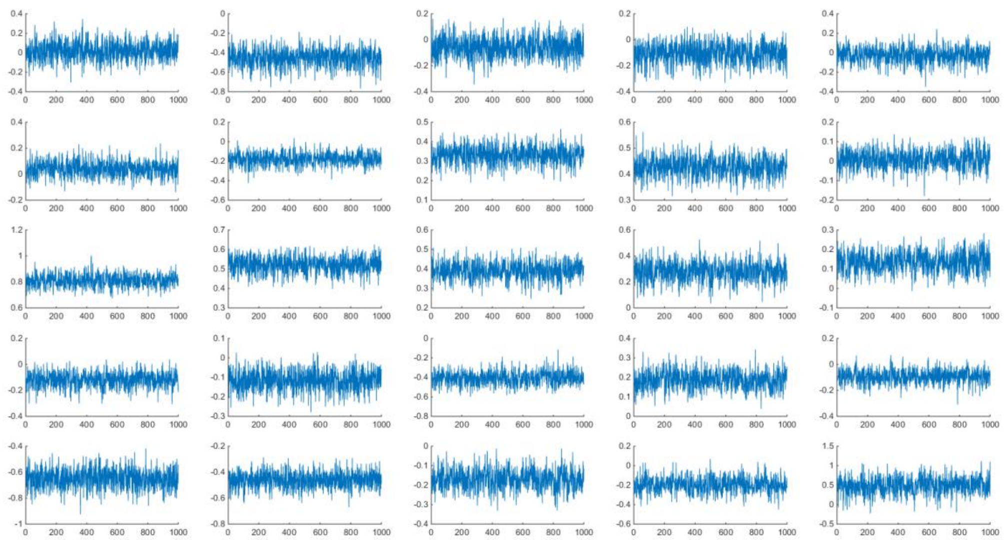

Figure 63: Traces for estimated recruitment co-ordinate parameters from 1000 posterior Markov Chain Monte Carlo (MCMC) iterations for Scenario 1.

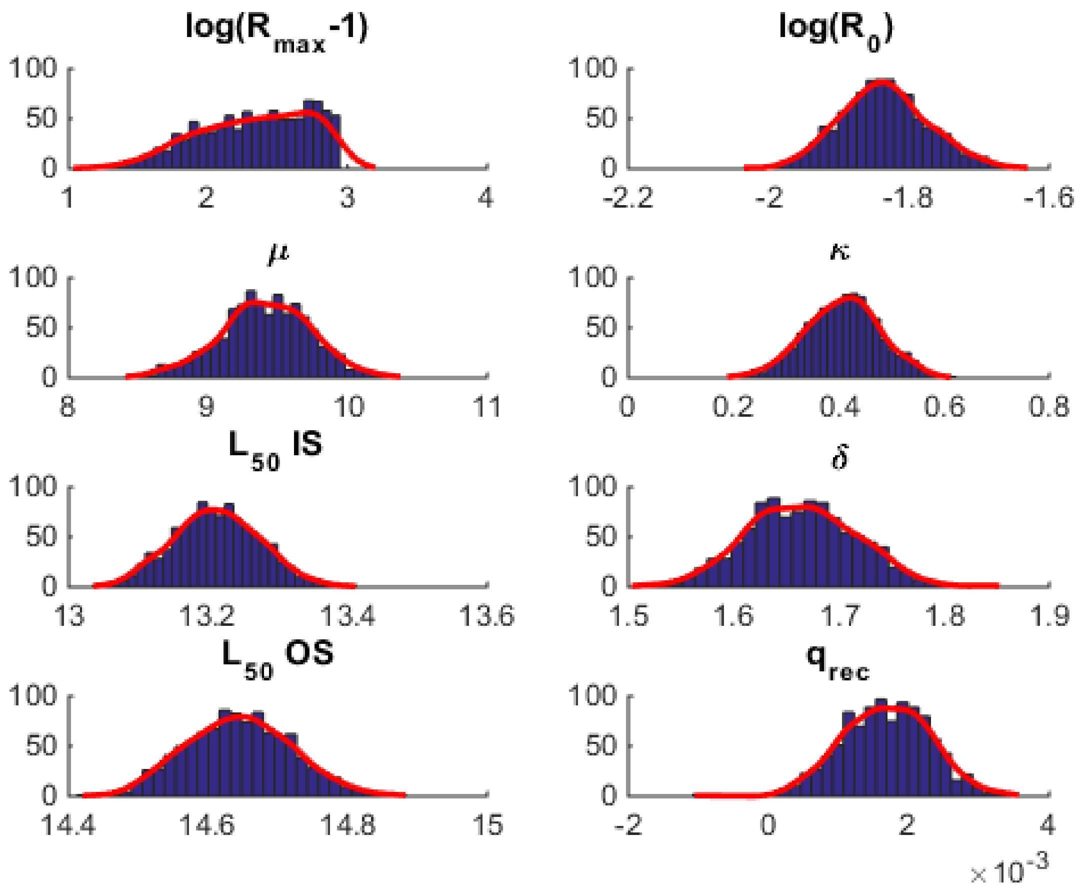

Figure 64: Posterior MCMC densities Moreton Region model, scenario1

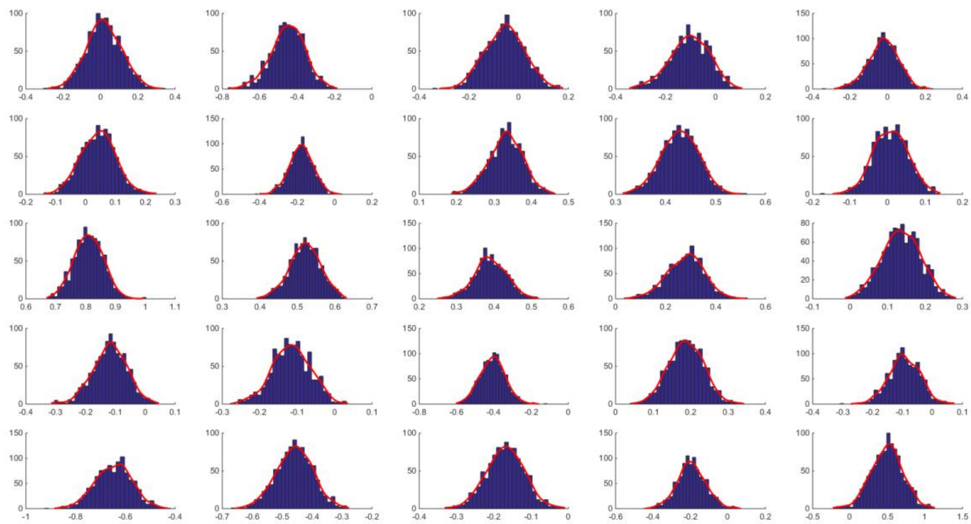

Figure 65: Posterior density of recruitment co-ordinate parameters Moreton Region model, scenario1

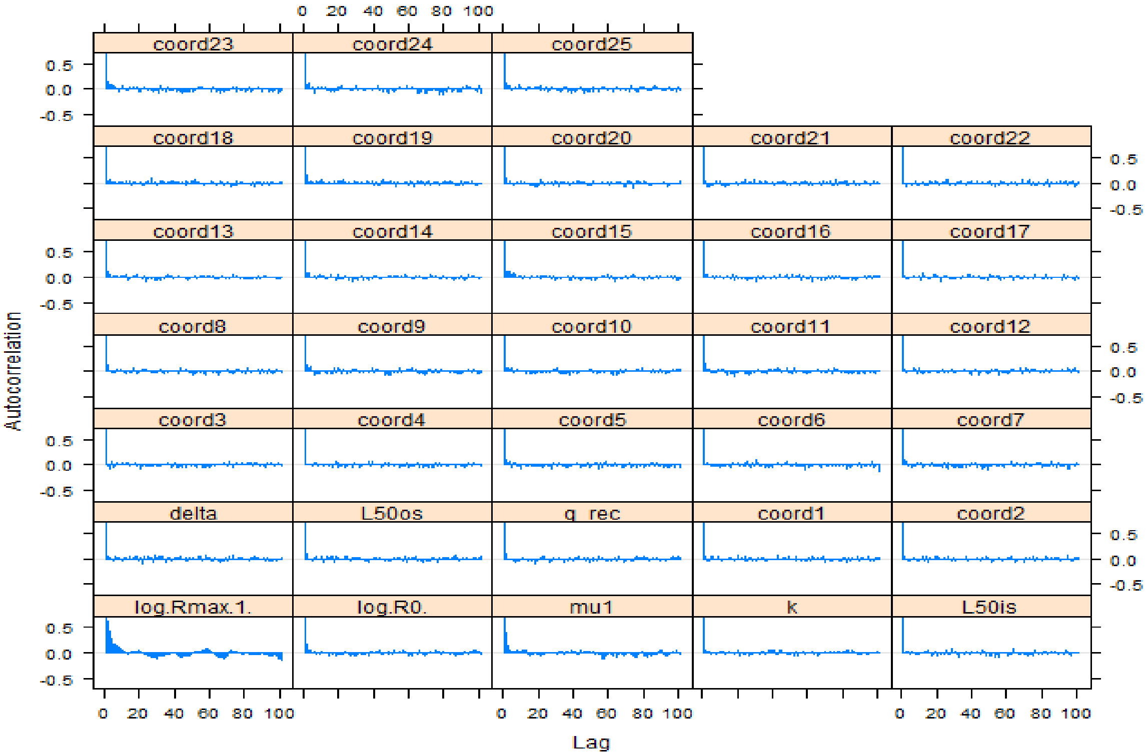

Figure 66: Auto correlations of all parameters used in the Moreton region model, scenario 1.

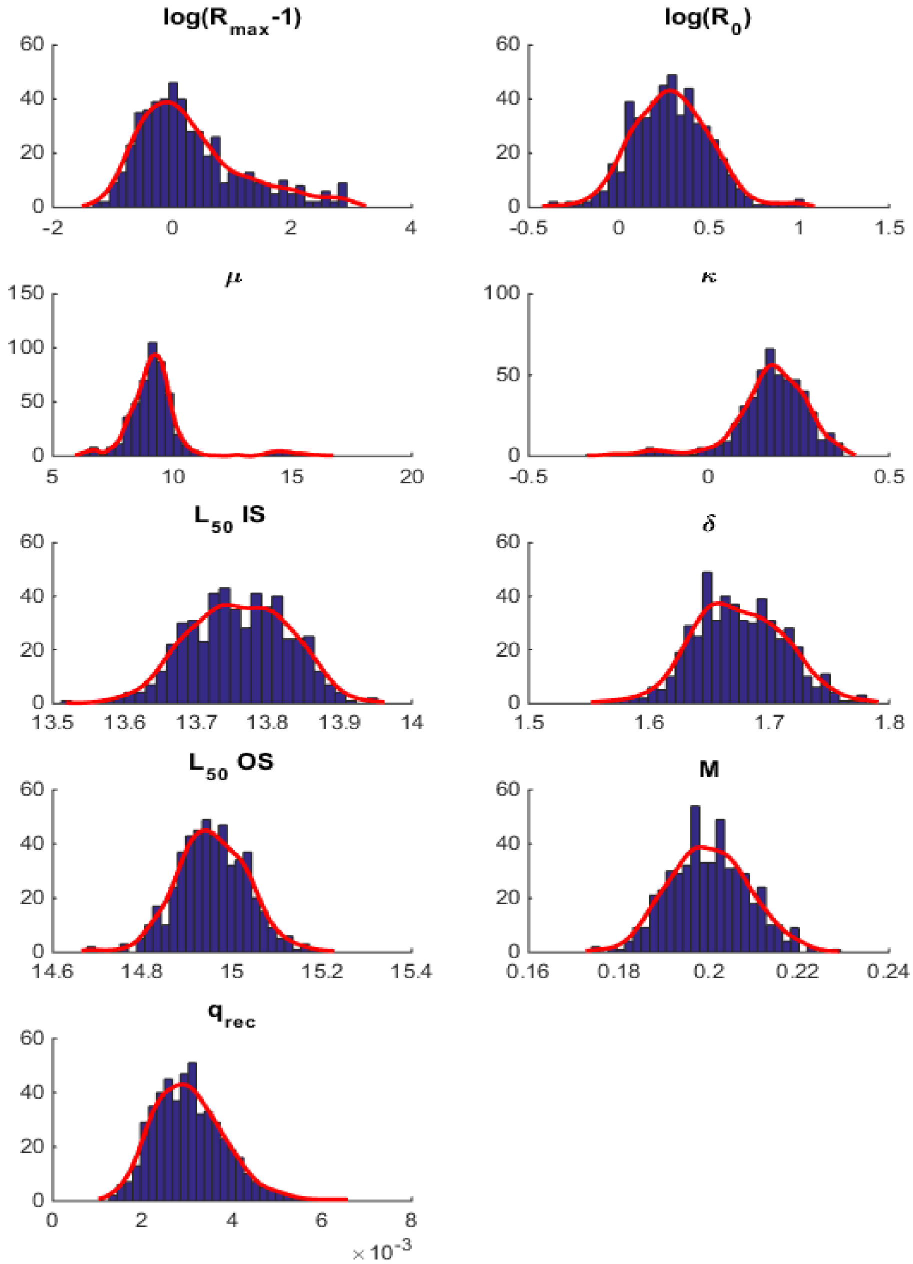

Figure 67: Posterior density of key model parameters for the Moreton Region model, Sceanrio 3.

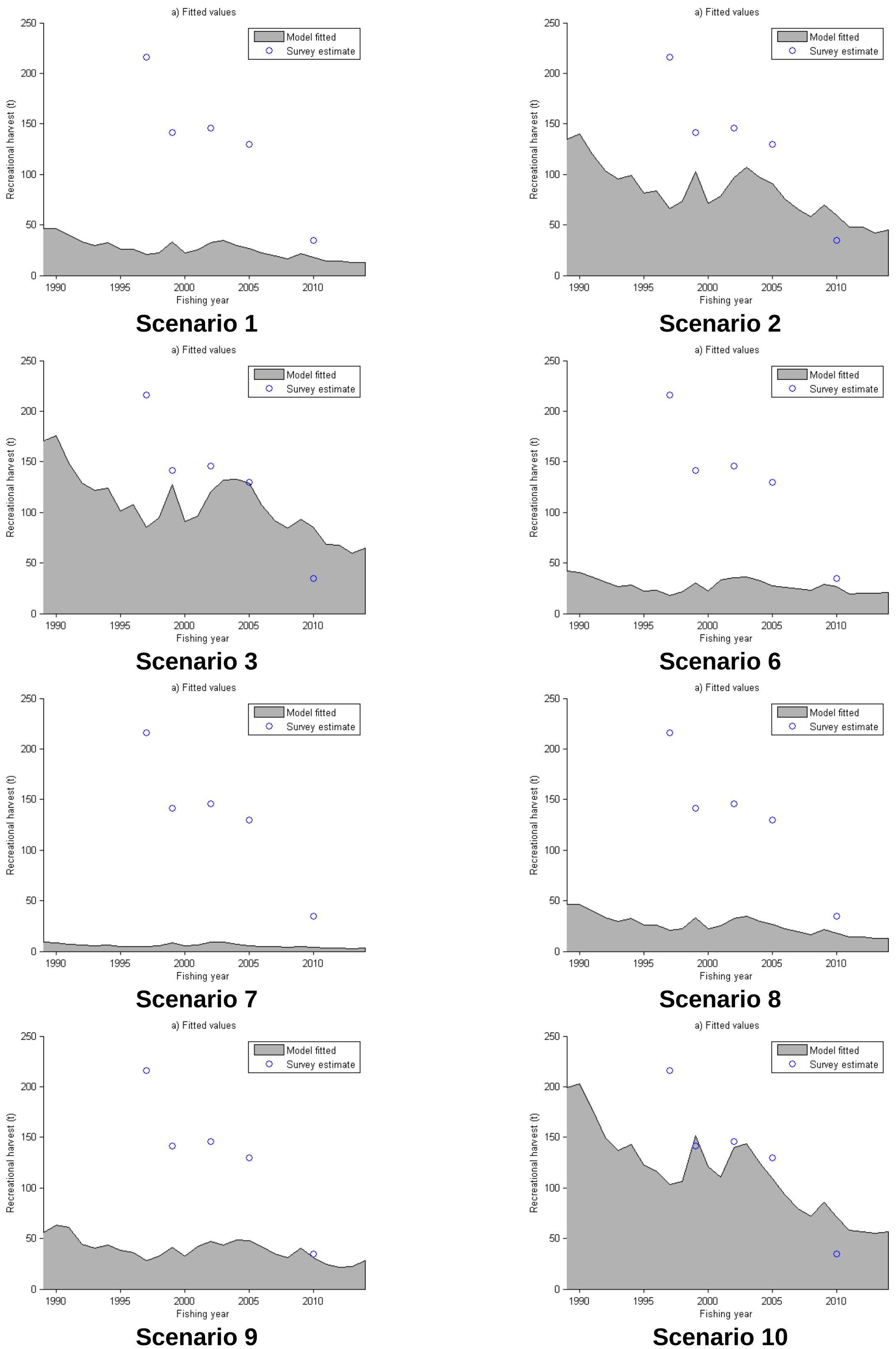

Figure 68: Fitted recreational blue swimmer crab harvests for each scenario of the population model. Also shown are the estimates derived from recreational fishing surveys conducted in Queensland. Note: Goodness of fit to the survey estimates was variable and generally non-significant as the indicated by q_{rec} posterior mcmc distribution for scenario 1 (Figure 64) and Table 21. In general, the recreational harvests were predicted to be less than the survey estimates. The magnitude of reported commercial harvests, particularly from the 2000–2005, may influence the predictions. Uncertainty in recreational catchability was included in the stock model confidence intervals presented in chapter 11.

Hervey Bay

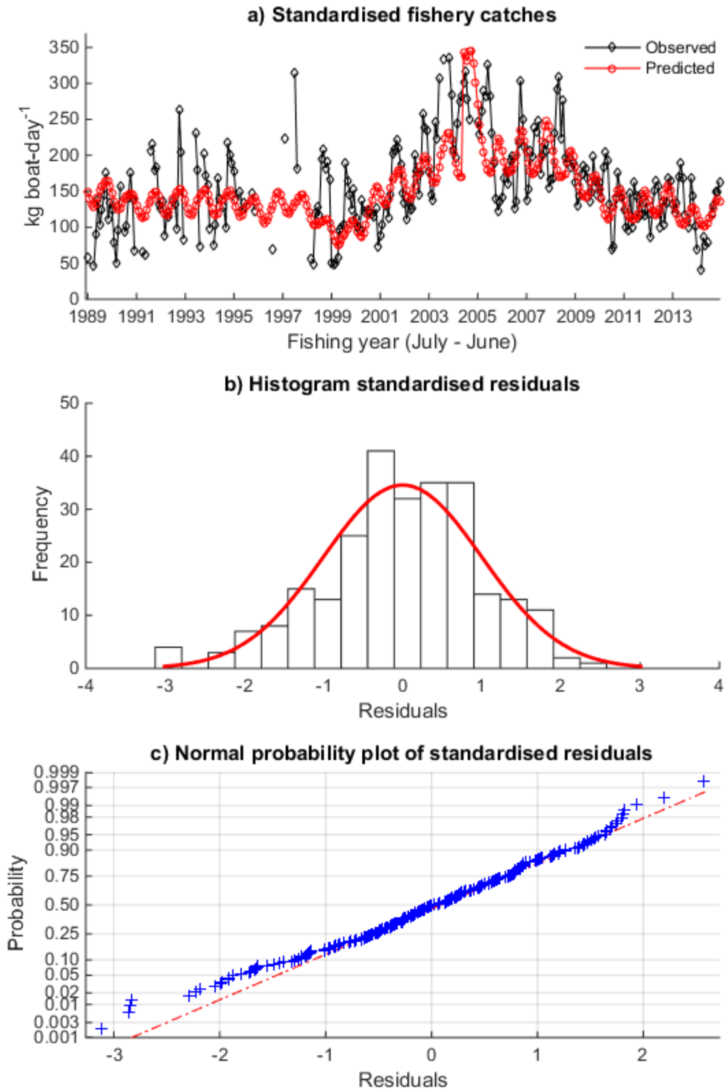

Figure 69: a) Model predicted catch rate (kilograms boat^{-1}day^{-1}) compared with observed standardised catch rates (described in Chapter 6), for the Hervey Bay region from Scenario 1. b) and c) Residual plots showing fit of modelled data to the standardised catch rates.

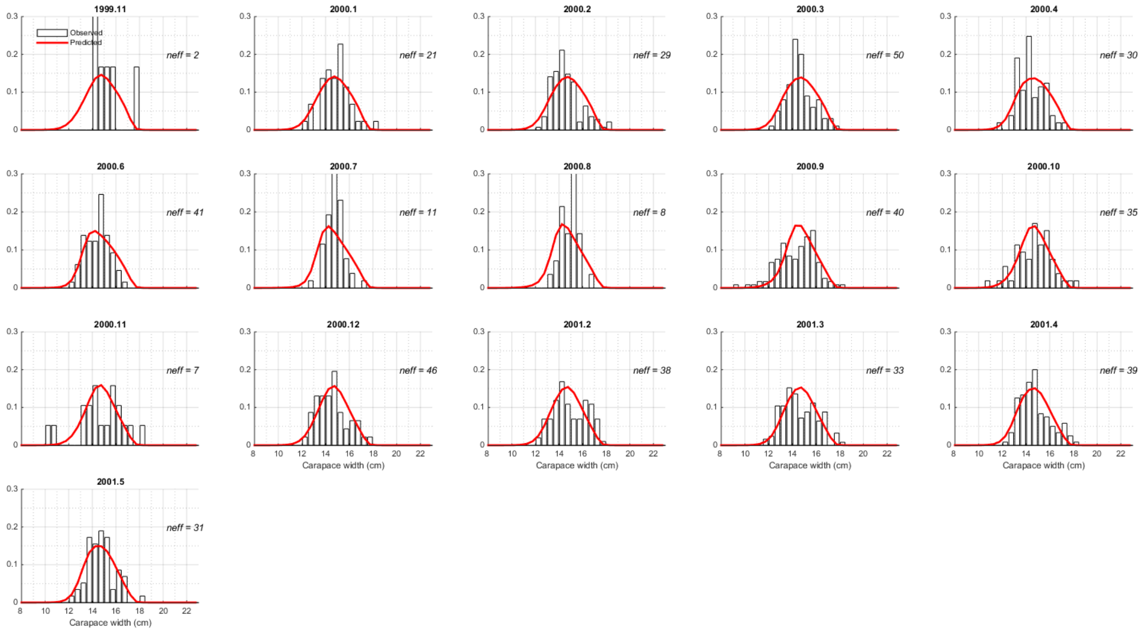

Figure 70: Predicted and observed length frequency distributions for female blue swimmer crabs from the Hervey Bay region for Scenario 1

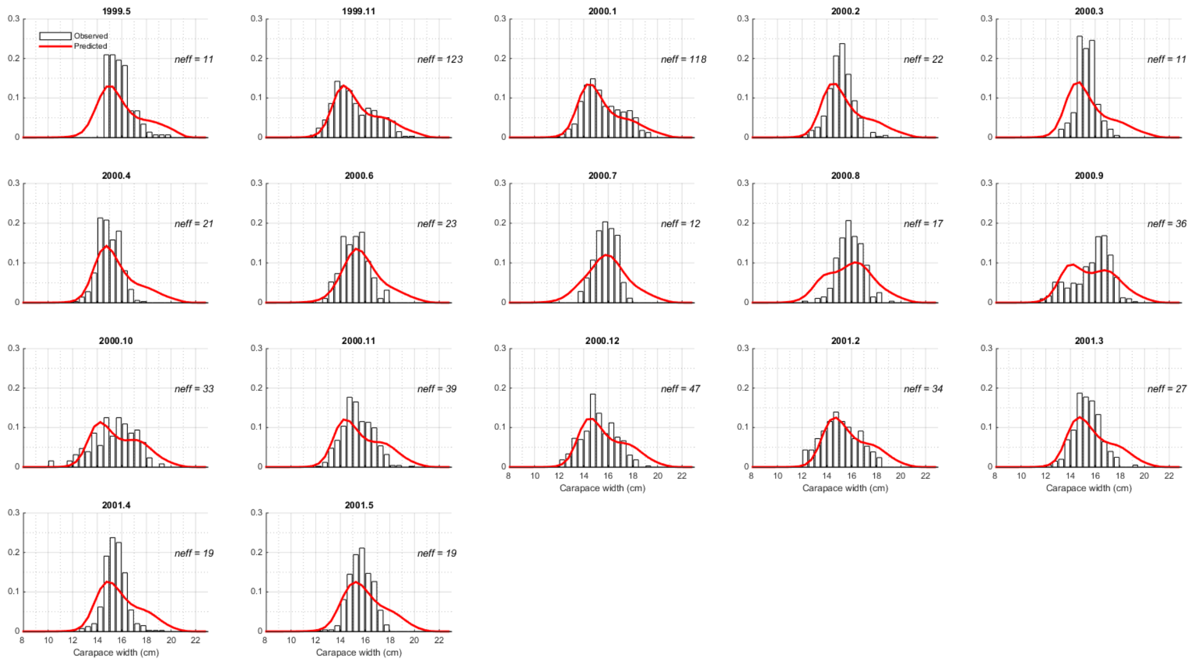

Figure 71: Predicted and observed length frequency distributions for male blue swimmer crabs from the Hervey Bay region for Scenario 1