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Population Dynamics and Management of Spanner Crabs (*Ranina ranina*) in Southern Queensland

by

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1 NON-TECHNICAL SUMMARY

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OBJECTIVES:

1. To estimate the size of the southern Queensland spanner crab stock.
2. To determine the appropriateness of the existing spawning closure arrangements.
3. To determine whether catch size-distribution can be used to estimate population age structure and growth rates.
4. To evaluate the impact of post-discard mortality amongst sub-legal crabs on yields, and promote the development (by industry) of less damaging apparatus.

Spanner crabs (*Ranina ranina*) represent a valuable resource to southern Queensland and northern NSW. The fishery became established in the late 1970s, and as a result of an almost exponential increase in fishing effort between 1992 and 1995 an output-controlled limited entry management arrangement was introduced. During that period catches increased from about 800 to over 3,000 t, as the fishery expanded northwards to previously unexploited grounds, and a profitable live-export market was developed in south-east Asia.

The Queensland fleet comprises some 240 vessels specifically licenced to take spanner crabs in Managed Area A, which is subject to a Total Allowable Commercial Catch (TACC), currently set at 2600 t. Another 310 vessels are licenced to fish only in Managed Area B (north of the main fishing grounds) where the TACC does not apply. At present the TACC is competitive, but in the near future an Individual Transferrable Quota (ITQ) system is to be introduced.

Trends in commercial fisheries catch-effort statistics indicate that the spanner crab stock in southern Queensland is currently being harvested at a sustainable level. However several questions remain with respect to the application of the commercial logbook data, possibly the most important of which is how well commercial catch-per-unit-effort represents stock abundance. The spatial distribution of spanner crabs is patchy, and the fishery operates such that patches are located, targeted and fished down. This can potentially lead to a situation of hyperstability, where the stock is actually declining despite catch rates remaining constant. This highlights the expected value of the fishery-independent monitoring programme currently being planned by QDPI with (in the case of the spanner crab fishery) a significant level of cost-recovery from industry.

Previous attempts to estimate growth rate of spanner crabs resulted in little consensus, due in part to inadequate sample sizes (length-based methods) and uncertainty surrounding the effects of tagging on growth (tag-recapture methods). Our initial objective was to determine whether the length-based methods would work if the samples were very large.

Variability in the size-structure of even very large samples of adult crabs was so great that we could place little confidence in growth estimates obtained from this type of data. Because of this, we negotiated a change in research direction with FRDC, focussing on two alternative approaches to the question of growth rates. The first was to investigate growth in pre-recruits. The second was to quantify the likely effect of tagging on moulting and growth, and to determine the extent of growth rate differences between NSW and Queensland.

Very small spanner crabs are not taken by baited tangle nets, regardless of mesh size, so a different sampling arrangement was required. A two-track channel dredge was successful in capturing intact megalopae and early juvenile stages, which provided length frequency data of considerable value to estimating pre-recruit growth. However because of its small size only very limited samples were able to be collected. To increase the sampling volume we developed a substantially larger, hydraulically-assisted dredge. This device has been field-tested on several occasions, but it has not yet been developed and used to full effect.

Laboratory experiments demonstrated that tagging had an adverse effect on weight increase and survival of spanner crabs, suggesting that growth rate estimates based on mark-recapture techniques may be biased. Of the several different types tested, anchor tags were superior in terms of ease of application and visibility. Recognising that the results may be biased, we released 4,804 tagged crabs at sites throughout the fishing grounds, to determine whether growth of spanner crabs in Queensland waters is significantly different from that in NSW, reported in a previous study. Fourteen of the 221 crabs recaptured in 1998 had moulted, with growth male growth increments being greater than those of females ($\bar{X}$ = 11.86 and 7.40 mm respectively). Recapture rates were significantly higher for males than females, and were also significantly greater for larger individuals of each sex. This suggests that tag mortality was greater in the smaller size-classes. Recaptured crabs had moved distances ranging from 0 to 45 km since release, but showed no tendency to move in any particular direction.

Our length-based assessment model has not yet been successful in producing useful estimates of the relevant stock performance indicators for use by management. This was due to the lack of contrast in the CPUE data, the relatively short data time-series, the extreme spatial and temporal variability in population size-structure and sex-ratio as represented in commercial catches and research samples, and the absence of definitive growth data.

Mitochondrial DNA analysis indicated that the east-coast spanner crab fishery comprises a single unit stock, and there thus appears to be no biological justification for separate management arrangements in different geographic areas.

Analysis of reproductive chronology indicates that the timing of the existing spawning closure is appropriate for minimising mortality amongst egg-bearing female spanner crabs across the entire fishery, and we recommend that the closure be retained in legislation.

Exploratory surveys for spanner crabs conducted in two areas outside the current fishing grounds did not reveal any significant quantity of crabs, although small numbers were captured at two sites amongst the Swain Reefs. From the available information it seems unlikely that there are any major unexploited populations of spanner crabs remaining in Queensland waters.

We have demonstrated that limb damage to undersized discarded spanner crabs has a major effect on their survival under natural conditions. Poor handling practices in the fishery result in considerable mortality amongst discarded small crabs, highlighting the need for continuing fisher education and ongoing investigation of alternative catching apparatus.

The two major issues for further research into the spanner crab fishery are (i) deriving a robust estimate of the species' growth rate, (ii) investigating the source of the extreme variability in size-frequency and sex-ratios in population samples.

2 BACKGROUND

Spanner crabs (*Ranina ranina*) live in sand substrata in offshore shelf waters throughout the tropical and sub-tropical Indo-Pacific region from the Seychelles Islands to Hawaii. These large, edible crabs are the subject of a number of distinct fisheries throughout this region, of which the Australian east coast fishery is by far the largest. This fishery is of recent origin, having developed initially in coastal waters off Moreton Island in the late 1970s. It has since expanded both to the north and the south in response to the discovery of new fishing grounds, the fishing-down of close inshore grounds, and the development of a live export market.

Spanner crab fisheries target adult crabs using baited tangle nets or 'dillies' placed on the sea floor. The broad flattened appendages of spanner crabs and their elongate body shape enable them to burrow rapidly and swim efficiently (Vicente *et al.* 1986), but also render them particularly susceptible to this method of fishing. Their swimming ability means that spanner crabs are attracted to bait from considerable distances (up to 70 m, Hill & Wassenberg, in ms.) while their broad, flattened appendages are easily entangled in the tangle nets.

The Queensland component of the East Coast spanner crab fishery is the largest commercial fishery in the state in terms of total catch weight of an individual species (Williams 1997). This status followed a spectacular increase in total landings of this species from 391 t in 1988 to 3,592 t in 1994: an increase of 910% in 6 years. Over that same period, the spanner crab fishery rose from being the 14th largest commercial fishery in Queensland, comprising 2.5 % of the state's total catch, to the largest commercial fishery in the state, comprising 18% of the total catch. The total catch of spanner crabs has declined from its 1994 peak due to a decline in fishing effort in 1995 and management restrictions on the fishery since 1996.

The increased total catch in Queensland in the early 1990's resulted from two main factors: -

1. *Increased fishing effort.* The total number of boat days spent fishing for spanner crabs increased from 2,733 in 1990 to 17,765 in 1994 (up 550% in 4 years). The actual increase in fishing effort was even greater due to an increase in fishing power with technological advancement, improvement in the knowledge and experience of crabbers, and improvements in vessel speed, seaworthiness and capacity.
2. *High catch rates in previously unexploited areas.* Increased effort coincided with the discovery and exploitation of previously unexploited areas between 23°S (Yeppoon) and 26°S (Double Island Point). In addition to increasing the latitudinal range of the Queensland spanner crab fishery by about 250%, these virgin areas yielded far higher Catches Per Unit Effort (CPUE) than previously exploited areas to the south.

CPUE doubled from 1988 to 1992 (from 143 kg/day to 290 kg/day) because of increased fishing power and efficiency, and the exploitation of previously unexploited resources. This increase was followed by a decline to 202 kg/day in 1994. Such a decline in CPUE in the face of ongoing improvements in fishing technology, vessel capacity and experience suggested that there had been a decline in the exploitable stock of spanner crabs in Queensland. In the face of this decline, the huge increase in effort (and concomitant increase in capitalisation) represented a serious threat to the sustainability of the fishery.

Commercial spanner crab fishers in Australia are restricted to a maximum of thirty baited dillies, which they attach to ropes (maximum of ten dillies per rope) which are then laid along the sea floor. Dillies are left in place for an average of about 45 minutes, before being retrieved. Crabs are then disentangled from the dillies, which are then re-set immediately. Each group of three ropes is called a

round, and crabbers typically set between six and twelve rounds per day. Spanner crabbers continue to work the same area (or patch) until catch rates decline, when they attempt to locate new patches of spanner crabs. Locating these patches has been assisted by technological advances in echo sounders and Global Positioning Systems (GPS) and improvements in vessel speed and personal experience. Many crab fishermen now travel to fishing grounds in excess of 60 nautical miles from port in order to maintain high catch rates.

Little is known about the ecology of spanner crabs. Aquarium studies by Skinner and Hill (1986 and 1987) reveal that adult crabs spend over 95% of their time buried just beneath the sand surface, with only their stalked eyes and antennae protruding. While buried, they can stop their hearts for periods of up to 20 minutes, relying on their *cor frontale* to circulate haemolymph to their brains, eyestalks and antennae (N. Gribble, personal communication). This inactive state may be a mechanism to conserve energy and to avoid predators such as sharks and rays which, according to Kalmijn (1971 and 1978), are capable of detecting electrical impulses of buried prey. When not buried, spanner crabs are preyed on by loggerhead turtles (Kirkwood, personal observation), and anecdotal evidence suggests they are also prey to several large fish species. Adult spanner crabs will emerge from the sand to feed on dead organisms, hence their attraction to baited dillies. In spawning season, adult males also emerge from the sand to search for females, which they then dig out and copulate with (Skinner & Hill 1986, 1987). The biology, ecology, distribution and behaviour of juvenile spanner crabs is poorly known at this stage.

3 NEED

Currently, there is little or no reliable information regarding spanner crab stock size, or their rates of growth, recruitment and mortality: parameters which are particularly important for the reliable management of a natural resource. In the absence of accurate information on these parameters, resource depletion may occur rapidly without warning even at current exploitation rates. The ongoing improvements in the fishers' ability to locate and return to crab patches, together with their exploitation of new grounds further from port, means they are able to maintain a consistent CPUE even if the resource is declining. Such a situation could mean that serious over exploitation of the resource is already occurring. Therefore, there is a pressing need for accurate data on these parameters to ensure optimal management of the spanner crab fishery for the maximum benefit of all stakeholders.

Considerable knowledge has been gained on spanner crab fisheries in Australia (e.g., Brown 1986, Kennelly 1989, 1992, Kennelly & Craig, 1989, Kennelly *et al.* 1990, Sumpton *et al.* 1993, Kennelly & Watkins 1994, Hill & Wassenberg in ms.) and elsewhere (e.g., Onizuka 1972, Brown 1985, Vicente *et al.* 1986, de Moussac & de San 1987, de Moussac 1988, Boulle 1995). Fisheries related studies have also generated valuable knowledge on spanner crab reproduction (Fielding & Haley 1976, Tahil 1983, Iwata *et al.* 1987, Minagawa 1993a, 1994, Minagawa *et al.* 1993a, 1994, Kennelly & Watkins 1994), morphometrics (Fielding & Haley 1976, Minagawa 1993b), larval development (Minagawa 1990a, 1990b, 1992, Minagawa & Murano 1993a, 1993b, Minagawa & Takahashi 1994, Minagawa *et al.* 1993b) and laboratory behaviour (Skinner & Hill 1986, 1987). However, despite all of the gains achieved through this published research, critical information on the dynamics of spanner crab populations is still lacking.

This shortfall in our knowledge of the population dynamics of spanner crabs is frustrating efforts to estimate stock abundance and determine appropriate management strategies for ensuring long-term sustainability of the fishery. In the mid-1990s a huge increase in effort and capital investment was seen as a serious threat to the sustainability of the fishery. A number of management restrictions were introduced to reduce this threat to the spanner crab fishery, including a total allowable commercial catch (TACC), daily catch limits, restrictions on the number of fishing days each week, and periodic fishery closures. As these catch restrictions have been introduced in the absence of crucial information on spanner crab population dynamics, there is no way to assess their effectiveness.

Fishing related mortality includes both those individuals harvested by fishermen, and those killed but not harvested. High mortality amongst discarded spanner crabs would mean that the resource was being wasted and would further threaten the sustainability of the fishery. Kennelly *et al.* (1990) reported that spanner crabs removed from dillies by commercial crabbers suffered high rates of limb damage or loss. They also found that the loss of an appendage led to their laboratory animals dying within a period of 8 days. This confirmed an earlier study by Onizuka (1972) who also found high rates of mortality amongst injured spanner crabs in the laboratory. There is an obvious need to determine whether the level of discard mortality found in the laboratory by Onizuka (1972) and Kennelly *et al.* (1990) also occurs under natural conditions. If this is the case then there may be a need to reduce discard mortality in the spanner crab fishery by changing crab handling procedures or adopting less injurious fishing apparatus. Sumpton *et al.* (1993) trialled a variety of alternative traps which might reduce the potentially high level of mortality resulting from limb damage, but without success.

Each year, the spanner crab fishery in Queensland is closed from 20 November to 20 December to avoid fishing related mortality during the crab's spawning season. However, gravid female crabs have been caught both before and after this spawning closure and some fishing industry representatives have called for an assessment of the timing of this closure. Such an assessment would need to

consider inter-annual variability in spawning chronology as well as differences between different latitudes.

To address the needs outlined above, this project aimed to develop reliable estimates of the stock size and growth rates of spanner crabs. It also aimed to investigate the appropriateness of the seasonal closure of the fishery and the levels of mortality of discarded undersize crabs that had been injured.

4 OBJECTIVES

1. To estimate the size of the southern Queensland spanner crab stock.

2. To determine the appropriateness of the existing spawning closure arrangements.

3. To determine whether catch size-distribution can be used to estimate population age structure and growth rates.

4. To evaluate the impact of post-discard mortality amongst sub-legal crabs on yields, and promote the development (by industry) of less damaging apparatus.

Approved modification to Objective 3:

Relatively early in the term of the Project it became apparent that size-based methods were not likely to be suitable for estimating population age structure and growth rates in spanner crabs. Even with very large sample sizes there was little evidence of distinct age-class modes. Moreover, even though a proportion of the crabs in the commercial catch is below the minimum legal size, the fishing gear is highly selective. The fact that juvenile crabs are not represented in the catch means that there is no information available on the relative abundance of early age-classes. Such information might have aided in the interpretation of the adult size-frequency data.

For this reason two alternative approaches to the question of age and growth were adopted, after approval by FRDC:

- Tag/recapture study to estimate growth rates of individual adults.
- Development of a device to collect quantitative samples of juveniles to enable estimation of growth rate by length-frequency analysis.

5 ESTIMATION OF STOCK SIZE

5.1 COMMERCIAL CATCH AND EFFORT DATA

5.1.1 Trends in commercial catch data

5.1.1.1 Introduction

Since 1996, the Queensland spanner crab fishery has been subject to output control, in the form of a competitive Total Allowable Commercial Catch (TACC). It has been the responsibility of the Crab Fishery Management Advisory Committee (CrabMAC) and more recently the Spanner Crab Stock Assessment Group (SAG) to recommend appropriate annual TACCs to the Queensland Fisheries Management Authority (QFMA) for the following year. The TACCs were to be based upon performance indicators to be derived from a comprehensive fishery model, which would take into account all available information about the biology and behaviour of the stock, as well as estimates of relative stock size. Our attempts to construct such a model of the fishery are detailed in Section 5.2.

Whether or not a model is developed that can reliably estimate useful performance indicators, information on temporal changes in stock abundance is required to set appropriate catch limits. This information may take the form of catch rate (CPUE) data from the fishery or from a source independent of the fishery (e.g. scientific surveys). The Queensland Department of Primary Industries (QDPI) is currently planning fishery-independent surveys of the spanner crab stock. However, until such surveys are implemented, the Spanner Crab SAG will continue to rely exclusively on fishery-dependent CPUE data as the index of *relative* stock abundance in this fishery.

Commercial catch and effort statistics, along with location and associated data, are collected routinely by the Queensland Fisheries Management Authority (QFMA) as part of the State-wide 'C-Fish' system. Since 1988 the commercial sector has been required to provide daily fishery statistics by way of fishery-specific logbooks. The data are transferred to the C-Fish database by QFMA staff, and then become available (at varying levels of detail) to authorised users. Although there are a number of reservations regarding its accuracy and applicability, this database is by far the most extensive source of information regarding spanner crab catches.

5.1.1.2 Methods

Catch and effort information was retrieved from the MIXED FISHERY database in C-Fish using a basic SQL dump script which selected records for a specific species code, geographic range and time period. The retrieved file was then downloaded to a PC and incorporated into a Microsoft Access™ database for subsequent processing.

As a result of the way the fishery has developed (in a geographic sense), five "assessment regions" within Managed Area A have been designated by the Stock Assessment Group (Table 5.1 and Figure 5.1). Managed Area A comprises almost all the known stock in Queensland waters. Remaining State waters fall within Managed Area B and are not subject to a TACC. Most of the analyses of the commercial data (i.e. catch, effort and CPUE) have been structured to reflect this spatial subdivision. Catch rates were estimated simply by dividing total annual catch by total annual effort.

Table 5.1 Queensland coastal regions used in the analysis of commercial spanner crab catch and effort data.

Area	Region	Description
-	0	No valid location data provided
B	1	Tidal waters north of 23°00'S or west of 151°45'E
A	2	Tidal waters between 23°00'S and 24°00'S, and east of 151°45'E
A	3	Tidal waters between 24°00'S and 25°00'S
A	4	Tidal waters between 25°00'S and 26°30'S
A	5	Tidal waters between 26°30'S and 27°30'S
A	6	Tidal waters between 27°30'S and 28°12'S
NSW	7	Tidal waters south of 28°12'S

5.1.1.3 Results

A synoptic impression of the development of the south Queensland spanner crab fishery can be gained from Figures 5.2 and 5.3, which show the amount of fishing effort (in net-lifts) expended by the fishery in each half-degree grid block each year between 1988 and 1997. The data upon which these figures are based have been extracted from the C-Fish database essentially without any "cleaning". As a result, the figures show some evidence of position reporting or data transcription error (viz. effort registered in grid blocks on land). However the overall trends are quite apparent. Initially (in 1988) most of the fishing effort was concentrated on the Sunshine Coast and Gold Coast, north and south of Brisbane respectively, with very little activity north of Fraser Island. By 1991 the Bundaberg grounds had become established and were being fished heavily, although not at the expense of the southern part of the fishery. Within the next 2-3 years the fishery developed to the stock's effective northern limit, and additional grounds off Fraser Island and in the Capricorn-Bunker Group became increasingly heavily exploited. Since 1995 the fishery has stabilised in terms of fleet size, effort and spatial distribution.

This temporal and spatial pattern of growth in fishing effort reflects changes in annual catches, depicted in Figures 5.4 and 5.5. Of particular interest is the shift in peak production from the southern part of the fishery to the northern part, with several grid blocks (approx. 900 square nautical miles) yielding in excess of 400 t of crabs annually in 1996 and 1997.

In the first half of the 1987/88 financial year, the Queensland spanner crab fishery produced about 180t (Figure 5.6) as a result of approximately 250,000 net lifts (Figure 5.7). From 1988/89 to 1991/92 catches increased from about 350t to nearly 1000t per annum, while effort increased to 0.7 million net lifts and CPUE increased from 0.7 kg/net lift to 1.1 kg/net lift (Figure 5.8). Effort increased rapidly from 1991/92 to 1994/95, with catches also continuing to increase until a 1994/95 peak, despite a small apparent decline in CPUE. Following the introduction of a TACC in 1996, effort levels fell from the 1994/95 peak of 4 million net lifts to a little under 2.5 million net lifts in 1997/98 (Figure 5.7). Catches also decreased after 1995/96 (Figure 5.6) and there was a slight increase CPUE which reached about 1.05 kg/net lift in 1997/98 (Figure 5.8).

Over the past 10 years, CPUE has apparently undergone greater change in the northern than in the southern regions (Figure 5.9). CPUE in each of the northern three regions was greatest early in the data series, with maxima occurring in 1989/90 (Region 3), 1990/91 (Region 2) and 1991/92 (Region 1). In Region 1, CPUE was less than 0.1 kg/net lift in 1988/89 and 1989/90 but apparently increased to over 7 kg/net lift in 1991/92 (Figure 5.9a). In Region 2 CPUE peaked at about 2.6 kg/net lift in 1990/91 (Figure 5.9b), and in Region 3 it peaked at about 1.8 kg/net lift in 1989/90 (Figure 5.9c).

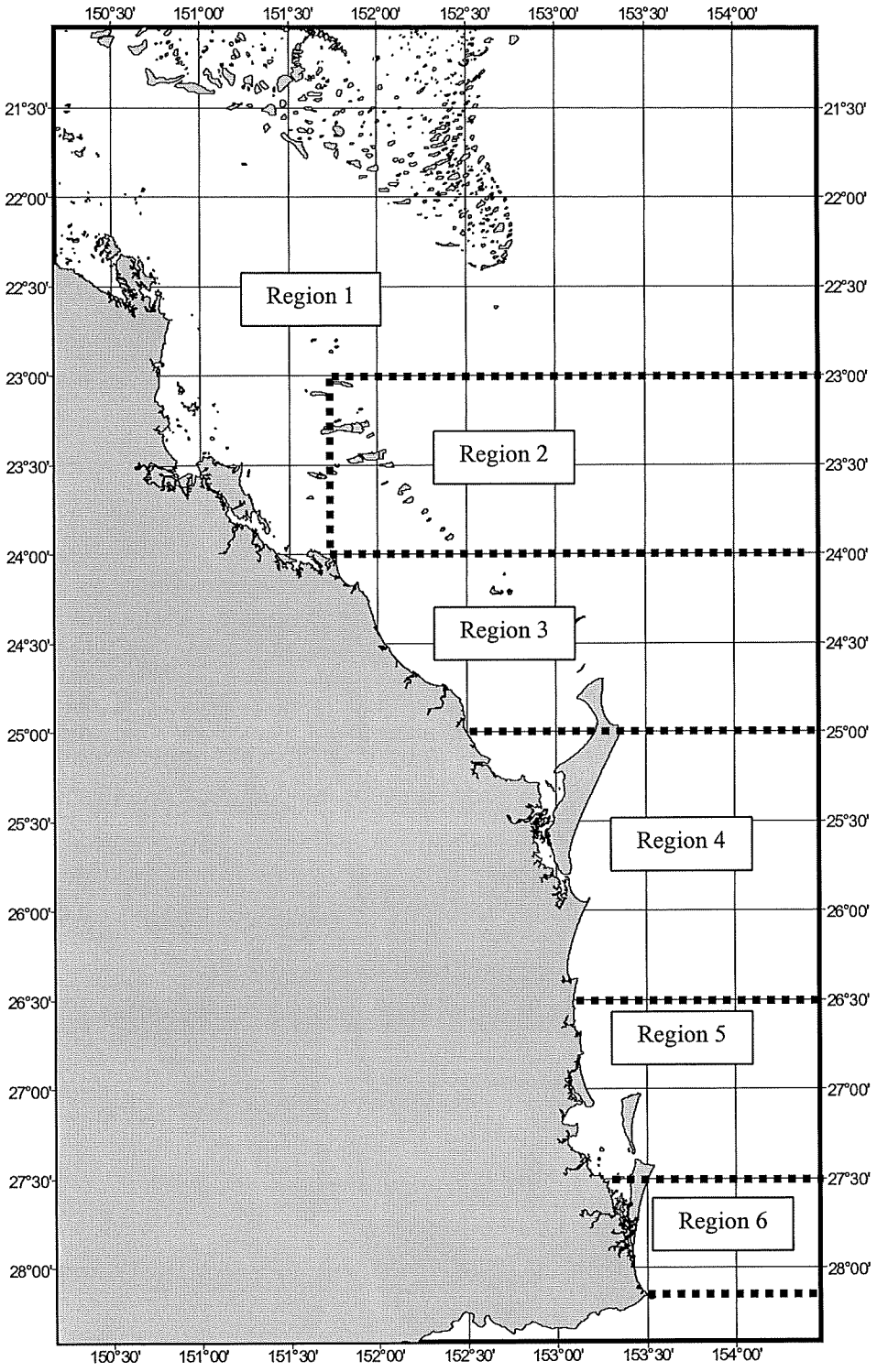

Figure 5.1 Queensland spanner crab fishery Assessment Regions. Note that Region 1 is in Managed Area B (not subject to TACC) while Regions 2-6 incl. comprise Managed Area A, subject to TACC.

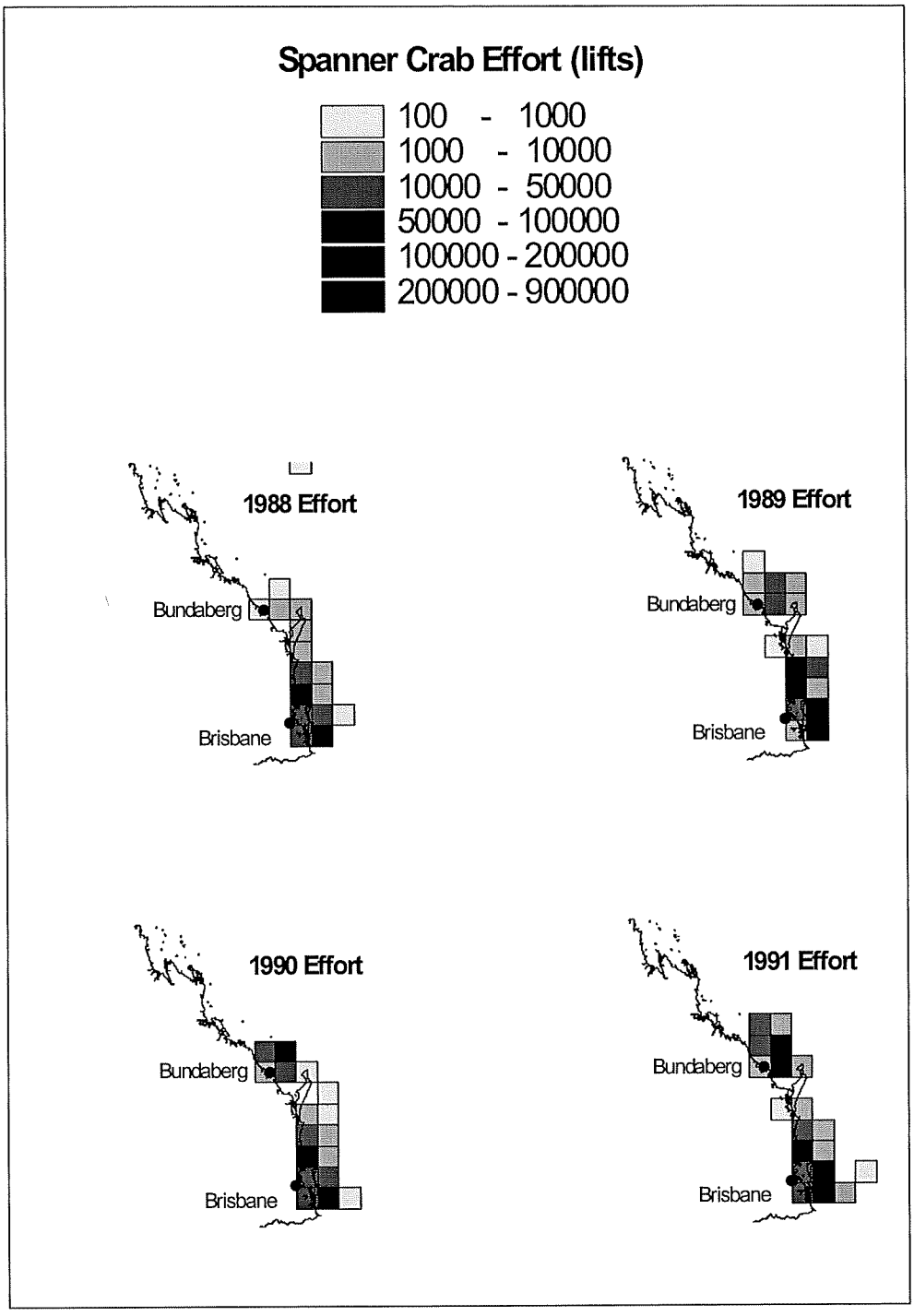

Figure 5.2 Annual fishing effort (number of net-lifts) in the south Queensland spanner crab fishery (1988 to 1991), displayed by 30' (half-degree) grid.

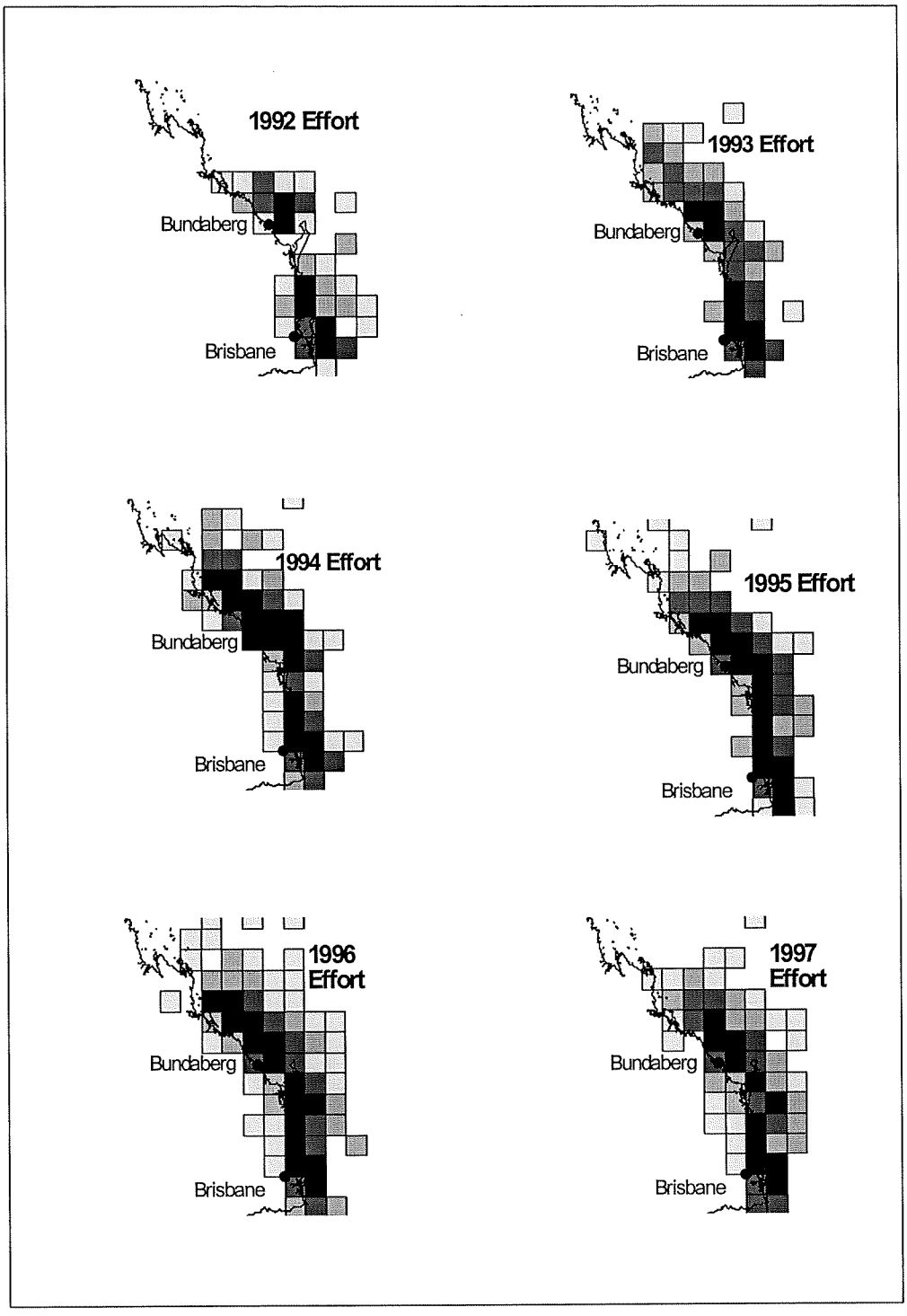

Figure 5.3 Annual fishing effort (number of net-lifts) in the south Queensland spanner crab fishery (1992 to 1997), displayed by 30' (half-degree) grid.

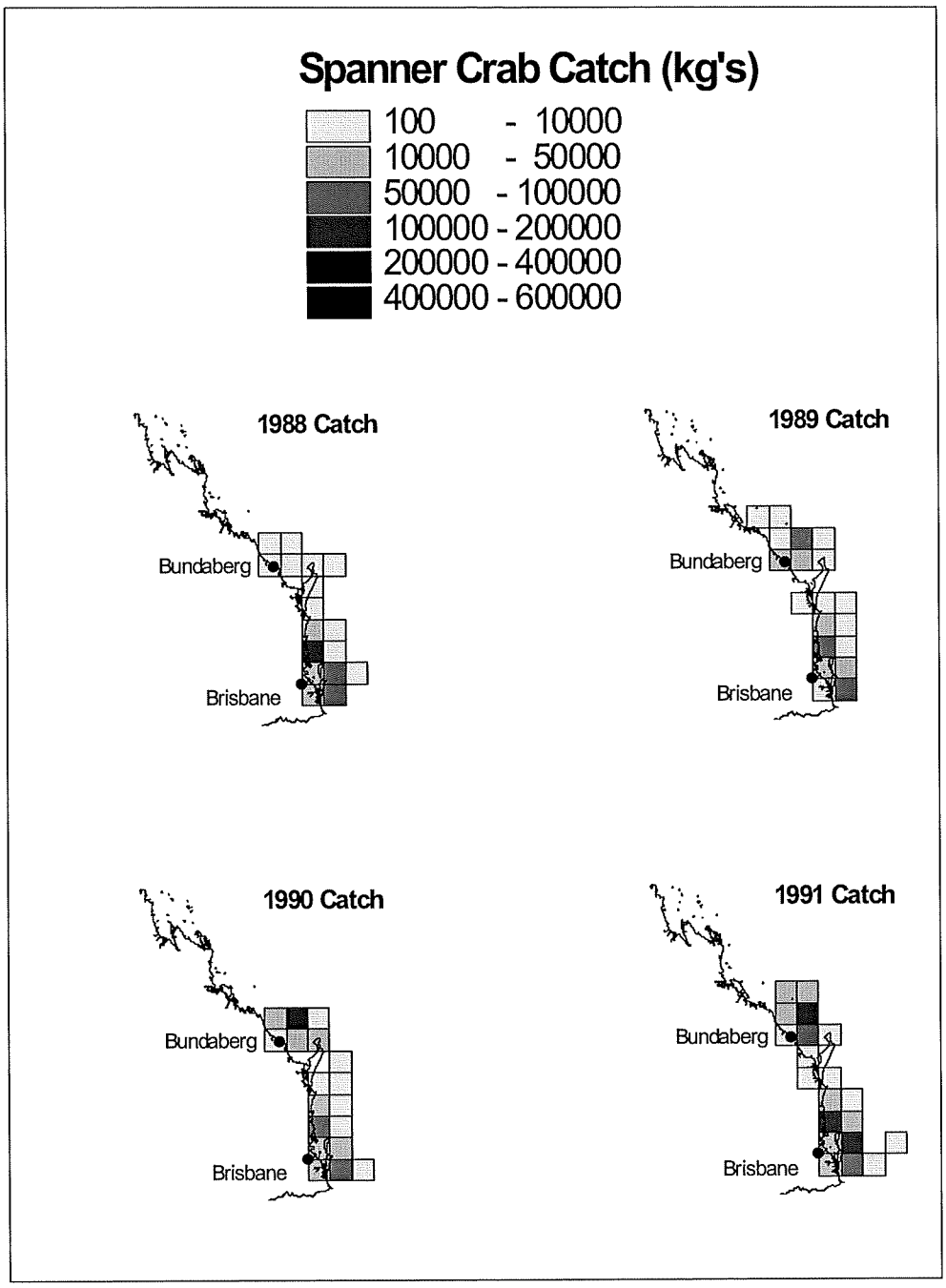

Figure 5.4 Annual catch (kg) of spanner crabs in the south Queensland fishery (1988 to 1991), displayed by 30' (half-degree) grid.

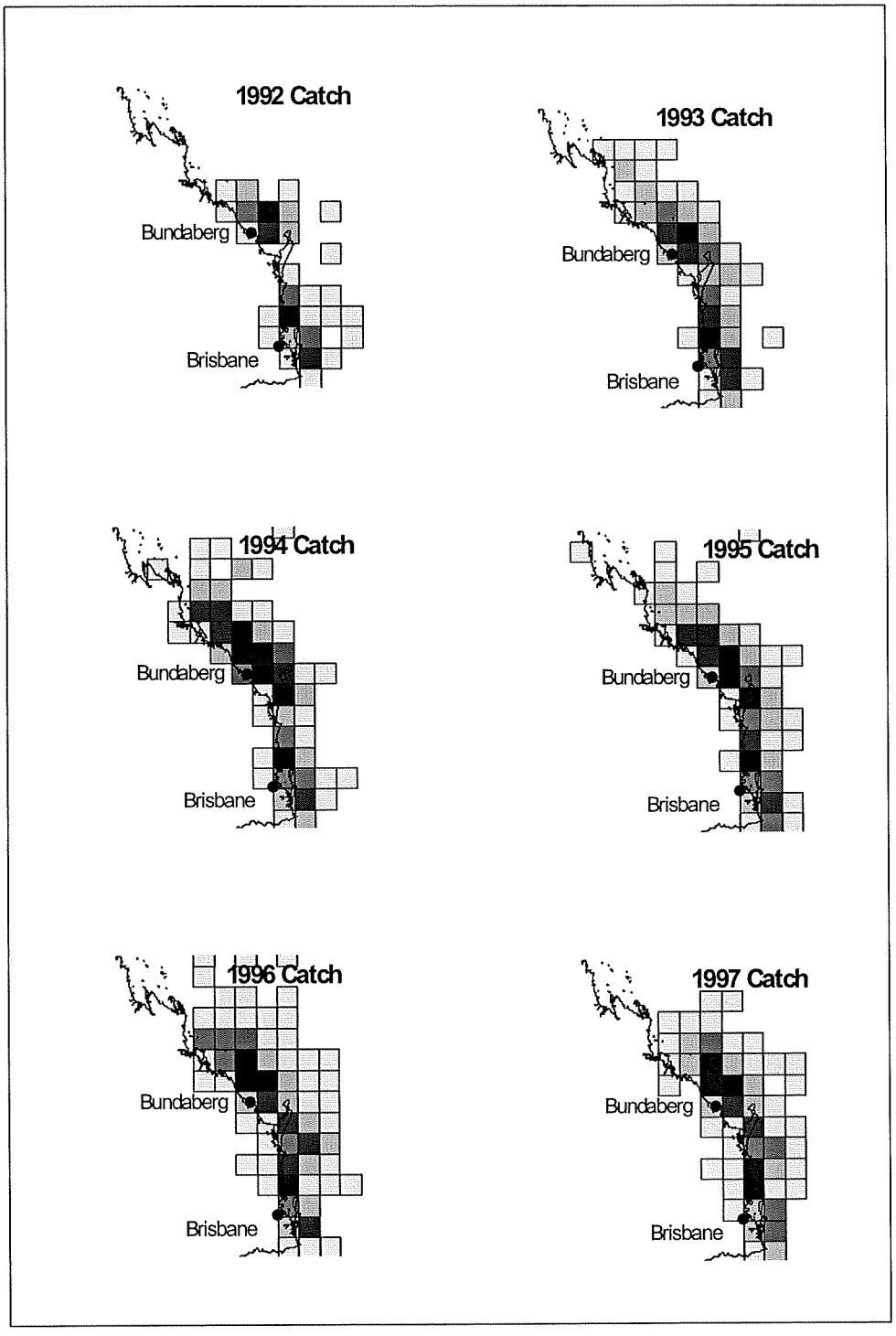

Figure 5.5 Annual catch (kg) of spanner crabs in the south Queensland fishery (1992 to 1997), displayed by 30' (half-degree) grid.

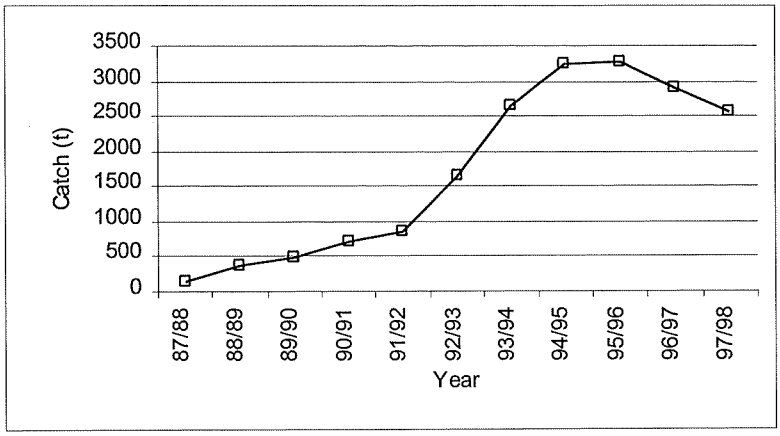

Figure 5.6 Annual trend in spanner crab catch (tonnes) in the southern Queensland fishery.

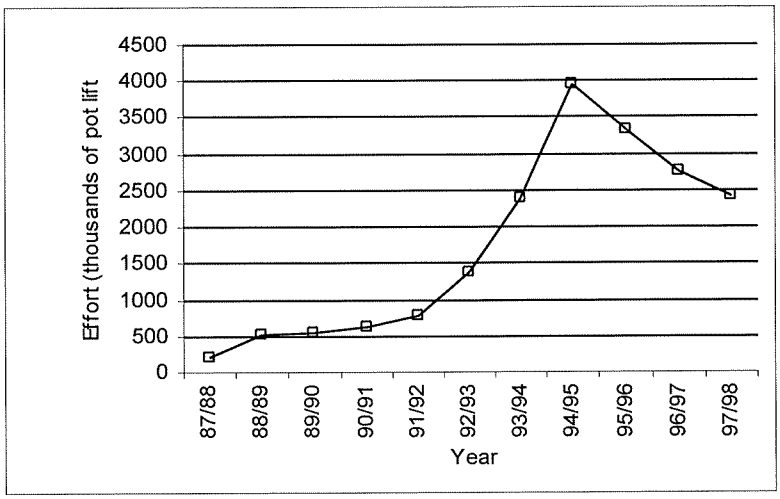

Figure 5.7 Annual trends in fishing effort (thousands of net or pot lifts) in the south Queensland spanner crab fishery.

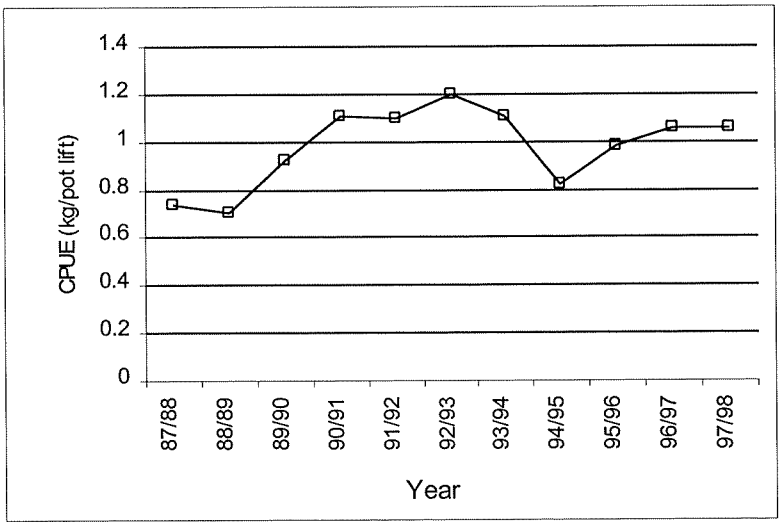

Figure 5.8 Annual trend in spanner crab catch per unit effort (CPUE), as estimated by weight per pot lift, in the southern Queensland fishery.

Since 1992/93, CPUE in all of the three northern regions has regularly exceeded 1.0 kg/net lift and has varied between 0.8 and 1.5 kg/net lift.

In contrast to the three northern regions, CPUE has exhibited no clear peaks in Regions 4, 5 and 6, and has usually been slightly less than 1.0 kg/net lift (Figure 5.9d, e & f). CPUE in Region 4 appears to have increased slightly since the late 1980's (Figure 5.9d) while there have been no apparent trends in Regions 5 and 6 (Figure 5.9 e & f).

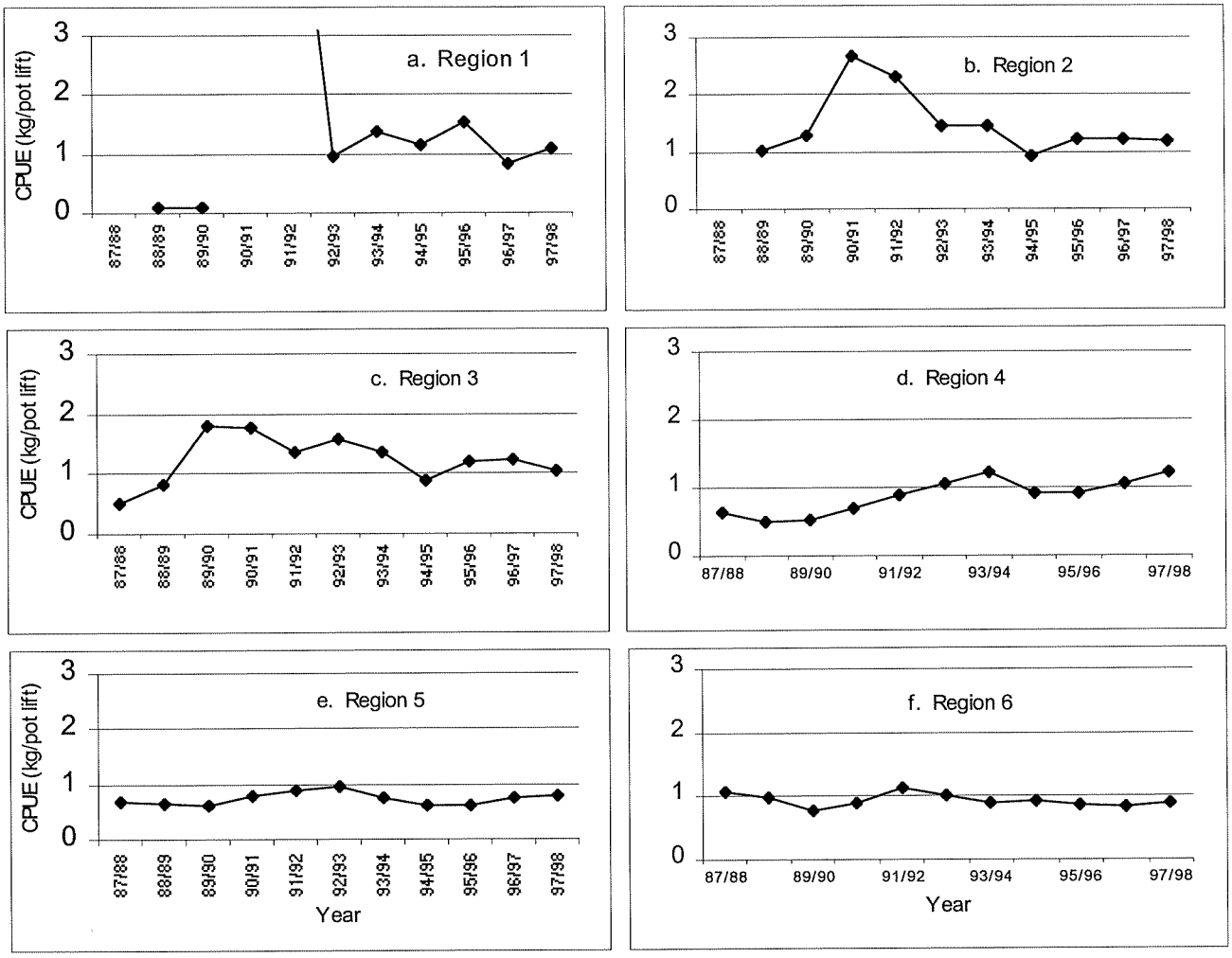

Figure 5.9 Whole of fishery annual catch rates by Assessment Region.

5.1.1.4 Discussion

The large increase in the total Queensland spanner crab catch during the early 1990s was due to increases in total effort and expansion of the fishery into areas that had not previously been fished.

Despite the probable limitations in the accuracy and applicability of CPUE data, catch rate trends were generally consistent with the history of spatial development of the fishery. The major areas of expansion in the late 1980s and early 1990s were in Region 3. This expansion into virgin grounds

probably explains the high CPUEs in Region 3 from 1989/90 to 1993/94. As the fishery continued to expand northwards, additional virgin grounds were located in Regions 1 and 2.

In the mid and late 1990s, CPUEs in the more northern regions were lower than in earlier years, presumably reflecting a decline in the size of the stock in those areas. This stock reduction scenario occurred only in the regions that were first exploited significantly in the last decade, and did not occur in Regions with a longer fishing history. The relative constancy in CPUE in the two southern-most regions (Regions 5 and 6) over the logbook period may reflect the prior removal of 'accumulated stock' from the fishery. The rise in CPUE in Region 4 in the late 1990s is probably due to the exploitation of new grounds off Double Island Point, Wide Bay and Fraser Island in recent years.

The extreme CPUE values recorded from Region 1 in 1988/89, 1989/90 and 1991/92 are the result of biases due to small sample sizes and the patchy distribution of the spanner crab stock, and should not be considered to be indicative of stock density at those times.

Region 1 (Managed Area B) has not been subject to the same management restrictions that have applied in Regions 2 - 6 since 1996. The bulk of the catch reported from Region 1 was taken adjacent to the northern and western boundaries of Region 2 (the northernmost part of Managed Area A). There is also a suspicion that some of the catch reported Region 1, where more lenient daily catch limits apply, may have actually come from Region 2. Occasional errors in reporting and/or transcribing location data have resulted in catches apparently having been taken from on land or in deep off-shelf waters.

The almost exponential increase in fishing effort in the first five years of this decade prompted the QFMA to introduce an output-based management system for the Queensland spanner crab fishery. It was perceived that unless action was taken to halt the increase in effort, there was every chance that the spanner crab stock would be in danger of serious overexploitation. Thus, despite its inaccuracies (see below), the C-Fish catch and effort data set has already provided a very useful tool for management.

Until higher-order dynamic models of the Queensland spanner crab population are able to provide better estimates of stock size, a set of decision rules based on changes in commercial CPUE data is being used by the Spanner Crab SAG to set TACs. The risk in this assessment approach is recognised, but with the establishment by QDPI of an ongoing fishery-independent monitoring programme, information on relative spanner crab stock abundance should increase in accuracy, and the risk reduced.

A number of factors may have contributed to variation, error and bias in reported catches and fishing effort, and in derived stock abundance indices. These include changes to management arrangements (e.g. TACCs, daily catch limits, periodic closures); variable accuracy or precision in catch, effort or location reporting; and problems with database quality control (system or transcription errors).

Since 1994, the following changes to the management of the spanner crab fishery have complicated the interpretation of catch and effort analyses:

1994	Investment warning issued.
1995	Gear configuration altered from a maximum of 50 dillies (either singly or in pairs) to 30 dillies (with up to 10 dillies on a line).
1995	Competitive TACC introduced, limiting catch in Managed Area A to 2,600 tonnes per annum.

1995	Annual TACC period changed from calendar year to financial year, enabling an increased catch in the latter half of 1995, extending the TACC period from 12 to 18 months and thus allowing additional catch.
1996-99	Succession of daily catch limits (200, 300 or 400 kg/day, or eight or 16 baskets), different between Managed Areas A and B.
1996-98	Fishery closures of variable duration in Managed Area A at the end of each quarterly TACC period.
1997-99	Fishing restricted to four days per week (Tuesday-Friday).

These management changes may have acted to increase or decrease CPUE. They have also had secondary effects on CPUE through altering the behaviour ofthe fleet in the following ways:-

i *High-grading*. Since the introduction of daily catch limits some high-grading occurs in areas where catch rates are highest. The effect of this is to underestimate total catch, and therefore CPUE.

ii *Working rougher weather*. The competitive nature of the TACC and the restriction in number of fishing days have induced crabbers to fish in rougher weather than they would normally. There is some anecdotal evidence that catch rates are depressed when sea conditions are rough; if this is so, then CPUEs may be underestimated relative to calmer periods.

iii *Transfer of catch between vessels*. Fishers who have exceeded their daily maximum catch frequently offload the excess to colleagues on other vessels. The extent of this practice is not known, nor are its implications for the assessment of CPUE.

iv *Falsification of catch records*. The introduction of daily catch limits has undoubtedly resulted in some crab fishers under-reporting their landed catch. This would underestimate CPUE unless an appropriate "adjustment" was made to reported effort. On the other hand, any announcement of a possible change to management arrangements (e.g. as associated with the Investment Warning) may result in over-reporting of the catch if fishers believe that their future level of involvement in the fishery is to be based on past catch history.

Variability in the accuracy or precision of data provided in fishery-wide logbook systems is a universal problem, and is certainly not restricted to the Queensland spanner crab fishery. In fact the legislative requirements of current management arrangements combined with the high level of specific surveillance activity by the Queensland Boating and Fisheries Patrol probably means that the catch figures from this fishery are (on the whole) very reliable. However it should be noted that prior to the introduction of daily catch limits some catch weights recorded in crab fishers' logbooks were estimated rather than measured. While fishers are generally very skilled in estimating catch weights, the actual accuracy of those estimates is unknown.

There is considerably more uncertainty surrounding the effort statistics. When compulsory logbooks were first introduced in 1988 there were varying interpretations of the appropriate effort index. The QFMA instructed crab fishers to report their effort in terms of number of 'net lifts' but this was misinterpreted by some operators who reported the number of times they deployed a series of nets and did not multiply this by the number of nets deployed. For this reason, catch-effort analyses initially used the 'fishing day' as the unit of effort. However catch per fishing day became meaningless as an index of stock abundance when daily catches were limited (to offset some of the disadvantages of the competitive TACC system), and subsequent analyses have used the 'net lift' as the unit of effort. Thus, effort data collected during the first few years of the compulsory logbook programme are of variable reliability.

As spanner crab fishing is a very labour intensive operation (with several hundred net lifts per day) crab fishers do not record effort each time they do a set. Effort figures are the operators' estimates at the end of the fishing day of the number of 'rounds' done during the day, multiplied by the number of nets or dillies used per 'round'. These estimates are likely to be fairly reliable, as the fishers frequently use plotted GPS marks to identify their fishing locations, and the number of nets used will normally be the maximum permitted. However we have little capacity to determine their actual accuracy, which may conceivably be influenced by catch size and psychological factors.

Crab fishers characteristically work the same area (or patch) until their catch rate declines to an uneconomic level. They then search for a new patch and repeat the process. Thus, a high CPUE can be maintained despite serial depletion of individual patches of spanner crabs. This hyperstability effect means that severe resource depletion may occur without showing up as a decline in CPUE.

As with most fisheries, there has been a considerable improvement over the past couple of decades in the technology employed in the spanner crab fishery, with more accurate Global Positioning Systems (GPS), video plotters and enhanced echo sounders. In conjunction with those advances, refinements in the construction of dillies, increased vessel sizes and the ongoing accumulation of experience in this new fishery have led to increased fishing power. This means that a 'net lift' in 1988 is not necessarily the same as a 'net lift' in 1998.

A final source of variability and difficulty in interpreting the catch-rate data derives from the passive nature of the fishing apparatus. The catch is very much dependent upon the behaviour of the crabs, and presumably whether or not they have recently fed. Moreover spanner crabs do not feed around the time of moulting and/or spawning, and this leads to seasonal cycles in CPUE (Skinner & Hill 1987). Spanner crabs in captivity have been observed to fight over food, and larger crabs frequently chase smaller crabs from food (Kirkwood, personal observation). Such agonistic interactions also occur around baited dillies and may result in larger crabs excluding smaller crabs from dillies, thus reducing CPUE when crab densities are very high (Hill & Wassenburg, unpublished ms).

The factors listed above indicate that spanner crab commercial CPUE data may not be a particularly accurate index of relative stock abundance, and this introduces an element of uncertainty into our interpretation of trends in commercial catch rates. To overcome some of the problems of using commercial CPUE data, Kennelly (1992) conducted a controlled sampling programme using standardised baited tangle nets to gain information on relative changes in spanner crab population density with depth, season, year and latitude. This would overcome the limitations listed above, with the exception of the unknown effects of changes in crab behaviour, but such advantages would have to be considered against the generally lesser statistical power of an independent survey.

Estimation of absolute stock size from CPUE data collected using baited fishing apparatus would require knowledge of the area of influence of the bait and the catchability of the target species (Miller 1989). Hill & Wassenberg (in ms.) have estimated the area influenced by a baited spanner crab dilly at about 3,750m^2 in 30 minutes and at a current speed of 9.6 $cm.s^{-1}$. However, the size and shape of this area would vary with current speed and direction and the rate of dispersion of the bait odour.

5.1.2 Effort standardisation

5.1.2.1 Introduction

Catch and effort data collected by commercial crabbers provide an estimate of relative stock abundance, but there is considerable uncertainty about the reliability of the data for stock assessment. The fact that changes in the structure and fishing power of the fleet can influence CPUE contribute significantly to that uncertainty. Even if accurately reported, catch and effort data have probably been affected by improvements in fishing power with technological advances in navigational equipment, increases in vessel speed, seaworthiness and capacity, and the ongoing accumulation of experience in the fishery. For example, there is frequent debate about the validity of comparing catch rates from large vessels with those from small vessels. If catch and effort data from the commercial fishery are to be used to estimate relative stock size then the reliability of that data must be known.

In seeking to derive a better index of relative stock abundance, we firstly examined the effects of various vessel characteristics to see which factors contribute significantly to fishing power. The commercial catch-rate data were then standardised by removing the effects of these factors from the CPUE signal.

5.1.2.2 Methods

Information on vessel characteristics recorded in the Queensland Fisheries Management Authority's licencing system were insufficiently detailed for our purposes, and to obtain them would have required a laborious and very time-consuming search of paper records. The alternative was to solicit the required information ourselves. To achieve this we sent a survey questionnaire to all licenced commercial spanner crabbers in the main geographical area of the Queensland spanner crab fishery. In the questionnaire (see Appendix 3 for details) we asked licence-holders for details of their vessels (hull length, construction, configuration and engine characteristics) and about the types of gear they used. We also took the opportunity to ask for comments on licence holders' perceptions regarding the reliability of the logbook data, spatial and temporal patchiness in the stock and the extent to which the skipper's skill was likely to affect catch rates.

The questionnaire was mailed out to 257 spanner crab licence holders and generated 84 responses, about 34% of the fleet. Even though the format of the survey questionnaire was carefully planned, and trialled by two experienced crab fishermen prior to the mail-out, some problems of interpretation were encountered. Almost all of the respondents had to be contacted individually by telephone to clarify certain points, particularly those relating to changes in vessel ownership and licence packages, and situations where the respondent (licence-holder) was not the vessel's skipper. Following this clarification, the information in 19 responses was still ambiguous or incomplete, leaving 65 responses to be used in CPUE standardisation.

The results of this survey were used in a general linear model analysis (Genstat™; Payne *et al.* 1993) to estimate the effects of the various factors on CPUE. The survey data were linked by vessel sequence number to date, location, catch and effort data in a subset of the C-Fish database. Because of shifts in fishing effort over time as the fishery expanded, some of the more northern regions were not fished in some years. Therefore a full interaction term was created by linking year and region ('Financial year - Region') for all combinations appearing in the data. As initial analysis showed that the CPUE data were log-normally distributed, they were log transformed prior to analysis (ln[x+0.1]). Predictors used in the model were 'Financial year-Region,' month, crew size (number of crew), skipper experience (low, moderate, high), duration of skipper's involvement in the spanner crab

fishery (months), hull length (m), cruising speed (knots) and engine horsepower. Predicted CPUE values for each of the fitted terms (adjusted for all other terms) were computed, together with estimates of their standard errors. The estimated CPUE values were back-transformed (CPUE = exp[ln x] – 0.1) and the asymmetric 95% confidence intervals approximated by exp(ln x ± 1.96 * s.e.) – 0.1. Estimated CPUE values for the predictor 'Financial year - Region' were then plotted against year for each region for comparison with trends in untransformed CPUE data. These patterns of change were also compared with the results presented in Section 5.1.1 to verify that the behaviour of the fleet sample (i.e. questionnaire survey respondent group) was consistent with that of the fleet as a whole.

In situations where data for specific fleet characteristics are unavailable, catch rates are often standardised on vessel identification number. This process does not capture temporal changes in fishing power of individual vessels, and clearly cannot identify specific vessel characteristics that are influential in causing differences in power between vessels. However the "vessel" itself, including crew, contains all of the (unidentified) factors contributing to fishing power. It is therefore of interest to know the extent to which the factors quantified by the fleet survey capture these differences in fishing power. We therefore performed a second general linear analysis, with 'Financial year-Region,' month and vessel sequence number as predictors, to estimate the total proportion of the variance associated with differences between vessels.

5.1.2.3 Results

An "all subsets regression" was run to determine which of the eight terms ('Financial year-Region,' month, crew size, skipper experience, duration of skipper's involvement in the spanner crab fishery, hull length, cruising speed and engine horsepower) contributed to explaining the observed variance. The best sequence of subsets is shown in Table 5.2. This set of terms all contributed significantly ($p < 0.05$) to the model, which explained about 27.5% of the total variance.

Table 5.2 Results of "all subsets regression" analysis testing the effect (cumulative % variance explained, or adjusted R^2) of all factors considered to have a potential influence on CPUE.

Model predictor	% variance explained
'Financial year - Region'	22.61
+ Month	24.99
+ Crew number	26.40
+ Skipper experience	26.57
+ Skipper involvement	26.76
+ Hull length	27.03
+ Cruising speed	27.39
+ Engine power	27.49

However (as expected) the various terms were not equally effective in this regard. The Year-Region complex contributed by far the most (22.6%) to the observed variance in CPUE, and Month an additional 2.4%. The remaining terms, which were those related to the characteristics of the fishing vessel, together contributed only another 2.5% to explaining the variance in CPUE. The analysis summary table (Table 5.3) shows that the regression fit for the final model was highly significant.

Table 5.3 Summary of general linear model analysis with ln(CPUE+0.1) as the response variate and 8 fitted terms as predictors.

Source	d.f.	s.s	m.s.	F	P
Regression	55	1064	19.3515	65.25	<0.001
Residual	9263	2747	0.2966		
Total	9318	3812	0.4091		

Temporal and spatial effects.

Patterns of change in regional standardised back-transformed mean annual catch rates from the survey sample corresponded generally with those from the entire fleet (presented in Section 5.1.1).

In Region 1 (outside Managed Area A) catch rates varied about a mean of 0.6 kg/net lift, with substantial inter-annual changes but no particular trend over the five year period (Figure 5.10a). The standardisation process had relatively little effect on interpretation of CPUE, as the unstandardised (i.e. simple mean log-transformed CPUE) trajectory, portrayed with the dotted line in Figure 5.10a, generally followed the model predictions quite closely.

Again, in Region 2 standardisation had little effect (Figure 5.10b) apart from increasing the predicted catch rate in 1992/93 to levels approaching those in the following year. Catch rates dropped suddenly from around 2.0 between 1992 and 1994 to less than 1.0 in 1994/95. Subsequently there was a consistent but slight increase to around 1.25.

In Region 3, CPUE dropped initially then recovered to levels similar to those in Region 2 (Figure 5.10c). The unstandardised data (dotted line) followed the standardised trajectory closely, indicating that there has been little change in fishing power of the fleet in this Region.

Standardised catch rates in Region 4 appear to have increased from around 1.0 in the three years prior to 1995/96 to about 1.5 in 1997/98 (Figure 5.10d). This trend followed that of the unstandardised data very closely throughout the time-series.

Region 5 (Sunshine Coast) has been fished more intensively and for the longest period of time of any of the Assessment Regions, and the relatively low catch rates in Figure 5.10e reflect this. The unusually high CPUE in 1990/91 is not reflected in the total fleet data, and is presumed to be an outlier resulting from a small sample size or a logbook data transcription error. There was, nevertheless, a substantial decline in catch rates (both predicted from the regression model and from unstandardised data) from 1.2 in 1992/93 to a little over 0.5 in 1993/94. It remained at that level for the next two years, but showed a slight recovery between 1995/96 and 1996/97.

The Gold Coast (Region 6) is another historically heavily-exploited sector of the fishery. The adjusted monthly mean CPUEs prior to 1995 remained fairly constant at about 1.2 kg/net lift, but with high variance as shown by the spread of the error bars (Figure 5.10f). Between 1994/95 and 1995/96 the adjusted CPUEs dropped to about 1.0, and were characterised by very much tighter confidence intervals, due to larger numbers of observations. There was some divergence between standardised and unstandardised catch rate trajectories prior to 1994/95, but thereafter they were much closer.

Factoring out the effects of year, area and vessel fishing power provides a much clearer picture of seasonal changes in the fishery. These may be due to changes in availability or catchability, which may in turn be the result of variation in hydrological conditions or cyclic physiological and behavioural changes such as those related to the reproductive process. They may also reflect changes in the pattern of recruitment of young crabs into the fishery.

For data pooled over years, the adjusted monthly mean catch rates (Figure 5.11) tended to decline during the first half of the year, increase suddenly between July and September, then drop to previous levels by about December. Peak season predicted catch rates (1.25 kg/net lift) were 50% higher than those in December (0.82 kg/net lift).

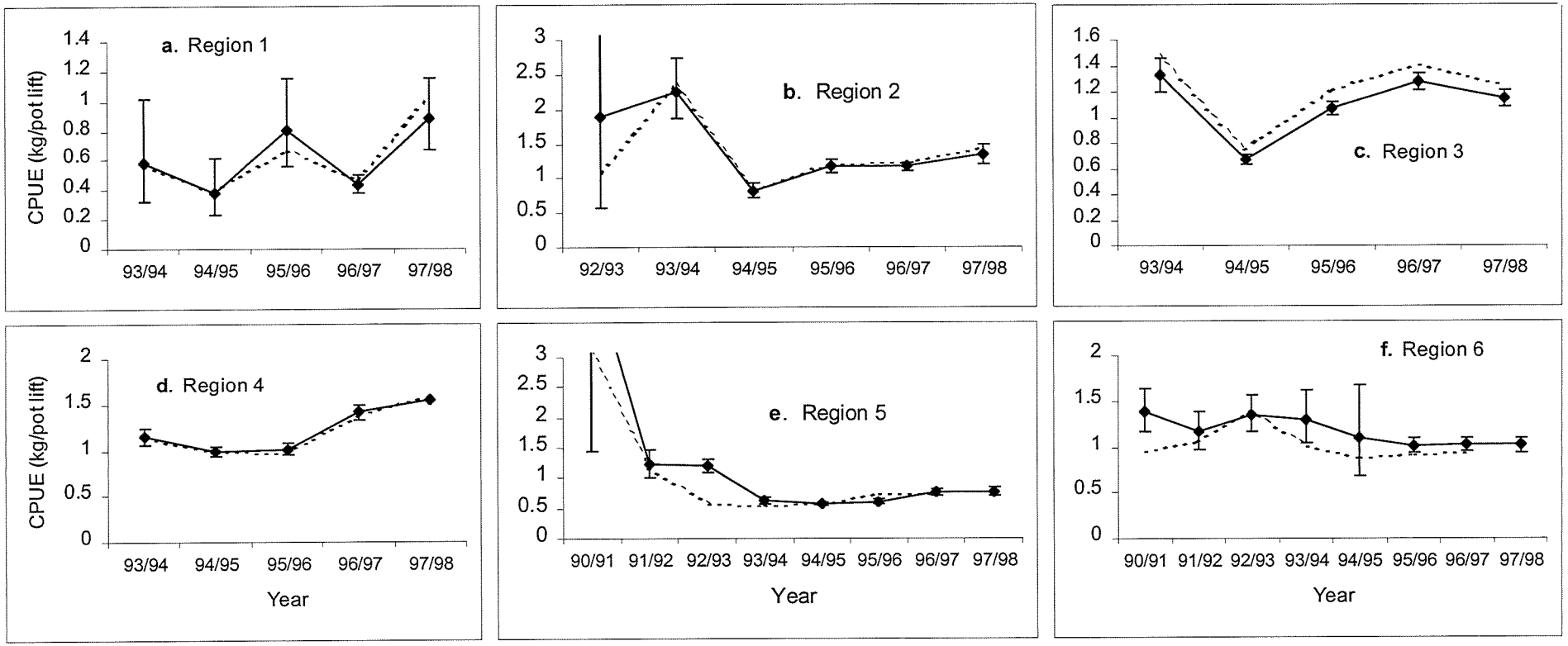

Figure 5.10 Trends in annual mean CPUE by Assessment Region (see Table in Sect. 5.1.1 for description). GLM predictions (adjusted means) are depicted by solid lines, and error bars are 2 standard errors either side of the mean. Unstandardised mean CPUEs (back-transformed logs) are shown by dotted lines.

Fishing power effects

Number of crew. Of the survey respondents, 32% said that their vessel was operated by the skipper alone, while 64% employed one crew member in addition to the skipper. The remaining 4% employed two crew. The presence of one deckhand appeared to make a significant contribution to the skipper's catch rate (the difference between 0.90 and 1.05 kg/net lift) (Figure 5.12). Likewise, vessels with two crew in addition to the skipper appeared to perform better than those with one crew, but because of the low numbers of vessels in this category the difference was not statistically significant.

Skipper experience. 54% of the survey respondents rated skipper experience as 'high' while 42% rated it as 'moderate'. Only 4% rated skipper experience as 'low'. The predicted CPUE of skippers whose experience was rated as 'high' was 1.04 kg/net lift, about 10% higher than the 0.95 kg/net lift of those rated as 'moderate' (Figure 5.13). The 'moderate experience' group's predicted CPUEs were, in turn, 30% greater than those in the 'low experience ' group.

Skipper involvement in fishery. Despite the fact that this variable may be considered a proxy of skipper experience, the model detected a slight but nevertheless significant decline in CPUE with increasing length of time in the fishery (Figure 5.14). The predicted CPUE of the skippers who entered the fishery most recently was 1.07

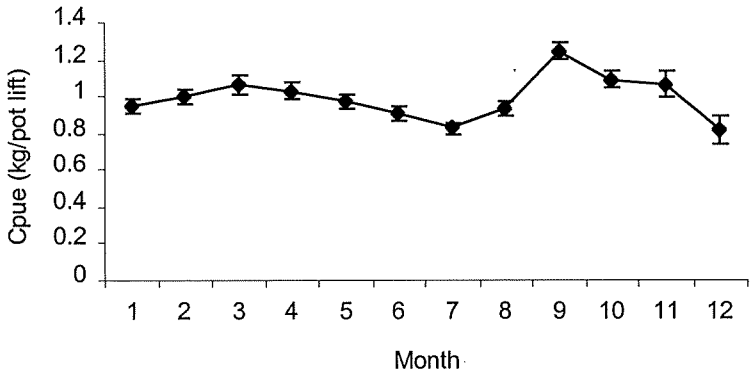

Figure 5.11 Monthly changes in predicted (adjusted) catch rate or CPUE, from the spanner crab fleet survey.

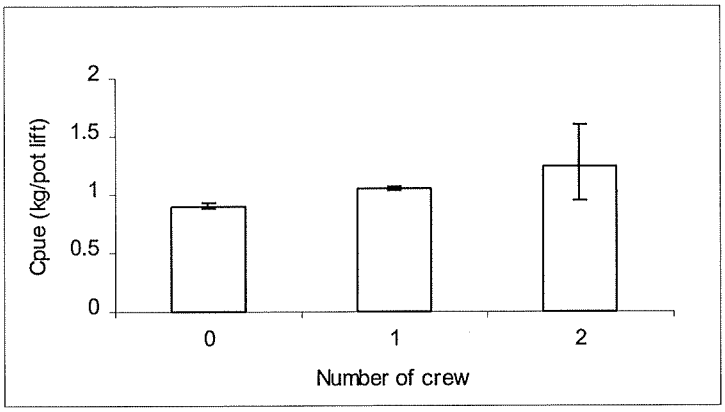

Figure 5.12 Predicted CPUEs and 95% confidence intervals for three levels of crew size from standardisation model.

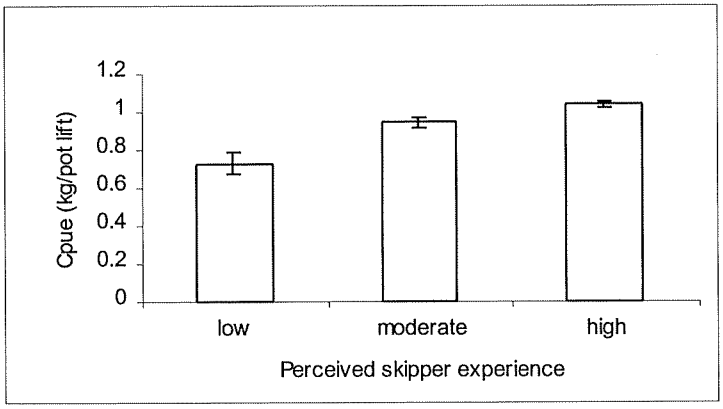

Figure 5.13 Predicted CPUEs and 95% confidence intervals for three levels of skipper experience from standardisation model.

kg/net lift, exceeding the 0.91 kg/net lift of the most experienced skippers by about 18%.

Hull length. The general linear analysis detected an increase in CPUE with increasing vessel size (Figure 5.15). The predicted catch rate of the largest vessel class (15m) was almost twice that of the smallest (1.43 vs 0.74 kg/net lift).

Cruising speed. The model predicted an increase in CPUE with increasing vessel cruising speed over the range of 11 to 29 knots. The fitted mean CPUE of the fastest vessels in that range was 1.21 kg/net lift, which exceeded the 0.90 kg/net lift of the slowest vessels by about 34% (Figure 5.16).

Engine power. There was a slight but significant negative correlation between engine power and adjusted catch rate (Figure 5.17), indicating that the lower the engine power the greater the catch rate within the range of the data. The least powerful engines of the survey respondents' vessels were 50 hp and had a fitted mean CPUE of 1.11 kg/net lift, about 11.5% greater than the fitted mean CPUE of 0.96 kg/net lift of the most powerful vessels (300 hp).

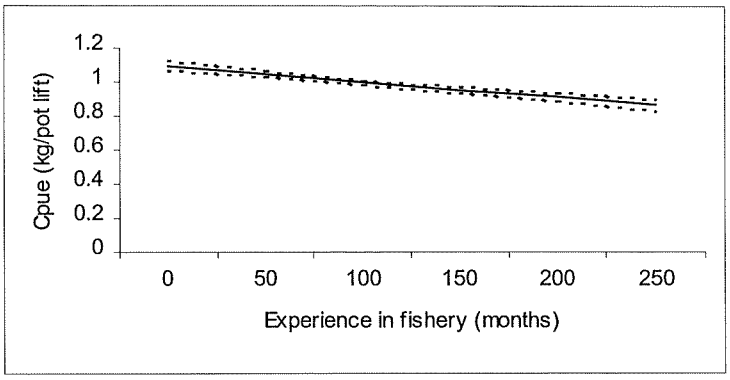

Figure 5.14 Predicted CPUEs and 95% confidence bands for a range of skipper experience levels, from standardisation model.

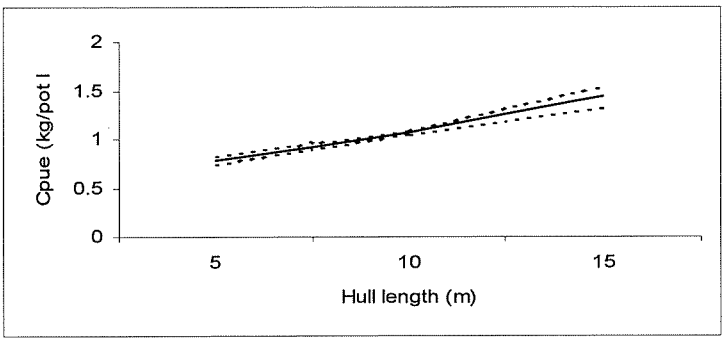

Figure 5.15 Predicted CPUEs and 95% confidence bands for a range of hull lengths, from standardisation model.

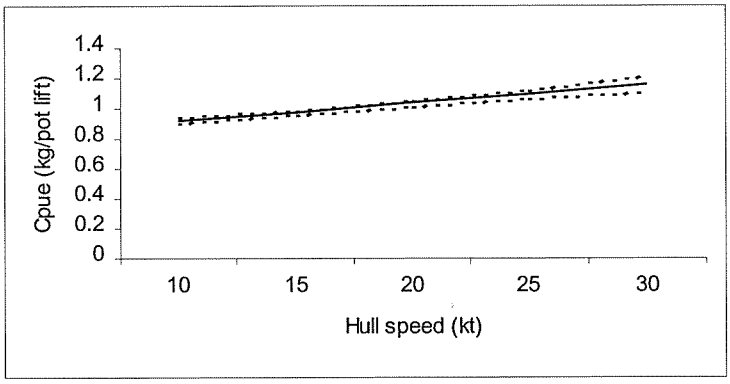

Figure 5.16 Predicted CPUEs and 95% confidence bands for a range of hull speeds, from standardisation model.

Standardisation on vessel number

The fleet survey data were subject to a second general linear regression analysis, which simply included month, 'Financial year - Region' and vessel sequence number as predictors in the model. This model explained 36% of the variance (adjusted r^2) in CPUE. This exceeded the 27.5% of variance explained by the first model. The adjusted (predicted) catch rates per vessel, after factoring out the effects of seasonal and spatial differences, varied from 0.38 to 1.52 kg/net lift (Figure 5.18). However the majority of vessels fell within the 0.7-1.3 kg/net lift range.

5.1.2.4 Discussion

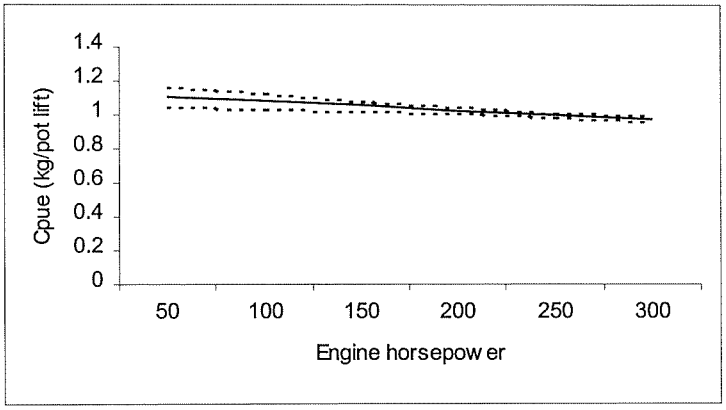

Figure 5.17 Predicted CPUEs and 95% confidence bands for a range of engine horsepowers, from standardisation model.

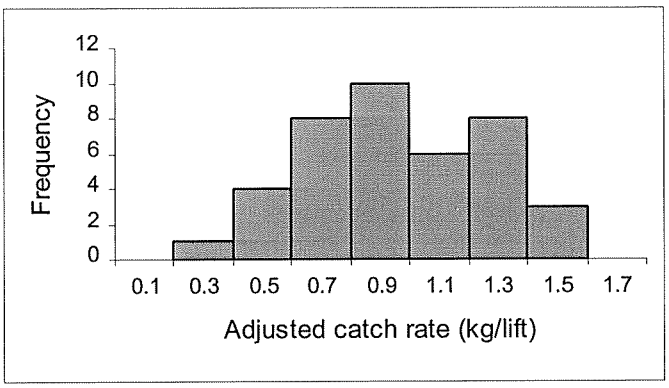

Figure 5.18 Frequency distribution of adjusted catch rates (CPUE) among individual vessels in the spanner crab fleet.

A number of vessel characteristics quantified by the fleet survey were shown to have a significant effect on the vessels' catching power. The number of crew carried (in addition to the skipper), the perceived level of the skipper's experience in the spanner crab fishery, and the vessel's size and cruising speed were positively correlated with catch rate. These relationships are consistent with expectations: more crew may speed up the gear retrieval and clearing process, allowing the vessel to locate highly productive areas more rapidly. A highly experienced skipper and crew should intuitively perform better than a crew with less experience in the fishery. Larger vessels may be generally more seaworthy, and hence be able to fish highly productive areas longer and more frequently than smaller vessels. Fast boats should in general be able to locate patches of crabs more quickly, and consequently achieve higher overall catch rates than slower vessels.

On the other hand, engine horsepower and the skipper's time-involvement in the fishery were negatively correlated with catch rate. This may appear paradoxical, but can be explained by the fact that the general linear regression model predicts the effects of a particular factor after having removed the effects of all previous factors in the model. It is very likely, for example, that most of the variation attributable to a skipper's time-involvement in the fishery is actually captured by their perceived experience levels. Once the model removes the effect of 'experience', the residual effect of a skipper's time involvement in the fishery may be minimal or (as in this case) even negative. It may be that, experience levels being equal, skippers who are new to the fishery may tend to be younger, more prepared to work harder, and less risk-averse than longer-serving skippers. More of the recent recruits may also tend to be company employees rather than owner-skippers, and subject to higher performance expectations.

The effects of these various factors in explaining variation in catch rates were significant, due largely to the size of the data set and the number of degrees of freedom in the analysis. However their combined effect (as a measure of fishing power) was quite small in comparison to the geographical area and between-year effects. In terms of improving the reliability of the CPUE data they made relatively little impact, and there was little difference in the annual trajectories of standardised and unstandardised CPUEs when examined region by region.

Seasonal changes in catch rate may be due to changes in availability or catchability, which may in turn be the result of variation in hydrological conditions, or cyclic physiological and behavioural changes such as those related to the reproductive process. The surprisingly low estimated monthly standard errors suggest that there is an underlying process that is consistent from year to year. The widely-held belief that the fishery is most productive for 2-3 months after August is confirmed by our analysis. However at this stage it is not known whether this is due to an increase in availability (resulting perhaps from seasonal moulting activity providing legal-sized recruits to the fishery) or catchability (resulting from the formation of pre-spawning aggregations).

The rather low CPUE in December may be due to the closure of the fishery between 20 November and at least 20 December each year. As there are very few available fishing days in December it is likely that a proportion of the more serious crabbing operations close down completely over the Christmas period.

By running a second general linear model analysis with vessel sequence number as a proxy for all vessel-related factors that contribute to fishing power, we were able to determine the extent to which our initial selection of factors explained differences in fishing power between vessels. Vessel sequence number contributed substantially more (about 9%) to explaining the variance in CPUE than did the suite of factors quantified by the fleet survey. Thus, there must have been some variation between vessels which affected CPUE but which was not included in the first model.

This suggests that either the vessel characteristics used in the first model only partly captured the between-vessel differences, or the survey questionnaires contained erroneous data, resulting possibly from confusion about the precise meaning of some of the questions. Perhaps there are other factors influencing fishing power that were not included in the survey questionnaire, or alternatively, if the most important factors were identified, they may not have been sufficiently or accurately quantified. The installation of advanced navigational aids is often shown to be a major contributor to the fishing power of a vessel. This factor did not appear in our general linear model because effectively the whole of the fleet sample used in the analysis had been using GPS technology since the start of the analysis period, and there therefore was no contrast in the data.

Additional information about the structure and composition of the Queensland spanner crab fleet (as at 1997-98) may be found in Appendix 3. While much of this information is not specifically related to the objectives of the present project, it does include opinions and observations germane to a better understanding of aspects of the fishery and evaluation of the commercial logbook data.

5.2 STOCK ASSESSMENT MODELLING

5.2.1 Introduction

Several models were applied to the spanner crab resource to obtain an understanding of the unknowns with regard to the dynamics of the resource. There were three broad objectives:

- To investigate the applicability to the Queensland resource of the different spanner crab growth rates obtained from studies in New South Wales and Seychelles,
- To estimate natural mortality, and
- To estimate dynamic parameters such as present biomass, the state of the resource and sustainable catches.

At present, no definitive growth studies have been completed on the Queensland spanner crab stock. This means that tentative growth parameters from other studies have been used. However, these studies have yielded very different growth parameter estimates, probably because they used different data types and different modelling techniques. The Seychelles study utilised length-based techniques to estimate von Bertalanffy growth parameters on various length frequency datasets for males and females separately and combined. This particular study is characterised by a rather small dataset. The New South Wales study estimated von Bertalanffy growth parameters, as well as stepwise growth functions, from tagging data.

To compare these studies, the von Bertalanffy parameters for males only were utilised. A smooth growth function was assumed, because insufficient is known about the timing and frequency of moulting to apply any other growth model at this stage. These growth parameters were used as inputs to an equilibrium size-based model which estimated natural mortality (M) and a shape parameter (β) for the gamma function that describes variance in growth for a given size. This model fits an estimated size frequency to an observed size frequency obtained from independent collections in 1980 and 1981. The size structure from these surveys was assumed to represent that of an unexploited resource, as the fishery was not highly developed and advanced at that time. The hypothesis is that if the growth equation is correct, then it should approximate size-frequency distributions at the start of fishing in the early 1980's given estimated natural mortality. Since in all the studies, the von Bertalanffy average maximum size (L_∞) was much larger than could be explained by the observed size frequency, a version of the model was run in which M, β and the two von Bertanaffy parameters were estimated.

To estimate population dynamic parameters such as present biomass, a dynamic version of the above size-based model was developed, but due to uncertainties in the applicability of the growth rates from other studies, this model has still to be applied. As a result, a second model was utilised. This second model is an observation error biomass dynamic model using the Schaefer form. This model was tuned to catch rate information and has been well described in texts such as Punt (1994).

5.2.2 Methods

5.2.2.1 Length-Based Dynamic Model

Basic dynamics

Two-millimetre length classes were utilised in this model. The equation which specifies the number of animals of sex s and in length-class l at the start of time-step t+1 takes account of natural mortality, fishing mortality, growth and recruitment:

$$N_{t+1}^{l,s} = \sum_{l'} X_{l,l',t}^{s}\, N_t^{l',s}\, e^{-M_{l'}} \left(1 - S_{l',t}^{s} F_t\right) + R_t^{l,s} \qquad (1)$$

where $N_t^{l,s}$ is the number of animals of sex s and in length-class l at the start of time-step t,

$X_{l,l',t}^{s}$ is the fraction of animals of sex s and in length-class l' which grow into length-class l at the end of time-step t (after mortality and movement),

M_l is the rate of natural mortality during a time-step for animals in length-class l,

$S_{l,t}^{s}$ is the selectivity (all gears combined) on animals of sex s and in length-class l,

F_t is the exploitation rate on fully-selected (i.e. $S_{l,t}^{s} = 1$) animals during time-step t, and

$R_t^{l,s}$ is the recruitment of animals of sex s to length-class l at the end of time-step t.

Growth

The mean growth distribution is based on the von Bertalanffy model:

$$I_l^s = (L_\infty^s - \bar{l})(1 - e^{-k^s}) \qquad (2)$$

where I^s_l is the annual length-class increment, l for each sex, s,

L^s_∞ is the average max length-class increment,

$\bar{l}$ is the average of the upper and lower limits of size-class l

κ is the intrinsic growth rate

A gamma distribution is used to represent the variation in annual growth:

$$g(I_l^s | \alpha, \beta, l) = \frac{1}{\beta^\alpha \Gamma(\alpha)} I_l^{s,\alpha-1} e^{-\frac{I_l^s}{\beta}} \qquad (3)$$

The mean length increment for a gamma function is also:

$$I_l^s = \alpha^s \beta^s \qquad (4)$$

and the variance is proportional to the mean, therefore:

$$\sigma^2 = \alpha(\beta^s)^2 = \beta I_l^s \qquad (5)$$

The expected proportion of individuals growing from length class l to length class j is:

$$X^s_{l,l+j} = \int_{l=j-1/2}^{l=j+1/2} g(I|\alpha_s, \beta_s, j)dx \qquad (6)$$

$$\text{if } j = 1,2,\ldots,(L_\infty - 1)$$

No negative growth is allowed. The length-weight function for each sex s and length l is:

$$W_l^s = a^s l^{b^s} \qquad (7)$$

where a^s, b^s are mass-length relationship parameters.

Selectivity

The selectivity of the commercial gear is assumed to be:

$$S^s_{l,t} = \begin{cases} 0 & \text{if } l < 63 \\ 1 & \text{if } l \geq 63 \end{cases} \qquad (8)$$

This is based on the size frequency of mesh size experiments done on spanner crabs where only animals above 63mm were caught and that the mean length of crabs caught was not significantly affected by mesh size (Sumpton *et. al.* 1995). This assumption was substantiated by video material of the commercial gear, which showed that many animals cross the dilly without being caught and that the probability of being caught is independent of size (Hill and Wassenberg *in press*). However, only animals above 60 mm are generally caught by the gear, which may be related to the type of bait used. The possible effect of ovigerity amongst females on the selectivity function is being ignored at this stage.

Settlement

The settlement during year y is defined to be the number of animals which reach the smallest length considered in the model, l_1 (taken in this model to be 10 mm) that year:

$$R_t^{l,s} = \begin{cases} \frac{1}{2}\dfrac{\alpha_r SB_t}{\beta_r + SB_t} & \text{if } l = l_1 \\ 0 & \text{otherwise} \end{cases} \qquad (9)$$

In the initial stages of the model, α_r is assumed to be R_0 and β_r to be zero.

Catches

The catch during time-step t is assumed to occur in a pulse at the start of the time-step (before natural mortality), so the fully-selected fishing mortality for time-step t is found by solving for F_t, the equation:

$$C_t = \sum_{l=\min}^{\max} \sum_{s} S_{l,t}^{s} F_t W_l^s N_t^{l,s} \qquad (10)$$

where *min* is the minimum legal size class,

and *max* is the maximum size class considered in the model.

The discards, D_t can b calculated as:

$$D_t = \sum_{l=0}^{\min-1} \sum_{s} dS_{l,t}^{s} F_t W_l^s N_t^{l,s} \qquad (11)$$

where d is the probability of survival given release.

The model is "conditioned" on catch. After the estimation of historical biomass is completed, the model can project 15 years into the future in order to test various management options.

The Likelihood Function

The quantity minimised to estimate the parameters, the negative of the logarithm of the likelihood function after removal of constants, is of the form:

$$L = L_a + L_b + L_c \qquad (12)$$

where L is the contribution to the overall negative log-likelihood. The following sections detail each of these contributions in turn.

Catch-per-unit -effort data

Assuming that catchability is independent of time, the expected catch-per-unit-effort is calculated as:

$$(C/E)_t = q\left[B_t^m + B_t^f\right] e^{\varepsilon_t} \qquad (13)$$

where $\varepsilon_t \sim N(0,\sigma_q^2)$

where m and f denote male and female respectively.

Therefore, given the above equation, the contribution of the catch-per-unit-effort (CPUE) data to the negative of the logarithm of the likelihood function is given by:

$$L_a = n_q \ell n\sigma_q + \frac{1}{2\sigma_q^2}\sum_t \left(\ell n\left(C/E_t\right) - \ln q - \ln\left(\hat{B}_t\right)\right)^2 \qquad (14)$$

where $_q$ is the standard deviation of the random fluctuations in catchability,
q is the catchability coefficient,
E_t is the observed effort for time-step t, and
n_q is the total number of time-steps for which estimates of effort are available (months for which there are less than 5 data points are ignored).

An analytical solution for q and σ can be found by taking the derivative of L_a, in terms of q and σ. The solution is therefore:

$$\hat{q} = e^{\left[\frac{1}{n_q}\sum_t \ln\left(\frac{C/E_t}{\hat{B}_t}\right)\right]} \qquad (15)$$

and

$$\sigma^2 = \frac{1}{n_q}\sum_t \left(\ln(C/E)_t - \ln(q\hat{B}_t)\right)^2 \qquad (16)$$

Length-frequency data

The expected size frequency is calculated as:

$$\hat{C}^s_{t,l} = S^s_{t,l} F_t N^{l,s}_t \qquad (17)$$

and represented in proportion as:

$$\hat{\rho}^s_{t,l} = \frac{\hat{C}^s_{t,l}}{\sum_{l'=\min}^{\max} \hat{C}^s_{t,l'}} \qquad (18)$$

Similarly for the observed sampled data:

$$\rho^{s,obs}_{t,l} = \frac{C^{s,obs}_{t,l}}{\sum_{l=\min}^{\max} C^{s,obs}_{t,l}} \qquad (19)$$

The length-frequency data (both commercial and scientific) are taken to be lognormal samples from the catch by the commercial and scientific traps, therefore:

$$\rho^{s,obs}_{t,l} = \hat{\rho}^s_{t,l} e^{\varepsilon_{t,l}} \qquad (20)$$

where $\varepsilon_{t,l} \sim N[0,(\sigma^s_{t,l})^2]$

where $\sigma^s_{t,l} = \dfrac{\sigma_\rho}{\sqrt{\hat{\rho}^s_{t,l}}}$ (21)

The negative log-likelihood for each of these sources is given by:

$$L_b = \sum_s \sum_t \sum_l \frac{1}{2} \ln\left[\frac{\sigma_\rho^2}{\hat{\rho}^s_{t,l}}\right] + \sum_s \sum_t \sum_l \frac{\hat{\rho}^s_{t,l}}{2\sigma_\rho^2}\left(\ln \rho^{s,obs}_{t,l} - \ln \hat{\rho}^s_{t,l}\right)^2 \quad (22)$$

which simplifies to:

$$L_b = n_\rho \ell n \sigma_\rho - \sum_s \sum_t \sum_l \ell n \sqrt{\hat{\rho}^s_{t,l}} + \frac{1}{2\sigma_\rho^2} \sum_s \sum_t \sum_l \hat{\rho}^s_{t,l} \ln\left(\frac{\rho^{s,obs}_{t,l}}{\hat{\rho}^s_{t,l}}\right)^2 \quad (23)$$

and the variance is calculated as:

$$\hat{\sigma}_\rho = \sqrt{\frac{1}{n_\rho} \sum_s \sum_t \sum_l \hat{\rho}^s_{t,l} \ln\left(\frac{\rho^{s,obs}_{t,l}}{\hat{\rho}^s_{t,l}}\right)} \quad (24)$$

Sex ratio

Commercial and survey sex ratio data is available for some of the years and is calculated by:

$$V_t^{obs} = \frac{\sum_{l=\min}^{\max} C^{f,obs}_{t,l}}{\sum_s \sum_{l'=\min}^{\max} C^{s,obs}_{t,l'}} \quad (25)$$

and the expected values by:

$$\hat{V}_t = \frac{\sum_{l=\min}^{\max} \hat{C}^f_{t,l}}{\sum_s \sum_{l'=\min}^{\max} \hat{C}^s_{t,l'}} \quad (26)$$

The error is assumed to normally distributed and therefore the relationship between observed and expected values are:

$$V_t^{obs} = \hat{V} + \varepsilon_t \quad (27)$$

where $\varepsilon_t \sim N(0,\sigma_v^2)$

The negative log-likelihood function would therefore simplify to:

$$L_c = \ln \hat{\sigma}_v + \frac{n_v}{2} \qquad (28)$$

where $\hat{\sigma}_v = \sqrt{1/n_v \sum_t \left(V_t^{obs} - \hat{V}_t\right)^2}$

Future Projections

The results of the basic estimation of present biomass levels using historical data is used to project 15 years into the future so as to examine different harvest strategies. This means that there are two procedures running in parallel, the operation procedure and the management procedure. The operation procedure keeps track of the future resource ('reality') and the management procedure estimates this reality based on the data from the operations procedure.

Operation procedure

This procedure simulates the 'real' resource using the parameters estimated in the initial parameter estimation procedure of present biomass conditions. This resource is projected a single year into the future and catch rate, length frequency and sex ratio data are simulated.

Management procedure

This procedure does a full estimation of parameters as per the above section and then sets the TACC using one of the following options:

Option 1 being $C_y^{obs} = \sum_{z=1}^{mzone} C_{y-1}^{z,obs}$ is a constant catch policy using the catch set in the 1996 season.

Option 2 sets the catch based on a combination of the previous years' catch and the slope of the previous 5 years' CPUE data. A γ parameter is pre-set to give different weight to the CPUE data. Mathematically, this can be described as:

$$\boldsymbol{C_y^{obs} = \sum_{z=1}^{mzone} C_{y-1}^{z,obs} \left(1 + \gamma \times slope(C / E_{y-1}^{y-5})\right)} \qquad (29)$$

The 3rd Option can be used when a Schaefer surplus production model is used to estimate the parameters, instead of a size-based model, and the $f_{0..n}$ policy can be used to set the catch, i.e.:

$$C_y^{obs} = \sum_{z=1}^{mzone} \varphi \frac{\hat{r}^z}{2} \hat{B}_y^z \qquad (30)$$

The model was tested by setting a new TACC each year or only every m years. Also management restrictions were put in place whereby a maximum decrease/increase in the TACC from one year to the next was set.

5.2.2.2 *Equilibrium Model and Initial Conditions of Dynamic Model*

Two-millimetre length classes were also utilised in this model. The equilibrium model applies the equilibrium equations only, whereas the dynamic model assumes pristine equilibrium conditions for each "stock" at the start of the fishery. The equilibrium numbers for class 1 can be calculated from:

$$N_{eq}^{1,s} = X_{1,1}^{s} e^{-M_1} N_{eq}^{1,s} + R_0^s \qquad (31)$$

which solves to:

$$N_{eq}^{1,s} = \frac{R_0^{1,s}}{1 - X_{1,1}^{s} e^{-M_1}} \qquad (32)$$

Similarly, for class > 1, equilibrium numbers are:

$$N_{eq}^{j,s} = \frac{\sum_{l=1}^{j} \left(X_{l,j}^{s} e^{-M_l} N_{eq}^{l,s} \right)}{1 - X_{j,j}^{s} e^{-M_j}}$$

Minimisation function and parameters estimated

In most model runs, the von Bertalanffy male growth parameters were used as input to the model and only two parameters would be estimated: natural mortality and beta from the gamma function. In both the New south Wales and Seychelles studies, the average maximum length (L_∞) was much larger than could be explained by the observed size frequency. As a result, growth was estimated as well, which required the model to estimate four parameters: natural mortality, beta from the gamma function, and L_∞ and K from the growth function. Due to possible selectivity against the capture of small animals, different starting size class values for the minimisation was utilised (min2 in Equation 33). Data from surveys in 1980 and 1981 were used as being representative of the size frequency of an unfished population. In all the equilibrium model versions, a sum of squares minimisation criterion was used:

$$SSQ = \sum_{l=\min 2}^{\max} \left(\rho_{1981,l}^{males,obs} - \hat{N}^{l,males} \right)^2 \qquad (33)$$

Table 5.4 gives the results of estimates using different starting length class values (min2) from which the sum of squares is estimated. The shape of the curve is affected by the selectivity of the gear at small classes. As a result, larger values of min2 will represent size classes that are more likely to be in the region where selectivity is 1.

Growth is modelled using a size-transition matrix described in the dynamic model above.

5.2.2.3 *Biomass Dynamic Model*

The Schaefer form of the Butterworth-Andrew observation-error biomass dynamic model (Butterworth and Andrew 1984 and Punt 1993) was used to provide estimates of model parameters and derived management variables.

The deterministic form of this model assumes that the fishery can be modelled by the equations:

$$B_{t+1} = B_t + rB_t\left(1 - \frac{B_t}{K}\right) - C_t \qquad (34)$$

and

$$\left(\frac{C}{E}\right)_t = \left(\frac{1}{2} q_t [B_t + B_{t+1}]\right) \qquad (35)$$

where

B_t is the biomass at time t,
C_t is the catch at time t,
E_t is the fishing effort, and
q is the catchability coefficient.

Lower 5 and upper 95 percentiles were calculated using a conditioned parametric bootstrap (Punt and Butterworth 1993). In all cases a linear relationship between catch rate and biomass is assumed.

Two further basic assumptions in each region were tested. The first assumption is that the first year of the catch data series represents an unexploited population and therefore B_0=K and implicitly that there is no recruitment variability. This may be valid for Regions 1 to 3. The second assumption was that $B_0 \neq K$ and therefore Bo does not represent an unexploited resource. In some regions, the early catch rate dataset was of an extremely small fishery and was therefore not included in the analysis e.g. Region 1.

5.2.3 Results

5.2.3.1 Equilibrium Size-based Model

In both the Seychelles and New South Wales studies, the estimated male L_∞ was much larger than could be explained by the observed data given realistic estimated natural mortality values. The model runs in which the growth parameters are estimated and using different starting length class values (min2) are given in Table 5.4. The fit to the size distribution data for two of the extreme parameter estimates of Table 5.4, as well as the results using the New South Wales parameter values, as input are given in Figure 5.19.

Table 5.4 Parameter estimates of model fit to various min2 (length-class) values.

Parameter	Min2=70 mm	Min2=80mm	Min2=90mm	Min2=100m m
M (Natural mortality (yr^{-1})	0.034	0.016	0.017	0.037
L_∞ (mm)	132.4	130.0	128.4	124.0
K (yr^{-1})	0.077	0.059	0.059	0.103
Beta of gamma function	0.166	2.271	0.281	0.461
Sum of Squares[1]	0.0089	0.014	0.006	0.007

[1] Note: Sum of Squares not comparable between columns as different lengths of data incorporated.

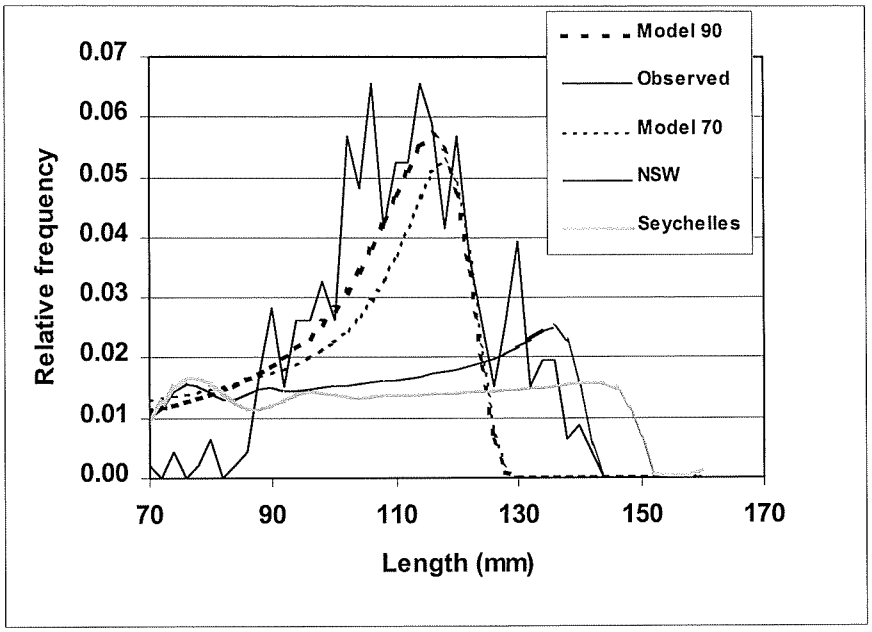

Figure 5.19 Model fit to 1981 spanner crab size frequency data from surveys for two extreme results of Table 5.4. Model 90 and Model 70 are the results of min2 = 90mm and min2 = 70mm respectively. The other possible alternatives for min2 range between the fits.

5.2.3.2 Biomass Dynamic Model Fit to CPUE

Figures 5.20 to 5.25 give the model fit to the observed catch rate (kg/net lift) data with both assumptions for each assessment region separately (including Region 1, which is not part of the fishery subject to TACC controls).

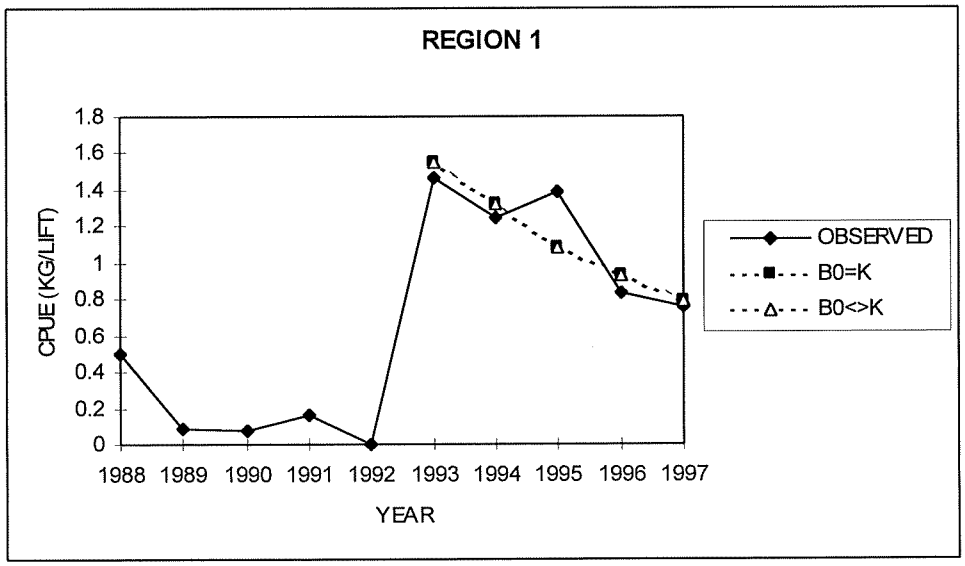

Figure 5.20 Results of observation error biomass dynamic model fitted to catch rate data (kg.lift^{-1}) from QFMA commercial logbook database for Region 1.

The parameter estimates shown in Table 5.5 ($B_0 = K$) and 5.6 ($B_0 \neq K$) were highly variable and not reliable (as evidenced by the generally very wide error range). Predicted TACCs under an f_{msy} policy for the subsequent year ranged from 2 t (Region 6) to 40,223 t (Region 4). The model outputs are clearly not biologically realistic and should not in any way be considered to reflect the status of the Queensland spanner crab stock. They are included here solely for completeness.

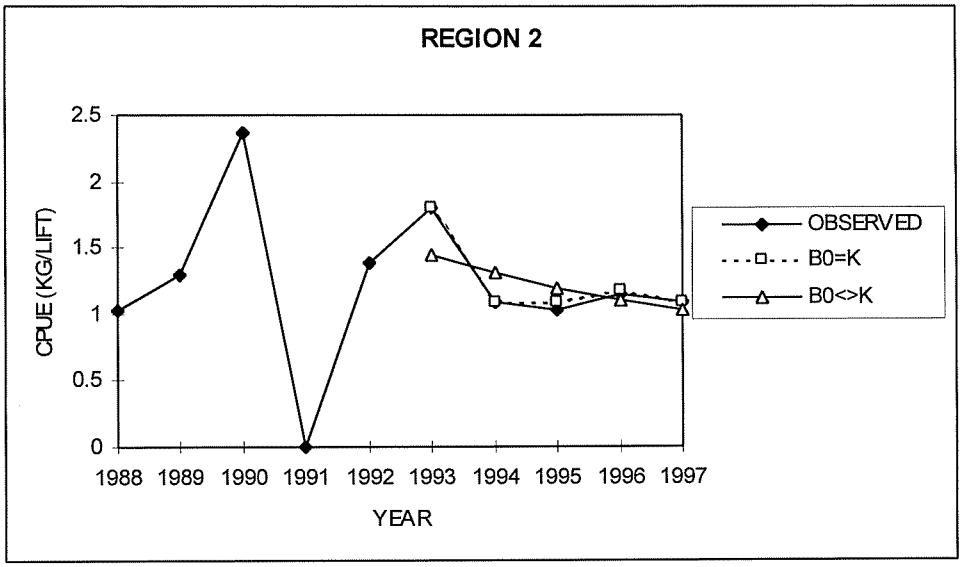

Figure 5.21 Results of observation error biomass dynamic model fitted to catch rate data (kg.lift^{-1}) from QFMA commercial logbook database for Region 2.

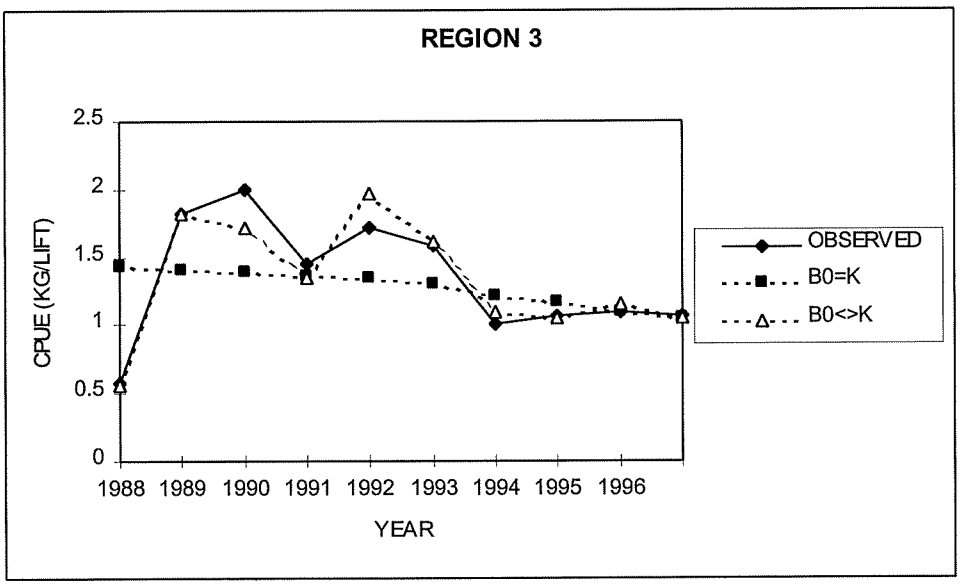

Figure 5.22 Results of observation error biomass dynamic model fitted to catch rate data (kg.lift^{-1}) from QFMA commercial logbook database for Region 3.

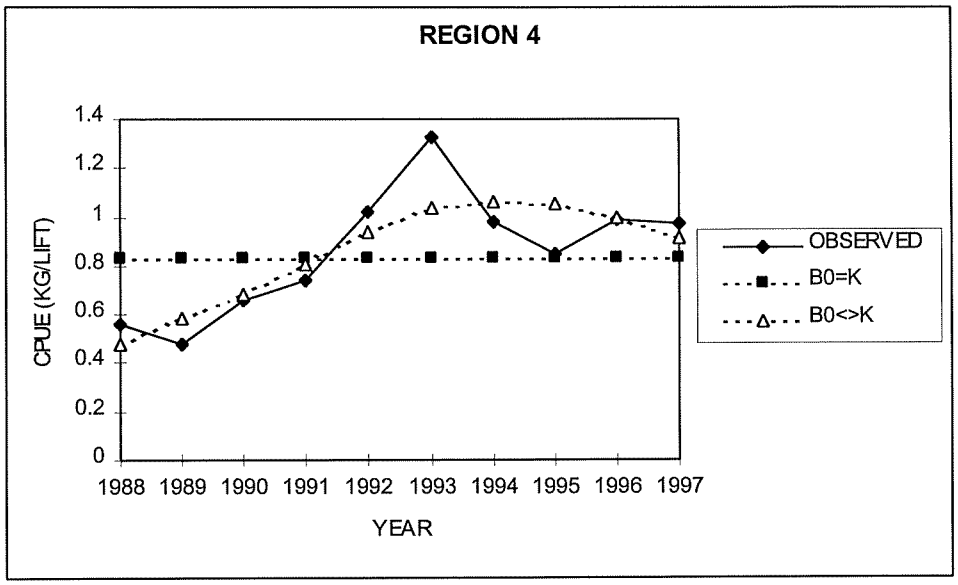

Figure 5.23 Results of observation error biomass dynamic model fitted to catch rate data (kg.lift^{-1}) from QFMA commercial logbook database for Region 4.

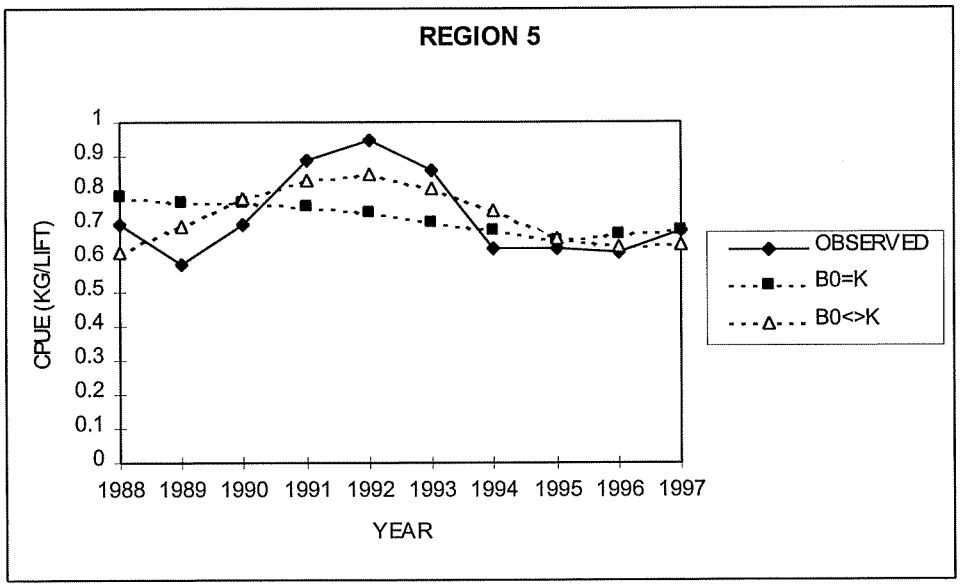

Figure 5.24 Results of observation error biomass dynamic model fitted to catch rate data (kg.lift^{-1}) from QFMA commercial logbook database for Region 5.

Table 5.5 Biomass dynamic model parameter estimates for each Assessment Region under the assumption $B_0 = K$.. Five 5 and 95 percentiles are shown in brackets beneath the parameter estimates.

Parameter	Description	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6
r	Intrinsic growth rate (yr^{-1})	0.10 [0-0.66]	3.03 [2.85-3.12]	0.11 [0-3.64]	0 [0-0]	0.11 [0-2.66]	0.001 [0-0.001]
K	Carrying capacity or virgin biomass (t)	963 [531-1488]	539 [529-571]	18221 [1542-huge]	8.2×10^8 [6×10^8-9×10^8]	16788 [1396-huge]	5603 [3680-17194]
B_{t+1}/K	Present biomass + 1 year relative to virgin biomass	0.49 [0.38-0.66]	0.51 [0.48-0.56]	0.72 [0.37-1]	1 [1-1]	0.8 [0.7-1]	0.75 [0.63-0.92]
B_{msy}	Biomass at maximum sustainable yield (t)	481 [265-724]	270 [265-285]	9111 [771-huge]	4.1×10^8 [3.43×10^8-3.4×10^8]	8394 [698-huge]	2802 [1840-8597]
MSY	Maximum sustainable yield (t)	24 [0-102]	409 [403-414]	489 [0.6-3697]	20112 [20112-24134]	458 [0.66-976]	1.3 [1.1-2.7]
TAC_{msy}	Total allowable catch of the f_{msy} policy for year present+1 (t)	24 [0-124]	412 [394-438]	696 [0.6-3797]	40223 [40223-48268]	760 [1.0-1876]	2 [1-5]
$TAC_{0.1}$	Total allowable catch of the $f_{0.1}$ policy for year present+1 (t)	22 [0-113]	388 [371-412]	628 [0.5-3580]	36201 [36201-43441]	686 [0.9-1688]	2 [1-5]
RY*	Replacement yield for year present + 1 (t)	24 [0-95]	408 [403-414]	395 [0-2720]	0.26 [0.26 : 0.31]	238 [0-630]	1 [1-1]

Table 5.6 Biomass dynamic model parameter estimates for each Assessment Region under the assumption $B_0 \neq K$.. Five 5 and 95 percentiles are shown in brackets beneath the parameter estimates.

Parameter	Description	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6
r	Intrinsic growth rate (yr^{-1})	0.01 [0-0.65]	0.08 [0-0.2]	2.43 [1.61-3.20]	0.20 [0.12-0.62]	0.17 [0.03-0.61]	0 [0-0]
K	Carrying capacity or virgin biomass (t)	37202 [2930-large]	7119 [164-large]	1700 [1297-2343]	55430 [3906-378232]	22394 [2693-large]	1572 [982-large]
B_1/K	Estimated start year biomass relative to virgin biomass (t)	0.03 [0-0.2]					
B_{t+1}/K	Present biomass + 1 year relative to virgin biomass	0.01 [0-0.12]	1.27 [0.06-53.6]	0.50 [0.40-0.62]	0.034 [0.016-0.832]	0.1 [0.04-0.6]	2.7 [2.21-4.82]
B_{msy}	Biomass at maximum sustainable yield (t)	18601 [1465-large]	3560 [82-large]	850 [648-1172]	Large [1953-large]	11197 [1347-huge]	786 [49-large]
MSY	Maximum sustainable yield (t)	84 [0.18-6196]	142 [0-large]	1033 [955-1149]	2793 [546-9783]	951 [384-1752]	0 [0-0]
$TACC_{msy}$	Total allowable commercial catch of the f_{msy} policy for year present+1 (t)	2 [0-56]	4350 [0-large]	1031 [897-1147]	201 [107-6030]	173 [108-567]	0 [0-0]
$TACC_{0.1}$	Total allowable commercial catch of the $f_{0.1}$ policy for year present+1 (t)	2 [0-51]	316 [0-large]	962 [748-1210]	182 [97-5440]	156 [97-517]	0 [0-05]
RY*	Replacement yield for year present + 1 (t)	4 [0-98]	0 [0-large]	1033 [909-1078]	372 [198-595]	305 [200-437]	0 [0-0]

* The replacement yield (RY) is the catch that leaves the biomass at the start of year t+2 the same as it was at the start of year t+1.

5.2.4 Discussion

5.2.4.1 Size-based model

The dynamic size-based model highlighted the following observations with regard to the input parameters and data:

- Observed sex ratios varied enormously between sites and years.
- Size-frequencies are highly variable spatially and temporally.
- New South Wales estimates of growth describes a population that grows much more slowly than the early 1980 scientific data would suggest. There are several possible reasons for this: (i) growth rates of northern NSW and southern Queensland spanner crabs are significantly different, (ii) the early 1980's size data are not truly indicative of the unexploited size population frequency, and therefore assumptions of equilibrium are invalid, or (iii) gear selectivity for large animals is not unity.

5.2.4.2 Biomass dynamic model

Highly variable success rates for the estimation of biomass and management parameters are achieved between the regions. In many cases, the catch rate of early years of exploitation increased contrary to the assumption of proportionality. This is probably due to spatial expansion of the fishery and increases in skipper experience. Generally the confidence intervals on estimates are very large. In most cases the results are not trustworthy, and a proper assessment using this methodology would require (i) investigations on the effect of catchability and (ii) a longer time series of catch, effort and size-frequency data.

5.3 DEPLETION ESTIMATES OF POPULATION DENSITY AND CATCHABILITY

5.3.1 Introduction

An alternative method of estimating the abundance of a particular stock is to sequentially remove individuals from it and follow the decline in the relative abundance of that stock. If all the individuals are removed, relative abundance (e.g. CPUE) should decline to zero and the initial stock size will have been equal to the total number of individuals removed (assuming no recruitment, mortality, emigration or immigration). Complete removal of all individuals in a stock is rarely (if ever) practicable or desirable in a wild population. However, if the index of relative abundance is directly proportional to stock size then during such a sequential depletion that index will be reduced at exactly the same rate as the population. By extrapolating from that decline it is possible to estimate the number of removals which would have been necessary to drive the index, and hence the population, to zero. The predicted number of removals would then equal the predicted initial stock size. Two models have been proposed to estimate population size through sequential depletion, the 'Leslie estimator' (Leslie & Davis 1939) and the 'DeLury estimator' (DeLury 1947).

Estimates of stock size in particular area can be used to derive estimates of catchability (q) from CPUE data for that area. Those estimates can then be applied to other CPUE data to estimate stock in other areas. However, q may vary over the temporal or spatial ranges from which CPUE data are collected. To assess the magnitude of this variability, we intended to derive estimates of q for each sex separately, at several times throughout the year and at different locations.

There are three assumptions implicit in using depletion estimators of q and stock size. These are:-

1. all individuals within a stock are equally susceptible to capture,
2. q does not vary over time the stock is depleted,
3. stock size is not affected by other factors (recruitment, mortality, immigration & emigration) over the time that the stock is depleted.

In reality, those assumptions cannot be met in wild populations. However, if the depletion is conducted over a relatively short time period then variations in catchability and changes in population size due to recruitment, mortality, immigration and emigration are likely to be minimal. If individuals do not vary in their susceptibility to capture, then once q has been estimated it can be applied to relative abundance data to estimate absolute stock sizes. In the case of the Leslie estimator, this relative abundance index can be measured independently of the process used to deplete the stock (Hilborn & Walters 1990), in which case q could be used to calibrate CPUE.

Estimates of q can also be derived from commercial catch data if instances of localised or general depletion can be isolated. As the spanner crab fishery operates through the serial depletion of small patches (see Section 5.1.1.4, above) it may be possible to derive estimates of q through analysis of the commercial CPUE data set. If it is possible to accurately standardise commercial CPUE data and to derive catchability coefficients for each sex at a wide variety of times, then it would be possible to estimate stock size using commercial fishing data.

5.3.2 Methods

Four depletion experiments were conducted to estimate the abundance of spanner crabs, and hence to derive estimates of their catchability (q), using

$$q = CPUE_0/N_0 \qquad \text{(Equation 36)}$$

Where $CPUE_0$ = the initial (pre-depletion) Catch Per Unit Effort from an area (in crabs/net lift), and N_0 = the initial (pre-depletion) number of crabs in the area.

The aim was to use the estimates of q to calculate absolute stock size from commercial CPUE data. These experiments were conducted in an area of the spanner crab grounds known as the 'Dog's Leg', north of Moreton Island (Table 5.7).

In addition to the four depletion experiments, the Leslie estimator was also applied to an instance of commercial depletion which was able to be isolated from C-Fish logbook records. The Leslie estimator is more robust and more widely applicable than the DeLury estimator (Hilborn & Walters 1990). It was not possible to derive further estimates of q from that database as C-Fish logbooks only record catch and effort data within grids measuring 900 nm^2 or sub-grids measuring 36 nm^2. Variation in catch rates over very small distances (B. Garner, personal communication) suggests that spanner crab patches are on very much smaller scales than either of those areas.

Table 5.7 Site details for depletion experiments conducted in the Dog's Leg area, north of Moreton Island in 1996 and 1997.

Expt. no.	Start Date	North-West corner Latitude	Longitude	Area (ha.)	Depths (m)	Duration (days)	Fishing intensity (dillies/day)	(dillies/ha)	Crabs returned
1	24.8.'96	26°56.50' S	153°24.38' E	9	29 – 34	4	225	25	Yes
2	2.9.'96	26°53.56' S	153°28.56' E	16	62 – 65	5	100	6.25	No
3	2.9.'96	26°54.20' S	153°26.50' E	16	51 – 53	5	100	6.25	No
4	21.4.'97	26°54.13' S	153°26.94' E	9	51 – 53	5	225	25	No

5.3.2.1 Experiment 1

The location of the experimental area was accurately determined with differential GPS to record the position of its north-west corner. Three ropes, each 300m long with fifteen dillies attached at 20 m intervals, were used to sample spanner crabs from this experimental area. Each dilly measured 1.0m x 1.0m, and was fitted with 25mm three ply mesh. Starting at the north west corner of the experimental area, the first rope containing fifteen dillies was laid along the sea floor in an easterly direction. The second and third ropes were laid out parallel to the first and at 100 m intervals to the south. Each rope was left on the sea floor for approximately 45 minutes before being retrieved, cleared of crabs and re-set 20 m to the south of its original position. This process was repeated five times (= five rounds), so that 225 dillies had been laid on a square grid (fifteen lines of fifteen dillies) at 20 m intervals. In this manner, an even fishing effort was applied to the whole 300 x 300m (9 hectare) area.

Upon retrieval, the number of spanner crabs on each dilly was recorded before they were carefully disentangled from the mesh. The sex of each crab was recorded and it was measured and individually numbered using a 'Markal – B' paintstick. Crabs were marked to enable a parallel density estimation using a Petersen mark-recapture model. At the end of each day, all

of these marked crabs were taken to the centre of the experimental area and released on the sea floor using a specially constructed release box. In this manner, we avoided the loss of crabs from the experimental area through predation or current drift.

Sampling was repeated each day until there was a marked decline in catch rates. Eight days following completion of this depletion experiment, the experimental area was resampled to collect marked crabs for population estimation using a Peterson mark-recapture model.

5.3.2.2 Experiments 2 & 3

Experiments 2 & 3 were conducted over the same time period as each other. Following the extremely rapid decline in catches in Experiment 1 (see Results), the experimental procedure was modified somewhat for Experiments 2 & 3. To reduce the rate of catch decline, dillies were spaced more widely (40m intervals) over a larger area (400 x 400m, = 16 hectares). As no marked crabs were recaptured during Experiment 1 (see Results), crabs were not marked and returned to the experimental area in Experiments 2 & 3. At the end of each day, all crabs caught were taken to a site remote from either experimental area and released on the sea floor using the release box.

5.3.2.3 Experiment 4

Experiment 4 was conducted to determine whether the rapid decline in catches in Experiment 1 was due to the high fishing intensity or to the fact that marked crabs were returned to the experimental area. The conduct of this experiment was the same as that of Experiment 1, except that captured crabs were removed from the experimental area, as in Experiments 2 & 3.

5.3.2.4 Commercial Depletion

For management purposes, the Queensland spanner crab fishery is sub-divided into two areas (Managed Areas A and B) with different regulations and controls. On 4 October 1996, Managed Area A was closed to spanner crabbing while Managed Area B remained open until 20 November 1996. This resulted in a large number of vessels moving from Area A to Area B for that period.

Over the course of the 47 days, fishing effort gradually became more concentrated on a single small area where high catch rates were being obtained. This area measured less than 0.2 km^2 on the northern slope of an east-west oriented submarine valley at 23°15'S, 151°39'E, just off North-West Reef. On any one day, up to 15 spanner crabbing vessels fished this tiny patch, resulting in a mean reported fishing effort of 1,307 dillies per day on 37 fishing days over the 47 day period.

This patch was isolated from other known patches of spanner crabs, and was the only patch of spanner crabs known to be fished in Grid T29 (23° to 23°30'S, by 151°30 to 151°45'E) during those 47 days. To determine whether this concentrated effort resulted in depletion of this particular patch of spanner crabs, commercial CPUE data from the C-Fish database were plotted against total catch for Grid T29 over the period 4 October to 20 November 1996. Stock size prior to 4 October and catchability (q) of spanner crabs at that site and time were estimated using the Leslie estimator. Fishing mortality was estimated by multiplying the estimated q by total reported effort over that period.

5.3.3 Results

5.3.3.1 Experiments 1 – 4

Of the four depletion experiments, only Experiment 1 showed a decline in catch rates over time (Figure 5.26). Regression analysis showed that there was a significant decline in CPUE in Experiment 1 from 0.92 to 0.08 crabs/net lift as cumulative catch increased ($F = 30.54$, $P = 0.03$). There was no significant change in CPUE over time in Experiment 2 ($F = 0.30$, $P = 0.62$). In Experiments 3 and 4, CPUE actually appeared to increase over the course of the experiments, although those apparent increases were not statistically significant at $P < 0.05$ ($F = 7.36$, $P = 0.07$ and $F = 9.84$, $P = 0.052$, respectively).

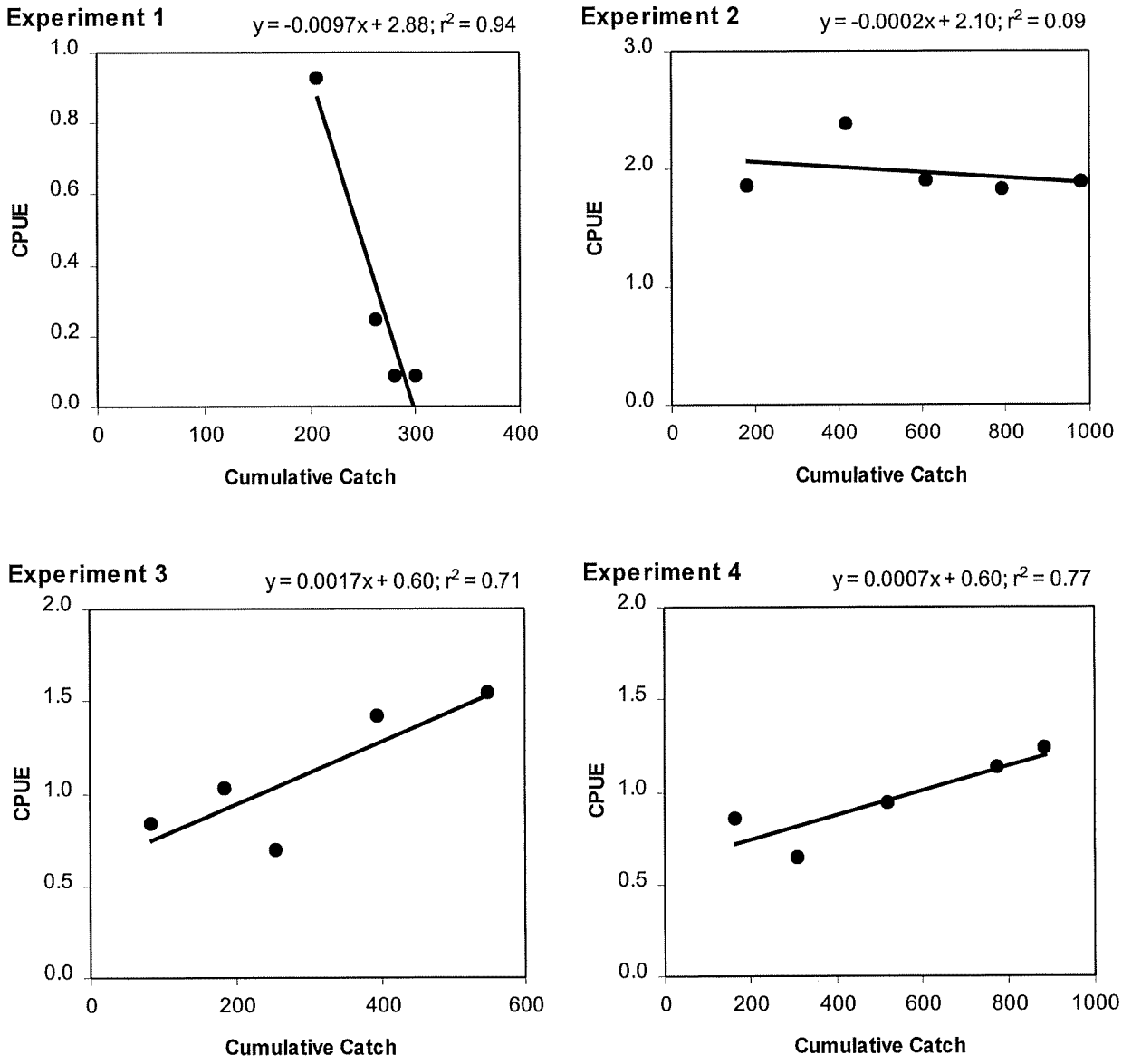

Figure 5.26 Results of four depletion experiments carried out at different sites north of Moreton Is between 24/8/96 and 21/4/97.

The two methods employed in Experiment 1 (Leslie depletion & Peterson mark-recapture) produced vastly different estimates of the population density in the experimental area. From the apparent depletion effect in Experiment 1 initial population size (N_o) in the nine hectare

experimental area was estimated to be 298 crabs (= 33 crabs.ha^{-1}), assuming constant catchability and no migration into or out of the experimental area. Catchability (q) was estimated to be 3.09 x 10^{-3} and fishing mortality (F) was estimated at 8.70. None of the 301 marked crabs released during Experiment 1 were recaptured during the four days of that experiment. Of 131 spanner crabs collected from the experimental area eight days after termination of the depletion experiment, three had been marked during the experiment. The estimated population of the experimental area from this mark/recapture study was 13,144 crabs (= 1,460 crabs.ha^{-1}), assuming no migration, no mortality or recruitment and no effect of previous capture on crab behaviour. The 95% confidence limits for this estimate were 4,893 and 49,071 crabs (544 – 5,452 crabs.ha^{-1}), with the large range being due to the low numbers involved.

5.3.3.2 Commercial Depletion

In 37 fishing days between 5 October and 20 November 1996, commercial fishermen recorded a total catch of 37.07 tonnes of legal sized spanner crabs from Area T29. Over that period there was a significant decline in CPUE from 1.36 to 0.46 kg/net lift (F = 27.02, P < 0.00001) (Figure 5.27). The estimated initial stock size (legal sized crabs only) in the area fished was 55.56 tonnes, with catchability (q) being estimated at 2.49 x 10^{-5} and fishing mortality (F) over the 47 days being 1.20.

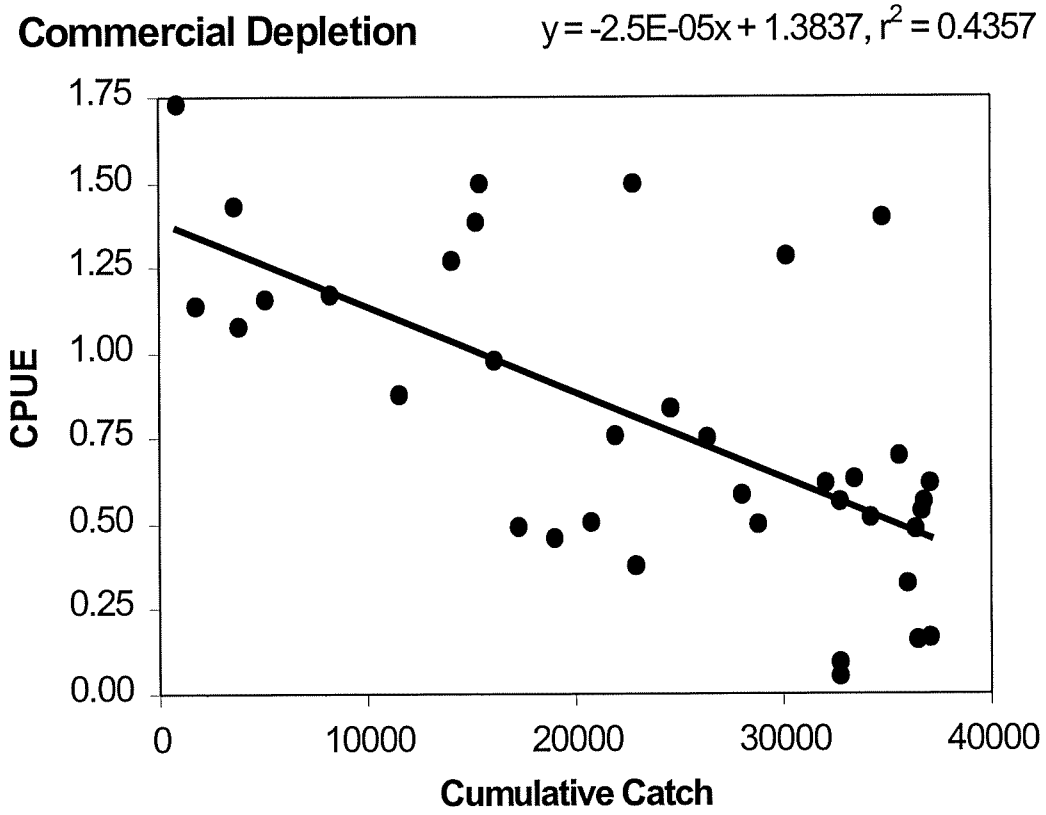

Figure 5.27 Results of commercial depletion of a large patch of spanner crabs near North-West Reef in October/November 1996.

5.3.4 Discussion

The large discrepancy between the estimates of population size using the Leslie depletion and the Peterson mark-recapture methods in Experiment 1 indicates that one or both of those estimates is incorrect. This error is almost certainly due to violations of the assumptions implicit in the methods.

Depletion estimators assume that all individuals within a stock are equally susceptible to capture, that q does not vary over time the stock is depleted and that stock size is not affected by other factors (recruitment, mortality, immigration & emigration) over that period. Although those assumptions cannot be met in wild populations, the short duration of Experiment 1 suggests that changes in population size due to recruitment, mortality, immigration and emigration were likely to be minimal. However, there may have been variation in individual susceptibility to capture, and q may have changed during the course of the experiment. In Section 5.1.2 we saw that the CPUE of spanner crabs varied considerably over an annual cycle (Figure 5.11). As the spanner crab appears to be a relatively slow-growing, long-lived species (see Section 7.1.4, below), such seasonal variation in CPUE exceeds that which could occur through recruitment and/or mortality. Thus, the annual variation in CPUE must be due either to changes in availability (perhaps through migration) or to changes in q. Skinner & Hill (1987) have previously demonstrated that there were seasonal changes in spanner crab q due to changes in feeding behaviour associated with reproductive cycles.

The feeding behaviour of a crab is also affected by temperature and light, as well as the crab's sexual development and moult condition (Skinner & Hill, 1987; Krouse, 1989; Hill & Wassenberg, in ms.). Thus, the q of crabs caught as a result of their behavioural response to a baited trap may be highly variable. In particular, the q of spanner crabs will depend upon the behavioural responses of individual crabs to the bait. The fact that no marked crabs were recaptured during Experiment 1 suggests that their behaviour was affected for at least several days following capture and release. At least some of those crabs were still present in the experimental area following the experiment, as they were caught there several days later.

The fact that unmarked spanner crabs were present in the experimental area a few days after its apparent depletion suggests either that they had recently moved into the area or that they were present in the area but were not susceptible to capture during the experiment. Either of these explanations is possible, and both violate the assumptions of depletion estimators and Peterson mark-recapture methods. Both of these methods assume that all individuals are equally susceptible to capture, and that no immigration occurs either during the experiment (Leslie depletion) or between marking and recapture (Peterson method). We considered the possibility of preventing movement of crabs into and out of the experimental area by erecting some kind of physical barrier (e.g. a low mesh-net) around the area. However the logistical problems associated with such an operation seemed almost insurmountable. The study areas were quite large (9-16 ha) and deep (29-65 m) and were situated in open shelf waters, making the erection of any effective barrier prohibitively expensive. Moreover the area is regularly traversed by ships, fished by bottom-trawlers, and subject to periodic violent movement of bottom water as a result of heavy seas.

One possible reason why some crabs present in the experimental area may not have been susceptible to capture is that their behaviour may have been influenced by the experiment. This may have occurred as a result of crabs being disturbed by the sampling activity, or by the presence of other crabs which had been caught and returned. Thus, Experiment 1 was repeated without caught crabs being returned to the experimental area (Experiment 4). The aim of that experiment was to indicate whether the decline in catches was due to a depletion effect or whether it was due to captured crabs being returned to the experimental area. The fact that there was no similar depletion in Experiment 4 suggests that returning crabs to the experimental area somehow influenced the behaviour of other crabs in the area. This may have occurred through the action of some stress pheremone which was released by spanner

crabs which had been caught and returned[1]. The high q observed in Experiment 1 was almost certainly an artefact of declining susceptibility and was not due to any depletion. Thus, the estimates of initial population size (N_o), catchability (q) and fishing mortality (F) from Experiment 1 are inaccurate and unreliable.

It is however quite possible that the assumptions implicit in the Peterson mark-recapture estimate were not violated. Although the behaviour of caught and released crabs was affected for at least four days following release, some post-release crabs were caught eight days after the experiment was completed. This suggests that their behaviour had returned to normal. Although we can't be certain that no migration or mortality occurred during that period, the estimated density of 1,460 crabs.ha^{-1} (95% c.l. = 544 to 5,452 crabs.ha^{-1}), or one crab per seven square metres, is our best estimate of spanner crab density to date. This estimate should not be extrapolated to other areas as the experimental area cannot be regarded as being representative of other areas and times.

Comparison between the Peterson mark-recapture estimate of population size in Experiment 1 and the Leslie depletion estimate of population size during the commercial depletion is not possible as the exact area of fishing operations during the commercial depletion cannot be accurately determined. However, assuming the samples collected from the commercial depletion site on 30 November 1997 to be representative of the pre-depletion population, the estimated stock of 55.56 tonnes of legal sized crabs would have weighed an average of 689.44 grams each. This gives a population estimate of 80,587 legal sized spanner crabs in the area. Again assuming the 30 November 1997 samples to be representative, 10.1% of the crabs in the area were of sub-legal size, giving a total population estimate of 89,623 spanner crabs in the area, of which about 53,769 were removed during the depletion. The estimated fishing mortality (F) during this experiment is probably an underestimate of the true F as an unknown number of discarded crabs would have also died (see Section 8.1 below).

The fact that there was no depletion effect observed in Experiments 2, 3 & 4 indicates either that q was very low, that it decreased during the course of each experiment or that immigration occurred during each experiment. In fact all three of those potential factors could have occurred. Hill & Wassenberg (in ms.) found that only 7% of spanner crabs that crossed a baited tangle net were retained by it upon retrieval. Such low gear retention would lead to a low q even if all available crabs were attracted to the bait. The commercial depletion also demonstrated that the q of spanner crabs was very low at that place and time. In the light of +such low q, it would require a very large fishing effort for any experimental sampling to achieve a depletion effect.

CPUE in Experiments 3 & 4 appeared to show an increase with cumulative catch. Although this apparent increase was not statistically significant at $P < 0.05$, such an increase could only occur if q declined during the course of the experiment or if immigration occurred. Thus, either the assumption of a consistent q or that of no immigration was violated, and possibly both were.

One likely cause of spanner crabs immigrating into an experimental area is that they are attracted there by the scent of the bait. Just as spanner crabs are attracted to baited dillies from within an experimental area, they will also be attracted to them from outside that area. Spanner crabs may detect a bait from outside an experimental area and move into (or towards) that area without being caught. This attraction may occur over several days or even weeks and lead to a continual immigration of spanner crabs from downcurrent of the experimental area. Such immigration would render a depletion experiment useless in terms of estimating stock size or q.

[1] In order to conduct a valid test for this possibility a number of replicate experiments would be needed, as well as further investigation into the effects of potential pheremones on spanner crabs. Such an investigation was considered to be beyond the scope of applied fisheries research.

In the absence of any reliable experimental depletion, the catchability estimated from the commercial depletion is the best estimate of q available at this stage. However, the reliability of that estimate is questionable given the unreliability of commercial catch and effort data (see Section 5.1.1.4 above). As the q of spanner crabs is apparently quite low and highly variable, and as immigration into experimental areas may alter stock size over time, it is unlikely that spanner crab q, F and stock size can be measured through experimental depletion. Depletion experiments using commercial fishing gear are not applicable to spanner crabs, and alternative methods are needed to estimate the stock size of this species.

5.4 SURVEY OF POTENTIAL NEW FISHING GROUNDS

5.4.1 Introduction

The northward expansion of the spanner crab fishery in the early 1990s contributed to speculation by some participants in the fishery that further commercially viable fishing grounds may be found north of the currently fished area. If this were true, then the threat to the sustainability of the fishery due to the explosion of effort between 1990 and 1994 may have been less immediate. This speculation was used by an element of the commercial fishery to argue for an increase in the TACC when output controls were first introduced.

Some support for this speculation was provided by the C-Fish database, which contained a number of records indicating that good catches of spanner crabs had been reported from several locations between Townsville and the Swain Reefs. The apparent fishing effort in these areas was small, but the reported catch rates were sufficient to signify the existence of potentially fishable stocks.

This speculation led Brown (1994) to conduct an extensive survey for spanner crabs north of the current fishery, between Cape Manifold (22°40'S) and Mackay (21° 00'S), between the mainland and the inner (western) edge of the Great Barrier Reef. No spanner crabs were caught, despite the setting of about 500 dillies at 27 sites spanning depths from 10 to 90 metres. Brown concluded that spanner crabs were either absent from the main lagoon area, or present in such low numbers as to preclude the establishment of commercial fishing operations, possibly because of inappropriate bottom sediments.

Despite the results of Brown's (1994) survey, several crab fishers continued to speculate that substantial populations of spanner crabs could be found in particular northern locations not specifically investigated during the survey. Investigation of the source of C-Fish records from north of the current fishery indicated that the locality data were probably incorrect, and that the catches had actually been taken within the main fishing grounds. Nevertheless, there have been reliable anecdotal reports of spanner crab catches from among the Swain Reefs. In addition, two spanner crabs were reported to have been taken by trawl gear in the vicinity of Percy Island (J. Evans, personal communication), and a number of fishermen strongly supported the need for further surveys to be conducted in the vicinity of the Duke & Percy Islands and the Swain Reefs. Those two areas were therefore surveyed as part of the current research.

The Duke & Percy Islands and the Swain Reefs are each approximately 160 km from the nearest presently exploited grounds. If spanner crabs do exist in those areas, they may belong to separate breeding stocks. Thus, in the event that any spanner crabs were located, samples would be collected for genetic analysis, morphometric analysis and measurement of gonosomatic indices for comparison with crabs from known grounds. Sex ratio, length frequency and CPUE data would also enable comparison of abundance and population structure with stocks from known grounds.

5.4.2 Methods

5.4.2.1 Duke & Percy Islands

This survey investigated claims made by Mr John Evans that a commercially viable population of spanner crabs existed in the vicinity of the Duke and Percy Island groups. Although Brown's (1994) survey found no spanner crabs in that area, many crabbers were critical of his

methodology. To avoid similar criticism, one of their number (Mr John Evans) was contracted to direct scientists to suitable crabbing areas. Mr Evans was an experienced spanner crabber keen to promote fisheries and other development in the vicinity of the Duke and Percy Islands.

Field sampling for this survey was conducted between 11 and 15 November 1996. As the primary aim was to determine whether or not spanner crabs were found in the area, sites were selected so as to provide the highest probability of catching crabs. The first day's sampling was conducted in the vicinity of the sites where the two spanner crabs had been found tangled in trawl gear in 1994 (one crab each at 21°34'S, 150°08'E and 21°30'S, 150°26'E). On subsequent days, sample sites were selected by Mr Evans on the basis of a number of factors such as depth, bottom slope, appearance on the echo sounder, proximity to chart contour lines and indications of bottom type provided on charts.

At most sites, either three lines of 10 tangle nets or two lines of 15 or 16 tangle nets were set for between 40 and 55 minutes. Each net was baited with Australian pilchards, *Sardinops neopilchardus*, which were held in a solid PVC tube attached to the middle of the net. A benthic grab was used to collect sediment samples at all sites. Sampling for spanner crabs was not conducted at several of the sites selected because benthic grab samples indicated that the substratum type was unsuitable for spanner crabs (either dense muddy clay, coral rubble or rock). A Stowaway Tidbit™ waterproof temperature logger was attached to one of the tangle nets at each station to provide data on bottom water temperature. Following the survey, spanner crabs were collected from known crabbing grounds to provide samples for genetic analysis and female gonosomatic index determination (Sites 20 & 21, see Results).

5.4.2.2 Swain Reefs

For this survey we contracted a commercial spanner crab vessel (*MV Crossbow*) and a skipper with substantial experience in the spanner crab fishery and in fishing and navigating around the Swain Reefs (Mr G Rohl). This survey also used commercial fishing gear operated by Mr Rohl and his crew.

Field sampling was conducted on two separate three-day voyages (12-14 June and 27-29 June 1998). Sample sites were selected so as to provide the highest probability of catching crabs, based on factors such as depth, bottom slope, appearance on the echo sounder, proximity to reefs and indications of bottom type from grab samples. Three lines of 10 tangle nets were set at each of 27 sampling sites (Figure 5.28) for between 45 and 90 minutes (mean = 60 mins). This included an extra round of three lines of 10 tangle nets at one station (Sites 19 & 20) where spanner crabs were found. Each net was baited with Australian pilchards, *Sardinops neopilchardus*, which were held in a plastic mesh bag attached to the middle of the net. All crabs caught were measured (RCL; mm) and sexed. Samples for genetic analysis were collected as follows: the terminal segment (dactylus) of one leg was removed carefully with alcohol-washed scissors, the integument cut and the tissue placed in a small labeled vial containing a 20% solution of dimethyl sulfoxide (DMSO). These did not require refrigeration or freezing. During the first three-day voyage bottom water temperatures were measured as described above.

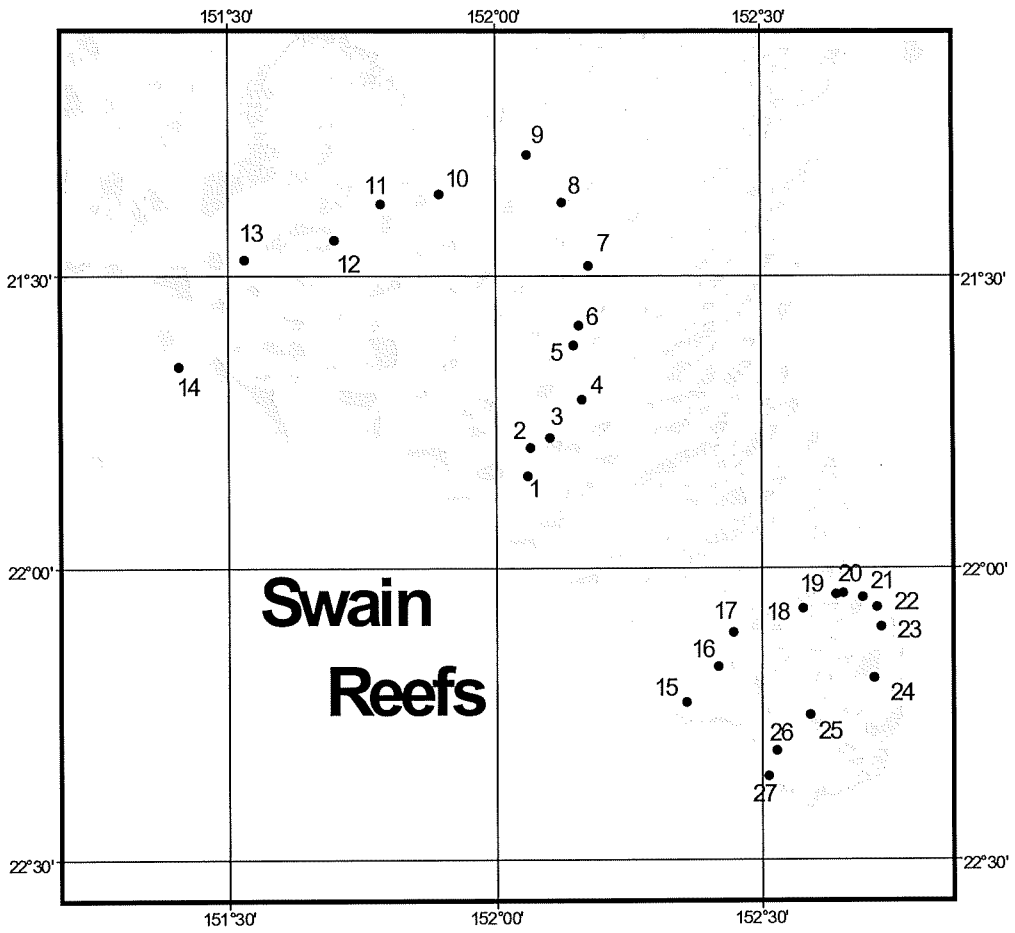

Figure 5.28 Chart of the Swain Reefs, showing sites sampled during the spanner crab survey in June 1998.

5.4.3 Results

5.4.3.1 Duke & Percy Islands

No spanner crabs were collected during the survey of the area around the Duke and Percy Islands (Table 5.8). Grab samples revealed the bottom sediments in the area to be coral rubble or thick clay-mud. Similarly, no spanner crabs were collected between the Duke and Percy Island area and 23° S. Following the survey, a total of 141 spanner crabs were collected in 50 net lifts from a known fishing ground at 23°00'S, 151°15'E ('Barren Patch') and were retained for genetic analysis.

5.4.3.2 Swain Reefs

A total of 21 spanner crabs was collected from 770 net lifts on both cruises (Table 5.9). Only one crab was caught in the central Swains (Site 8) from a total of 420 net lifts, a CPUE of 0.002 crabs/net lift. The southern part of the group yielded a total catch of 20 crabs, all except one of those coming from 2 adjacent sites (19 and 20) in 55 and 48 m depth respectively (Table 5.9). This catch was the result of 350 net lifts, giving a CPUE for the area of about 0.05 crabs per net lift.

Table 5.9 Details of sites sampled in the Swain Reefs area, and the numbers of spanner crabs caught at each. Three strings of 10 nets were generally set at each site.

Site	Date	TimeSet	TimeLift	Depth (m)	Latitude	Longitude	Catch (no.)
1	12-06-98	07:59	08:45	58.0	21°50.49'	152°03.77'	0
2	12-06-98	09:19	10:30	58.7	21°47.69'	152°04.07'	0
3	12-06-98	11:09	12:30	51.7	21°46.62'	152°06.35'	0
4	12-06-98	13:14	14:19	55.3	21°42.65'	152°09.94'	0
5	12-06-98	15:11	15:56	29.3	21°37.15'	152°08.97'	0
6	12-06-98	16:28	16:54	60.3	21°35.03'	152°09.54'	0
7	13-06-98	06:58	08:10	60.0	21°28.97'	152°10.69'	0
8	13-06-98	08:54	09:50	52.3	21°22.37'	152°07.74'	1
9	13-06-98	10:39	11:38	57.7	21°17.29'	152°03.80'	0
10	13-06-98	12:34	13:31	42.0	21°21.45'	151°53.83'	0
11	13-06-98	14:18	15:15	61.0	21°22.48'	151°47.20'	0
12	13-06-98	16:03	16:46	61.0	21°26.29'	151°41.99'	0
13	14-06-98	07:14	08:40	54.7	21°28.26'	151°31.96'	0
14	14-06-98	09:45	10:30	71.3	21°39.34'	151°24.62'	0
15	27-06-98	12:31	13:40	67.0	22°13.92'	152°21.72'	0
16	27-06-98	14:23	15:20	62.7	22°10.29'	152°25.35'	0
17	27-06-98	15:56	16:32	64.0	22°06.66'	152°27.09'	0
18	28-06-98	07:14	08:36	58.3	22°04.21'	152°34.94'	0
19	28-06-98	09:13	10:17	54.7	22°02.75'	152°38.46'	4
20	28-06-98	10:54	11:55	48.3	22°02.61'	152°39.28'	15
21	28-06-98	12:29	14:03	55.0	22°03.15'	152°41.46'	0
22	28-06-98	14:37	15:54	56.7	22°04.07'	152°43.14'	0
23	28-06-98	16:15	16:55	53.0	22°06.18'	152°43.53'	0
24	29-06-98	06:58	08:14	47.7	22°11.32'	152°42.83'	0
25	29-06-98	09:04	10:11	44.0	22°15.21'	152°35.69'	1
26	29-06-98	10:50	11:45	58.0	22°18.81'	152°31.93'	0
27	29-06-98	12:25	13:31	89.0	22°21.46'	152°30.99'	0

The sample of crabs caught in the Swains survey was very small (n = 21) with a sex ratio of approximately 1:1 (10 males and 11 females). All except one of the male crabs were above the minimum legal size (Figure 5.29), as were about two-thirds of the females. Male crabs ranged in length from 94 to 137 mm RCL, and females from 96 to 120 mm (Figure 5.29). None of the females was ovigerous.

5.4.4 Discussion

The two exploratory operations carried out during the course of this project support the results of Brown's (1994) survey of the greater lagoon area between Cape Manifold and Mackay. Evidence strongly indicates that by far the greatest proportion of the East Coast spanner crab stock is concentrated south of 23° S. While some good catch rates have been reported from north of this latitude in Managed Area B, the total commercial fishing effort outside Managed Area A appears to have been focussed on a relatively few small productive areas close to the border between the two Managed Areas.

There is a strong suspicion that some of the catch reported from Area B might actually have been taken in Area A, but incorrectly reported, possibly because of the exclusion of the former

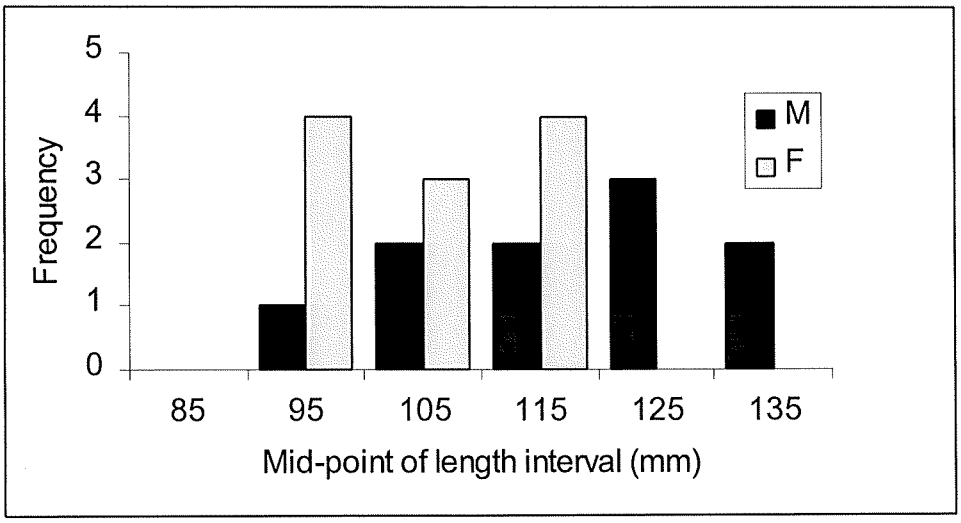

Figure 5.29 Size-frequency of all spanner crabs caught in the Swain Reefs survey (12-29 June 1998).

from the TACC provisions. This management strategy, which includes a more generous daily catch limit in Area B than Area A, was developed partly to encourage the fleet to explore promising new areas. In 1996 some 15 commercial vessels spent around a month of exploratory fishing north of 30° S but failed to locate any viable quantities of crabs. However little exploration appears to have taken place further afield; if it has, it has been very low-key, and without any attempt to report or publicise the results. Personal contact with the fishers concerned revealed that most of the catch reported from distant locations appears to have been the result of erroneous location reporting.

No crabs were captured in what some commercial crabbers considered may have been suitable grounds around the Duke and Percy Islands. This area is subject to large tidal amplitude and strong tidal currents. Brown (1994) had established that the bottom sediments in surrounding areas (i.e. the lagoon between the mainland and the inner edge of the Great Barrier Reef) are high in fine silts and muds, and apparently unsuitable for sustaining populations of spanner crabs. Grab samples from the present study confirmed bottom sediments in the vicinity of the Duke and Percy Islands to be composed of mud or coral rubble. It may be that the absence of spawning stock in the broader area surrounding these rocky mainland islands inhibits successful recruitment. If a colony of crabs managed to become established in the vicinity of the islands by chance, the strong tidal and current flows probably preclude self-maintenance of the population, as it is highly unlikely that the larvae would remain in the area for the several weeks prior to settlement.

Spanner crabs are rarely caught in trawl gear, because of their burying behaviour. Therefore the reported trawl catch of merely two individual animals near the Percy Islands in 1994 suggested that a local population of spanner crabs *may* exist. However it is possible that the crabs had actually been caught elsewhere, as the person reporting the catch was unsure as to how long they had been in the net.

Brown's (1994) survey was criticised by some commercial fishers who believed that a different result would have would have occurred had an experienced crab fisher directed the operation. We are able to counter this argument with respect to the two surveys undertaken during the present Project, as both included experienced commercial spanner crab fishers in the team. Moreover, these fishers were specifically invited to nominate areas and sites to investigate, on the basis of their skill and experience in the industry.

In the second survey (of the Swains Reefs), we found some evidence of a spanner crab population. However only two sites near the eastern edge of the reef group yielded more than a single crab. The size structure of this sample suggested that the population is well-stablished, although the low number of small crabs (below minimum legal size) could be interpreted as indicating that recruitment might be quite variable from year to year. Commercial crabbers who fish the northernmost part of the main fishing grounds do so mainly between October and December, as they consider that the crabs are not sufficiently abundant at other times. If this is the result of seasonally reduced availability or catchability, and assuming a similar situation applies further east in the Swains, it is possible that our survey seriously underestimated the abundance of crabs in that area. Our work was carried out in winter rather than spring-summer to minimise the risk of encountering cyclonic weather.

The length-frequency distribution of spanner crabs from the Swain Reefs was similar to that from the two most northerly fished sites within Managed Area A: North-West Reef Patch (23° 15' S, 151° 31' E) and Barren Patch (23° S, 151° 15' E). Ninety-six percent of the males and 67% of the females caught at these two sites were above the minimum legal size, as were 90% of the males and 64% of the females caught in the Swain Reefs.

The results of the present surveys, along with previous work north of the present fishing grounds (Brown 1994), indicate that there is unlikely to be any major unexploited spanner crab resource in Queensland waters. The lack of consistent (even small) catches signifies that even in the Swains Reefs the population is likely to be small and probably very patchy. It is unlikely therefore to be a significant contributor of recruits to the main fishing grounds. The remoteness of the area and the lack of any positive indication of an abundant resource will not be attractive to the commercial fishery.

5.5 STOCK STRUCTURE

5.5.1 Introduction

This part of the study was aimed at testing for the presence of genetic subdivision within the commercial Australian spanner crab population to assist with sustainable management of the resource. Previous work by Worland (1990) using gel electrophoresis had indicated some stock structure in the area between northern NSW and Bundaberg, but the results were inconclusive. There was some concern on the part of commercial fishers that spanner crab populations north and south of Fraser Island may constitute different spawning stocks, in which case the application of a single TACC across the entire fishery may not be appropriate.

5.5.2 Methods

Crabs were sampled from six sites off the southeastern Queensland coast (A-F and H, Table 5.10) from the Swains Reef in the north to the Gold Coast in the south. Samples consisted of leg muscle tissue preserved at room temperature in 70% ethanol or dimethyl sulphoxide (DMSO) solution. Crabs were also obtained from Hawaii and the Seychelles Is. In response to preliminary genetic results on spanner crabs, and to test specific hypotheses, secondary samples were taken from sites A and B (Table 5.10). Secondary samples consisted of material from each crab for three different types of analyses; leg muscle for DNA extraction, hepatopancreas tissue for allozyme determination and whole body for morphometric analyses. It is planned to take additional secondary samples from other sites, especially A, C, D and E.

Table 5.10 Collection sites and sample size (N, primary 1^O and secondary 2^O collections) for spanner crabs to 23rd September 1998

Site	Name	N1°	N2°	Coordinates
A	Dog's Leg; north of Moreton Is	30	34	26° 55.2'S, 153° 26.4'E
B	Gold Coast	30	104	27° 58'S, 153° 33'E
C	North Hervey Bay	30	39	24° 38'S, 153° 01.2'E
D	Off Fraser Island	30		25° 20'S, 153° 15'E (approx.)
E	Off Barren Is (near Yeppoon)	30		22° 59.9'S, 151° 15.6'E
F	Swain Reefs	21		22° 02.61'S, 152° 39.28'E
H	Necker Reef (Hawaii)	13		23° 20.270'N, 164° 15.776'W
H	Maro Reef (Hawaii)	37		25° 17'N, 170° 38'W
S	Seychelles Is	48		5° 12.0'S; 56° 50.6'E

We extracted total DNA from specimens using proteinase K and an ion exchange resin (Chelex). Using the polymerase chain reaction and total DNA as a template, we amplified a region of the cytochrome oxidase I (COI) gene from the mtDNA. A Perkin Elmer Cetus thermal cycler was used with the following cycle profiles; 1 cycle of 4 m at 95 C, 45 s at 60 C and 2 m at 72 C followed by 35 cycles of 30 s at 95 C, 1 m at 40 C and 2 m at 72 C. Each reaction was performed in sterile 200 microlitre tubes in 48 microlitres of reaction mix containing 20 mM Tris pH 8.8, 10 mM KCL, 10mM $(NH_4)2SO_4$, 2 mM $MgSO_4$, 0.1% triton-X, 0.75 mM dNTPs, 1.5 mM $MgCL_2$, 0.5 mM of each primer, 0.2 units of Taq DNA polymerase (Promega) plus 2 microlitres of diluted template DNA.

A pair of primers was used to generate double-stranded DNA:
L-CO1490 5' GGTCAACAAATCATAAAGATATTG 3'; and

H-CO2198 5' TAAACTTCAGGGTGACCAAAAAATCA 3' (COI, Folmer *et al.* 1994). The same primers were used for sequencing. Sequences were obtained using an ABI automated sequencer using the chain termination method with dye terminators.

The sequences from all taxa and from each gene were aligned and checked using Sequencher v1.0. We used PAUP Star (4.0d64) to estimate phylogeny using the neighbour-joining (NJ) algorithm from total character differences. Nucleotide sequence distance between pairs of crabs was calculated using Kimura's 2-parameter method in PAUP Star.

5.5.3 Results and Discussion

The genetic analysis of spanner crab populations could not be completed within the time-frame of the FRDC project. However, analyses are continuing on an informal basis in an attempt to satisfy the stated aims. To date only a subset of crabs, from primary and secondary collections, have been sequenced (site A; 6 crabs; B, 28; C, 4; D, 6; E, 3; F, 4 and H, 7). Sequence polymorphism across 441 base pairs of the COI region was high; 42 variable positions were found. All but one of the 58 taxa had unique sequences. Details of the full 621 COI base-pair sequences and the associated polymorphic sequences are presented in Appendix 4.

Nucleotide sequence differences showed that three crabs (B109, B5 and C11) were about 2-3% divergent from the remainder. Crab B4 was about 1% divergent from the remainder. These four crabs form a well-supported monophyletic clade (Figure 5.30), which is supported by bootstrap values of 86% and above. Amongst the remaining 54 crabs there was no obvious phylogenetic pattern.

There are several possible interpretations of the presence a distinct genetic clade within the spanner crab population. In a few species mitochondrial genes have not been reliable indicators of genetic similarity. For example, Natalie Baker (Ph.D. student, QUT) suspects that this has occurred with the COI gene in the freshwater crayfish (redclaw) that she is studying. There is at least one similar report from a crab (*Mennippe* spp.). The existence of two clades of spanner crabs could be due to this phenomenon. To explore this possibility, sequence will be obtained from crabs that are representative of both the monophyletic clade and the remainder using the 16S gene, which is 90 degrees (4kb) away from the COI gene in the circular mitochondrial genome of crustaceans.

Assuming the clade is confirmed as a distinct entity by ongoing work, its presence on the east coast of Australia could be explained by immigration from a geographically remote population. Evolution (mutation and drift) in geographic isolation often results in genetically distinct populations. This hypothesis is being tested by analysis of material from overseas. None of the seven samples from Hawaii were distinct from southeastern Queensland crabs. Crab samples have been obtained quite recently from the Seychelles Is, but have not been analysed to date. Alternatively, the spanner crab population may be a mixture of two subspecies. Worland (1990) reported a "Wahlund effect" or lack of heterozygotes amongst polymorphic allozyme loci from spanner crabs, that may indicate sympatry and reproductive isolation. The divergent clade could also be a consequence of the maternal mode of inheritance of the genetic marker used (mitochondrial DNA) and the large, ancient nature of the spanner crab population.

To test these hypotheses, we hope in the near future to identify further members of each clade using a quick and inexpensive alternative to full nucleotide sequencing; restriction enzyme fragment length polymorphism (RFLP). If necessary, these crabs will be analysed by morphometrics and allozymes to determine whether they are physically or otherwise genetically distinct from the remainder. Three polymorphic allozyme loci (FDH, GPI and PGM), successfully resolved in a pilot study of 118 crabs, are available if required.

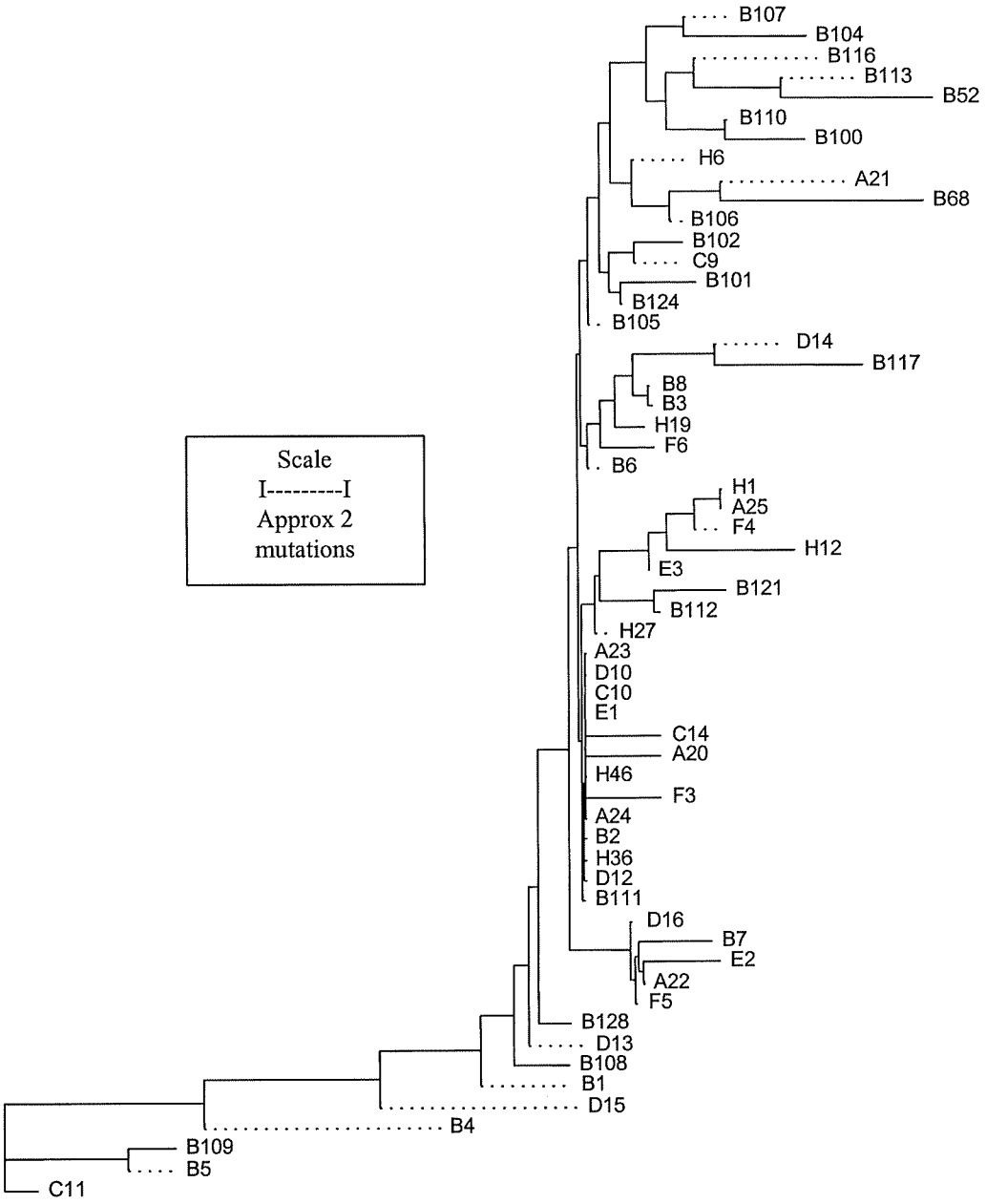

Figure 5.30 Neighbour joining phylogram from total character distance between pairs of crabs based on 441 base pairs of single-stranded Cytochrome Oxidase I sequence. Negative branch lengths (effectively of zero length) are indicated by dotted lines.

6 ASSESSMENT OF CURRENT SEASONAL CLOSURE

6.1 INTRODUCTION

One traditional fisheries management procedure has been to close the fishery to legal exploitation at the time of year when the target species is spawning. Spanner crabs are known to spawn from October to January, with maximum spawning occurring in late November and December (Brown 1986). The spanner crab fishery in Queensland is subject to a spawning closure from 20 November to 20 December each year to coincide with that peak in spawning. This closure reduces the incidence of ovigerous spanner crabs in the commercial catch.

Female spanner crabs which have recently ovulated retain fertilised egg masses attached to their pleopods until the eggs hatch, and are referred to as being in 'berried' condition. Such berried crabs are rare in catches taken on commercial gear, as female spanner crabs normally do not feed around spawning time (Skinner & Hill 1987) and so are rarely attracted to baited nets. However, as spanner crab spawning occurs over a period of several months, berried females are sometimes caught outside the period of the spawning closure.

There has often been strong representation from the industry to examine the timing of the spawning closure, to determine whether it is still appropriate. Various strategies, including earlier application of the closure in the northern part of the fishery and later in the south, have been suggested. This part of the Project relates directly to Objective 2 (see Section 4).

6.2 METHODS

Samples of thirty female crabs were collected from single sites within each of three regions along the south Queensland coast at various times of the year. The sampled regions were (i) Gold Coast (27° 30' to 28° 12'S), (ii) Sunshine Coast (25° 45' to 27° 00'S) and (iii) North Hervey Bay/ Bunkers (23° 45' to 24° 30'S). Additional samples were also collected from sites within the Capricorn region (23° 00' to 23° 30'S), in late October-November each year, as the fishery in that region only operated in that time-period. In 1995 and 1996 most samples were collected aboard commercial fishing vessels during regular catch measurement trips (see 7.1.2.1 below). Those samples were supplemented by samples from collected from the Sunshine Coast region aboard *RV Warrego* during periods when the fishery was closed by management. In 1997 sampling frequency was increased by arranging for three spanner crab fishers (one from each of the above three regions) to collect crabs for the Project, under permit from the Queensland Fisheries Management Authority (QFMA). Each crabber supplied 30 adult female spanner crabs at 28-day intervals from February to July, and at 14-day intervals between August and November, except for periods when the fishery was closed.

Each sample consisted of the first thirty females caught on a particular date. All samples collected by scientific staff included any female regardless of size or reproductive condition, and commercial crabbers were instructed to do the same. However, the crabber collecting samples from the North Hervey Bay/Bunker Islands region informed us after the study that he had deliberately excluded gravid (berried) females from his samples. It was not possible to stipulate the area where crabbers were to collect samples, as they concentrated their fishing efforts in different areas at different times of the year. Thus, sample locations varied between sampling dates (Table 6.1).

All samples were stored frozen until required for dissection. Prior to dissection, the crabs were thawed for one hour in running water, inverted several times to drain excess water from their

branchial chambers, and blotted dry before measurement (Rostral Carapace Length, ± 0.1mm) and weighed on a Sartorius 1404 balance (Body Wet Weight, ± 0.01g).

Table 6.1: Dates and sites at from which samples of female spanner crabs were collected for determination of Gonosomatic Index (GSI).

Capricorn (Region 1)			
Date	Latitude	Longitude	n
16/ 11/ '95	23° 00' S	151° 15' E	27
15/ 11/ '96	23° 00' S	151° 14' E	28
30/ 10/ '97	23° 15' S	151° 39' E	30
		Total	85

Sunshine Coast (Regions 4&5)			
Date	Latitude	Longitude	n
8/ 11/ '95	26° 43' S	153° 22' E	32
10/ 11/ '95	26° 56' S	153° 23' E	3
15/ 7/ '96	26° 53' S	153° 20' E	30
26/ 8/ '96	26° 51' S	153° 21' E	30
2/ 10/ '96	26° 49' S	153° 18' E	30
17/ 12/ '96	26° 57' S	153° 24' E	21
16/ 1/ '97	26° 57' S	153° 24' E	25
17/ 3/ '97	26° 15' S	153° 27' E	19
7/ 4/ '97	26° 15' S	153° 36' E	30
22/ 4/ '97	26° 35' S	153° 15' E	30
20/ 5/ '97	26° 46' S	153° 22' E	30
12/ 6/ '97	26° 46' S	153° 19' E	30
16/ 7/ '97	26° 45' S	153° 15' E	30
12/ 8/ '97	26° 35' S	153° 11' E	30
10/ 9/ '97	25° 57' S	153° 40' E	30
23/ 9/ '97	25° 57' S	153° 40' E	30
9/ 10/ '97	25° 58' S	153° 38' E	31
23/ 10/ '97	25° 57' S	153° 37' E	30
11/ 11/ '97	26° 41' S	153° 22' E	30
18/ 12/ '97	26° 46' S	153° 19' E	30
		Total	519

Hervey Bay/Bunker (Regions 2&3)			
Date	Latitude	Longitude	n
30/ 10/ '95	24° 38' S	153° 01' E	31
22/ 12/ '95	24° 17' S	152° 52' E	24
4/ 10/ '96	24° 30' S	152° 36' E	31
20/ 3/ '97	24° 27' S	152° 52' E	32
22/ 4/ '97	24° 30' S	152° 53' E	25
26/ 5/ '97	23° 55' S	152° 17' E	30
11/ 6/ '97	23° 54' S	152° 27' E	30
16/ 7/ '97	23° 54' S	152° 30' E	30
1/ 8/ '97	23° 55' S	152° 27' E	29
13/ 8/ '97	23° 40' S	152° 16' E	30
28/ 8/ '97	23° 40' S	152° 20' E	29
10/ 9/ '97	24° 23' S	152° 40' E	31
23/ 9/ '97	24° 26' S	152° 47' E	31
7/ 10/ '97	24° 25' S	152° 53' E	31
17/ 10/ '97	24° 20' S	152° 48' E	30
3/ 11/ '97	24° 31' S	152° 57' E	30
4/ 11/ '97	24° 20' S	152° 59' E	30
12/ 11/ '97	24° 20' S	152° 46' E	28
		Total	532

Gold Coast (Region 6)			
Date	Latitude	Longitude	n
1/ 10/ '96	28° 03' S	153° 32' E	30
18/ 3/ '97	27° 35' S	153° 35' E	31
22/ 4/ '97	27° 53' S	153° 28' E	32
20/ 5/ '97	27° 54' S	153° 24' E	30
11/ 6/ '97	27° 59' S	153° 36' E	32
15/ 7/ '97	27° 37' S	153° 36' E	30
12/ 8/ '97	27° 35' S	153° 35' E	32
10/ 9/ '97	28° 02' S	153° 33' E	30
23/ 9/ '97	28° 03' S	153° 33' E	31
15/ 10/ '97	28° 03' S	153° 34' E	30
24/ 10/ '97	28° 02' S	153° 33' E	30
12/ 11/ '97	28° 03' S	153° 33' E	30
16/ 1/ '98	27° 35' S	153° 35' E	30
17/ 2/ '98	27° 53' S	153° 24' E	30
		Total	428

Dissection involved removal of the anterior half of the dorsal carapace, and removal of the intact ovary. Freshly removed ovaries were weighed whole (Ovary Wet water from their branchial chambers, then blotted dry before being measured. Gonosomatic Index (GSI) was calculated by dividing Ovary Wet Weight by Body Wet Weight, and expressing the result as a percentage. In addition, the occurrence of gravid females was recorded in all samples collected for other purposes (e.g. tagging, length frequency analysis).

6.3 RESULTS

A total of 1,597 female spanner crabs were collected and dissected for determination of gonosomatic index. The ovaries of female spanner crabs underwent a gradual development from July until spawning occurred in late November/December (Figure 6.1).

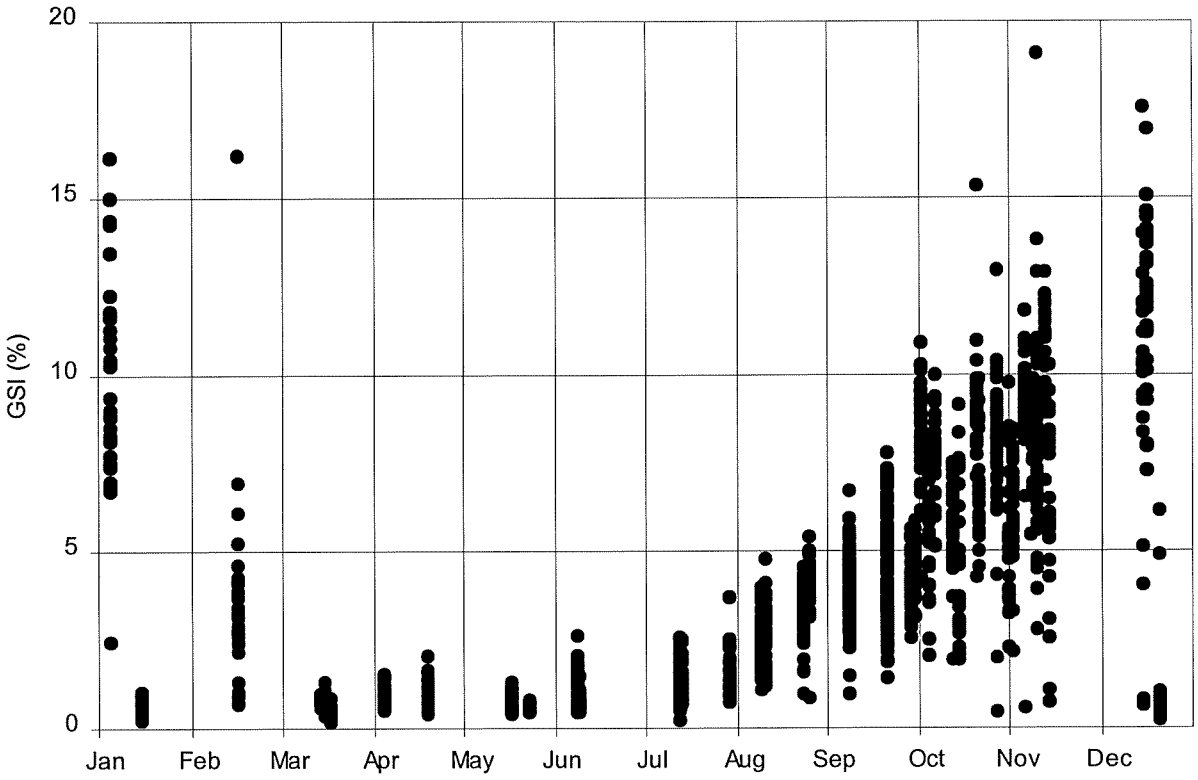

Figure 6.1 Gonosomatic indices of 1,597 female spanner crabs plotted against date of capture (all years pooled).

Two-way ANOVA of 1997 GSI data showed a highly significant interaction between month and region ($F = 20.69$, $df = 20/953$, $P<0.001$), indicating that ovarian development was not consistently more advanced in any region. A series of separate one-way ANOVAs for each month demonstrated that there were no significant differences (at Bonferroni $P = 0.0045$) in GSI between the three regions from July to early September ($P > 0.03$). However, GSI was significantly higher in Sunshine Coast samples than in those from either the Gold Coast or Hervey Bay regions from late September to October ($P < 0.001$, Figure 6.2).

Inter-annual comparison of gonosomatic indices was restricted by fishery closures, but samples were collected from the three regions in the first week of October in 1996 and 1997. Two-way ANOVA of those data revealed a highly significant interaction between region and

year (F = 15.74, df = 2, 174, P < 0.0001) indicating that ovarian development of female spanner crabs was not consistently more advanced in any region (Figure 6.3).

Of the 9,103 females which were examined externally for the presence of eggs, only 118 (1.30%) were in berried condition (Table 6.2). Females collected for GSI measurement by

Table 6.2: The occurrence of gravid (= 'berried') female spanner crabs in samples collected for length frequency analysis or as part of the tagging study (years and areas combined). The shaded area represents annual spawning closure of the fishery.

Dates	No. days	No. females	No. gravid	% gravid
1 Jul - 11 Oct	103	2,062	0	0.00
12 - 21 Oct	10	551	0	0.00
22 - 31 Oct	10	1,221	7	0.57
1 - 10 Nov	10	203	8	3.94
11 - 20 Nov	10	1,376	28	2.03
21 - 30 Nov	10	0	0	-
1 - 10 Dec	10	0	0	-
11 - 20 Dec	10	79	70	88.61
21 - 30 Dec	10	65	0	0.00
31 Dec - 9 Jan	10	79	1	1.27
10 - 19 Jan	10	324	1	0.31
20 - 29 Jan	10	275	2	0.73
30 Jan - 8 Feb	10	536	0	0.00
9 - 18 Feb	10	207	1	0.48
19 - 28 Feb	10	19	0	0.00
1 Mar - 30 Jun	122	2,106	0	0.00
TOTAL	365	9,103	118	1.30

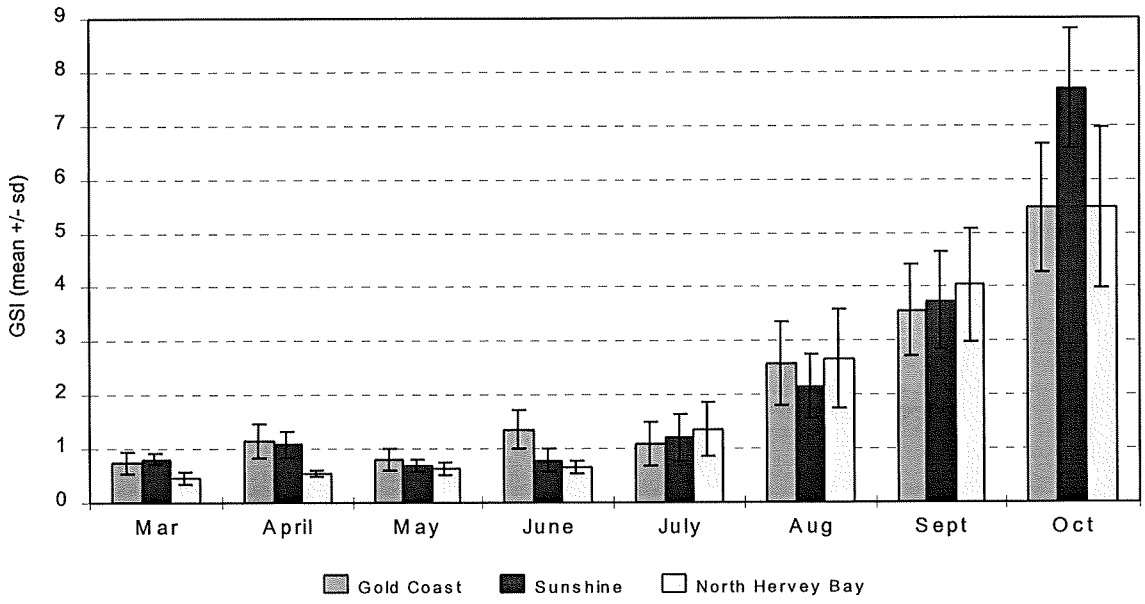

Figure 6.2 Gonosomatic indices (means +/- sd) of female spanner crabs collected in 1997 from three regions of the Queensland coast. Gold Coast = Region 6, Sunshine = Regions 4 & 5, North Hervey Bay = Region 3.

commercial crabbers were not included in this count as at least one of those crabbers deliberately excluded berried females from his samples. The 118 gravid females were present in samples collected between 24 October and 11 February. Only 1.12% of the females

collected in that period, but outside the spawning closure, were gravid. However, 88.61% of the females collected during the spawning closure (20 November to 20 December), were in berried condition (Table 6.2). Forty three gravid females were collected before the closure and only five were collected afterwards. Gravid individuals made up a significantly higher percentage of the female spanner crabs before the closure (1.54 %) than afterwards (0.34 %, X^2= 12.61, df =1, P< 0.005).

6.4 DISCUSSION

During 1997, the ovaries of spanner crabs sampled from the Sunshine Coast were significantly more developed in late September and October than those sampled from the Gold Coast (to the south) or Hervey Bay/Bunker Group (to the north). However, in the previous year there was no evidence of any difference in the timing of reproductive development between crabs in the three regions. The slight differences observed in late September and October 1997 may have been due to differences between regions or between sites within regions.

The gonosomatic index data indicated that as late as early January a significant proportion of ovaries were still in an advanced state of development, suggesting that the animals had yet to ovulate. It is known that females held in aquaria are capable of producing at least two batches of eggs per season, and it is therefore possible that the high late-season GSI values were in fact the precursor to a second (or even perhaps a third) ovulation event. However the evidence for widespread multiple ovulation in the wild does not appear to be supported by observations of female crabs examined for the presence of egg-masses throughout the year. While some crabs were carrying eggs as early as October and as late as February, the percentage of females that were ovigerous in any month was less than 4%, except during the spawning closure. Over 88% of the females examined between 11 and 20 December (almost the end of the closure) were ovigerous, suggesting perhaps the there might be an argument to extend the closure somewhat. However none of the female crabs taken at the end of December was ovigerous, and in subsequent months the highest rate of ovigerity was little more than 1%.

Samples were collected from 26°57'S (off Cape Moreton) in January, 26°15'S (off Mt. Coolum) in March and April, 26°46'S (off Caloundra) from May to July and in December, 26°35'S (off Cooloola National Park) in late April and August and from 25°57'S (off Double Island Point) in September and October. This frequent changing of sample location over a range of one degree of latitude (108.6 km) means that differences over time may have been confounded by latitudinal changes. There were also large latitudinal ranges in sample location in the Hervey Bay/Bunker Region (58' or 105 km) and the Gold Coast Region (28' or 51 km).

If the differences were the result of inter-site effects, it would suggest that factors which regulate female reproductive chronology may act at a particularly localised level. In such a case the spatial scale would be far too small to allow meaningful redefinition of the (seasonal) spawning closure according to geographical boundaries.

Spawning closures have traditionally been justified in terms of protecting the spawning stock. However, it could be argued that there is little reason why mature individuals need greater protection when they are spawning than at any other time. Because female spanner crabs feed less when they are carrying eggs (Skinner & Hill 1987), their catchability by baited fishing apparatus is reduced at that time. However the male crabs still remain vulnerable to capture during the peak of the spawning season, as is evidenced by the high commercial CPUEs.

The demonstration by Skinner & Hill (1987) of some reduction in the catch rate of male crabs during the females' period of ovigerity may be due to the fact that their data were collected

relatively early in the development of the fishery. Many crab fishers now believe that crabs aggregate during the spawning season, and have presumably acquired knowledge of the whereabouts of such aggregation locations over the years. This 'fleet learning' effect may have led to an increase the male crabs' vulnerability, compensating for their reduced catchability.

Most crab fishing in Managed Area B (on the northern fringes of the main fishing grounds) occurs in October and November, just prior to the spawning closure, when the crabs aggregate at known locations (G. Rohl, personal communication). At other times of the year their distribution is unknown, and they may be so dispersed that fishing is not economically viable.

Prior to the introduction of output controls, increased vulnerability of male crabs during the spawning season due to aggregation would have meant that a spawning closure would have limited the potential total annual catch to some extent. Since 1996 when the TACC was introduced, the spawning closure would have had little effect on total catch.

Spawning closures can, however, be effective if there is a close link between egg production and recruitment. If a mature female crab has survived the effects of natural and fishing mortality for 11 months, a one-month spawning closure will ensure that only mortality due to natural causes will prevent the animal from contributing progeny to the next generation. If there is a strong stock-recruitment relationship, this could have a significant effect on subsequent stock size. As we have no indication of the stock-recruitment relationship in spanner crabs, and we assume that the harvesting of male crabs has not resulted in gamete-limitation, this 'objective' of the spawning closure is purely precautionary.

Spawning closures can also be beneficial in cases where fishing activity has a disruptive effect on the reproductive process. This is most likely to occur where there are spawning aggregations (as there appear to be in this species). Skinner & Hill (1987) reported a high level of copulatory behaviour between spanner crabs in aquaria over the period from August to December, and the occurrence of a seemingly protective post-copulatory behaviour, where males 'guarded' the mated females. It may be that the female spanner crabs aggregate first, attracting males that mate with them and subsequently guard them for an indeterminate period of time, perhaps until ovulation.

The extent to which fishing activity might disrupt such behavioural patterns, and thus reduce the population's reproductive success, is difficult to judge, and so the existing spawning closure may be seen as a precautionary measure. The closure has been in place for a considerable period of time and is generally well supported by most of the fishing community, which suggests that unless there is a very good and well justified reason to do otherwise, it will remain. Our research has shown that the timing of the closure (20 November - 20 December) is appropriate across the entire Queensland fishery to minimise the capture of ovigerous female spanner crabs.

7 ESTIMATION OF POPULATION GROWTH AND AGE STRUCTURE

7.1 LENGTH-FREQUENCY ANALYSIS

7.1.1 Introduction

The growth rate of a species (in terms of both individual growth and recruitment) limits the amount of fishing mortality that it can sustain. Knowledge of the species' capacity to accumulate biomass through growth is therefore of extreme value to the assessment and management of exploited stocks of that species.

Four unpublished studies (Brown, 1986; de Moussac, 1988; Boullé, 1995; Chen & Kennelly, 1999) have attempted to estimate spanner crab growth parameters, but their results have been widely divergent. The first three studies estimated growth from length frequency distributions by using computer models to fit von Bertalanffy growth curves. Chen & Kennelly (1999) measured the growth increments of adult crabs via a tag-recapture study, and then applied a variety of models to their data to estimate growth throughout the crab's adult life. Comparison between von Bertalanffy growth parameters estimated by these authors demonstrates very little agreement (Table 7.1, Figure 7.1). The models of Brown (1986) and Boullé (1995) predicted very rapid growth, with both sexes being recruited to the fishery within two years of settlement. In contrast, the models of de Moussac (1988) and Chen & Kennelly (1999) predicted very slow growth.

Table 7.1 Comparison between von Bertalanffy growth parameters for spanner crabs estimated by different authors.

[1] L_∞ values of other authors converted from Orbital Carapace Length (OCL) to Rostral Carapace Length (RCL) for comparison with Brown (1986).
[2] Est. age recruited = age at which crabs would reach 100 mm RCL.
NB: Chen & Kennelly (1999) did not estimate juvenile growth from adult data, so could not estimate age at recruitment.
[3] Boulé (1995) did not distinguish between the sexes.
[4] Boulé (1995) re-analysed de Moussac's (1988) data by combining the sexes and using a different model.

		L_∞[1]		Est. age recruited[2]	
Author/s	Sex	(mm)	K	years	months
Boullé (1995)[3]	combined	155	0.545	1	6
Boullé (1995) de Moussac[4]	combined	151	0.578	1	4
Brown (1986)	Male	162	0.90	1	1
de Moussac (1988)	Male	161	0.30	3	7
Chen & Kennelly (1999)	Male	154	0.216		
Brown (1986)	Female	122	1.00	1	9
de Moussac (1988)	Female	144	0.14	8	10
Chen & Kennelly (1999)	Female	145	0.078		

These large differences in estimates of growth are unlikely to be due to differences between stocks. Both Brown (fast growth) and Chen & Kennelly (slow growth) worked off the Australian East Coast, while both Boullé (fast growth) and de Moussac (slow growth) worked with material from the Seychelles Islands. The differences are more likely to be due to the inapplicability of the growth models used and the possible effects of tagging on growth (Chen & Kennelly, 1999). Thus, there is no agreement as to the growth rate of spanner crabs, and none of the previous studies can be clearly identified as being the most accurate.

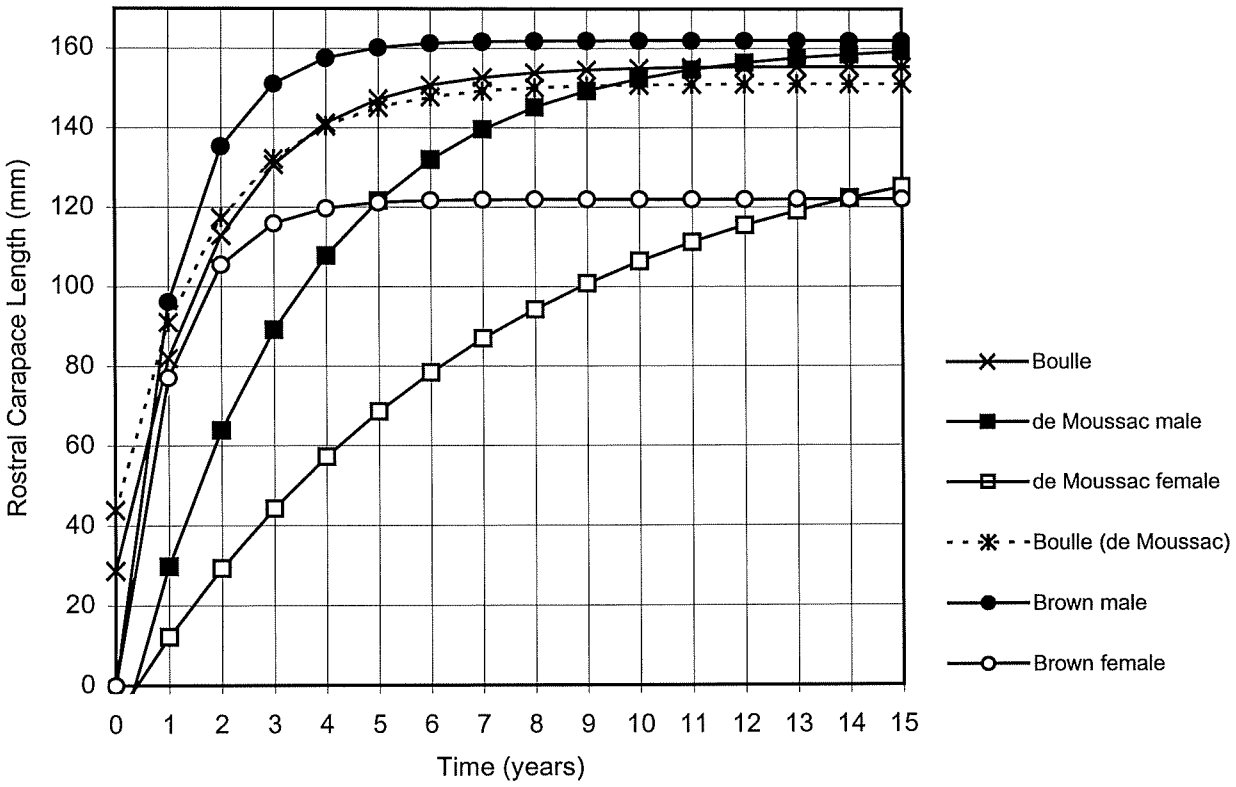

Figure 7.1 Growth curves derived from von-Bertalanffy growth parameters estimated by Brown (1986), de Moussac (1988) and Boullé (1995). It was not valid to plot a curve from growth parameters estimated by Chen & Kennelly (1999) as they explicitly stated that their data could not be extrapolated to juveniles.

7.1.2 Methods

7.1.2.1 Sampling using commercial spanner crab fishing gear

Length frequency measurement of commercial spanner crab catches was performed at sea aboard commercial fishing vessels. In this way, each crab brought on board was measured, whether it was of legal size or not. Crabbers fished in their normal manner, but placed all crabs caught in the one box, rather than separating crabs on the basis of size and returning undersize crabs to the sea. The Rostral Carapace Length of each crab was measured (± 0.5 mm), and data were recorded verbally using a voice-activated cassette recorder. Location and date information was also recorded on tape.

Length frequency measurement was conducted on vessels fishing in five regions (Gold Coast, Sunshine Coast, Wide Bay, North Hervey Bay and Capricorn/Bunker). Sampling from the Gold Coast, Sunshine Coast and North Hervey Bay Regions was conducted twice each year (in October/November and in March/April). Sampling from the Wide Bay region commenced in late 1997 as more crabbers moved into the region. Sampling from the Capricorn/Bunker region was conducted off the Capricorn coast once each year (in October/November) as commercial spanner crabbing from that port was conducted only in the spring. This sampling was supplemented by samples collected from near Lady Musgrave Island (Bunker Islands) in February 1996.

Additional length frequency data on adult spanner crabs were derived from samples collected aboard the Fisheries Research Vessel *Warrego*. These samples were collected and measured in the same manner as aboard commercial fishing vessels. However, they were frequently collected for purposes other than length frequency measurement (e.g. as part of depletion experiments or tagging studies), and were usually collected over periods of several days. Samples collected as part of depletion experiments were collected from either one or two specific sites (see Section 5.1.2.1) whereas samples collected as part of tagging studies generally came from over a wide area (see Section 5.3.3.2). Samples collected from the Gold Coast area during the tagging study were supplemented by undersized crabs collected on behalf of QDPI by a commercial crabber so length frequencies were biased towards individuals of sub-legal size.

7.1.2.2 Sampling using channel dredge

As commercial spanner crabbing gear catches only adult spanner crabs, this study incorporated the development of two prototype dredges to sample the juvenile sector of the population. These dredges are referred to as the channel dredge (as it cut two narrow channels) and a new type of hydraulic dredge (see Section 7.1.2.4 below).

The channel dredge consisted of two angled cutting blades, each leading to a rectangular 5mm mesh woven wire cage. Each blade cut a shallow trench (200 mm wide by up to 20 mm deep) and lifted the sand up to the wire cage which filtered out all particles larger than 5 mm across. A series of narrow bars was set 50 mm apart in front of each cage to exclude larger items from entering the cage.

Sampling with this dredge was conducted using the *RV Warrego* in the 'Dog's Leg' area, north of Moreton Island, at regular intervals in 1997 and 1998. Initial samples were collected during trials of the dredge, which involved a series of 10 or 15 minute tows along the seafloor at a variety of depths. From March 1997, sampling involved four replicate 15 minute tows at each of four depth ranges (0-10 m, 10-20 m, 20-30 m and 30-40 m). Sampling was conducted in the months of February to July 1997 and January to May 1998. Sampling was not conducted from August to December 1997 as catch rates declined to such low levels in July that further sampling was uneconomic. Because of the low catch rates, samples from both years were combined for length frequency analysis.

After each tow, the contents of each cage (which generally consisted of several kilograms of shell fragments) were emptied on to the vessel's deck and carefully sorted to remove any spanner crabs or pieces of spanner crabs. Live spanner crabs were kept in seawater and transferred to the laboratory for measuring and weighing before being fixed in 70% ethanol. Prior to weighing, each individual was removed from the seawater and carefully rolled on blotting paper for several seconds. It was then measured using a vernier caliper (± 0.1mm), and weighed using a Sartorius 1700 pan balance (± 0.001g). Carapace lengths of megalopae were measured from the posterior to the anterior edges of the carapace, as the rostrum of spanner crab megalopae consists of a very small flexible spine which could not be measured accurately. Carapace lengths of juveniles were Rostral Carapace Lengths.

Because this dredge only cut to a maximum depth of 20 mm, it cut larger crabs in two. As spanner crabs normally have their eyes and antennae protruding from the substratum, the dredge tended to retain the anterior portion of a larger crab's cephalothorax. These anterior portions were fixed in 70% ethanol, and stored for later measurement. The width of each anterior portion was measured from the distal edges of the base of the third antero-lateral spine cluster, or 'horn', (± 0.1mm). A regression of Rostral Carapace Length (RCL) against Carapace Width (CW) was calculated from 37 intact juvenile carapaces collected by Brown (1986) from Fraser Island in 1982:

$$RCL = 1.038 + 1.219 \times CW \qquad \text{(Equation 7.1)}$$

This regression was highly significant ($F = 8{,}640.48$, $df = 1,36$, $P = 1.69 \times 10^{-43}$), with carapace width explaining 99.6% (adjusted r^2) of the variation in carapace length of juveniles in the 10 to 48 mm carapace length range.

7.1.2.3 Estimation of von Bertalanffy parameters from length frequency data

Length frequency data from samples collected by both dilly and dredge were analysed using the 'Powell-Wetherall's plot' and 'ELEFAN I' routines contained in the FAO-ICLARM Stock Assessment Tools (FiSAT) software package (Gayanilo *et al.* 1994). Those routines can be applied to length frequency data to estimate the L_∞ and K parameters of the von Bertalanffy growth function (Equation 2, von Bertalanffy 1938). Powell-Wetherall plots use a single (or pooled) series of length frequency data to estimate the L_∞ parameter of that function (Powell 1979, Wetherall 1986), while ELEFAN I uses a variety of procedures to estimate K and/or L_∞ values (Gayanilo *et al.* 1994).

$$L_t = L_\infty (1 - e^{-K(t - t_0)}) \qquad \text{(Equation 7.2)}$$

where L_t = mean length at age t, L_∞ = mean the size that animals of a population would reach if they were allowed to grow indefinitely (asymptotic length), K = the curvature parameter and t_0 = the 'age' at which an animal would have had a length of zero if its growth had always occurred according to the model. This t_0 value adjusts the model for growth which occurred during the spanner crab's planktonic larval stage.

As the Powell-Wetherall plot uses a single length frequency distribution, this routine was applied to pooled length frequency data for each sex to obtain overall estimates of L_∞ values for spanner crabs throughout the Queensland fishery. This routine was also used to estimate L_∞ values for each sex in each of the five regions by pooling length frequency distributions for each. It was not valid to apply Powell-Wetherall plots to estimate L_∞ from dredge samples, as those samples did not contain any crabs that were approaching maximum size.

The ELEFAN I routine of FiSAT offers four different methods to fit a growth curve to length frequency data, each of which requires the user to enter estimates of between three and five variables prior to analysis (Gayanilo *et al.* 1994). The least subjective option within ELEFAN I is the 'Scan of K values' which requires user foresight of just three variables (L_∞, C [a parameter expressing the amplitude of any seasonal oscillations in growth rate] and WP ['Winter Point', the time of year at which the growth rate was lowest]) to estimate the von Bertalanffy K value. Given estimates of L_∞, C and WP, the scan of K values option applies a range of potential K values (0.10 to 9.90 $year^{-1}$) to each series of length frequency measurements, and plots those values against a 'goodness-of-fit' index (R_n). The potential K value which produces the highest R_n value is deemed to provide the best estimate of the actual K value (Gayanilo *et al.* 1994).

For the present analyses, L_∞ values were objectively estimated using Powell Wetherall plots, but we had no idea whether there were any seasonal oscillations in spanner crab growth rates, let alone the amplitude (C) and timing (WP) of any such oscillations. As it was impossible to make any reliable guess of the values of C and WP, those values were set at zero to obtain estimated K values at annual average growth rates. Alternative estimates of von Bertalanffy growth parameters were made by applying the von Bertalanffy model to the length-at-age data estimated from dredge samples, using the L_∞ values calculated for the entire length frequency data set.

7.1.3 Results

7.1.3.1 Length frequency samples collected using commercial gear

A total of 33,736 spanner crabs were measured at sea during the course of this project, with 25,453 being measured aboard commercial fishing vessels, and the remainder measured on sampling trips aboard the *RV Warrego* (Table 7.2). All were collected using standard commercial spanner crab fishing gear.

Pooling all samples collected using commercial fishing gear, the length frequency distribution of each sex was unimodal and approximately normal (Figure 7.2). The carapace lengths of male spanner crabs collected by that gear ranged from 53 to 157 mm, while females ranged

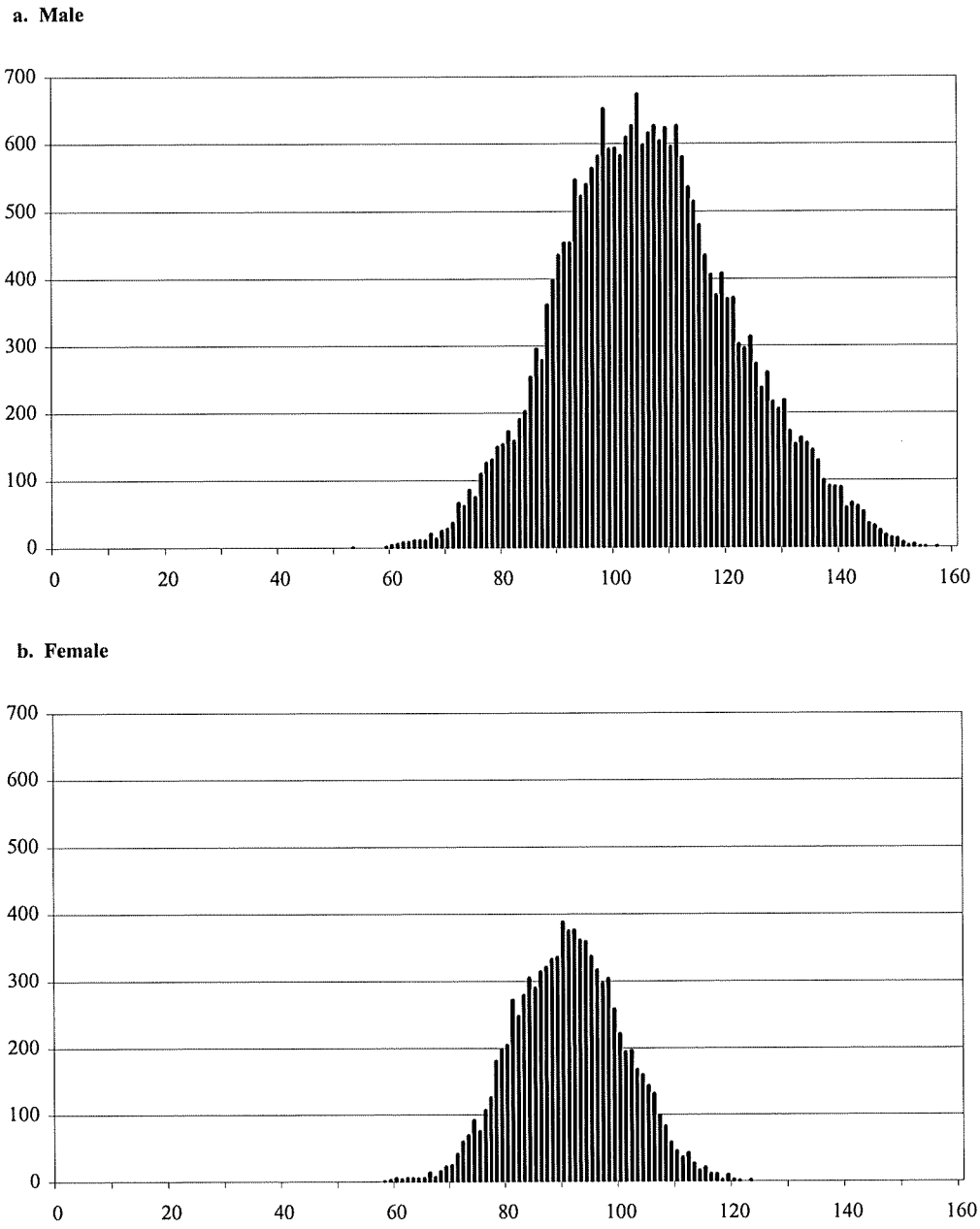

Figure 7.2 Spanner crab length frequencies in all samples collected using commercial fishing gear from off the south Queensland coast between October 1995 and April 1998. a. Males (n = 24,682), b. Females (n = 9,054).

from 58 to 123 mm. The length frequency distribution for males showed a very slight positive skew, with the mean length being 105.90 mm (Table 7.2) and the mode 104 mm (Figure 7.2a). Females did not reach as large a size as males, and had a mean length of 90.92 mm (Table 7.2) and a mode of 90 mm (Figure 7.2b). The minimum legal size of 100 mm was exceeded by 64.3% of all males, but by only 18.7% of females.

Sex ratios were highly variable in these samples, with catches at particular sites being comprised of between 31 and 100% males. Overall, males comprised 73.2% of the spanner crabs collected during this study (Table 7.2).

Length frequency distributions were also highly variable between regions and on different dates within regions (Figures 7.3 - 7.10). This latter variability was almost certainly due to the fact that fishermen collected crabs from different sites on the different dates, as there was often a high degree of variability between sites within a region that were sampled on the same date. An obvious example of this was on 4 October 1996 (Figure 7.4e & g). The length frequency distribution of males at 24°29.9'S 152°36.2'E had a positively skewed distribution, with a modal carapace length between 91 and 98 mm and a mean of 101.4 mm (Figure 7.4e). Eighteen nautical miles (33 km) away at 24°26.5'S, 152°55.0'E, males had a negatively skewed length frequency distribution, with a modal carapace length of 116 mm and a mean of 112.0 mm (Figure 7.4g). This spatial variability precluded the detection of modal progression.

Estimation of growth rates from length frequency data was also restricted by the fact that almost all of the length frequency distributions were unimodal (Figures 7.5 - 7.10). However, although all female length frequency distributions were unimodal, two modes could be clearly distinguished in about one third male length frequency distributions (e.g. Figures 7.3g, 7.4e, 7.5a & e, 7.6a, c & e, 7.7a, 7.10a, c & g).

The mean length of spanner crabs of both sexes was significantly greater in recently exploited fishing grounds north of 23°30'S than it was in fishing grounds south of that latitude (most of which had been exploited for several years) (Table 7.3). Related to this, significantly higher proportions of both sexes exceeded the legal minimum size (RCL = 100 mm) in those recently exploited northern grounds. However, there was no significant difference in the sex ratios between the recently exploited northern grounds and the more southerly spanner crab fishing grounds (Table 7.3).

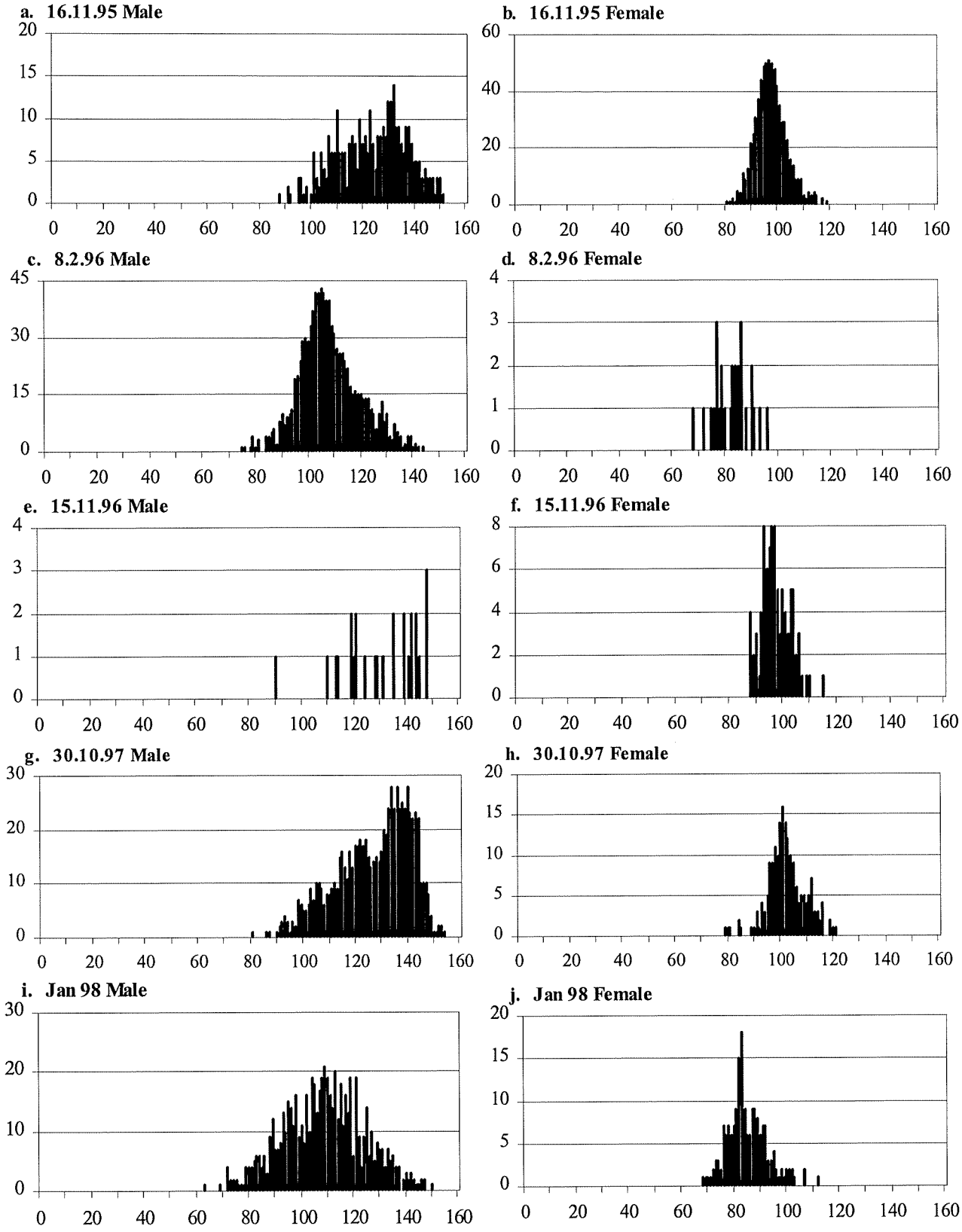

Figure 7.3 Spanner crab length frequencies in samples collected from between 23-24°S (off the Capricorn Coast and in the Capricorn-Bunker Group) from November 1995 to January 1998.

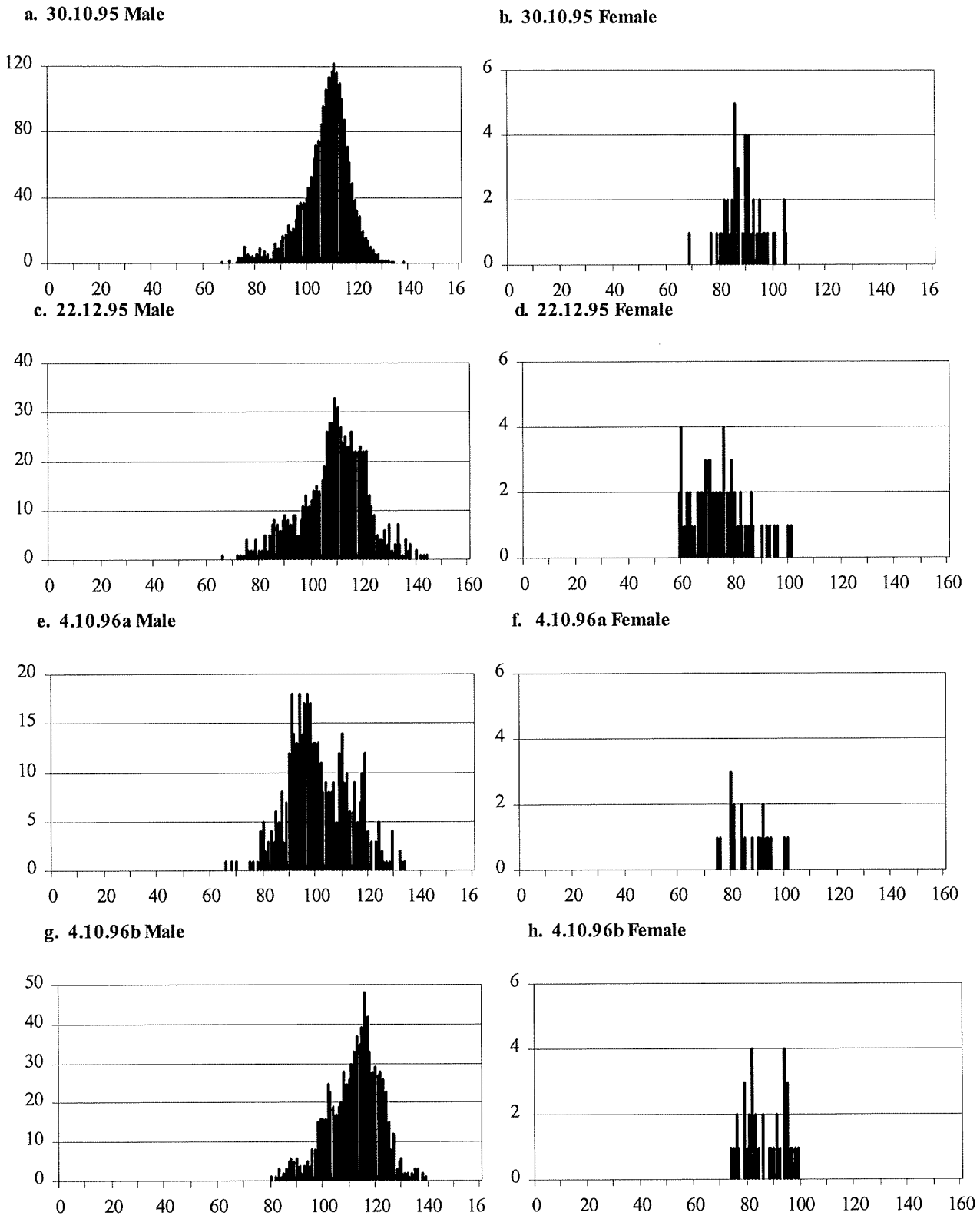

Figure 7.4 Spanner crab length frequencies in samples collected from between 24-25°S (north of Hervey Bay) from October 1995 to October 1996.

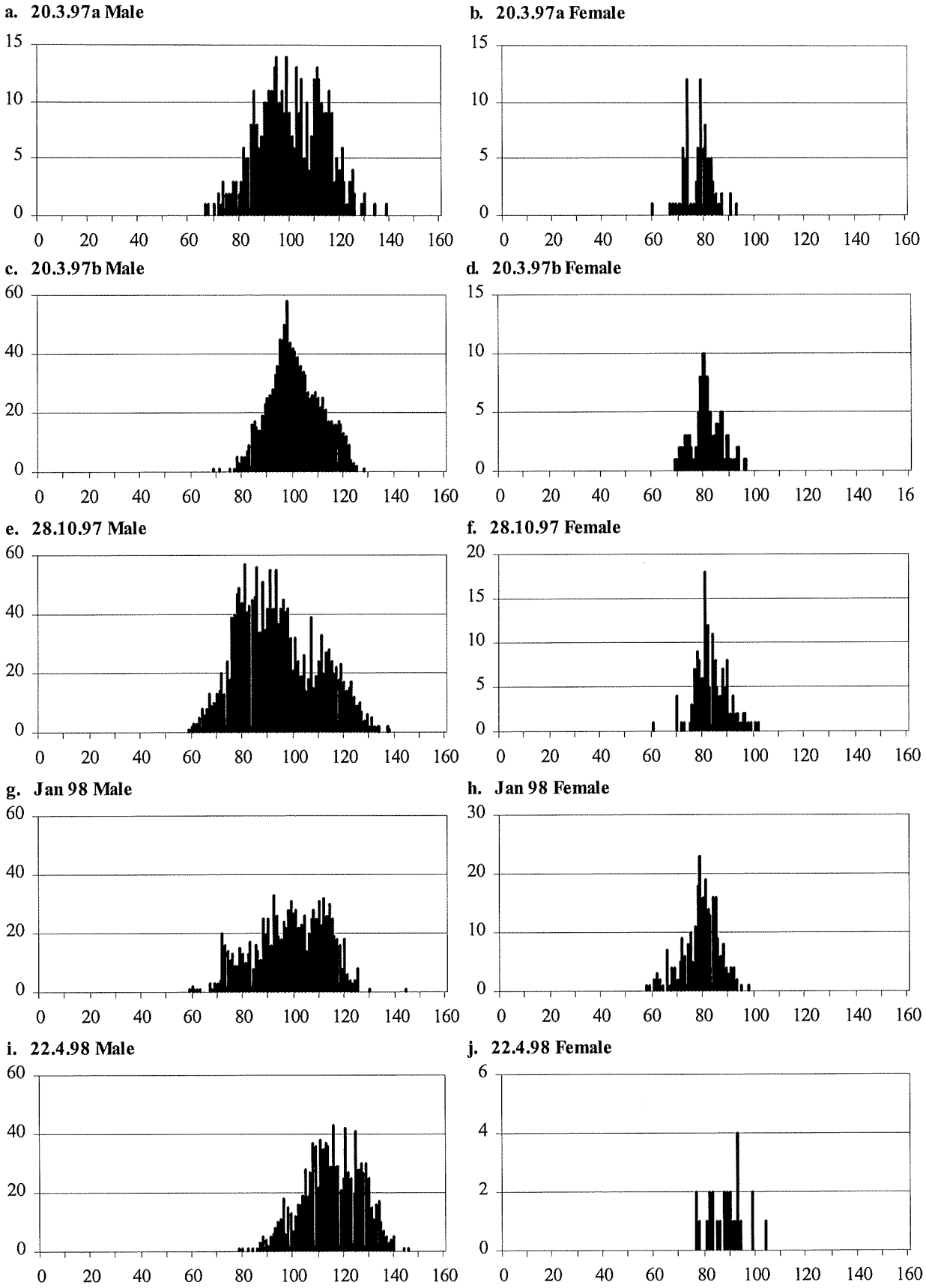

Figure 7.5 Spanner crab length frequencies in samples collected from between 24-25°S (north of Hervey Bay) from March 1997 to April 1998.

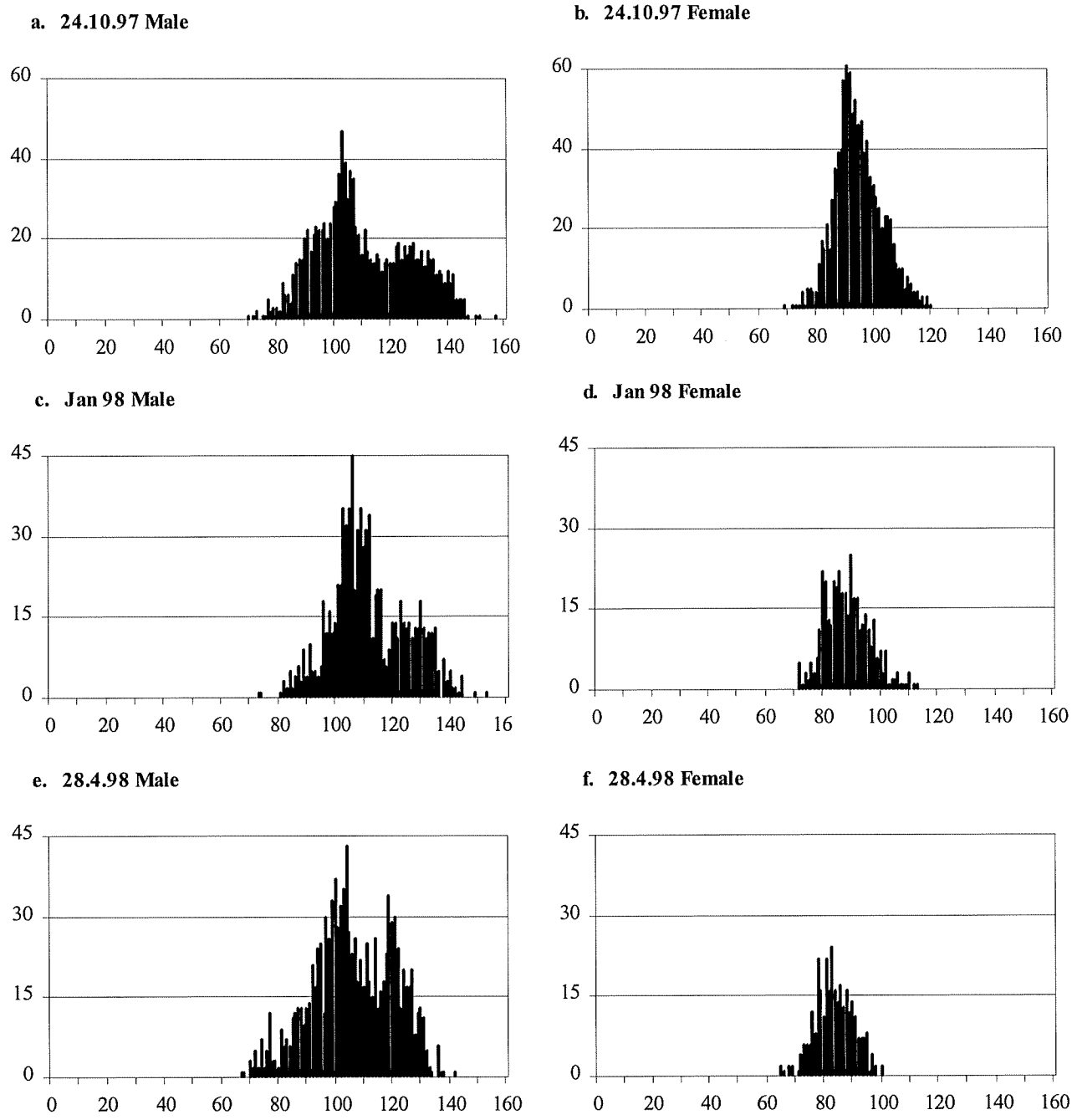

Figure 7.6 Spanner crab length frequencies in samples collected from between 25-26°S (Fraser Island to Double Island Point) from October 1997 to April 1998.

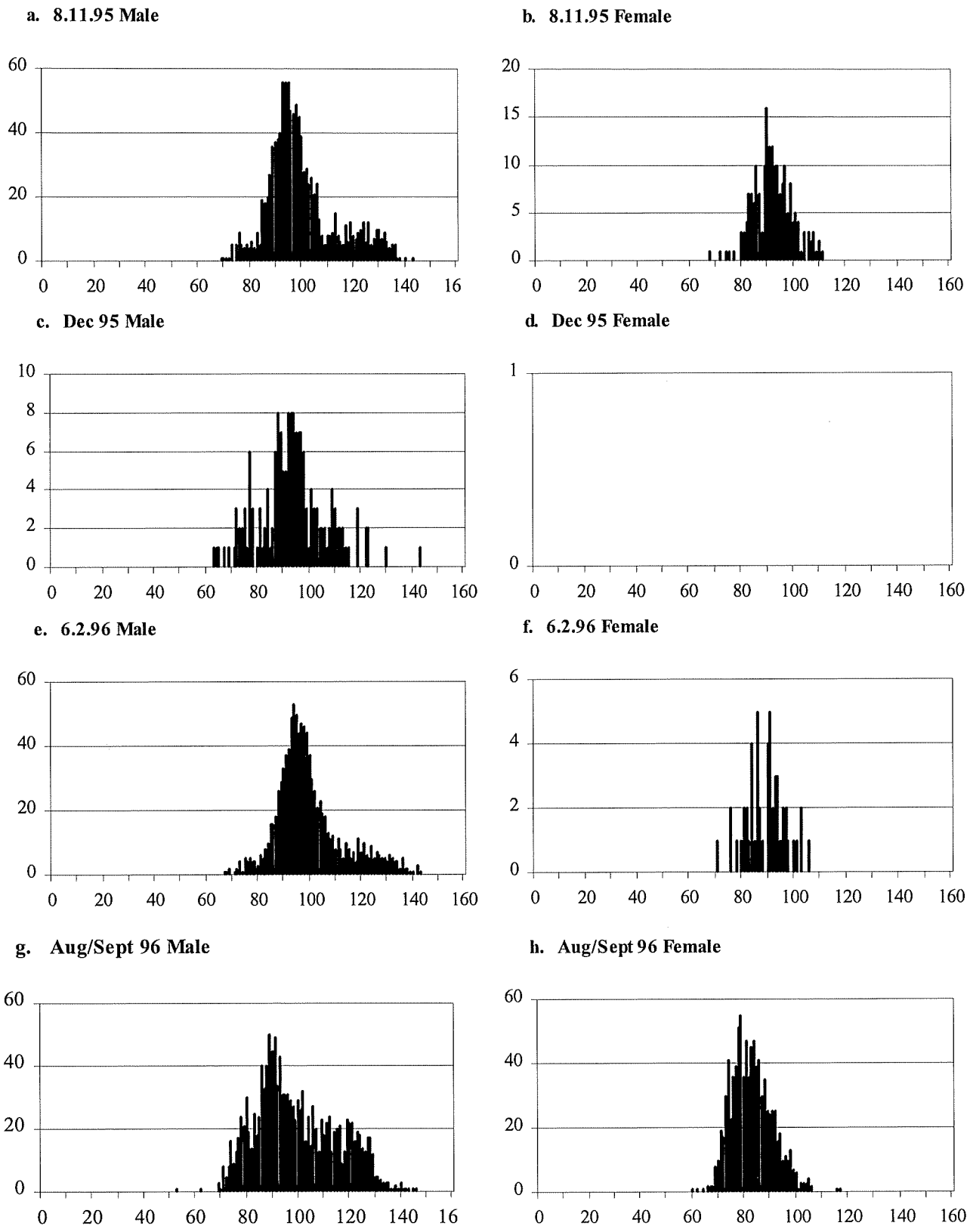

Figure 7.7 Spanner crab length frequencies in samples collected from between 26°30'-27°S (Sunshine Coast) from November 1995 to September 1996.

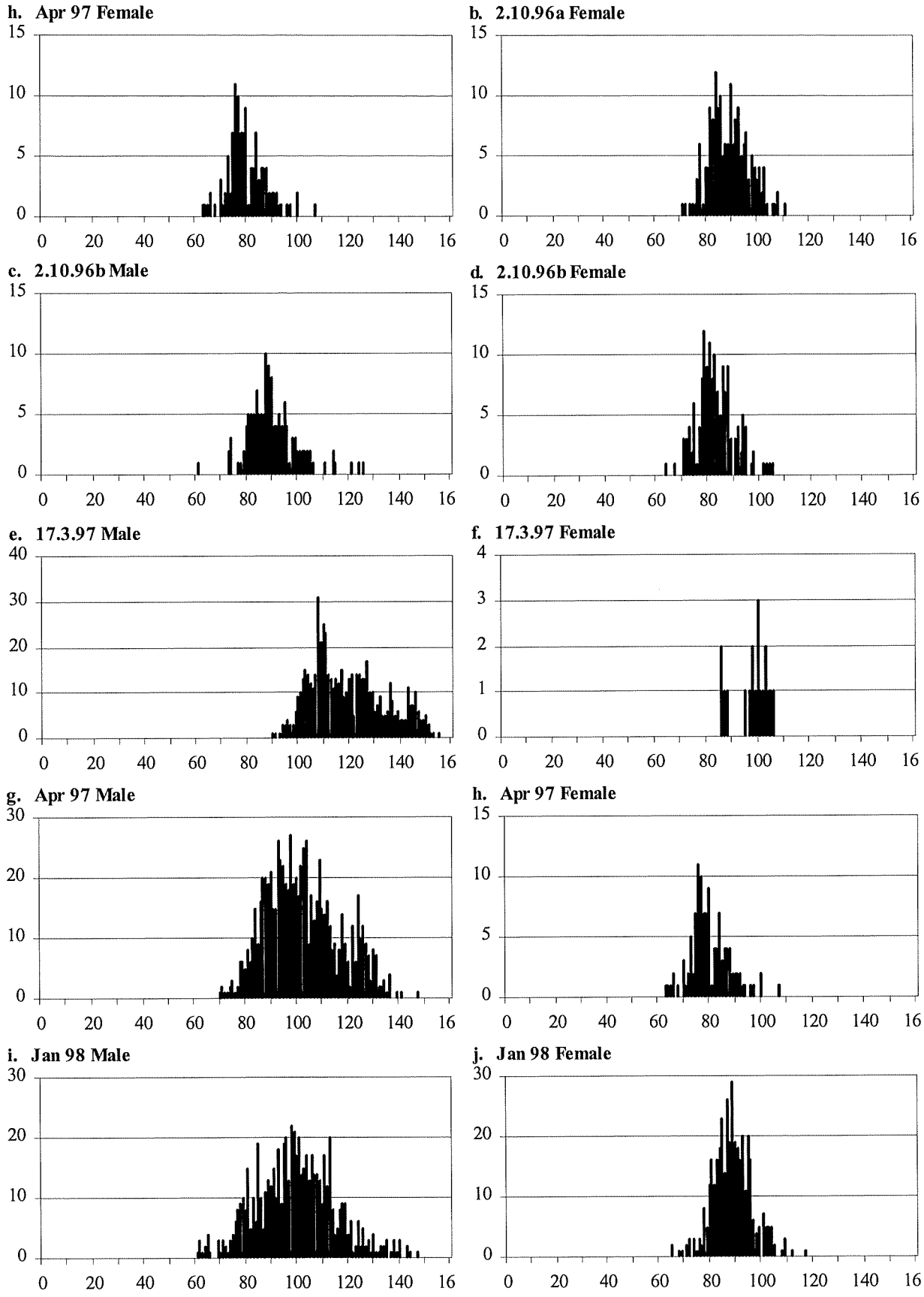

Figure 7.8 Spanner crab length frequencies in samples collected from between 26°30'-27°S (Sunshine Coast) from October 1996 to January 1998.

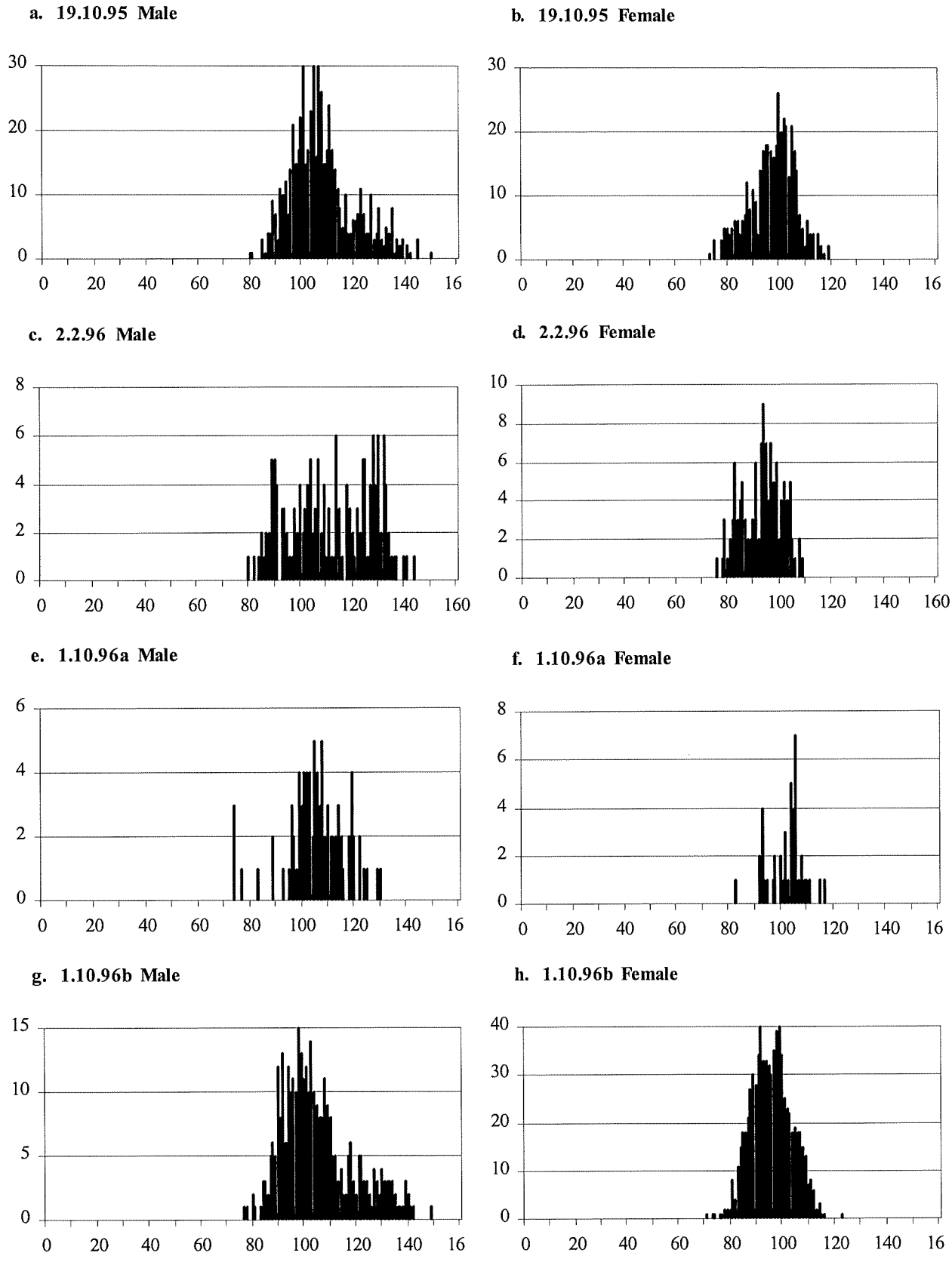

Figure 7.9 Spanner crab length frequencies in samples collected from between 27°30'-28°12'S (Gold Coast) from October 1995 to October 1996.

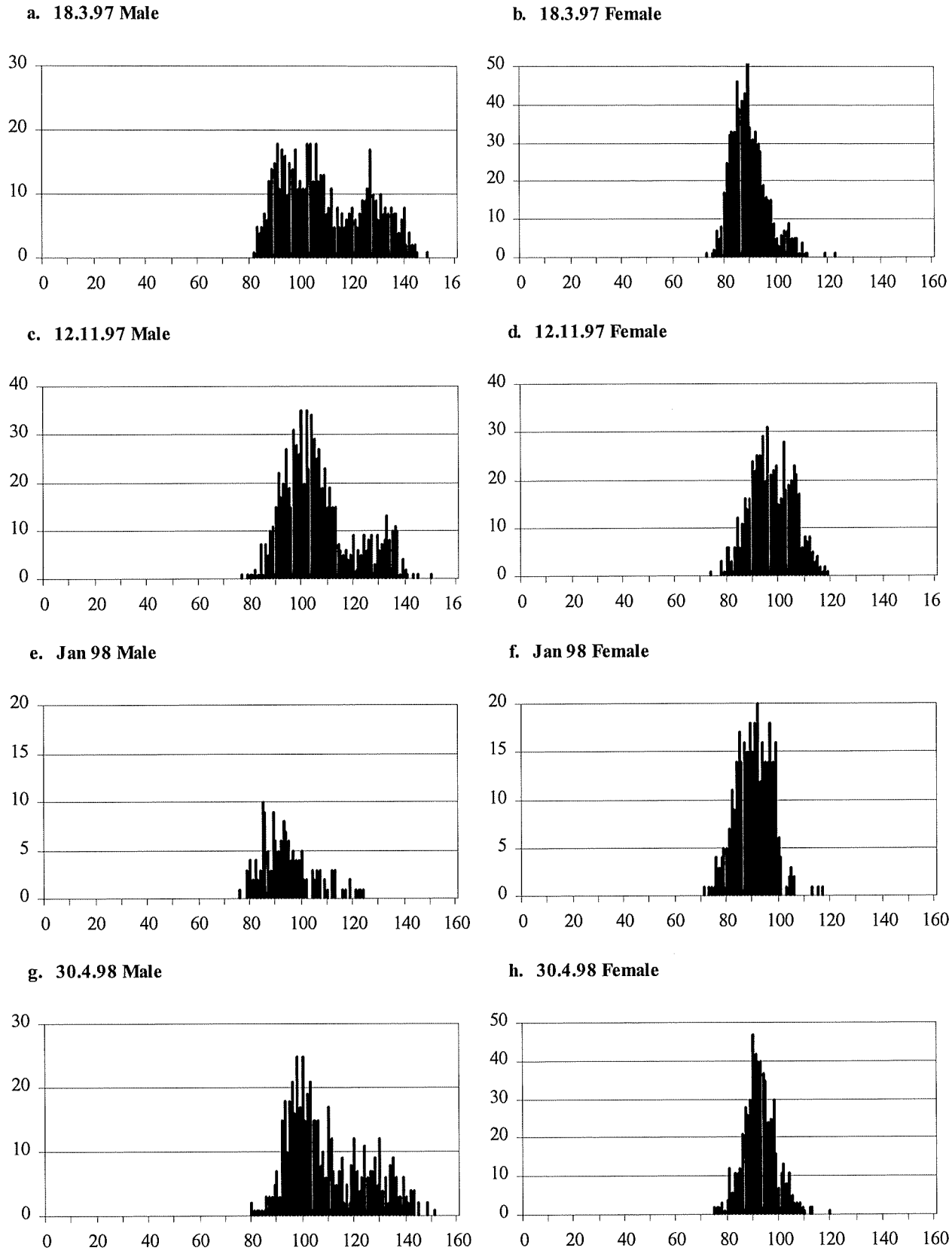

Figure 7.10 Spanner crab length frequencies in samples collected from between 27°30'-28°12'S (Gold Coast) from March 1997 to April 1998.

Table 7.2 Summary of spanner crab samples measured for length frequency analysis on board **a)** commercial fishing vessels, and **b)** *RV Warrego*.

a) Commercial Vessels

Region	Date	Counts			Sex ratio	Mean RCL (mm)		Proportion legal size	
		Male	Female	Total	(M/F)	Male	Female	Male	Female
Capricorn/Bunker (23 – 24°S)									
	16.11.95	334	691	1,025	0.48	123.73	97.64	0.96	0.34
	8.2.96	973	27	1,000	36.04	108.13	82.59	0.79	0.00
	30.10.97	787	190	977	4.14	126.87	102.20	0.96	0.37
	Sub Total	**2,094**	**908**	**3,002**	**2.31**	**117.66**	**98.15**	**0.88**	**0.34**
North Hervey Bay (24 – 25°S)									
	30.10.95	2,131	43	2,174	49.56	107.68	89.33	0.84	0.12
	22.12.95	746	65	811	11.48	108.69	74.65	0.79	0.03
	4.10.96	422	20	442	21.10	101.42	87.10	0.50	0.10
	4.10.96	856	37	893	23.14	112.00	86.46	0.88	0.00
	20.3.97	398	87	485	4.57	100.68	78.14	0.51	0.00
	20.3.98	1,098	77	1,175	14.26	100.87	80.83	0.52	0.00
	20.10.97	1,823	143	1,966	12.75	93.93	83.69	0.32	0.01
	22.4.98	1,062	26	1,088	40.85	115.44	88.42	0.90	0.04
	Sub Total	**8,536**	**498**	**9,034**	**17.14**	**104.72**	**82.17**	**0.66**	**0.02**
Wide Bay (25 – 26°S)									
	24.10.97	1,154	988	2,142	1.17	110.36	94.73	0.73	0.26
	28.4.98	1,077	312	1,389	3.45	106.06	83.63	0.68	0.01
	Sub Total	**2,231**	**1,300**	**3,531**	**1.72**	**108.28**	**92.07**	**0.70**	**0.20**
Sunshine Coast (26 – 27°S)									
	8.11.95	1,096	192	1,288	5.71	100.29	92.16	0.40	0.15
	6.2.96	1,005	51	1,056	19.71	99.64	89.31	0.39	0.10
	2.10.96	272	171	443	1.59	104.26	89.38	0.61	0.11
	2.10.96	132	148	280	0.89	90.51	83.39	0.15	0.03
	17.3.97	584	19	603	30.74	119.46	97.79	0.96	0.53
	Sub Total	**3,089**	**581**	**3,670**	**5.32**	**103.63**	**89.04**	**0.59**	**0.17**
Gold Coast (27 – 28°12'S)									
	19.10.95	586	408	994	1.44	108.18	98.23	0.76	0.47
	2.2.96	155	118	273	1.31	111.92	93.31	0.75	0.22
	1.10.96	84	43	127	1.95	105.69	102.28	0.77	0.72
	1.10.96	344	741	1,085	0.46	105.13	95.86	0.59	0.32
	18.3.97	586	675	1,261	0.87	109.55	89.57	0.66	0.09
	12.11.97	785	567	1,352	1.38	106.60	97.30	0.66	0.40
	30.4.98	545	579	1,124	0.94	109.37	92.59	0.69	0.12
	Sub Total	**3,085**	**3,131**	**6,216**	**0.99**	**108.03**	**94.46**	**0.68**	**0.27**
	TOTAL	**19,035**	**6,418**	**25,453**	**2.97**	**106.92**	**93.05**	**0.67**	**0.24**

b) *RV Warrego*

Region	Date	Counts			Sex ratio	Mean RCL (mm)		Proportion legal size	
		Male	Female	Total	(M/F)	Male	Female	Male	Female
Cap/Bunk	15.11.96	26	90	116	0.29	130.35	97.52	0.96	0.34
Cap/Bunk	Jan-98	650	183	833	3.55	108.54	85.39	0.71	0.06
N.Hervey	Jan-98	1,027	259	1,286	3.97	98.42	79.34	0.50	0.00
Wide Bay	Jan-98	848	381	1,229	2.22	111.85	88.60	0.85	0.09
Sunshine	Dec-95	169	0	169	-	93.59	-	0.26	-
Sunshine	Aug/Sep 96	1,376	902	2,278	1.53	99.55	82.99	0.45	0.03
Sunshine	Apr-97	769	116	885	6.63	102.41	80.34	0.53	0.03
Sunshine	Jan-98	635	381	1,016	1.67	99.57	88.77	0.49	0.08
Gold	Jan-98	147	324	471	0.45	94.37	90.44	0.25	0.06
	TOTAL	**5,647**	**2,636**	**8,283**	**2.14**	**102.45**	**85.74**	**0.55**	**0.06**
GRAND TOTAL		**24,682**	**9,054**	**33,736**	**2.73**	**105.90**	**90.92**	**0.64**	**0.19**

Table 7.3 Comparison of spanner crab sex ratios, mean Rostral Carapace Lengths (RCL) and the proportion of individuals exceeding the minimum legal size (RCL = 100mm) between recently exploited fishing grounds north of 23°30'S and more southerly grounds.

Statistic	Sex	New grounds (N of 23°30'S)	Older grounds (S of 23°30'S)	F ratio	df	P
Sex ratio	(M/F)	1.18	2.91	1.17	1,31	0.288
Mean RCL	Male	126.03	104.91	31.17	1,32	<0.001
(mm)	Female	98.52	90.01	7.89	1,31	0.009
Proportion	Male	0.96	0.58	8.30	1,32	0.007
> legal size	Female	0.40	0.15	4.87	1,31	0.035

7.1.3.2 Length frequency samples collected using the channel dredge

Catch rates using the channel dredge were very low, with a total of 103 juvenile spanner crabs being collected from 152 samples. Newly settled megalopa stage larvae were collected only from 26 February to 8 April, with juvenile stage 1 crabs being collected from 26 February to 5 May and subsequent juvenile stages being collected at progressively later dates (Table 7.4).

Table 7.4 Spanner crab samples collected using the channel dredge, tabulated by date of collection and stage of development. Data for 1997 and 1998 pooled.

Stage	RCL (mm)	19-Jan	26-Feb	24-Mar	8-Apr	5-May	2-Jul	Total
Megalopa	8.3 – 9.8		18	4	13			35
Juvenile 1	10.2 – 12.0		3	19	7	7		36
Juvenile 2	13.0 – 14.5			2	3	8		13
Juvenile 3	15.9 – 16.3					1	1	2
Juvenile 4	19.0						1	1
Later stages	>31.0	4	3	4	3		2	16
Total		4	24	29	26	16	4	103
# samples	1997		8	16	16	16	16	72
	1998	16	16	16	16	16		80
Catch rate (crabs/sample)		0.25	1.00	0.91	0.81	0.50	0.25	0.68

It was not possible to determine the sex of spanner crabs collected by the channel dredge. Crabs smaller than 19 mm carapace length showed no apparent sexual dimorphism, and the dredge only retained the anterior portion of crabs larger than 31 mm. No crabs between 19 and 31 mm carapace length were present in any of the samples collected using the channel dredge.

Based on the mean dates of collection, juvenile spanner crabs took an estimated mean of 16.7 days to complete stage 1 and 37.1 days to complete stage 2. The 35 stage 1 juveniles had a mean carapace length of 10.7 mm, while the two stage 3 juveniles had a mean length of 16.1 mm. Thus growth of 5.4 mm took an average of 53.8 days at a mean rate of 0.1005 mm.day^{-1} (36.73 mm.year^{-1}). As growth rate declines with age, this is likely to be the maximum rate of growth during the lifetime of a spanner crab.

By pooling all samples collected between 19 January and 2 July, the length frequency distribution of spanner crabs collected by the channel dredge showed two distinct modes,

separated by 12.4 mm (Figure 7.11). The first mode contained 86 crabs with carapace lengths ranging from 8.3 to 19.0 mm. All crabs between 12.0 and 19.0 mm were caught after 24 March (Figure 7.12). The second mode contained 15 crabs with carapace lengths ranging from 31.4 to 47.7 mm (mean = 39.7 mm). Given the clear separation of the two modes and the short annual spawning season, the second mode would appear to have comprised crabs that had settled the previous year. These crabs would have grown an average of 30.55 mm since settlement as megalopae. Based on mean dates of collection, and assuming that the second mode represented the previous year-class (353 days old), they had grown at a rate of 0.0864 $mm.day^{-1}$ (31.55 $mm.year^{-1}$), which is slightly less than that estimated for stage 1 juveniles above.

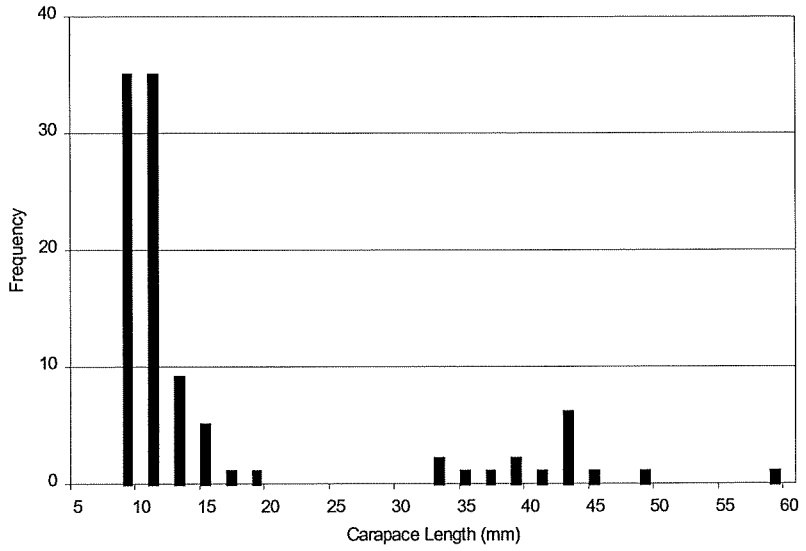

Figure 7.11 Length frequency of spanner crabs collected in channel dredge samples from January to July in both 1997 and 1998. Data from all samples pooled.

The slow growth rate of newly settled spanner crabs was also apparent when length frequency distributions were plotted for each sample date (Figure 7.12). There was a slow progression in the mean length of the first mode over the sampling period, but no apparent modal progression in the second mode. These data will be analysed further in the next section.

7.1.3.3 Estimation of von Bertalanffy parameters from length frequency data

Pooling all samples, the L_∞ values were estimated to be 155.93 mm for males (n = 24,682) and 121.71 mm for females (n = 9,054), using Powell-Wetherall plots in FiSAT. There were some differences in L_∞ values estimated for different regions, but no clear trend in those values with latitude (Table 7.5). The product-moment correlation coefficients were very high for all of the estimated L_∞ values.

Von Bertalanffy K values were estimated for each region by applying the estimated L_∞ value for that region to length frequency data collected using commercial fishing gear from the same region. Those L_∞ values varied widely between regions, and the 'goodness of fit' indices (R_n) were extremely low (Table 7.5a). Scans of potential K values produced very flat R_n response

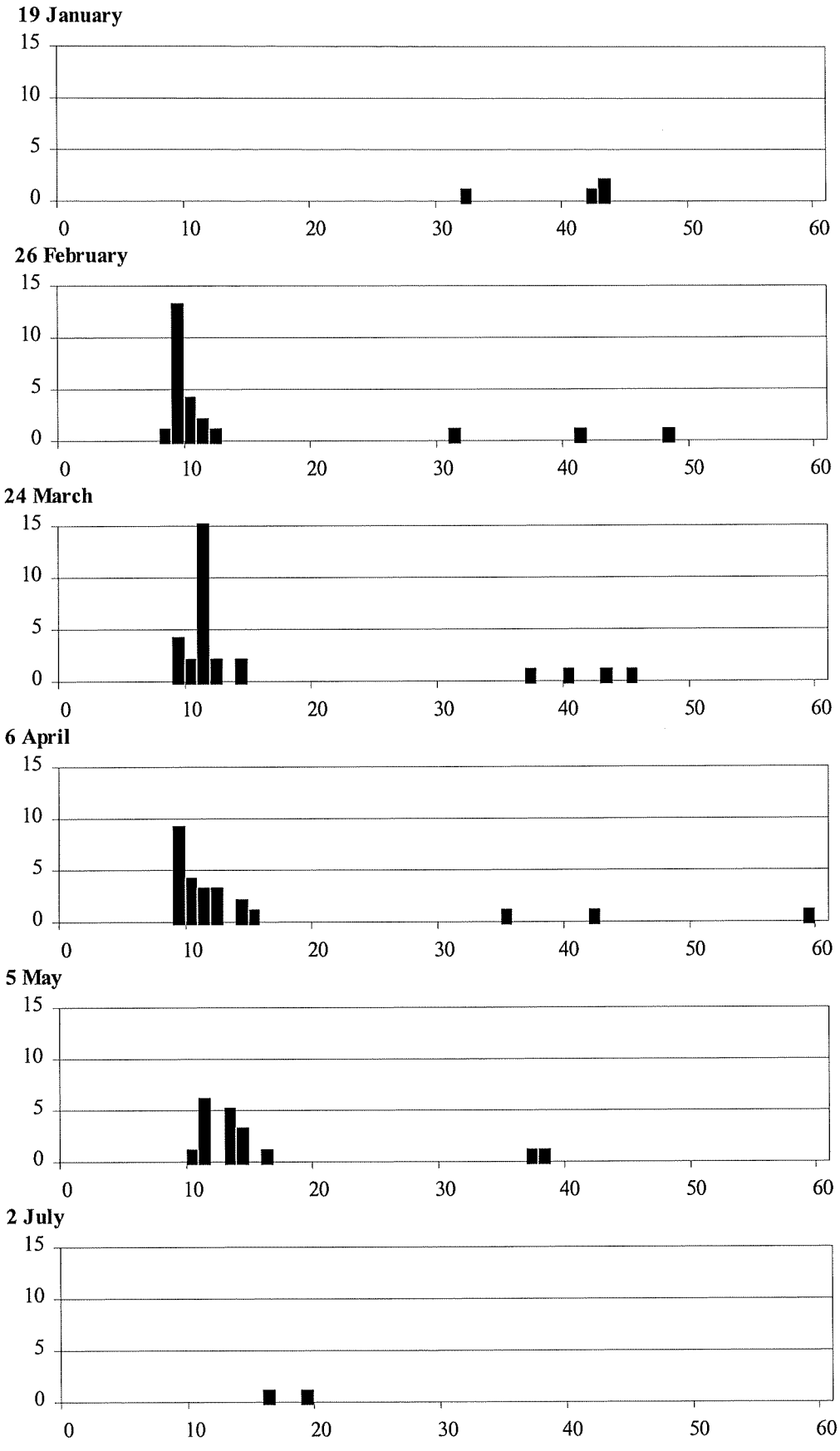

Figure 7.12 Length frequencies of spanner crabs collected in channel dredge samples in 1997 and 1998. Data for both years and all sites combined due to low numbers of crabs in individual samples.

Table 7.5 Estimates of von Bertalanffy growth parameters, L_∞ and K, derived from spanner crab length frequency data using routines in the FiSAT package.

a) Parameters estimated from samples collected using commercial crabbing gear. ELEFAN I estimates of K were calculated for each region based on both the L_∞ value estimated for that region and on that estimated for Queensland (all regions combined). **NB:** length frequency samples were collected from different sites on different dates, and showed no apparent modal progression. Thus the K values estimated from commercial samples are likely to be inaccurate, and are presented merely for the sake of completeness.

b) K values estimated from samples collected using the channel dredge and various L_∞ values estimated in **a)**.

a)

	Powell-Wetherall Plot		ELEFAN I (region L_∞)		ELEFAN I (Qld L_∞)	
	L_∞ (mm)	r	K	R_n	K	R_n
Females						
Queensland	121.71	0.989	-	-	-	-
Capricorn	122.38	0.977	0.84	0.184	0.80	0.183
North Hervey	109.49	0.986	3.30	0.130	0.70	0.133
Wide Bay	128.60	0.988	0.41	0.196	0.76	0.181
Sunshine	111.83	0.993	1.80	0.146	1.10	0.144
Gold Coast	120.68	0.983	1.90	0.145	1.30	0.149
Males						
Queensland	155.93	0.999	-	-	-	-
Capricorn	148.85	0.999	1.90	0.134	1.50	0.135
North Hervey	153.29	0.990	0.84	0.141	0.81	0.143
Wide Bay	149.36	0.990	1.40	0.134	0.80	0.135
Sunshine	160.63	0.997	2.70	0.127	2.00	0.126
Gold Coast	152.49	0.987	2.70	0.132	1.00	0.134

b)

	Seeded L_∞ value		ELEFAN I	
Dredge samples	L_∞ (mm)	from	K	R_n
Sunshine	160.63	M Sunshine	0.13	0.282
	155.93	M Qld	0.21	0.265
	138.82	median	0.15	0.266
	121.71	F Qld	0.26	0.278
	111.83	F Sunshine	0.29	0.278

curves, suggesting that there was little difference in how well (or how poorly) a wide range of K values fitted the data. The K values estimated from length frequency data collected using the dredge were less variable, although the R_n values were also very low (Table 7.5b). Scans of potential K values for those data showed clear peaks between K values of 0.13 and 0.29, suggesting that values in that range fitted the data better than values outside.

Alternative estimates of von Bertalanffy growth parameters were derived by fitting the von Bertalanffy growth model to the length-at-age data estimated from dredge samples above (Section 6.3.1.2) and the L_∞ values estimated for the entire stock (Table 7.6). The resulting parameter estimates were used to plot predicted growth curves (Figure 7.13).

Table 7.6 Estimates of von Bertalanffy growth parameters derived from length-at-age estimates based on dredge samples and L_∞ values estimated by Powell-Wetherall plots of pooled length frequency data.

Sex	L_∞ (mm)	K	T_0
Female	121.711	0.3295	-0.2380
Male	155.933	0.2424	-0.2502

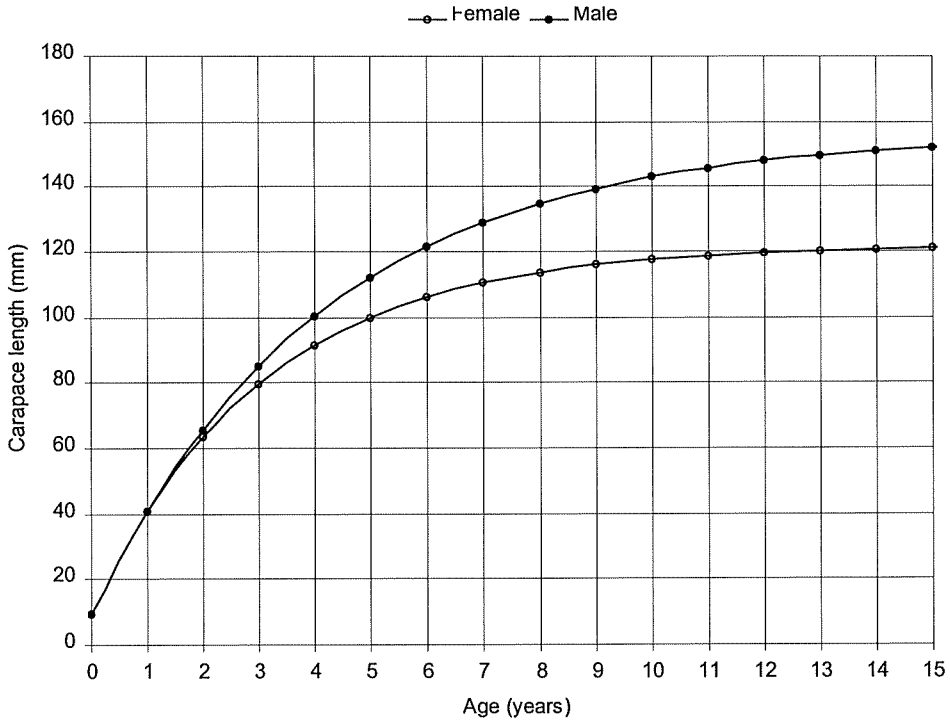

Figure 7.13 Mean growth curves for male and female spanner crabs based on the von Bertalanffy growth parameters presented in Table 7.6. Those parameters were derived from length-at-age estimates based on dredge samples and L_∞ values estimated using Powell-Wetherall plots of pooled length frequency data.

7.1.4 Discussion

The slow growth rates predicted from the length-frequency analysis of dredge samples are consistent with the fact that clear modes were rarely present in the adult length-frequency samples (Figures 7.3 to 7.10). There were, however, a number of male length-frequency graphs that did show two or more apparent modes. Identifying modes in length-frequency distributions is a highly subjective process, and it is common for different observer to perceive different numbers of modes in the same graph. Nevertheless, there were several male length-frequency graphs two obvious and distinct modes, the most apparent being Figures 7.6a, 7.6c, 7.6e and 7.10c. In these four cases the two most apparent modes were at 105 & 124 mm, 103 & 127 mm, 103 & 120 mm, and 103 & 125 mm respectively. If those modes represent successive age-classes, then they indicate that a male crab of 103-105 mm could be expected to grow to a length of 120-127 mm in one year. Growth parameters estimated from the dredge samples and adult male L_∞ predict that such an increment should have taken two years, rather than one. Thus these particular four data sets are apparently at variance with the data from the dredge samples. This may be due (i) to a missing year-class resulting from poor recruitment in one year, (ii) to a lack of congruence between the growth trajectories of juvenile and adult

crabs, or (iii) to the possibility that the growth rates derived from the juvenile samples are not representative of the entire stock.

Although there is an apparent contradiction between some of the adult male length-frequency data and the growth rates determined from dredge samples, this is not the case for all datasets. There are several male l/f data sets that have indistinct modes which (if interpreted as separate age-classes) would support the growth rate predictions from dredge samples. These include Figures 7.5a, 7.5g, 7.7g and 7.8e, each of which has a number of indistinct modes separated by 7-11 mm. Growth rates between 7 and 11 mm per annum amongst adult male crabs are consistent with the predictions of the model shown in Figure 7.13.

The great majority of adult length-frequency distributions, including all those of female crabs, provide no useful information on possible adult cohorts. Furthermore, no series of adult l/f data showed any evidence of modal progression. Thus ELEFAN was unable to achieve a good fit of the von Bertalanffy growth function to any length-frequency distribution series.

A possible source of error common to the previous estimates of spanner crab growth parameters (Brown 1986, de Moussac 1988, Boullé 1995, and Chen & Kennelly 1999) is that they were based on samples of adult crabs caught using baited dillies. All crabs caught with dillies in our Project were above the minimum size for sexual maturity - the smallest crab we captured measured 53 mm. Only 0.02% of the total number were less than 60 mm, and 0.65% less than 70 mm. However, samples collected by the channel dredge demonstrated that large numbers of crabs smaller than 50 mm were present in the area. The absence of overlap in the size ranges of crabs collected by the two methods suggests that both were extremely size-selective. There may be further size-selectivity in samples collected using baited dillies, as larger individuals may travel greater distances to the bait and may exclude smaller individuals from dillies by aggressive interactions (Hill & Wassenberg, in ms.).

Hilborn and Walters (1992) stated that 'the best "fit" growth curve to size frequency data will only be the actual growth curve if the gear is totally unselective' (p 424). As commercial spanner crab gear is extremely size selective, it is difficult to obtain an accurate growth curve for spanner crabs from size frequency data based on samples collected using that gear.

Brown (1986), de Moussac (1988) and Boullé (1995) estimated spanner crab growth using only data from adult crabs, inferring early growth from the assumption that the VBG function describes the younger stages (from settlement until recruitment) equally well. If this is not be the case (see Chen & Kennelly 1999), then the estimates are likely to be biased and not constitute a good description of the species' growth.

A second potential source of error in the growth estimates of Brown (1986), de Moussac (1988) and Boullé (1995) is that they were based upon apparent modal progression in small samples of spanner crabs collected at different sites on different occasions. In the present study, spatial variability in length frequency distributions swamped any modal signals, despite the large sample sizes. In small samples, spatial variability can sometimes lead to apparent modal progressions in sequential length frequency distributions collected from different sites. We found that length frequency samples of fewer than two hundred individuals frequently contained apparent modes (evidently random effects) which disappeared with increasing sample size.

The subjectivity of the length-based methods (ELEFAN 1 and NORMSEP) used in these previous studies also undoubtedly contributed to error in the growth estimates. Little reliance can be placed on the results of these methods unless repeated trials with different combinations of starting parameters converge on the same estimates. Even so, however, the models' output can be biased by the particular mix of initial seed values.

Faced with the problem of small sample sizes, Boullé (1995) pooled length frequency data for the two sexes, which probably resulted in some modes comprising predominantly females and others males. There is no evidence that spanner crabs change sex, so the apparent modal progression seen by Boullé (1995) is unlikely to be a reliable representation of growth.

In summary, we conclude that it is not feasible to estimate spanner crab growth rates from length frequency data derived from the catch of baited tangle nets, because:-

- the gear is highly selective
- length frequency distributions for either sex are rarely multimodal
- length frequency distributions are highly variable spatially
- programs that fit growth curves to length frequency data are subjective.

Chen and Kennelly (1999) conducted a tag recapture study to estimate spanner crab growth rates, and a similar study was also conducted as part of the present research (see Section 7.3 following). During the 1998 Stock Assessment Review Workshop (Dichmont *et al.*, 1999), the Spanner Crab Workimg Group combined the tagging data of Chen and Kennelly (1999) with size-frequency data from our channel-dredging study to provide another estimate of spanner crab growth parameters, considered at the time to be the best available. We believe that those estimates (see Dichmont *et al.*, 1999) may be biased, in light of the results of our tagging experiments (see Section 7.3).

Given the extremely poor fits achieved by ELEFAN I, and the problems associated with other studies, the parameter estimates in Table 7.6 may be the best growth estimates currently available. However, the accuracy of these estimates is limited by the small sample sizes upon which length-at-age estimation was based, and the assumption that the two juvenile modes represent groups of individuals separated by one year in age. Further modelling may improve these growth parameter estimates (and their associated error) from the existing data (Kirkwood *et al.*, in prep.). However, more extensive sampling of juvenile spanner crabs using an appropriate dredge is needed for reliable growth estimation. Further sampling of juvenile crabs, and the application of novel ageing techniques such as lipofuscin assay, might enable regional comparisons of spanner crab growth as well as estimations of longevity, mortality and population age structure (Sheehy 1990, Sheehy *et al.* 1998).

There are many possible causes for the high spatial variability in sex ratios and length frequency distribution of spanner crabs. These include the effects of temperature or nutrition on growth at different locations, spatial variation in the size and timing of recruitment, spatial variation in mortality, behavioural aggregations and different histories of exploitation. Although the effects of these potential factors are merely speculative, there is some evidence to suggest that either latitude or the history of exploitation of a particular area may influence the length frequency distribution of spanner crabs. The mean lengths of spanner crabs caught from recently exploited locations towards the northern end of the current fishery are significantly larger than those caught further south (Table 7.3). The sample of spanner crabs collected from unexploited grounds amongst the Swain Reefs was also dominated by larger individuals. It is not possible to determine whether or not this difference in length frequencies is due to differences in latitude or in exploitation histories. If the spatial differences in population size distribution are real, consistent, and due to factors such as recruitment and mortality described above, it would suggest that there is little mixing within the population. It would certainly not support the hypothesis of major spawning migrations.

Whatever the cause of this spatial variability, it would seem that the critical issue with respect to age estimation is the lack of consistent multimodality in the length-frequency data. If spanner crabs are slow-growing and long-lived, the absence of modal resolution probably means that growth is quite variable, and that there is a very significant amount of overlap between the size-distributions of adjacent age-classes. This being the case, one might expect there to be (i) a poor correlation between premoult carapace length and the magnitude of the

moult increment, (ii) highly variable intermoult period regardless of size, or (iii) a combination of the two.

From 1981 to 1984, Brown (1986) collected a total of 11,491 spanner crabs from between 26°40'S (Pt Cartwright) and 27°27'S (Pt Lookout, Stradbroke Island) in Region 5. In the present study, we collected 7,565 spanner crabs from between 26°40'S (Pt Cartwright) and 27°00'S (Cape Moreton, Moreton Island) in Region 5, from 1995 to 1998. Although we did not collect samples from south of Cape Moreton in Region 5, comparison between the two studies conducted 14 years apart may give some indication of historical trends in the fishery (Table 7.7).

Comparing the length frequency distributions for Region 5, the present study found a substantially lower proportion of males in the 100 to 140mm RCL range than did Brown (1986). Related to this, we also found the modal carapace length to be about seven to ten millimetres less than that found by Brown (Table 7.7). There was no apparent difference between the studies in the proportion of females in different length classes, nor in the modal length of females (Table 7.7). Such differences are consistent with a reduction in the abundance of legal sized males due to fishing pressure. However, they may also have been influenced by the fact that Brown (1986) included samples from east of Moreton Island whereas the present study did not.

In addition to having fewer males in the 100 to 140 mm size class, the present study found more very large males than did Brown (1986). We found 137 males greater than 140 mm RCL (2.3%), whereas Brown (1986) only found about ten (c. 0.1%)($X^2 = 169$, df = 1, $P < 0.00001$). We also found eleven males larger than Brown's reported maximum size of 150 mm RCL. One potential explanation for this apparent increase is that spanner crabbers may have located some previously unexploited grounds in Region 5 since Brown's (1986) study. The progressive expansion of the spanner crab fishery into new grounds has lead to larger spanner crabs having been found in recent years. Most of that expansion has occurred to the north, and most of the larger crabs have come from more northerly fishing grounds (Figure 7.3, Table 7.3). However, although spanner crabs of both sexes were significantly larger on newly exploited grounds than on more established fishing grounds, that may have been due to latitudinal differences rather than short exploitation histories.

Table 7.7: Comparison of the sex ratios, modal lengths (RCL = Rostral Carapace Length) and percentages of spanner crabs greater than the legal minimum size between Brown's (1986) study in Region 5, and samples collected from Region 5 in the present study. Note: Brown's study included the area east of Moreton Island (27 to 27°27'S) whereas the present study did not.

Years sampled		Brown (1986) 1981-1984	Present Study 1995-1998
Number sampled	Male	8,632	6,013
	Female	2,859	1,552
	Total	11,491	7,565
Sex ratio	(M/F)	3.02	3.88
Modal length	Male	102-105	95
(RCL, mm)	Female	87 - 90	90
Percentage	Male	54.34	50.78
> 100mm RCL	Female		10.09

The samples collected by the channel dredge clearly demonstrated that juvenile spanner crabs were present in the area to the north of Moreton Island in 1997 and 1998, yet they were not collected in any samples collected using commercial spanner crab fishing gear. In fact, there were no spanner crabs of less than 53 mm RCL caught using commercial gear at any time throughout this study. While many crab fishers (including N. Morgan, M. Thomson, A. Jones, and R. Freeman, personal communications) have reported catching spanner crabs smaller than 50 mm, they stress that it occurs only very rarely.

There are three possible reasons why juvenile spanner crabs are not susceptible, or have an extremely low susceptibility, to capture from commercial fishing gear. Either they are not attracted to the bait, they cannot reach the baited dillies or they are not caught by the gear after having been attracted to the bait.

Supporting evidence for the first hypothesis comes from laboratory observations of the behaviour of juvenile spanner crabs[1]. Spanner crab megalopae and juveniles could not be induced to leave the sand to feed upon non-living food items, despite being offered a wide variety of potential foods including fish (*Sardinops neopilchardus*, *Sillago robusta*), commercial prawn pellets and high protein crab food. They did however feed readily on live *Artemia salina* (brine shrimp). Thus juvenile spanner crabs may be unlikely to be attracted to fishing gear baited with non-living food (usually *Sardinops neopilchardus*).

Further supporting evidence for juvenile spanner crabs not being attracted to bait comes from a small experiment conducted in the same area that juvenile spanner crabs were collected using the channel dredge on 8/ 4/'98 (Kirkwood, unpublished data). Ten spanner crab dillies were covered with a fine felt mesh used to collect settling megalopae of other species, before being baited and set in the normal way. No juvenile spanner crabs were caught on those dillies, although they did catch eleven adults. A total of nine juveniles and megalopae were caught in the same area using the channel dredge on that day. Thus, juveniles were present in the area, but were not caught on the modified baited dillies.

Although it is possible that juveniles are attracted to baited dillies on some occasions, their behaviour in the laboratory suggests that they normally feed only on live prey which they have detected visually. It therefore seems likely that spanner crabs undergo a change in feeding preferences after they reach sexual maturity. For a spanner crab to be attracted to a bait, the

[1] Spanner crab megalopae were collected from Cylinder Beach, Stradbroke Island by Mr Neville Todd on 2 February 1996, having emerged from intertidal sand flats at low tide.

benefits of scavenging would have to outweigh the risks associated with leaving the sand. Adult spanner crabs have thicker carapaces than juveniles, and approach or exceed the size of many of the fish (e.g. dart, *Trachinotus spp*., D. McPhee, personal communication) that are known to prey on juveniles. Thus, they would be subject to less risk of predation than juveniles when emerged. Adult spanner crabs may also have a greater food requirement than juveniles, and may therefore be less selective in what they eat.

Alternative explanations for the absence of juvenile spanner crabs from samples collected using commercial gear are that they may not be able to reach the gear because of their poor swimming ability against the prevailing currents, or they may not be caught by the gear. However, while those factors may explain the absence of very small juvenile crabs from dilly caught samples, they do not explain their lack of attraction to non-living food in the laboratory.

7.2 TRIALS OF HYDRAULIC DREDGE PROTOTYPE

7.2.1 Introduction

From the length frequency analyses above (Section 7.1), it can be clearly seen that commercial spanner crab fishing gear is very size selective. No spanner crabs smaller than 53 mm RCL were caught using dillies, and crabs smaller than 70 mm were captured only rarely. This was despite the fact that samples collected using the channel dredge clearly demonstrated that spanner crabs of as small as 8.3 mm CL were present in the study area.

In addition to not sampling juvenile spanner crabs at all, commercial spanner crab gear may not collect representative samples of the adult spanner crabs present in an area. This is because that crab gear relies on the behavioural attraction of crabs to bait in order for them to be captured. Adult spanner crabs do not feed close to spawning or moulting, and probably at other times such as immediately after feeding, and thus are not attracted to baited dillies at those times (Skinner & Hill 1987). Of the crabs that are attracted to the bait, there is a tendency for small crabs to be excluded by aggressive interactions with larger crabs (Hill & Wassenberg, unpublished ms.). Thus, there may be further size selectivity amongst crabs which are susceptible to capture using baited traps.

Because of the limitations of commercial fishing gear as a reliable quantitative sampling tool for spanner crabs, alternative sampling gear is needed to collect spanner crabs of all sizes. Adult spanner crabs normally spend over 95% of their time buried just beneath the sand surface, emerging only to feed and mate (Skinner & Hill 1986, 1987), and the megalopae and juveniles emerge only to feed (Kirkwood, personal observation). Thus, the alternative sampling gear would need to collect spanner crabs from within the sand without relying on the crabs coming to it. We designed two types of dredge to achieve this end, the channel dredge described in Section 7.1.2.2 (above) and a new type of hydraulic dredge.

The hydraulic dredge was designed in order to overcome some of the limitations of the channel dredge. Although that dredge was successful in capturing very small spanner crabs, its utility as a sampling tool was somewhat limited. Most importantly, it did not collect whole crabs larger than 19 mm RCL, although it did collect measurable portions of several crabs of up to 59 mm RCL. The carapace lengths of spanner crabs in the 19 to 48 mm size range could be accurately estimated from the retained portions using Equation 7.1. However, a number of crabs in that size range were too damaged for accurate measurement, and only isolated shell fragments were retained from larger crabs. It was not possible to estimate the size of crabs from those fragments, nor even to tell whether they had come from previously dead or alive crabs. In addition, it was not possible to determine the sex of spanner crabs from the portions retained as there was no apparent sexual dimorphism in the anterior part of the cephalothorax of juvenile crabs.

The other major limitation of the channel dredge was that it yielded very low catch rates – as few as one crab per hour of operation (Table 7.4). In addition to this, the dredge collected several kilograms of small shell fragments in each sample, making it a laborious process to sort through the sample. Because of the very low catch rates and labour intensive sample sorting, sampling using the channel dredge provided little return for a considerable expenditure of effort and resources.

As a result of the inability of commercial gear to collect samples of small crabs and the limitations of the channel dredge, an alternative dredge was needed. Ideally that dredge would collect and retain whole spanner crabs over a wide range of sizes in sufficiently good condition to enable length measurement. It would also have a sufficiently high catch rate to enable estimation of population density and to make sampling a cost-effective operation. We decided that an hydraulic dredge would best meet these criteria. Existing hydraulic dredges which

penetrate the sediment to a sufficient depth rely on high pressure water jets which squirt downwards into the substratum. Such high pressures would blast small spanner crabs apart, and may cause sufficient damage to larger crabs as to render them unmeasurable. Thus, a completely new concept in hydraulic dredges was designed and tested in order to collect quantitative samples of spanner crabs over a wide size range and in good condition.

7.2.2 Methods

The basic operating principle of hydraulic dredges is that they inject water into the substratum (usually sand) in front of the dredge blade so as to turn that substratum into a sand-water slurry through which the dredge blade can pass. This enables the hydraulic dredge to collect samples from sediments which other dredges cannot penetrate effectively.

The hydraulic dredge designed for this study incorporated three features not found in existing hydraulic dredges:-

- It operated using high volume-low pressure pumps to reduce the risk of damaging smaller and more fragile crabs.
- It injected the water under the sand, at the cutting blade, so as to push the sand and crabs upwards and into the body of the dredge. This also avoided the necessity of the high outlet pressures of other hydraulic dredges.
- It incorporated an angled hydroplane, to hold the dredge firmly on the sea floor and create a negative pressure above the cutting blade to assist in lifting the substratum.

A prototype version of a new hydraulic dredge was constructed for field testing (Figure 7.14). This prototype incorporated seven forward facing high-volume water jets into a cutting blade which was set at a depth of 100 mm beneath the sand surface. Each jet had a diameter of 25 mm. To ensure a consistent water pressure in each jet, water passed through a large diameter manifold before reaching the jets.

The dredge was towed along the sea floor on two skids which ensured a constant depth of cut. The front portion of the dredge contained an angled hydroplane, which acted to hold the dredge firmly on the sea floor, and also created a negative pressure above the cutting blade to assist in lifting the substratum. Immediately behind the blade was a cage section constructed of 10 mm steel mesh. This section filtered out all particles greater than 10 mm across, and passed them back to a mesh bag which also had a 10 mm mesh diameter. This mesh size was selected to minimise the volume of shell fragments while ensuring the retention of juvenile spanner crabs. Although most megalopae would pass through a 10 mm mesh, they could be adequately sampled using the channel dredge, which had a 5 mm mesh.

Water was pumped down to the dredge using a surface mounted pump. It is envisaged that in its final form the dredge would incorporate a submersible pump powered by hydraulic pressure from the towing vessel. Although submersible pumps would be more efficient as they would not need to overcome a pressure differential, surface mounted pumps were more appropriate for trials as they could be borrowed or hired. Three different pump/vessel combinations were trialed on three different days (Table 7.8). A number of tows were attempted on each day, several of which were observed underwater by divers.

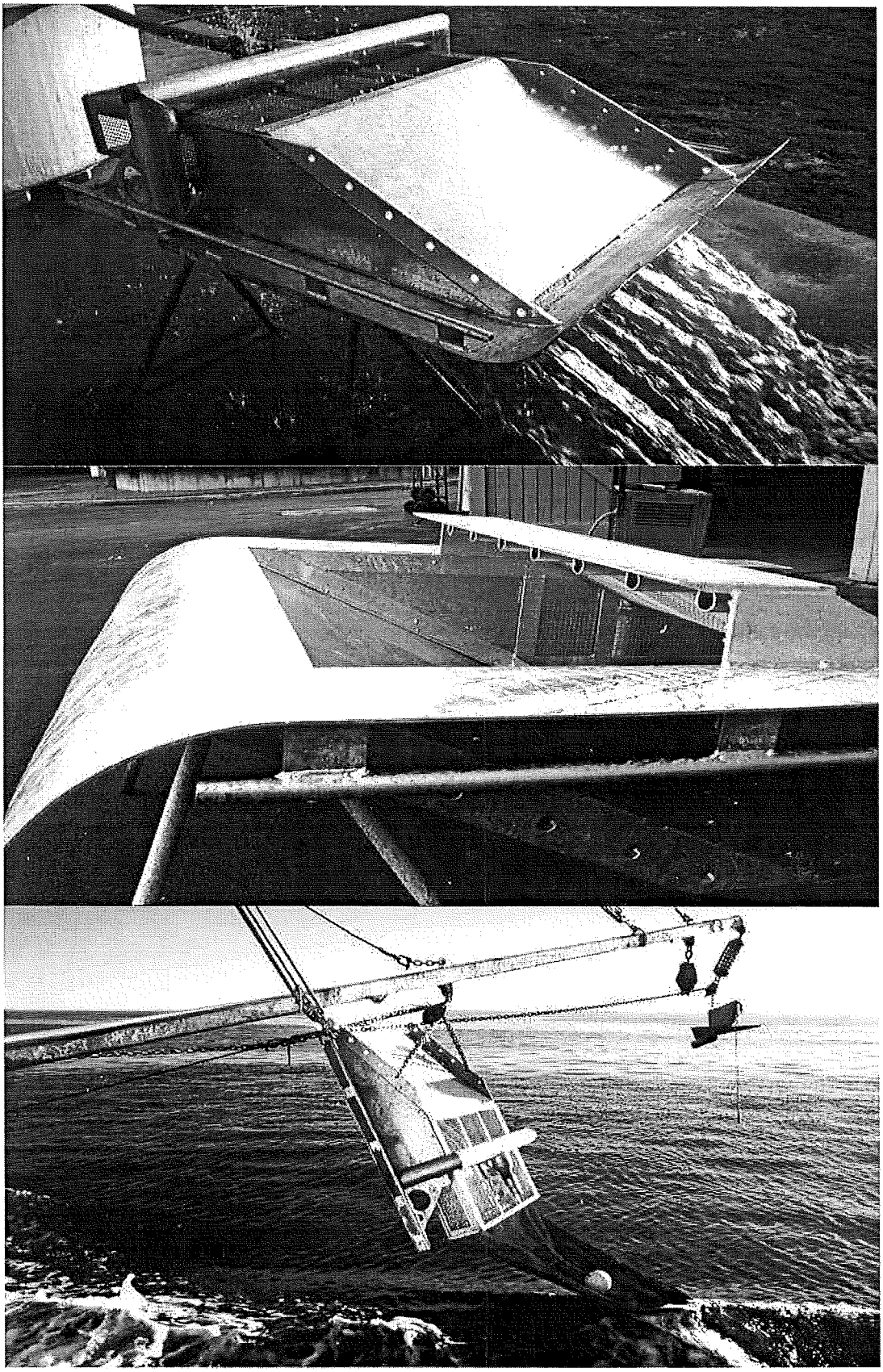

Figure 7.14 Hydraulic dredge prototype. Top: upper side of dredge, showing hydroplane section, manifold and water jets. Middle: lower side of dredge showing cutting blade and water outlets. Bottom: dredge on trawl arm prior to hose attachment (note mesh bag).

Table 7.8 Details of areas of operation, vessels and pumps used in trials of the hydraulic dredge. Maximum flow rates are expressed in litres.min^{-1} (lpm). *The actual flow rate of this pump was much less than this as the power of the diesel motor had been limited.

Date	16/ 7/98	14/ 8/98	20/ 9/98
Area	N. of Moreton Is.	N. of Moreton Is.	Moreton Bay
Vessel	*Warrego*	*Diamond Vee*	*Diamond Vee*
Vessel type	Planing hull	Trawler	Trawler
Pump type	16hp. petrol	2 cyl. Diesel	4 cyl. diesel
Weight (kg)	30	750	1,250
Maximum flow rate (lpm)	500	1,500*	2,700
Maximum pressure (kPa)	600	830	870
Substratum	Sand	Sand	Mud/sand

7.2.3 Results

In the first trial (16/7/98), the 16 hp fire pump did not pump a sufficient volume of water for the dredge to operate effectively. Although divers estimated that the *Warrego* maintained a towing velocity of about 5-10 metres.min^{-1}, that velocity was imperceptible aboard the vessel. Although no spanner crabs were caught, twelve small burrowing sand crabs (*Matuta sp.*) were collected from a depth of 7 metres in a towing time of 30 minutes. Those crabs covered the size range of juvenile spanner crabs, having carapace widths ranging from 15 to 70 mm.

In the second trial (14/8/98), the two-cylinder diesel pump did not deliver the 1,500 lpm it was capable of as the supplier had limited the output of the diesel motor, so did not deliver a sufficient volume of water for the dredge to operate effectively. The towing velocity was similar to that of the first trial and was also imperceptible aboard the vessel. As in the first trial, no spanner crabs were caught, although eight *Matuta sp.* of between 15 and 28 mm carapace width were collected in a total towing time of 45 minutes. Several attempts were made to deploy the dredge while the vessel was moving, but because of the vessels speed and the limited amount of hose available, it was not possible to let out sufficient line for the dredge to penetrate the sea floor. A variety of small epifaunal invertebrates (mainly holothurians and echinoids), but no infauna, were collected when the dredge was deployed in this manner.

In the third trial (20/ 9/98), a series of logistical difficulties prevented adequate testing of the gear. Because the four-cylinder diesel pump weighed almost 1,500 kg with a full load of fuel it seriously affected the trim of the *Diamond Vee*. It was therefore unsafe to operate the vessel in open waters, so the trial was conducted in the partially smooth waters of Moreton Bay. The substratum in the test area was muddy sand, which was unsuitable for spanner crabs and for operation of the dredge. The first time it was deployed, the hydroplane section of the dredge came loose and ceased to function. When lowered to the sea floor without this hydrofoil in place, the dredge failed to penetrate the substratum whether the vessel was stationary or in motion. Further trials were cancelled because of time constraints.

7.2.4 Discussion

Numerous logistical difficulties were experienced in conducting sea trials of the hydraulic dredge. Neither of the first two pumps produced a sufficient water volume to operate the dredge, although the two-cylinder diesel pump may have been capable of doing so had it not been limited mechanically. The third pump was too heavy for the trawler to operate safely on

the spanner crab grounds, and could not be tested properly because of damage to the dredge. The trawler which was chartered (*Diamond Vee*) was a fairly small vessel, and was not configured to enable stern trawling. Also, it was not capable of the very slow speed operations necessary for towing an hydraulic dredge. As a result of those logistical difficulties, and others, it was not possible to adequately trial the hydraulic dredge.

Although the first two trials were conducted in an area where spanner crabs had been caught with the channel dredge, they failed to collect any spanner crabs. There are several possible explanations for this, including:-

- spanner crabs were present in the area, but were not collected because the hydraulic dredge sampled an insufficient area of substratum
- spanner crabs were present in the area, but were able to avoid the dredge
- spanner crabs were absent from the area at the time

Catch rates using the channel dredge declined over the first six months of the year, reaching a minimum of one crab.hr^{-1} in June (after which sampling was discontinued). This decline in apparent abundance may have occurred as a result of juvenile spanner crabs moving out of the area, or by the density of juveniles in the area declining due to mortality. Thus, the failure of the hydraulic dredge to collect any spanner crab juveniles may have simply been due to their low abundance at the time of sampling. The fact that the hydraulic dredge did collect samples of the infaunal crab *Matuta sp.* over a similar size range to that of juvenile spanner crabs suggests that the dredge may have been successful in collecting spanner crabs had they been present in sufficient numbers.

Despite a considerable effort, the best estimate of spanner crab growth rates produced so far come from the limited samples collected using the channel dredge. However, the accuracy of those estimates is limited by the small sample sizes, and by the limitations of the channel dredge. The hydraulic dredge may enable accurate, reliable estimates of spanner crab growth rates, and comparison of growth rates from different areas.

In addition to enabling more accurate growth estimation, the hydraulic dredge may also enable accurate estimation of the absolute abundance and distribution of spanner crab adults and juveniles. Samples collected using baited tangle nets may only provide an estimate of relative abundance, and are subject to the vagaries of spanner crab behaviour as well as the unknown effects of currents and bottom topography on the size of the area from which crabs are attracted. Quantitative sampling of spanner crabs over a wide size range should also enable estimation of larval settlement rates, recruitment and mortality.

7.3 ESTIMATION OF GROWTH RATES FROM TAG-RECAPTURE PROGRAM

7.3.1 Introduction

As it was not possible to estimate growth rates from length frequency data collected using commercial gear (see Section 7.1, above) we attempted to estimate growth using a tag-recapture study. Chen and Kennelly (1999) have estimated relative spanner crab growth using a tag-recapture study. They applied a number of growth models to their data, including a 'probablistic stepwise' growth model which attempted to describe the growth trajectory of an individual crab. However, they also applied the von Bertalanffy model which enabled their estimates to be compared to those from other studies. Chen & Kennelly (1999) concluded that adult spanner crabs grow extremely slowly, in line with the estimates of de Moussac (1988). This was in contrast to the other Australian study (Brown 1986) and the study of Boullé (1995). However Chen and Kennelly (1999) warned that their results should not be extrapolated to estimate the growth rates of juvenile crabs, which were not caught in their fishing apparatus.

One potential source of error in tagging studies of growth is that the presence of the tag may affect growth rate. Such effects may have biased growth estimates downwards. To determine whether tagging did in fact influence the growth of spanner crabs, we conducted a number of laboratory trials of various tagging methods, prior to tagging spanner crabs in the field. The laboratory experiments also enabled selection of the most appropriate tagging method using the following criteria, of:-

- causing minimal mortality,
- having minimal effect on moulting success,
- having minimal effect on growth measured by change in length,
- having minimal effect on growth measured by change in weight,
- being immediately apparent to crabbers, and
- being easily and rapidly applied at sea.

7.3.2 Methods

7.3.2.1 Experiment 1: Effect of tagging location using 't-bar anchor' tags

The aim of this experiment was to determine whether there were any differences in the survival, weight gain and growth of crabs which had been tagged with t-bar anchor tags in either of two places and that of control crabs. It also enabled a qualitative assessment of the relative ease of tagging and tag visibility in the two tagging locations. The two tagging locations were 'Carapace Tagged' and 'Leg Tagged'. 'Carapace Tagged' crabs were tagged according to Chen and Kennelly (1999), viz: "The tags were inserted into the dorsal ecdysial suture line between the posterior margin of the carapace and the first abdominal segment. To avoid the gut, nerve chord and main artery the tags were inserted into the leg musculature to the right side of the centre of the dorsal surface" (Chen and Kennelly, 1999). Insertion of the tagging needle left a small hole (2-3 mm diameter) in the posterior margin of the carapace. 'Leg Tagged' crabs were tagged through the soft integument at the base of the third right pereiopod, between the coxa and the ventral plate. This method of tagging left no permanent hole in the exoskeleton. Control crabs were untagged.

Experimental crabs were collected from 26°54′S, 153°27′E, in the 'Dog's Leg' area, north of Moreton Island, on 29 May 1997 using standard commercial crabbing techniques. All crabs were carefully disentangled from the tangle nets, and were inspected to ensure that they had suffered no damage. Intact crabs were transported to the Southern Fisheries Centre, and were placed in a 3m diameter holding tank within six hours of capture. This tank was supplied with

a constant flow of fresh, oxygenated seawater, which was maintained at a depth of 90 cm. Crabs were inspected again the following morning, and 84 active uninjured crabs (48 males and 36 females) were retained for experimental purposes.

Each crab was marked which an individual number, which was written on its carapace with a 'Markal-B' paintstick. Each crab was then randomly assigned to one of three treatments: 'Carapace Tagged', 'Leg Tagged' or Control (16 males and 12 females per treatment). The tags used were standard 't-bar' anchor tags, each consisting of a 10 mm long, 1 mm diameter vinyl anchor attached to a 60 mm, 0.5 mm diameter shaft. The distal 30 mm of the shaft was covered by a 1.75 mm sheath containing identification information. These tags were almost identical to those used by Chen and Kennelly (1999) for their field tagging study of spanner crabs. Between tag injections, the tagging needle was soaked in absolute ethanol and smeared with antiseptic cream.

The experiment commenced on 30 May 1997. Each crab was marked, measured, weighed and tagged (if appropriate) before being randomly assigned to one of four experimental tanks. Seven crabs from each treatment group (four males and three females) were placed in each 3m diameter tank. Thus, there were 21 crabs per tank, at an initial density of 2.97 crabs.m^{-2}. The base of each tank was lined with a 20 cm layer of washed pit sand, so that the crabs could bury themselves completely. Each tank was supplied with a constant flow of fresh, oxygenated seawater, which was maintained at a depth of 90 cm. The crabs in each tank were inspected daily for the first 40 days, and then on each week day (Mon.-Fri.) for the next 40 days. At each inspection, any dead crabs were removed, measured, weighed and dissected. In some instances, crabs were partially decomposed when discovered, so were not weighed or dissected. Dissection involved inspection of the tag location to look for any sign of infection or encapsulation of the tag.

After 40 days, the experimental tanks were drained and all surviving crabs were removed for measurement and weighing. The tanks were the re-filled, crabs were returned to their initial tanks and the experiment was continued for another 40 days. After 80 days, the experimental tanks were again drained and all crabs removed for measurement and weighing. All sand was removed from the experimental tanks, and the tanks were thoroughly cleaned and acid washed in preparation for the second experiment. All surviving crabs were placed in Tank 4 for longer term monitoring and/or use in future experiments. Throughout the experiment, crabs were fed on Mondays, Wednesdays and Fridays. At each feeding five stout whiting *Sillago robusta,* fork lengths 15-20 cm, were supplied to each tank. The fish were left in the tanks for four to five hours, after which uneaten fish were removed.

Mortality data were analysed using a two-way randomised complete blocks design, with the experimental tanks being the blocks, and the factors being sex and treatment. As there were different mortalities in each treatment group, comparison of weight gains for each sex and treatment would involve a two-way ANOVA with unequal and disproportional class sizes. This disproportionality would lead to some treatment groups influencing the analysis more strongly than others, causing non-orthogonality (Sokal & Rohlf 1995). We therefore pooled data for both sexes to analyse percentage growth data using a simple one-way ANOVA with unequal sample sizes.

7.3.2.2 Experiment 2: Trial of alternative tagging technologies

This experiment followed on from Experiment 1 (above) which demonstrated that tagging spanner crabs using T-bar anchor tags in either of the two sites trialed was unsatisfactory. Tagging in the posterior margin of the carapace had significant adverse effects on the crab's survival and weight gain, and tagging in the soft integument at the base of the third pereiopod was logistically difficult and rendered the tag less apparent (see Results, Section 6.3.2.1). It

was therefore decided to conduct further experiments using alternative technologies for tagging and marking crabs.

The aim of this second experiment was to determine whether there were any differences in the survival, weight gain and growth of crabs which had been tagged or marked using a variety of methods. It also enabled a qualitative assessment of the relative ease of use of the different methods and the visibility of the marks or tags.

Experimental crabs were collected on 27 August 1997 from the same site as in Experiment 1, and handling prior to the experiment followed the same procedure. A total of 112 active uninjured crabs (56 males and 56 females) were retained for experimental purposes. Each crab was randomly assigned to one of seven treatments: 'Carapace Tagged', 'Visual Implant Elastomer (VIE)', 'Visual Implant Alphanumeric (VIA)', 'Coded Wire Tag (CWT)', 'Branded 20 seconds', 'Branded 5 seconds' or Control (8 males and 8 females per treatment). 'Carapace Tagged' crabs were tagged in the same manner as in Experiment 1, while Control crabs received no mark, tag or brand.

'Visual Implant Elastomer (VIE)' crabs were marked with a fluorescent coloured elastomer (synthetic rubber) which was injected in liquid form and cured to form a pliable, bio-compatible solid. The VIE mark was injected under the transparent integument at the base of the first periopod, between the coxa and the ventral plate. Between injections, the needle was wiped clean with a sterile ethanol soaked swab and washed in absolute ethanol. This method of marking left no permanent hole in the exoskeleton.

'Visual Implant Alphanumeric (VIA)' crabs had a 3mm x 1mm vinyl tag inserted under the transparent integument at the base of the first periopod, between the coxa and the ventral plate. Each VIA tag had a unique 3-digit alphanumeric code (e.g., 'E23') which was visible through the crab's integument. Between tag insertions, the insertion tool was wiped clean with a sterile ethanol soaked swab and washed in absolute ethanol. This method of marking left no permanent hole in the exoskeleton.

'Coded Wire Tag (CWT)' crabs had a 1.10mm long piece of 0.25mm diameter stainless steel wire inserted into the right side of their second abdominal segment. The insertion site was selected to avoid tissue which may have been eaten by a human consumer, and to avoid the crab's intestine. Each CWT was etched with two rows of notches forming a unique code which would enable identification of individual crabs by microscopic examination (after dissection and removal of the CWT). Between tag insertions, the insertion tool was wiped clean with a sterile ethanol soaked swab and washed in absolute ethanol. This method of marking left a very small (< 1.0mm diameter) hole in the exoskeleton. The presence of a CWT in a crab could be determined by passing an inductive sensor above the abdomen.

Branded crabs were cryogenically branded with a 35mm long by 4mm wide brass cattle brand, in the shape of the number '1'. This brand was chilled to –196°C in liquid nitrogen, and was applied to the dorsal carapace above the leg musclature on the right side. This branding site was selected to avoid damage to internal organs. The brand was applied either for 5 seconds (= 'Branded 5 seconds') or for two 10 second applications on the same site, with the brand being re-chilled between applications (= 'Branded 20 seconds').

VIE and branding were used to mark batches of crabs rather than tag individuals. These methods could not be used to identify individual crabs unless they were used in conjunction with another method. T-bar anchor tags, VIA and CWT could be used to identify individual crabs.

The experiment commenced on 28 August 1997. Each crab was marked, measured, weighed and tagged (if appropriate) before being randomly assigned to one of three experimental tanks. Four crabs from each treatment group (two males and two females) were placed in Tank 1,

while six crabs from each treatment group (three males and three females) were placed in Tanks 2 & 3. Thus, there were 28 crabs in Tank 1 (initial density = 3.96 crabs m^{-2}), and 42 crabs in each of Tanks 2 & 3 (initial density = 5.94 crabs m^{-2}). The reason for these unequal densities was to ensure that each treatment-sex combination was equally represented in each tank. Tanks were configured in the same manner as in Experiment 1. Each tank was inspected on each week day for 40 days. At each inspection, any dead crabs were removed, measured, weighed and dissected. In some instances, crabs were partially decomposed when discovered, so were not weighed or dissected. Dissection involved inspection of the tag location to look for any sign of encapsulation of the tag or infection. The experiment was terminated at Day 40, when the tanks were drained and all surviving crabs were removed for measurement and weighing. The experimental tanks were re-filled and all surviving crabs were returned to their initial tanks for longer term monitoring and/or use in further experiments. The feeding regime throughout this experiment was the same as that used in Experiment 1.

7.3.2.3 Experiment 3: Effect of tagging site with a t-bar anchor tag on ecdysis

The aim of this experiment was to determine whether t-bar anchor tags in two different locations were retained through ecdysis, and whether they affected moulting success. As none of the crabs from the first two experiments had moulted in captivity, two alternative methods were used to induce ecdysis; injection with ecdysterone and eyestalk ablation.

This experiment commenced on 14 November 1997 (Day 0) and used crabs surviving from Experiment 1, which commenced on 30 May 1997. The use of crabs which had been tagged 24 weeks earlier avoided mortality or other physiological or behavioural short-term effects of tagging. A total of twelve crabs were initially selected for this experiment, with four crabs (2 male and 2 female) being randomly selected from each of the three treatment groups ('Carapace Tagged', 'Leg Tagged' and Control). Each crab was placed in a separate 54 litre (60 x 30 x 30 cm) tank, the base of which was covered with a 12 cm layer of washed pit sand. Tanks were filled with filtered seawater (replaced each second day) and aerated. Crabs were not fed during this experiment.

To induce ecdysis, each crab was injected with 20-hydroxy-ecdysterone at a dosage rate of $4\mu g.kg^{-1}$ body weight. This ecdysterone was diluted with sterile seawater, and injected into the leg musculature through the soft integument at the base of the third right pereiopod. Five of the experimental crabs had died (2 'Carapace Tagged', 2 'Leg Tagged' and 1 Control) by 17 November (Day 3) so they were replaced with crabs randomly selected from the same treatment group and sex. As none of the seven surviving crabs had moulted at that stage, both old and new experimental crabs were injected with a higher dosage of ecdysterone ($8\mu g.kg^{-1}$ body weight). No experimental crab had moulted by 24 November (Day 10), and one of them had died ('Leg Tagged') so was replaced by a crab randomly selected from the same treatment and sex. Eyestalk ablation was then used in a further attempt to induce ecdysis in the eleven surviving crabs and one additional crab. Eyestalk ablation involved cauterising the base of the right eyestalk to remove the Green gland which secretes moult inhibiting hormone. This ablation technique was applied to reduce the potential of mortality occurring due to blood loss.

7.3.2.4 Experiment 4: Effect of manner of application of t-bar anchor tag on ecdysis

The aim of this experiment was to determine whether t-bar anchor tags applied to the posterior margin of the carapace (= 'Carapace tagged') by two different methods were retained through ecdysis, and whether they affected moulting success. As neither injection with ecdysterone nor single eyestalk ablation induced successful moulting, double eyestalk ablation was used in order to induce ecdysis in this experiment.

This experiment used previously untagged crabs surviving from Experiments 1 and 2. Two different tagging methods were employed: 'Carapace tagged' crabs were tagged as in previous experiments and 'Drilled Carapace tagged' crabs were tagged in the same site through a 2.5mm diameter hole drilled using a cordless electric drill. Prior drilling of a tagging hole enabled the depth of tag penetration to be more precisely controlled, and avoided the formation of large irregular holes in the carapace. A total of twelve crabs were used for this experiment, with four crabs (2 male and 2 female) being randomly allocated to each of the three treatment groups ('Carapace Tagged', 'Drilled Carapace Tagged' and Control). Each crab was placed in a separate 54 litre (60 x 30 x 30 cm) tank, the base of which was covered with a 12 cm layer of washed pit sand. Tanks were filled with filtered seawater (replaced each second day) and aerated. Crabs were not fed during this experiment.

Crabs were tagged on 1 December, and had their eyestalks ablated on 2 December 1997 (Day 0). Eyestalk ablation followed the same procedure as in Experiment 3. Crabs were inspected daily and were not fed throughout this experiment. At the conclusion of this experiment all surviving crabs were returned to the sea.

7.3.2.5 Field Tagging Experiments

Following consideration of the results of the laboratory experiments it was decided to use a field tagging tagging method which was virtually identical to that used by Chen and Kennelly (1999) This method was quick and easy to apply in the field, provided a clearly visible individual tag and enabled more valid comparisons to be made between the results of the two studies (see Section 6.3.3.4 below for more details).

Field tagging trials were conducted in the Dog's Leg area on 18 December 1997 and 6 January 1998. The aim of these trials was to finalise details of tagging methodology and train personnel to ensure consistency of handling and tagging methods. A total of 420 spanner crabs were tagged and released on those two days. The majority of field tagging was conducted between 15 January and 11 February 1998, when a further 3,822 crabs were tagged and released between 23°00' and 28°12'S. An additional 562 crabs were tagged and released off the Sunshine Coast on 29 May 1998 so as to make the tagging effort more even between the five regions in Managed Area A. Thus a total of 4,804 spanner crabs were tagged and released along the Queensland coast south of 23°00'S. Of those, only 37 were tagged and released in Managed Area B owing to extremely low catch rates from that area.

Spanner crabs were caught from areas of known concentrations using standard commercial crabbing techniques. All crabs were carefully removed from the dillies, and only healthy whole crabs were retained for tagging. Injured crabs were either retained for genetic analysis or discarded. Healthy whole crabs were sexed, and measured from the posterior edge of the carapace to anterior tip of the rostrum (= Rostral Carapace Length, RCL) prior to being tagged. Crabs with broken rostra were measured from the posterior edge of the carapace to posterior margin of the eye orbit (= Orbital Carapace Length, OCL) and lengths converted to RCL using a regression (Brown 1986).

Crabs were tagged in the same manner as 'Carapace tagged' crabs in the laboratory and in the previous spanner crab tagging study by Chen and Kennelly (1999). Between tag injections, the needle was wiped clean with cotton wool saturated in hospital grade Betadine®. This solution (10% w/v Povidine-Iodine) is a bactericidal, sporocidal, fungicidal and virucidal antiseptic, which also promotes coagulation. The tags used were standard 't-bar' anchor tags, each consisting of a 9.5mm long, 1mm diameter vinyl anchor attached to a 65 mm, 0.5 mm diameter shaft. The distal 38 mm of the shaft was covered by a 1.75 mm diameter sheath containing a unique four digit number and the words 'RETURN CRAB QDPI – REWARD.' This sheath was blue in colour so as to be easily seen against the orange coloured crabs These

tags were almost identical to those used by Chen and Kennelly (1999) for their field tagging study of spanner crabs.

After tagging, crabs were left in air for at least 30 minutes to facilitate coagulation. They were then lowered to the sea floor in groups of up to 105 crabs using a specially designed release box which opened using a trigger mechanism when the box reached the sea floor. Observation of released crabs showed that crabs which were released individually remained inert on the sea floor for periods of up to 20 minutes (Kirkwood and Brown, 1998), but virtually all crabs which were released *en masse* were immediately active, and had buried themselves within one minute of release (Kirkwood, unpublished data).

For the purposes of this study, the spanner crab fishery was sub-divided into five regions: Capricorn/Bunker (23-24°S), North Hervey Bay (24-25°S), Wide Bay (25-26°S), Sunshine Coast (26-27°S) and Gold Coast (27-28°12'S).

7.3.3 Results

7.3.3.1 Experiment 1: Effect of tagging location using 't-bar anchor' tags

No crab moulted during the course of this experiment so no changes in length occurred. There was also no tag loss during the course of this experiment.

There was no interaction between sex and tag location (Table 7.8). Crabs which had been tagged in the posterior margin of the carapace had significantly higher mortality than either 'Leg Tagged' or control crabs (Figure 7.15, $F = 3.96$, $df = 2,15$, $P = 0.041$). Mortality was slightly higher for females than for males in each treatment group, but that apparent difference was not significant at the $P < 0.05$ level (Table 7.8, Figure 7.15).

Table 7.8 Experiment 1: Randomized complete-blocks ANOVA of the effects of tag site and sex on the mortality of spanner crabs after 80 days.

a) ANOVA table.

b) *Post hoc* comparison (Fisher's protected LSD) of mean mortalities of crabs tagged at different sites, 80 days after tagging. Treatments grouped by the same letter were not significantly different at $P = 0.05$.

a)

Source	df	SS	MS	*F*	*P*
Blocks (Tanks)	3	1,004.2	334.7	0.46	0.817
Sex	1	2,780.6	2,780.6	3.86	0.068
Tag Site	2	5,717.9	2,858.9	3.96	0.041
Sex x Tag Site	2	162.0	81.0	0.11	0.894
Error	15	10,819.4	721.3		

b)

Treatment	Mortality (%)		Group
	Mean	se	
Control	19.78	8.62	**A**
'Leg Tagged'	26.04	7.46	**A**
'Carapace tagged'	55.20	11.57	**B**

Pooling mortality data for each treatment group, total mortality was significantly higher amongst crabs that were smaller than the overall median carapace length than amongst those that were larger (paired t-test, $t = 6.880$, $df = 2$, $P = 0.010$, Figure 7.16). Pooling treatments, mortality rates were higher for smaller crabs, and declined steadily with increasing size. The

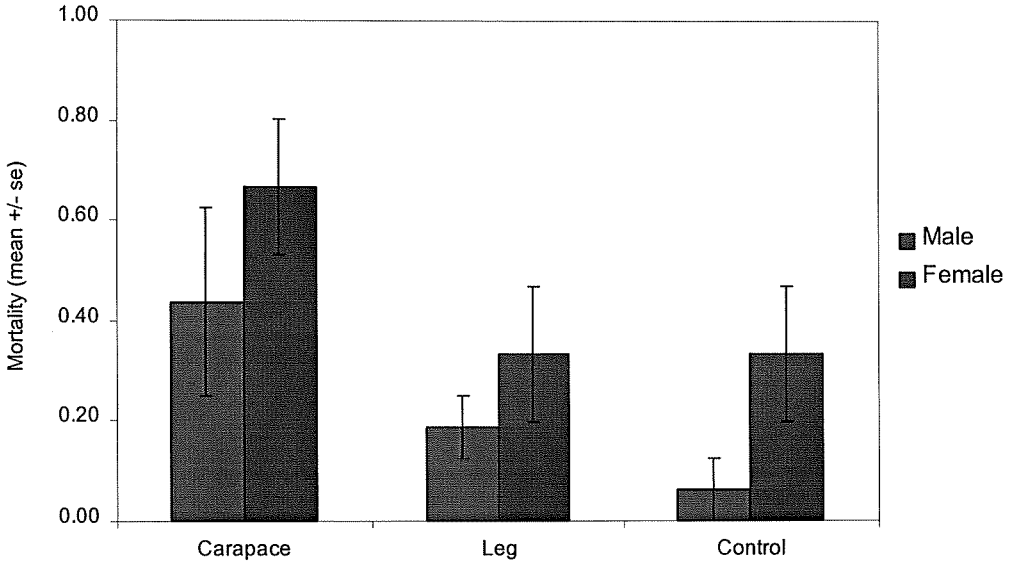

Figure 7.15 Mortality of male and female spanner crabs 80 days after being tagged in either the posterior margin of the carapace ('Carapace') or the soft integument at the base of the third right pereiopod, between the coxa and the ventral plate ('Leg') compared with untagged ('Control') crabs.

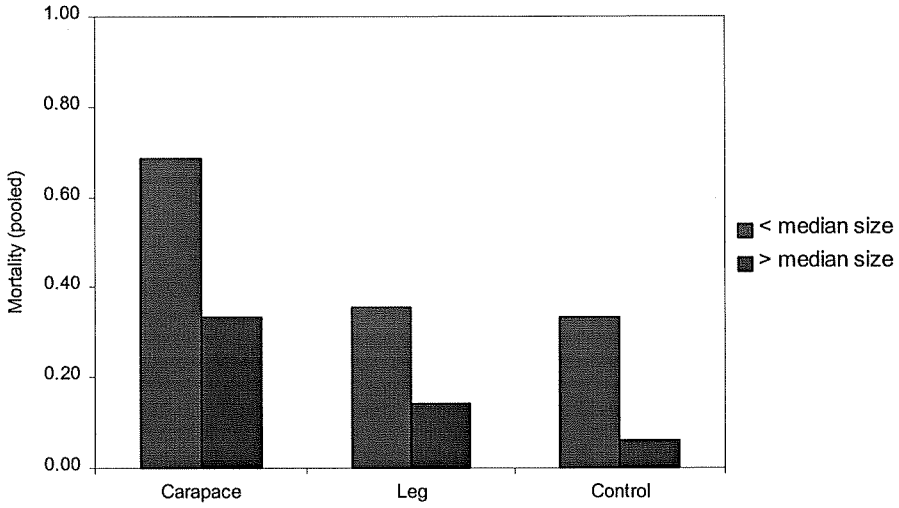

Figure 7.16 Mortality of spanner crabs by size class (< or > overall median size) 80 days after being tagged in either the posterior margin of the carapace ('Carapace') or the soft integument at the base of the third right pereiopod, between the coxa and the ventral plate ('Leg') compared with untagged ('Control') crabs.

smallest six crabs used in the experiment (all female – 1 'Carapace Tagged', 2 'Leg Tagged' and 3 Controls) all died while only one of the largest ten crabs died (male 'Carapace Tagged').

Pooling data for surviving crabs of both sexes, 'Carapace Tagged' spanner crabs gained significantly less weight than 'Leg Tagged' or control crabs during the 80 days of this

experiment (Table 7.9, Figure 7.17). Analysis of data for each sex separately showed a significant difference between treatments for males (F = 3.27, df = 2,34, P = 0.05) but not for females (F = 2.41, df = 2,17, P = 0.12). Those reduced significance levels were due the small amount of difference between treatments and to high variability within each treatment. As a result of the high levels of mortality in some treatments, insufficient power was available to detect such small changes. Although there was no significant effect of tagging location on weight change of females, female weight change did follow the same trend as that for males (Figure 7.18).

Nine of the 57 surviving spanner crabs lost weight during the course of the experiment. There was a significant difference between treatments in the proportion of surviving crabs which had lost weight ($\chi^2 = 7.336$, df = 2, P = 0.026). Five of the 13 surviving 'Carapace Tagged' crabs lost weight (38.5%), whereas only three of the 21 surviving 'Leg Tagged' crabs (14.3%) and one of the 23 surviving Control crabs (4.3%) did. The maximum percentage weight gain by a spanner crab in this experiment was 5.13% by a 'Carapace Tagged' male, while the maximum percentage weight loss was 3.69% by a 'Carapace Tagged' female.

It was easier and faster to tag crabs in the posterior margin of the carapace (= 'Carapace Tagged') than in the soft integument at the base of the third right pereiopod, between the coxa and the ventral plate (= 'Leg Tagged'). Although forcing the tagging needle through the hard exoskeleton of the carapace was more difficult than inserting it through the soft integument, the latter method was less efficient due to the necessity of holding the crab stationary with its ventral surface uppermost. Restraining the crab in this position was more difficult than restraining it with its dorsal surface uppermost due to a greater risk of the crab pinching the tag operator with its chelipeds and rapid movements of the pereiopods making it difficult to insert the needle in the correct site.

Table 7.9 Experiment 1: One-way ANOVA of the effects of tag site on weight gain by spanner crabs after 80 days.

a) ANOVA table

b) *Post hoc* comparison (Fisher's protected LSD) of mean weight gains by crabs tagged at different sites, 80 days after tagging. Treatments grouped by the same letter were not significantly different at $P = 0.05$.

a)

Source	df	SS	MS	*F*	*P*
Tag Site	2	33.485	16.743	5.78	0.005
Error	54	156.292	2.894		

b)

Treatment	Weight gain (%)		Group
	Mean	se	
Control	2.17	0.288	**A**
'Leg Tagged'	1.40	0.354	**A**
'Carapace Tagged'	0.16	0.628	**B**

Tags inserted in the posterior margin of the carapace were more apparent than those inserted in the soft integument at the base of the third right pereiopod. This is because the latter tags frequently folded under the body of the crab and were obscured by its body and pereiopods. Tags inserted in the posterior margin of the carapace were immediately apparent to both experienced and inexperienced operators.

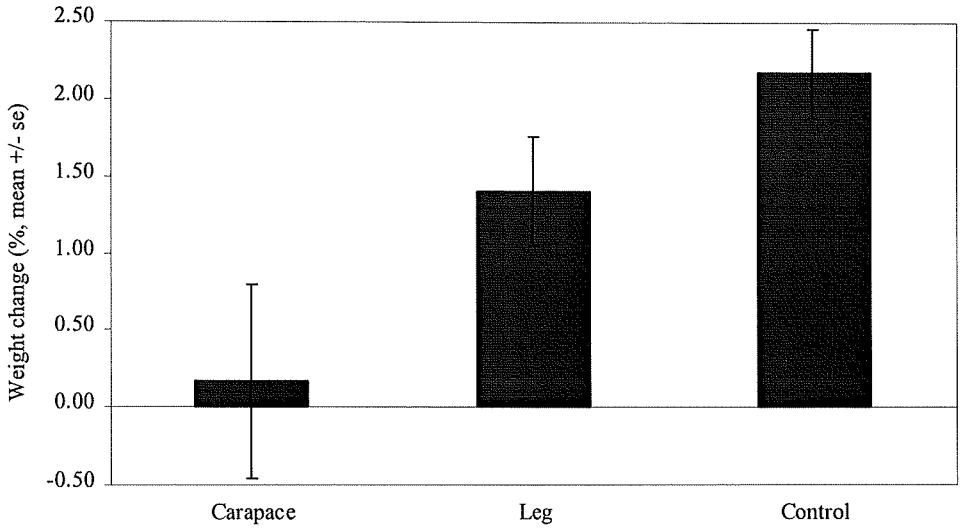

Figure 7.17 Weight change of spanner crabs (sexes pooled) 80 days after being tagged in either the posterior margin of the carapace ('Carapace') or the soft integument at the base of the third right pereiopod, between the coxa and the ventral plate ('Leg') compared with untagged ('Control') crabs.

In terms of the initial criteria (first paragraph, Section 7.2.2), the Carapace tagging location caused significant mortality and caused a significant reduction in weight gain, but had the advantage of being easily and rapidly applied at sea and being immediately apparent to crabbers. It was not possible to determine the effects of either tagging location on growth in length or moulting success as no moulting occurred during this experiment.

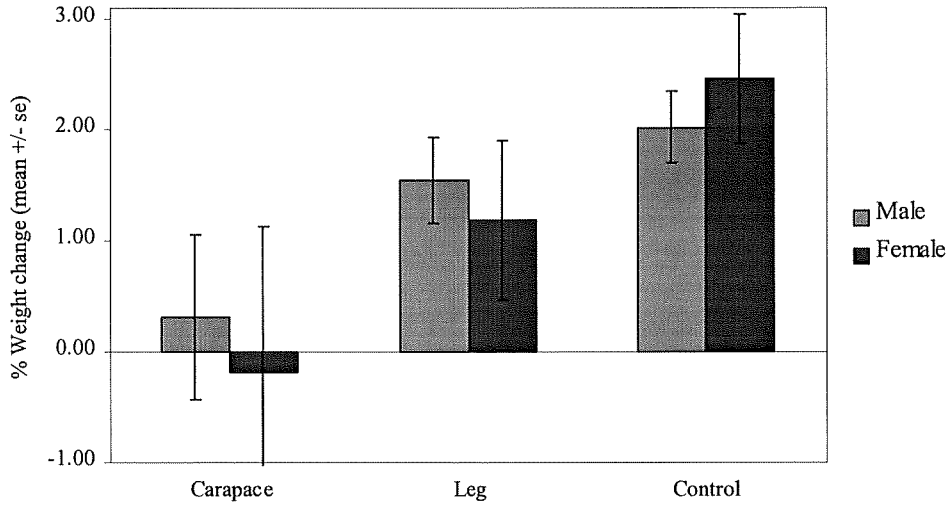

Figure 7.18 Weight change of male and female spanner crabs 80 days after being tagged in either the posterior margin of the carapace ('Carapace') or the soft integument at the base of the third right pereiopod, between the coxa and the ventral plate ('Leg') compared with untagged ('Control') crabs.

7.3.3.2 Experiment 2: Trial of alternative tagging technologies

No crab moulted during the course of this experiment so no changes in length occurred. There was also no tag loss during the course of this experiment.

Analysis of variance of mortality data was not possible as there was no mortality (and hence no variance) in eight of the fourteen combinations of sex and treatment. Pooling data for both sexes, there was no significant difference in the frequency of mortality between the seven treatment groups ($\chi^2 = 4.536$, df = 6, P = 0.587, Figure 7.19).

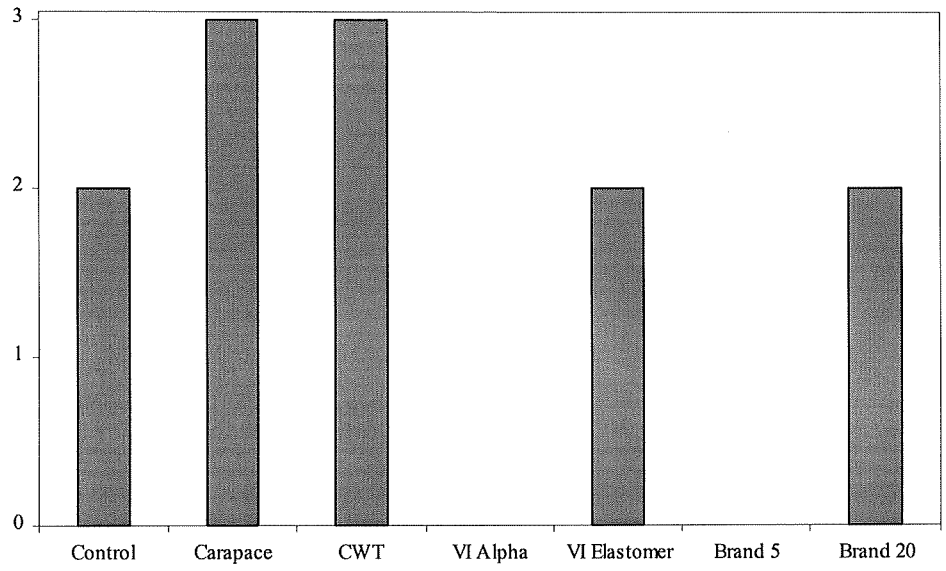

Figure 7.19 Mortality of spanner crabs (sexes pooled) 40 days after being tagged or marked using six different methods, compared with untagged ('Control') crabs. 'Carapace' = tagged in the posterior margin of the carapace using a T-bar anchor tag, 'CWT' = coded wire tag, 'VI Alpha' = alphanumeric visible implant tag, 'VI Elastomer' = visible implant elastomer mark, 'Brand 5' = branded for 5 seconds, 'Brand 20' = branded for 20 seconds.

There was no significant difference in the weight gain of either sex between the seven treatments (Table 7.10). Pooling treatments, females increased their body weight by an average of 9.21% (sd = 3.35%); signicantly more than the average increase in male body weight of 1.81% (sd = 1.36%; F = 202.2, df = 1,98, P < 0.0001; Figure 7.20). Dissection of female spanner crabs revealed that this increased weight was largely due to an increase in the weight of ovarian tissue. Of the 100 surviving spanner crabs at the end of this experiment (48 males and 52 females), only three males had lost weight. The maximum percentage weight gain by a spanner crab in this experiment was 17.61% by a VI Alpha tagged female, while the maximum percentage weight loss was 2.44% by a VI Elastomer tagged male.

Table 7.10 Experiment 2: One-way ANOVA of the effects of six different tagging or marking techniques on weight gain of male and female spanner crabs after 40 days.

a) Males

Source	df	SS	MS	*F*	*P*
Treatment	6	0.090	0.015	0.788	0.585
Error	41	0.784	0.019		

b) Females

Source	df	SS	MS	*F*	*P*
Treatment	6	0.768	0.128	1.155	0.347
Error	45	4.981	0.111		

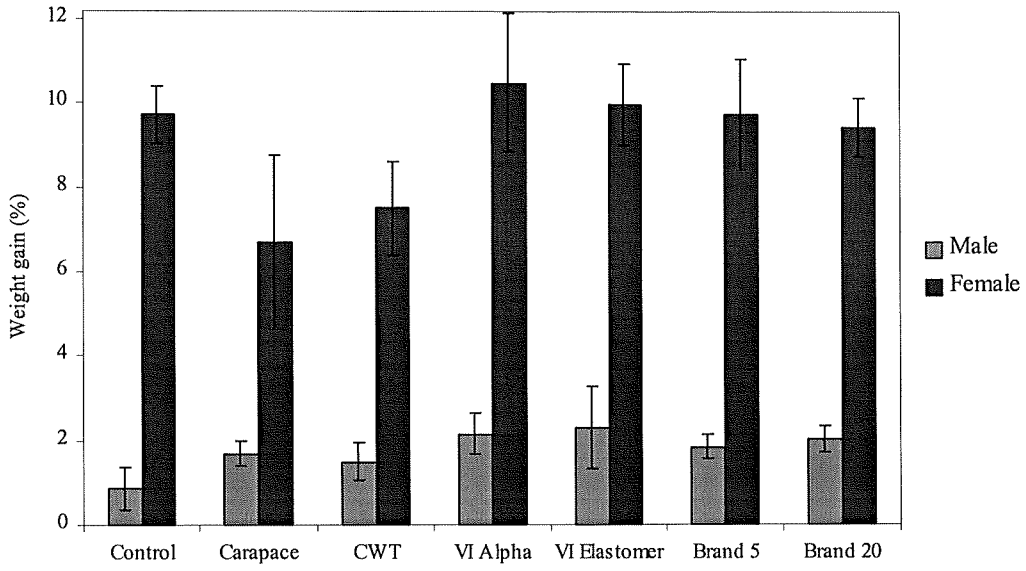

Figure 7.20 Weight gain of spanner crab males and females 40 days after being tagged or marked using six different methods, compared with untagged ('Control') crabs. 'Carapace' = tagged in the posterior margin of the carapace using a T-bar anchor tag, 'CWT' = coded wire tag, 'VI Alpha' = alphanumeric visible implant tag, 'VI Elastomer' = visible implant elastomer mark, 'Brand 5' = branded for 5 seconds, 'Brand 20' = branded for 20 seconds.

It was easier and faster to tag crabs using either the T-bar anchor tag or the Coded Wire Tag than it was to insert the VI Alpha tag. This was due to the need to insert the VI Alpha tag under the soft integument at the base of a pereiopod, and the accompanying difficulty in restraining the crab in a suitable position (see results of Experiment 1, Section 7.2.3.1). Tags inserted in the posterior margin of the carapace were immediately apparent to both experienced and inexperienced operators. VI Alpha tags required careful inspection of each crab, and the tags were sometimes missed by inexperienced operators. In addition to being more time consuming to find, VI Alpha tags were sometimes difficult to read as they had a tendency to flip over to the non-labelled side as the crab moved its pereiopod. Coded Wire Tags were not visible externally, and needed to be located using an electromagnetic detector and then dissected from the crab for reading. It was not practicable to provide all 257 licensed commercial crabbers with electromagnetic detectors so this tagging method was only suitable if used in conjunction with an externally visible mark.

Neither of the two marking methods (VI Elastomer and Branding) was as rapid as any of the three tagging methods, and both required substantially more preparation time. Inserting the VI Elastomer mark in the soft integument at the base of a pereiopod was similarly difficult and time consuming as inserting a T-bar anchor tag or a VI Alpha tag there. In common with those two tagging methods, the VI Elastomer mark was not immediately apparent and required the operator to invert the crab and inspect the soft integument. Neither 5 nor 20 second branding left a visible external mark on unmoulted crabs. As no crab moulted during the course of the experiment it was not possible to determine whether a brand mark would be visible on crabs which had moulted since branding.

In terms of the initial criteria (first paragraph, Section 7.2.2), no method caused significant mortality or a significant effect on weight gain. Only the T-bar anchor tag (Carapace location) and the Coded Wire Tag were able to be easily and rapidly applied at sea, and only the former was immediately apparent to crabbers. It was not possible to determine the effects of any technique on change in length or moulting as no moulting occurred during this experiment.

7.3.3.3 Experiment 3: Effect of tagging site with a t-bar anchor tag on ecdysis

Two crabs attempted to moult during the course of this experiment, and both of those died during ecdysis (Table 7.11). Six of the seventeen crabs which were injected with ecdysterone died prior to eyestalk ablation, and six of the twelve crabs whose eyestalks had been ablated died up to the end of the experiment. As there were no successful moults during the course of this experiment it was not possible to determine whether tag location had an affect on moulting success.

Table 7.11 Mortality of spanner crabs subjected to injection with ecdysterone (Dose 1 and/or Dose 2), and right eyestalk ablation, tabulated against tag site, sex, rostral carapace length (RCL) and weight. Shading indicates the death of a crab.

Tank	Tag site	Sex	RCL (mm)	Weight (g)	Dose 1 (µg) 14/11/97	Dose 2 (µg) 17/11/97	Ablation 24/11/97	End 30/11/97
6	Carapace	Female	77.5	144	0.6	1.2	Y	
11	Carapace	Female	93.6	257	1.0	Died		
11.2	Carapace	Female	69.5	99		0.8	Y	moult death
1	Carapace	Male	137.0	885	3.5	7.1	Y	
5	Carapace	Male	81.6	166	0.7	Died		
5.2	Carapace	Male	76.4	134		1.1	Y	
4	Control	Female	83.5	181	0.7	1.4	Y	moult death
8	Control	Female	88.6	217	0.9	1.7	Y	died
9	Control	Male	97.8	298	1.2	2.4	Y	
12	Control	Male	115.5	510	2.0	Died		
12.2	Control	Male	108.0	399		3.2	Y	died
7	Leg	Female	82.4	174	0.7	1.4	Y	
10	Leg	Female	80.3	161	0.6	1.3	Y	died
2	Leg	Male	122.0	608	2.4	Died		
3	Leg	Male	111.5	455	1.8	Died		
2.2	Leg	Male	111.4	453		3.6	died	
3.2	Leg	Male	107.1	399		3.2	Y	
2.3	Leg	Male	87.7	209			Y	died

7.3.3.4 Experiment 4: Effect of manner of application of t-bar anchor tag on ecdysis

No crab moulted during the course of this experiment. Nine of the twelve experimental crabs died up until Day 3, but there were no further mortalities until the experiment was terminated on Day 10 (12/12/97). Two of the four control crabs died, as did three of the four crabs whose tag was injected directly through the carapace and all four of the crabs whose tag was applied injected through a drilled hole.

7.3.3.5 Field Tagging Experiments

Of the 4,804 crabs which were tagged and released, 221 (4.60%) were recaptured and returned to QDPI by commercial crabbers in 1998 (Table 7.12). The first recapture occurred on 14 January and the last for 1998 was on 19 November, the day before the fishery closed. The recapture rate has varied considerably between regions, with by far the greatest number of

returns coming from a few sites off the coast from Double Island Point and Wide Bay (Table 7.12). Over 90% of the total number of tagged crabs returned came from the three southern regions, with fewer than 10% of the returns coming from north of Fraser Is.

Table 7.12 Details of spanner crab tag releases and returns in 1998, by region.

Region	Name	No. of crabs tagged	No. of tagged crabs returned	% returned
1	Capricorn Coast	37	0	0.00%
2	Bunker Islands	796	9	1.13%
3	North Hervey Bay	1,285	13	1.01%
4	Wide Bay / Fraser	1,231	153	12.43%
5	Sunshine Coast	982	27	2.75%
6	Gold Coast	473	19	4.02%
Total	Queensland	4,804	221	4.60%

The return rate of tagged males (200 returns from 3,278 tagged) was significantly higher than that of tagged females (21 returns from 1,526 tagged, $X^2 = 49.14$, df = 1, P <0.0001). The return rates of crabs in larger size classes were also significantly higher than return rates in smaller size classes ($X^2 = 188.07$, df = 6, P < 0.0001, Figure 7.21). Although 56.7% of the crabs tagged were under the legal minimum size, only 14.0% of the crabs which were returned were under that size.

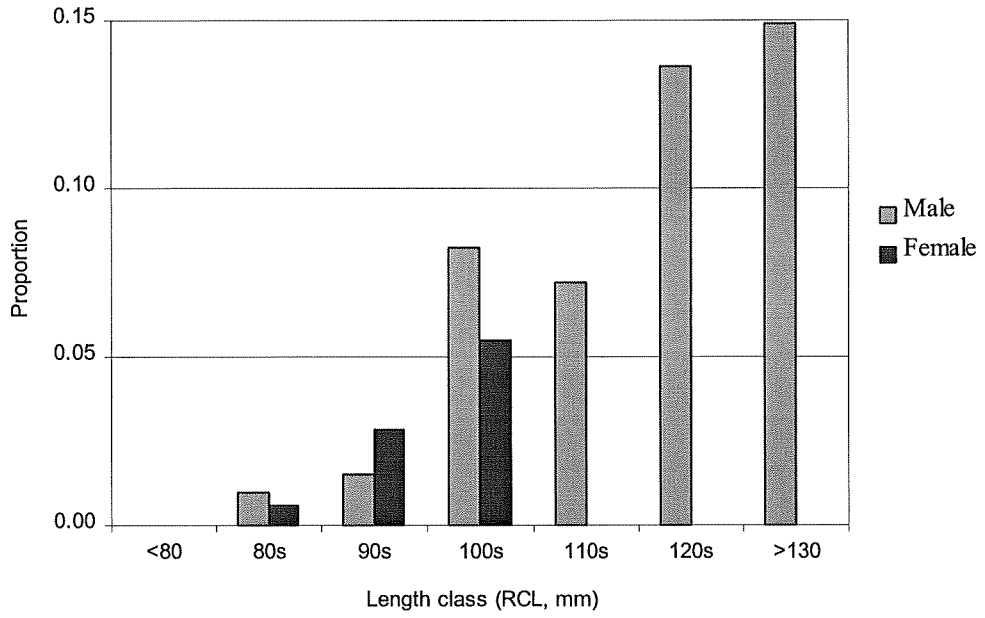

Figure 7.21 The proportions of tagged male and female spanner crabs of seven different size classes which were caught and returned by commercial spanner crabbers

Only fourteen of the 221 crabs returned prior to the closure had actually grown, eleven males and three females (Table 7.13). The mean growth increment of those eleven males of 11.88 mm (sd = 2.48mm) was significantly higher than that of the three females of 7.40mm (sd = 2.17mm)(F = 7.49, df = 1,12, P = 0.019). The first tagged crab which had moulted was a female which had been tagged and released off the Gold Coast on 15 January 1998, and was recaptured on 18 August 1998 (Table 7.13). From August until the fishery closed on 20

November, the proportion of returned crabs which had moulted increased slightly each month (Figure 7.22).

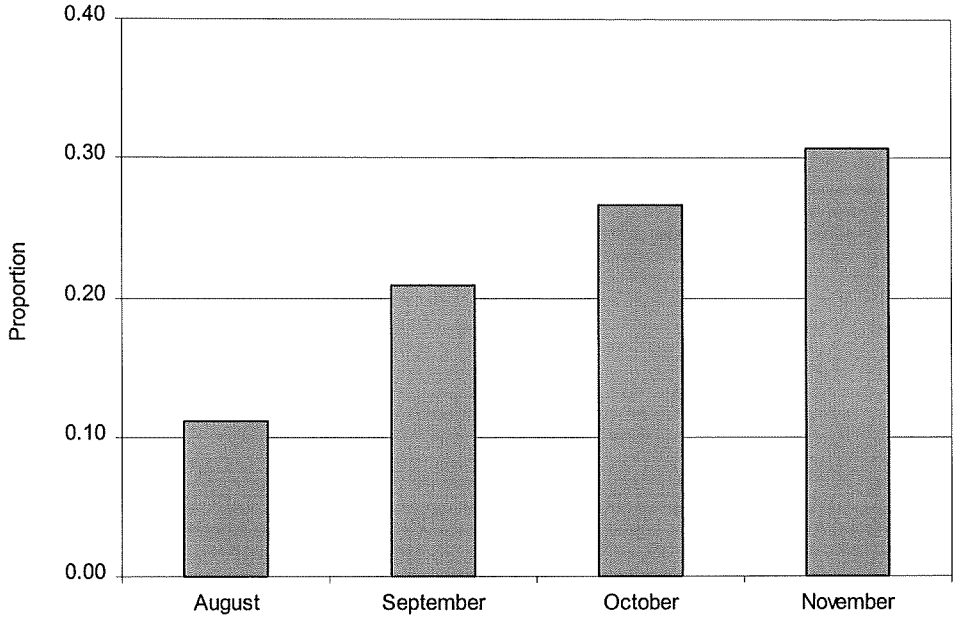

Figure 7.22 The proportion of returned spanner crabs which had moulted since being tagged, by month of recapture in 1998. No crab prior to August had moulted since tagging.

Tagged spanner crabs were recaptured anywhere from 0 to 45 km from where they were released. Fourteen percent of returned crabs had been recaptured within one kilometre of where they had been released, while 49.5% had travelled between one and five kilometres and 36.5% had travelled in excess of five kilometres. The maximum mean rate of movement of a recaptured spanner crab was 433 metres.day^{-1} by a male measuring 99.9mm (RCL) which was at liberty for 14 days, while a 126.3 mm long male which had been at liberty for 111 days (29 May to 17 September 1998) had moved 45.03 km at a mean rate of 406 metres.day^{-1}.

The mean distances moved by tagged spanner crabs which were recaptured in the months of September to November were significantly greater than the distances moved by tagged crabs recaptured from January to May (Figure 7.23) ($F = 5.88$, $df = 9, 160$, $P < 0.001$). Although some crabs recaptured from September to November were within 1 km of where they had been

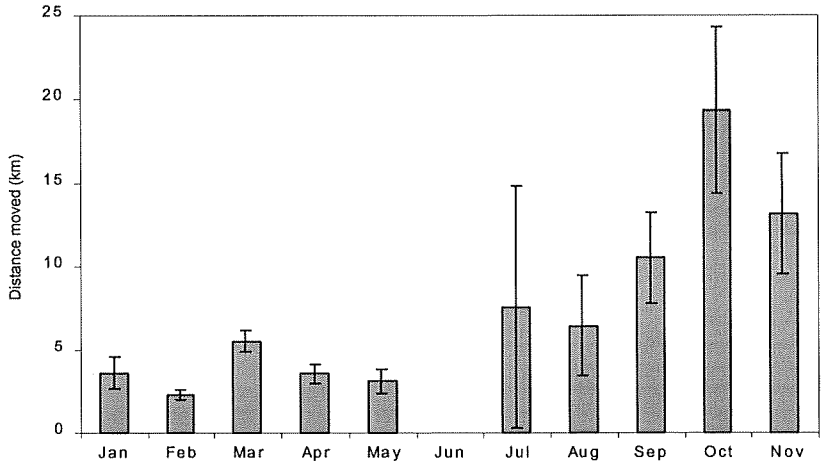

Figure 7.23 Distances moved by recaptured spanner crabs between tagging and recapture (mean +/- sd).

tagged, a significantly higher proportion (65.9%) had moved more than 5 km than had done so in previous months (26.2%) ($X^2 = 22.38$, df = 1, $P < 0.001$). All spanner crabs which had moved distances in excess of 20 km were recaptured in the second half of the year.

Recaptured spanner crabs had moved in all directions since being released, with no apparent trend to movement in any particular direction, although seven of the twelve crabs which had moved in excess of 20 km whilst at liberty, had done so in a south-easterly direction (Figure 7.24).

Table 7.13 Release and recapture dates and lengths of the fourteen tagged spanner crabs which moulted during 1998.

			Release		Recapture			Growth
Sex	Region	Tag no.	Date	RCL (mm)	Date	RCL (mm)	Days	(mm)
M	4 Wide Bay	4020	11/ 2/'98	104.8	2/10/'98	118.9	233	14.1
M	4 Wide Bay	1095	20/ 1/'98	105.1	1/ 9/'98	118.1	224	13.0
M	4 Wide Bay	3974	11/ 2/'98	114.5	17/ 9/'98	122.4	218	7.9
M	4 Wide Bay	1176	20/ 1/'98	88.1	28/10/'98	95.5	281	7.4
M	5 Sunshine	4437	28/ 5/'98	117.9	1/10/'98	132.2	126	14.3
M	5 Sunshine	74	18/12/'97	108.0	3/ 9/'98	117.9	259	9.9
M	6 Gold	644	16/ 1/'98	104.1	1/ 9/'98	119.0	228	14.9
M	6 Gold	738	16/ 1/'98	91.5	14/10/'98	104.9	271	13.4
M	6 Gold	1007	16/ 1/'98	105.4	11/11/'98	118.7	299	13.3
M	6 Gold	555	15/ 1/'98	98.6	22/ 9/'98	110.3	250	11.7
M	6 Gold	507	15/ 1/'98	94.9	1/10/'98	105.7	259	10.8
F	6 Gold	693	16/ 1/'98	89.2	17/11/'98	97.9	305	8.7
F	6 Gold	726	16/ 1/'98	86.6	6/11/'98	95.2	294	8.6
F	6 Gold	529	15/ 1/'98	94.5	18/ 8/'98	99.4	215	4.9

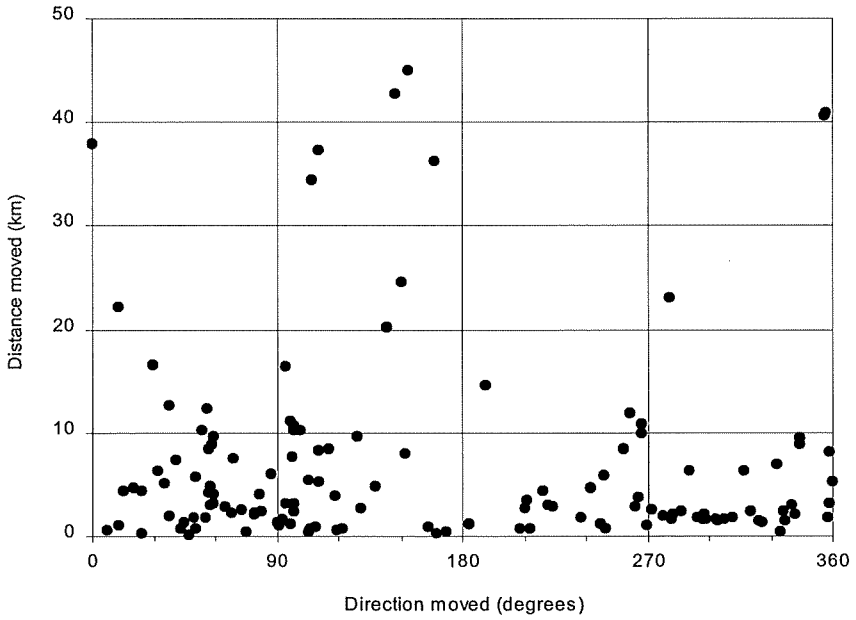

Figure 7.24 Distances and directions moved by individual recaptured spanner crabs between tagging and recapture. 0° = North, 90° = East, 180° = South, 270° = West, 360° = North.

7.3.4 Discussion

The results of Experiment 1 demonstrated that spanner crabs tagged through the posterior margin of the carapace had a significantly higher mortality and a significantly lower weight gain than untagged crabs. Thus, tagging spanner crabs in that location may have sub-lethal effects on the crab's physiology which results in reduced weight gain and increased mortality. However, this significantly increased mortality and decreased weight gain was not apparent in similarly tagged crabs in Experiment 2.

Because of those contradictory results, it is not possible to say that tagging spanner crabs in the posterior margin of the carapace definitely leads to increased mortality and decreased weight gain. These contradictory results may have been caused by laboratory artefacts, or may simply reflect the fact that there were fewer replicates in Experiment 2, and so less power to detect significant effects. Although there were no significant differences between the mortalities under different treatments in Experiment 2, carapace tagged spanner crabs did suffer a mortality which was the equal highest of any treatment group (Figure 7.19). The mean weight gain of females which had been carapace tagged also appeared to be lower than that for any other treatment group, although that apparent difference was also not statistically significant.

One possible explanation for the significantly higher mortality and lower weight gain of carapace tagged crabs in Experiment 1, but not in Experiment 2 is that the experimental conditions varied between the two experiments. Prior to Experiment 1, and between Experiments 1 and 2, all experimental tanks were thoroughly washed and fresh sand was placed in each tank. In the second experiment, his fresh sand was obtained from a different supplier than in the previous previous experiment. This new sand had a lighter colour, caused less turbidity when first washed with fresh seawater and required less washing for turbidity to become negligible. Thus, the first load of sand contained more visible impurities than the second load, and that those impurities may have effected the health of the spanner crabs. Crabs which had a wound in their carapace may have been more susceptible to those impurities than uninjured crabs, and this increased susceptibility may have lead to increased mortality and sub-lethal effects on growth in Experiment 1. Thus, the adverse findings of Experiment 1 may have been due to an experimental artefact associated with impurities in the sand used in that experiment.

None of the tagging methods trialled in these experiments proved to be wholly successful for tagging spanner crabs. Coded Wire Tags required an external mark to identify those crabs which had been tagged, and required dissection to identify the tags. Such a tagging method was not suitable for field identification by commercial crabbers. Similarly, visible implant tags were also not suitable for field identification by commercial crabbers as they were not clearly visible. It would be unrealistic to expect commercial crabbers to closely examine each of the crabs they pull on board in order to find such a tag. Branding of spanner crabs left no visible mark. It is possible that branding may have left a mark on the post-ecdysal carapace, but such a mark would not have enabled individual identification. Of all the methods trialled, only coded wire tags and T-bar anchor tags could be easily and rapidly applied at sea, and only the latter was immediately apparent to crabbers.

Although none of the tagging methods satisfied all of the initial criteria, T-bar anchor tags (Carapace location) did at least satisfy the logistical criteria (i.e. immediately apparent to crabbers and easily and rapidly applied at sea). As the tags needed to be immediately apparent to commercial crabbers (who may not have seen a tag previously and who spends an average of 2-4 seconds removing each crab from a dilly), the Carapace tagging location was the only one which met the criterion of being immediately apparent. Thus, despite serious reservations about their likely adverse effects on spanner crab mortality and growth, they were the only tags which could be practically applied in the field experiment.

Although T-bar anchor tags inserted in the posterior margin of the carapace were likely to cause increased mortality and (probably) impaired growth, they were selected for the field tagging experiment. Because of those likely adverse effects, the results of growth estimates based on this tagging method should be considered to contain a possible bias. However, tagging spanner crabs using this method did enable studies of spanner crab movements and allowed comparison with the results of a NSW study of Chen & Kennelly (1999) which used identical methods.

Prior to the field tagging experiment, further laboratory studies were conducted in order to determine whether the tagging method selected had adverse effects on spanner crab moulting success and subsequent survival and whether the manner of tag application could be improved to reduce moult related mortality. Those experiments relied upon artificial methods (injection with ecdysterone and/or eyestalk ablation) in order to induce moulting. The very high mortality in all treatment groups in Experiment 3 led to those experiments being terminated. Any effect of tagging would have been swamped by the high mortality and probable other adverse effects of eyestalk ablation. The adverse effects of those methods of inducing moulting were so severe as to invalidate any conclusions about growth or moulting from Experiments 3 and 4.

The fact that the return rate of smaller crabs was significantly less than that of larger crabs may have been due in part to spanner crabbers not examining smaller crabs as closely as they examined larger crabs. Several crabbers have reported their reticence to retain undersized crabs, and this may also have contributed to the reduced return rate of undersize crabs. However, this does not explain the steady increase in return rate with increased length within both legal sized and sub-legal size categories (Figure 7.21). In sub-legal crabs of both sexes, the return rates were significantly lower for crabs smaller than 90 mm RCL than for crabs between 90 and 100 mm RCL. The smallest crab returned measured 82.1 mm RCL, yet 708 crabs smaller than that length had been tagged. Similarly, there was a significantly higher return rate for male crabs larger than 120 mm RCL than for males between 100 and 120 mm RCL. There most likely explanation for this size-related effect on return rate is that smaller crabs are less likely to be recaptured than larger crabs. This could occur through two mechanisms:-

- Smaller crabs may be in far greater numbers than larger size classes, but have a greatly reduced catchability. This would lead to a lower proportion of the small crabs present in an area being caught.
- Smaller crabs may experience a higher tag-related mortality than larger crabs.

In addition to tag return rates being significantly lower for smaller size classes, they were also significantly lower for females than for males. This is most likely to be due to the effect of length on tag return rate as females reach a smaller maximum length than males. The fact that tag return rates were smaller for females than males could also occur through either of the two aforementioned mechanisms. Chen & Kennelly (1999) also reported a lower tag return rate for females than for males.

The increased mortality and reduced weight increments in spanner crabs due to T-bar anchor tagging brings into question the validity of growth estimates based on field tagging studies. Growth parameter estimates from the 'stepwise' model of Chen & Kennelly (1999) may suggest a lower growth-rate than is actually the case for spanner crabs, and may explain why these authors reported the slowest growth rates of any available study. Chen and Kennelly (1999) recognise that their growth rate estimates are relative, as data were available only for animals larger than about 65 mm CL (the smallest sizes tagged). Because there were no length-at-age data for younger size/age-classes, the model will have difficulty in accurately establishing the initial slope of the growth curve, and will be unable to shed much light on the number of age-classes likely to exist below the size at first tagging. Consequently, the predicted K value may not be estimated well. During the 1998 Stock Assessment Review

Workshop (Dichmont *et al.* 1999) an attempt was made to combine the NSW tagging results with the length-frequency data from our channel-dredge sampling operations (which provided information on the size and relative abundance of the smallest size-classes). Several scenarios were examined, depending on the supposed periodicity of the dredge length-frequency modes. The best composite model fit was obtained under the assumptions that (i) the first L/F mode represented 0+ crabs (early juveniles), (ii) the second mode (between about 30 and 50 mm) represented 1+ crabs, and (iii) the smallest of the crabs tagged in NSW were in the 2+ age-class. Under this scenario, L_∞ was estimated at 168.5 mm, K at 0.229 and t_0 at -0.201 (see Dichmont *et al.* 1999 for details). It is interesting that our alternative growth parameter estimates (using the channel-dredge L/F data and an independent estimate of L_∞) were not dissimilar, with L_∞ = 155.9 mm, K = 0.242 and t_0 = -0.250. We believe that the latter estimate of L_∞ is possibly the more realistic, at least for the Queensland stock.

The fact that spanner crabs collected in the second half of the year had moved further than those returned earlier may simply be due to the fact that their average time at liberty was greater. However, there is considerable anecdotal evidence to suggest that spanner crabs migrate to spawning grounds in September and October. This spawning migration may also explain the increased distances of movement seen in those months. Additional tag returns in future years may tell us whether or not those movements are part of a cyclic migration pattern.

It is difficult to draw any conclusions from the movement direction data. Spanner crabs appear to be just as likely to have moved in any direction between release and recapture. The location of recaptured crabs is also strongly influenced by fishing patterns, so may give a false impression of actual movements.

8 POST-DISCARD MORTALITY [1]

8.1 EFFECT OF LIMB DAMAGE ON SURVIVAL AND BURIAL TIME

8.1.1 Introduction

Minimum legal size regulations in fisheries establish the smallest size at which an individual may be legally retained if caught (Hill, 1990). The aim of releasing under-size individuals is to ensure that those animals have the opportunity to attain sexual maturity before being subject to fishing mortality. Minimum legal size regulations also aim to reduce the total fishing mortality. Obviously, these two objectives cannot be achieved if fishing leads to high mortality amongst animals smaller than the minimum legal size.

Disentangling spanner crabs whose legs have become enmeshed in a tangle net can be very time consuming. To remove spanner crabs from tangle nets, crabbers use the following methods: (i) careful disentangling, (ii) breaking off entangled dactyli from one or more legs, (iii) seizing crabs by the carapace and quickly pulling them from the mesh, (iv) slamming the net frame against a solid surface so as to dislodge crabs by inertia or (v) scraping the net surface against a solid bar. Methods (i) and (ii) cause the least damage, and are employed for crabs bound for market (mostly live export), whereas any of these methods may be employed to remove undersize crabs. Kennelly *et al.* (1990) found that crabs removed using method (i) rarely showed any damage, those removed by method (ii) lost an average of 3.95 dactyli, whilst those removed by method (iii) lost an average of 2.9 dactyli and 0.8 limbs. Several crabbers have described the effects of methods (iv) and (v), which are not used when observers are present, and say that they cause the loss of many appendages (A. Gosbell, N. Morgan, K. Silcox, pers. comm.). As the spanner crab fishery is very labour intensive, crabbers are motivated to use the fastest, and most damaging, methods to remove discarded crabs (regardless of the level of injury inflicted) and may frequently return crabs to the sea with legs or segments of legs missing. The aim of this research was to follow the fate of these discarded crabs.

In a laboratory experiment, Kennelly *et al.* (1990) found that 100% of spanner crabs which had entire legs removed were dead after 8 days, and 62.5% of those which had one or more dactyli removed were dead after 50 days. In an earlier laboratory experiment, Onizuka (1972) found that 70% of spanner crabs which had lost an entire leg died, while undamaged controls suffered only 6.4% mortality over the same unspecified time period. The high rates of injury reported by Kennelly *et al.* (1990), and the high mortality of injured crabs reported in both studies, suggested that the majority of undersized crabs returned to the sea were likely to die within a few days.

However, crabs which have survived the loss of one or more appendages are frequently seen in commercial catches, and the results of Kennelly *et al.* (1990) are viewed with scepticism by some commercial crabbers who maintain that the results of laboratory experiments may not accurately reflect what happens in a species' natural habitat. Thus, the present experiments were conducted in the ocean under conditions as close as practicable to natural, in order to determine whether the results of Kennelly *et al.* (1990) provided an accurate estimate of post-discard mortality in the wild. Although Kennelly *et al.* (1990) did conduct a field experiment to validate their laboratory experiment, they did not provide details of what damage their experimental animals received, and their field experiment was terminated after 24 hours when the cages lifted from the sand substratum and were lost.

[1] This chapter is a slightly modified form of Kirkwood & Brown (1998)

In addition to the direct effects of stress or injury, post-discard mortality may also occur as the result of increased exposure to predation (Hill & Wassenberg, 1990, Juanes & Smith 1995). Spanner crabs normally spend over 95% of the time buried in the substrate (Skinner & Hill, 1987), which would presumably reduce their vulnerability to predators. Recently discarded spanner crabs are subject to predation by loggerhead turtles (*Caretta caretta*) before they bury themselves in the substratum (Kirkwood, personal observation) and may also be vulnerable to other potential predators. As limb damage may reduce the ability of spanner crabs to bury themselves, it may expose these crabs to a greater risk of predation. Thus, a second experiment was performed to determine whether limb damage had any effect on the time it takes discarded spanner crabs to bury themselves.

8.1.2 Methods

8.1.2.1 Effect of limb damage on survival

Five experimental cages were installed at 27°01.6'S, 153°26.1'E, just off the north coast of Moreton Island, Queensland. The depth at this site varied from seven to eight metres depending upon tidal height. This site was selected because it had clean oceanic water, a suitable sand substratum for spanner crabs (which naturally occur there), low current speeds and was sheltered from prevailing winds. Cages were constructed from galvanised steel mesh (mesh size 50 x 50 mm, 5 mm diameter wire) supported by a galvanised steel frame. This mesh size was small enough to retain all crabs with a Rostral Carapace Length (RCL) of >70mm, and the wire diameter was sufficient to prevent the dactyli of spanner crabs from becoming entangled. Each cage measured 2.4 x 2.4 x 0.7 metres, had a hinged lid of 2.4 x 2.4 metres, and weighed 150 kg. Their large size and weight, together with the fact that they were partially buried to a depth of 0.3 m, ensured that the cages could not be washed away.

The five cages were placed about five metres apart on the sea floor and partially buried (to a depth of 0.3m) using a venturi sand sucker operated by SCUBA diver and powered from the surface by a fire pump. This enabled crabs to bury completely without having to come into contact with the cage. Cages were left in place for eight days prior to commencement of the experiment to allow the substratum to stabilise. The study site was marked by a Special Mark (a 2m diameter yellow buoy, with a 3m high tower topped by a yellow flashing light) to reduce the likelihood of interference to the experiment from vessels trawling or anchoring in the vicinity.

Experimental animals were collected on 9 April 1996 (day 0) using standard commercial fishing techniques. These crabs were collected from depths of 20 to 30 metres in the vicinity of 26°57'S, 153°23'E. Each crab was carefully disentangled from the net and inspected to ensure that it was undamaged. Crabs with a rostral carapace length (RCL) of between 70 and 100 mm were retained for use in the experiment. Crabs smaller than 70mm RCL are rarely collected on tangle nets, and may have escaped from the experimental cages, whilst crabs larger than 100mm RCL are retained by crabbers so were not relevant to this study. Crabs were separated on the basis of sex, and collection was continued until at least 50 crabs of each sex had been collected.

Crabs were then transported to the study site 10 km away. During transport, crabs were shaded by wet hessian bags and were sprinkled lightly with fresh seawater. These crabs were kept out of water for between one and two hours, depending upon when they were collected. Previous experience showed that spanner crabs which had been exposed to air for periods of up to eight hours survived in the laboratory for in excess of 90 days with no apparent adverse effect on their health from the exposure.

One hundred spanner crabs were each randomly assigned to one of five different treatment groups: twenty crabs per treatment (10 males and 10 females). The experimental treatments

were no damage (O); one dactylus removed (D1), three dactyli removed (D3), one walking leg removed (L1) and one cheliped removed (C1). Each crab was measured, individually numbered and coded with the treatment it was to receive using both a non-toxic permanent marker ('Markal Paintstik') and a label glued to its carapace. Four crabs (2 males and 2 females) were randomly selected from each of the five treatment groups to be placed in each experimental cage. Thus, each cage contained a total of twenty crabs with all five treatments being equally represented in each cage. The initial density of crabs in each experimental cage was 3.47 crabs m^{-2}; low enough to avoid the mortality due to intraspecific aggression which had been observed in crabs maintained under crowded conditions (12 – 16 individuals m^{-2}) in the laboratory.

Immediately prior to being released into the cages, treatment crabs were damaged according to their randomly assigned code by removing dactyli or whole appendages in a manner which mimicked the damage inflicted by rapid removal by spanner crabbers. All twenty crabs to be placed in a cage (four from each of the five treatments) were taken to the sea floor in a perforated plastic box and placed into the cage by SCUBA divers.

Cages were initially inspected daily by SCUBA divers, but inspection intervals were gradually increased as the rate of mortality declined through the experiment. Each inspection involved a visual scan of the sand surface, after which two divers raked through the sand with their arms for 15-20 minutes per cage. All dead crabs were removed and their identities and dates of death recorded. The experiment was forcibly terminated on the night of 1 May 1996 (Day 22), when a trawler apparently collided with the Special Mark buoy and dragged a trawl net through the experimental area. Cage 4 was lost, and both Cage 5 and the buoy sustained slight damage and had sections of trawl net attached to them. Cages 1, 2, 3 and 5 were retrieved on 10 May 1996.

Percentage mortality data at 21 days were analysed by a randomized complete-block-design analysis of variance (ANOVA), with cages being the blocks.

8.1.2.2 Effect of limb damage on burial time

Experimental animals for this experiment were collected on 3 July 1996 from the same area and using the same procedures as for the previous experiment. Crabs of between 70 and 100 mm RCL were retained for use, and were transported to a study site 600 m west of the previous experiment at 27°01.5'S, 153°25.8'E. The depth at this site was eight metres.

Five crabs of the same sex were selected at a time, and each crab was randomly assigned to one of the five experimental treatments used in the previous experiment, viz:- no damage (O); one dactylus removed (D1), three dactyli removed (D3), one walking leg removed (L1) and one cheliped removed (C1). Immediately after treatment, crabs were individually returned to the water, and their behaviour was observed by a SCUBA diver. The order of return to the water was pre-determined as follows:- male O, male D1, male D3, male L1, male C1, female O, female D1, female D3, female L1, female C1. This pre-determined order of release ensured that the diver knew to which treatment group each crab belonged. This cycle was repeated four times, so that a total of 40 crabs were used (4 of each sex in each treatment). Crab release occurred on an ebb tide, between the hours of 12:30 and 15:00 on 3 July 1996.

During observation, the diver remained motionless on the sea floor at a distance of at least five metres from the experimental animal. This distance was selected as previous experience had demonstrated that stationary divers at a distance of greater than two metres had no observable effect of the behaviour of spanner crabs. The exact time when each crab was released (t_1) was recorded by an experimenter on board the vessel, and (when possible) by the diver. The diver also recorded the time at which the crab first reached the sea floor (t_2), and the time when it had completely buried itself (t_3). Sinking time was calculated by subtracting t_1 from t_2, while

burial time was calculated by subtracting t_2 from t_3. Burial time usually included a period when a crab remained motionless on the sea floor. Data were $\log_{10}$ transformed to reduce a strong positive skew, prior to ANOVA.

8.1.3 Results

8.1.3.1 Effect of limb damage on survival

There was no significant interaction between sex and treatment and no significant difference between the mortalities of each sex, but there was a highly significant difference between the mortalities experienced by spanner crabs subject to different treatments (Table 8.1a). Post-hoc comparison (Fisher's LSD) revealed that mortality was significantly higher amongst crabs in C1 than in all other treatment groups (Table 8.1b). Crabs in L1 had significantly higher mortality than those in D1, D3 or 0, but there were no significant differences among these last three groups.

Table 8.1 **a)** Randomized complete-blocks ANOVA on the effects of treatment and sex on the mortality of spanner crabs 21 days after release.

b) *Post hoc* comparison (Fisher's protected LSD) of mean mortalities under different treatments 21 days after release. Treatments grouped by the same letter were not significantly different at $P = 0.05$.

a)

Source	df	SS	MS	*F*	*P*
Blocks (Cages)	4	4200	1050.00	1.465	0.2331
Treatment	4	45700	11425.00	15.942	< 0.0001
Sex	1	50	50.00	0.070	0.7932
Treatment X Sex	4	700	175.00	0.244	0.9113
Error	36	25800	716.67		

b)

Treatment	Mortality (%)		Group
	Mean	se	
Control	5.00	5.00	a
1 Dactylus	20.00	9.36	a
3 Dactyli	25.00	7.91	a
1 Pereiopod	55.00	16.58	b
1 Cheliped	90.00	6.12	c

Most of the mortality observed in this experiment occurred within the first few days, and no mortality occurred in any of the five cages from Day 13 until the experiment was terminated on Day 21 (Figure 8.1). There were no further mortalities in the four cages retrieved on 10 May 1996, 31 days after the experiment commenced.

8.1.3.2 Effect of limb damage on burial time

Crabs took an average of 31.2 seconds to reach the sea floor, giving a mean sinking rate of 0.26m.sec^{-1} (sd = 0.03 m.sec^{-1}). Limb damage had no significant effect on the time it took crabs to bury themselves once they had reached the substratum ($F = 0.306$, df = 4,35, $P = 0.983$). Most crabs landed on the sea floor on their backs, and all but one of them remained motionless for a period ranging between four seconds and 20 minutes. The one exception (a female with one leg removed, L1) commenced burying as soon as it reached the sea floor, and was buried within six seconds. After a period of inactivity, each of the remaining 39 crabs became active and either immediately buried themselves (31 crabs) or swam for between 0.5

and 4 metres before burying themselves (8 crabs). Overall time from reaching the sea floor to burial for these 39 crabs ranged from ten seconds to twenty minutes. Sixty five percent of crabs had buried themselves within 68 seconds, but the remaining 35% took between two and twenty minutes.

Further observation of released spanner crabs showed that resumption of activity by inert crabs could be triggered by a diver approaching to within one metre, and all crabs touched by a diver responded by immediately becoming active and burying.

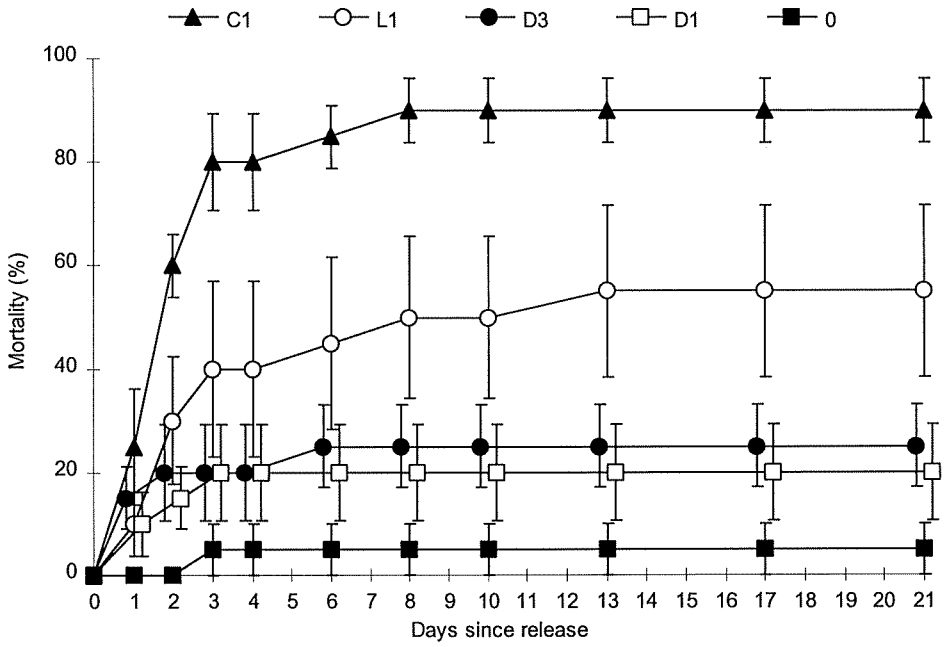

Figure 8.1 Percentage mortality (mean +/- s.e.) of spanner crabs over 21 days following application of five different treatments.
C1 = 1 cheliped removed, L1 = 1 leg removed, D3 = 3 dactyli ('spades') removed, D1 = 1 dactylus ('spade') removed, 0 = control, no damage.

8.1.4 Discussion

It is clear that limb damage leads to increased mortality in discarded undersize spanner crabs, but it is difficult to determine the extent to which this damage frustrates the aims of minimum size legislation. This is because it is not possible to reliably assess the overall extent of limb damage which is inflicted on discarded spanner crabs. Although Kennelly *et al.* (1990) estimated the amount of damage inflicted by different methods of removal, estimation of how often each method is employed by commercial crabbers is problematic because it is likely that crabbers modify their behaviour in the presence of an observer. Whenever an observer was on board a crabbing vessel, all crabbers removed undersize crabs either by careful disentanglement or by breaking one or a few dactyli. However, anecdotal evidence suggests that many crabbers employ more damaging methods to remove crabs from their nets. A number of crabbing vessels have been observed at sea with large numbers of detached spanner crabs appendages littering their decks and individual crabbers report that many of their colleagues employ the more damaging methods.

Although the overall extent of limb damage inflicted on discarded spanner crabs by commercial crabbers cannot be reliably determined, it is certain that many crabs are returned to the sea with appendages damaged or removed. Even with very careful disentanglement some

loss of appendages still occurs. The present work suggests that over half of the crabs returned to the sea after suffering the loss of an entire appendage are likely to die within a few days.

Similar results were reported by Onizuka (1972) and Kennelly *et al.* (1990), although direct comparisons are limited by the fact that different experimental treatments were used in each study. There was no significant difference in the mortality of undamaged crabs in the three studies ($X^2 = 0.55$, df = 2, P > 0.5), but the mortality of crabs which had sustained similar damage was lower in both the present field experiment and Onizuka's (1972) study than in the laboratory experiment of Kennelly *et al.* (1990) (Table 8.2). The higher mortalities observed by Kennelly *et al.* (1990) may have been caused by artefacts associated with laboratory conditions, including the potential effects of intraspecific aggression. The initial density of crabs in the experiment of Kennelly *et al.* (1990) was 30.30 individuals m^{-2}, compared with 3.47 crabs m^{-2} in the present study. Injury to decapods is known to increase their vulnerability

Table 8.2 Comparison between mortalities (mean %, numbers of crabs in parentheses) of damage spanner crabs reported in three studies.

Damage	Onizuka (1971)	Kennelly *et al.* (1990)	Present study
Nil	6.4 (94)	12.5 (16)	5.0 (16)
1 Dactylus	7.7 (13)	62.5 (16)	20.0 (16)
3 Dactyli	-	-	25.0 (16)
4 Dactyli	9.3 (54)	62.5 (16)	-
8 Dactyli	20.0 (15)	-	-
1 Pereiopod	70.0 (10)	-	55.0 (16)
2 Pereiopods	-	100.0 (16)	-
1 Cheliped	-	-	90.0 (16)

to attack from conspecifics (Juanes & Smith 1995). Spanner crabs maintained under crowded conditions (12 - 16 individuals m^{-2}) frequently display intraspecific aggression to such an extent that injured conspecifics were attacked, further damaged and eventually killed (Kirkwood, unpublished).

Two methods have been employed in attempts to reduce the level of injury to discards: *(i)* informing commercial crabbers of the effects of limb damage on post-discard survival, and *(ii)* employing alternative, less damaging, crabbing methods. The first method has met with some success, but many crabbers still use more damaging methods of removal, and the extent of those activities is difficult to monitor. Several alternative methods of fishing for spanner crabs have been trialed by Sumpton *et al.* (1993) and by the present authors (Section 8.5), but they have proven ineffective in comparison with current methods. Sumpton *et al.* (1993) conducted trials on the efficacy of a series of alternative non-entangling traps in catching spanner crabs. They found that the best catch rates of any of the alternative traps they trialed were less than 18% of those of tangle nets. Such reduced efficiency would almost certainly render the fishery economically non-viable. Thus, the alternative traps trialed by Sumpton *et al.* (1993) do not provide a practical solution to the problem of post-discard mortality.

A third option could be to remove the current minimum size. At present, total fishing mortality is the sum of the number of crabs taken to fill the annual Total Allowable Commercial Catch (TACC, in tonnes) and the unknown number of crabs which die after being discarded. If all crabs which are caught are retained, then fishing mortality would be limited by the prevailing catch quota. In this case, the total number of crabs required to fill the TACC would exceed the number required under the current minimum size limitation (Table 8.3).

For the legal minimum size legislation to actually reduce the number of crabs killed by fishing, the number of crabs retained for market (R) and the proportion (y) of discarded crabs (D) which subsequently die must be less than the estimated catch if all crabs were retained (C).

$$R + yD < C \qquad (1)$$

For the 1996 TACC of 2,670 tonnes for Queensland, C is estimated at 7,121,871 individual crabs. Substituting data calculated in Table 8.3 into Equation 1:

$$5{,}299{,}548 + y4{,}626{,}535 < 7{,}121{,}871 \qquad (2)$$

Thus,
$$y < \frac{7{,}121{,}871 - 5{,}299{,}548}{4{,}626{,}535} \qquad (3)$$

$$< \quad 0.3939 \qquad (4)$$

Thus, if more than 39.4% of discarded crabs actually die as a result of having been caught and

Table 8.3 Comparison between the estimated number of spanner crabs caught in the State of Queensland under the present minimum size limitation of 100mm, and the estimated number that would have been caught had that limitation not existed. Mean weights and percent discards based on length frequency data (summarised in Section 7.1.4) and length-weight relationships (Brown 1986).

	Minimum size limit (100mm) enforced	
	Yes	No
Mean wt. retained crabs (g)	504	375
1996 TACC (tonnes)	2,670	2,670
Total catch (no. crabs)	5,299,548	7,121,871
Discarded (%)	46.61	0
Discarded (no. crabs)	4,626,535	0
Total catch (no. crabs)	9,926,084	7,121,871

released, then the current minimum size legislation actually acts to increase fishing mortality.

Despite these figures, we would certainly not advocate removing the size limit from spanner crabs: they are included specifically to demonstrate the sort of impact that careless handling (and subsequent post-discard mortality) can have on the resource. There are several reasons for this, including changes in market demand (which is currently favouring larger crabs) and unpredictable changes in the fleet's fishing strategy upon introduction of the individual transferrable quota system. The latter, in the absence of a competitive quantity-based strategy, may well include a more careful selection of fishing grounds to optimise profit margins. The time-cost in carefully extracting a small crab from the net is probably greater – certainly not less - than that of extracting a large crab, while the value of the product in both absolute and relative terms would be less.

While buried, a spanner crab can stop its heart for periods of at least 20 minutes, relying on its *cor frontale* to circulate haemolymph to its brain, eyestalks and antennae (N. Gribble, personal communication). While obviously conserving energy, this behaviour would also render the crab less easily detectable to predators such as rays and hammerhead sharks which can detect electrical impulses from buried prey (Kalmijn, 1971 & 1978). Thus, this state of inactivity may be a predator avoidance mechanism.

When hauled on board a vessel by commercial crabbers, spanner crabs are usually inactive or very sluggish. This is in contrast to the very active swimming and walking behaviour displayed when they emerge from the sand (Skinner & Hill, 1986). This remarkably docile behaviour of when captured may also be due to a reduction in heart rate as a predator avoidance mechanism.

On the basis of the work of Kennelly *et al.* (1990), Juanes & Smith (1995) reported that the spanner crab was the only decapod crustacean known which does not undergo autotomy in response to predator attack. However, recently moulted soft-shelled spanner crabs do undergo autotomy when attacked by conspecifics or handled by people (Kirkwood, unpublished). This reflex severance of an appendage is thought to be a predator avoidance mechanism (Robinson *et al.*, 1970), but it does have several adverse consequences in the longer-term such as reductions in growth rate, competitive ability, foraging efficiency and mating success, and an increase in vulnerability to attack (Juanes & Smith, 1995). As spanner crabs can apparently reduce their likelihood of detection by predators through entering a dormant state, the selection pressure for them to undergo autotomy may be exceeded by the selection pressures of those adverse effects. This situation may be reversed when crabs are particularly vulnerable to attack after moulting, so that autotomy may be preferable at those times. Kennelly *et al.* (1990) offered the alternative explanation that the spanner crab's apparent lack of the ability to undergo autotomy may reduce the risk of losing an appendage due to the stresses of digging through the sand.

Virtually all spanner crabs released as part of the burial-time experiment remained immobile for periods ranging from a few seconds up to 20 minutes upon reaching the sea floor. This immobility may be due to them stopping their heartbeat as a predator avoidance mechanism, triggered by the stress of capture and handling. The fact that there was no relationship between this behaviour and the degree of damage suffered by the crabs suggests that it was not due to stress caused by injury. Thus, a discarded crab is likely to be subject to an increased risk of predation, but the level of this increased exposure is probably only slight.

8.2 TRIAL OF NEW TRAP DESIGN

8.2.1 Introduction

The discard mortality experiment (Section 8.1 above) clearly demonstrated that there is likely to be high mortality amongst discarded spanner crabs that suffered limb damage during disentanglement. Although it is not possible to accurately determine the rate of limb damage which occurs in the commercial fishery, any apparatus which catches crabs by entanglement is likely to lead to some damage of the crabs during disentanglement. Sumpton *et al.* (1995) trialed a series of alternative traps which did not rely on entanglement to collect spanner crabs. However, none of those traps proved successful, with the most efficient having a catch rate of about 18% of the catch rate of tangle nets.

To reduce the risk of discard mortality to a minimum, an ideal spanner crab fishing apparatus would selectively catch only legal size crabs. Any trap which involves entanglement is likely to catch spanner crabs over a wide size range, so an alternative trap was devised which did not involve entanglement and would enable under size crabs to escape.

8.2.2 Methods

The alternative trap consisted of a solid steel wire frame, with the top and bottom being constructed of welded wire mesh (50 mm apertures) and the sides consisting of pivoting arms which permitted crabs of any size to enter the trap, but prevented large crabs from exiting. Undersize crabs could leave the trap at any time by passing between the pivoting arms, which were set 50mm apart, or through the wire mesh at the top of the trap. Those undersize crabs which had not left the trap prior to retrieval would tend to fall through the trap bottom as it was being recovered. As the wire mesh had a diameter of 5mm, and was rigid, it was unlikely to cause entanglement of spanner crabs, particularly those of less than 100 mm RCL.

This trap was trialled at six locations in the Dog's Leg area on two dates, 3 & 17 December 1996. To ensure that the trap landed on the sea-floor the correct way up, it was lowered on a separate rope attached to the four upper corners, rather than being attached to a line of dillies. Spanner crabs were sampled using both this new trap and standard commercial spanner crab dillies. Each sample involved placing the trap and three strings of ten dillies on the sea floor in close proximity to each other for a period of 60 minutes. Three replicate samples were collected with each apparatus on each day, a total sampling time of six hours. Sample sites were selected haphazardly, on suitable sand substrata in a depth range of 23 to 64 metres. Upon recovery, all crabs were carefully removed from each apparatus and measured (RCL). Catch per unit effort was recorded for both legal and sub-legal size crabs.

8.2.3 Results

Only two spanner crabs were collected in six replicate samples using the trap, while 196 spanner crabs were collected in 180 replicate dillies on 18 replicate lines. Thus, the mean CPUE of the new trap was 0.33 crabs/trap and that of commercial tangle nets was 1.09 crabs/net lift or 10.89 crabs/line (Table 8.4). Both of the crabs caught using the trap were of legal size, but only 70 of the 196 crabs caught using the tangle nets were greater than 100 mm RCL. Thus, the legal CPUE of the trap remained at 0.33 crabs/trap whereas the legal CPUE of the dillies was reduced 0.39 crabs/net lift, or 3.89 crabs/line (Table 8.4). The new trap was considerably heavier and required more effort and time to deploy and retrieve than a single dilly, but less time and effort than a line of ten dillies.

Table 8.4 Comparison of Catches Per Unit Effort (CPUE) between the new trap design and commercial tangle nets (dillies), either singly, in lines of 10 dillies or in rounds of 3 lines. CPUE is sub-divided into 'Sub-legal' (RCL < 100mm) and 'Legal' (RCL > 100mm) size classes.

Unit of Effort		CPUE Sub-Legal	CPUE Legal	CPUE Total
Trap	Mean	0.00	0.33	0.33
(n = 6)	(sd)	(0.00)	(0.52)	(0.52)
Dilly	Mean	0.70	0.39	1.09
(n = 180)	(sd)	(1.04)	(0.74)	(1.44)
Line (10 dillies)	Mean	7.00	3.89	10.89
(n = 18)	(sd)	(4.99)	(3.68)	(7.72)
Round (3 lines)	Mean	21.00	11.67	32.67
(n = 6)	(sd)	(10.70)	(6.41)	(14.12)

8.2.4 Discussion

Statistical comparison between the catch rates of dillies and the new trap was limited by the small sample sizes, and the fact that the trap caught either one crab or none (binomial distribution). Further comparative sampling would be required to determine whether or not the CPUE of the new trap was significantly different from that of dillies. Direct comparison of the CPUEs of both gears is also limited by the fact that the units of effort are different, one trap lift is not the same as one net lift. However, the trap did catch fewer spanner crabs per unit soak time than any of the dillies, and fewer legal sized crabs than all but one of the dillies (which also caught a mean of 0.33 crabs per deployment).

The amount of effort (in terms of time) involved in operating one trap exceeded that involved in operating one dilly, but was less than that involved in operating a line of ten dillies. Thus, a spanner crabbing vessel would not be able to deploy as many traps in a day as dillies. As the catch rate of the trap appears to less than that of a dilly, this would lead to a reduction in the maximum catch which could be taken using traps. In addition, the size and weight of the new trap design would make it difficult for small vessels to carry as many traps as they do dillies. Thus, replacement of the current spanner crab fishing apparatus with the trap design trialled here would lead to a reduction in catch, as well as an increase in gear handling taime and in increased need for deck space.

It is possible that with further fine tuning, the catch rate of the new trap design could be improved. In addition to this, further development of this trap design could enable it to be lighter and more easily deployed. While the dilly remains the most efficient, effective and practical spanner crab fishing apparatus, there is the possibility that further development could yield an equally efficient and effective apparatus which may overcome the problem of discard mortality.

8.3 INDUSTRY INVOLVEMENT IN GEAR OPTIMISATION

Objective 4 of the Project was (in part) to "promote the development by industry of less damaging apparatus". The standard spanner crab dilly is arguably one of the simplest and most cost-effective pieces of fishing gear, with the exception of the hook and line. Underwater video studies have revealed that it may not be particularly efficient in terms of the proportion of crabs approaching the net that actually get caught, but at the same time (with present mesh size regulation) it is reasonably selective for large crabs. That is not to say, however, that the catch of undersize crabs by this apparatus is negligible – at times there are very significant numbers of "small" crabs taken, mostly individuals between about 75 and 100 mm RCL.

Throughout the development and maturation of this fishery there has been concern from a number of quarters about the way some crabbers clear the catch from their nets. It is a time-consuming process to untangle the legs of each crab without breaking them, and there is always a temptation with undersized animals to break off enmeshed legs and claws to reduce clearing-time. Previous studies in aquaria have demonstrated that for some reason spanner crabs do not have the ability to "throw" claws and legs and to re-generate them easily. If appendages are broken, there is a real risk that the animal will die. In the previous sections we have quantified the effect of limb damage on survival rates in the crabs' natural environment.

However there is still seen to be a need to investigate new forms of spanner crab apparatus that will be easier to clear than the tangle nets, and will therefore result in lower mortality rates among juvenile and undersized crabs. Previous studies (including the collaborative Qld/NSW FRDC Project 90/5) have investigated many varieties of net and trap for catching spanner crabs, but without a great deal of success. Enclosed nets such as those used in the blue swimmer and mud crab fisheries will certainly catch spanner crabs, but not at a sufficient rate to maintain commercial viability. Despite this work, many crab fishers believe they know how to construct a net that will catch crabs in reasonable quantity, and be easy to clear and result in greatly reduced discard mortality rates.

Because of the way the current fisheries legislation is structured in Queensland, only certain designated apparatus is permitted in any fishery. This severely limits the ability of commercial fishers to experiment with their apparatus and develop superior designs and modifications. For this reason we have been actively promoting the concept of industry itself being encouraged to experiment with different gear, but within the context of a fixed-term program sanctioned and supported by the Queensland Fisheries Management Authority.

In 1993-94 the Queensland Commercial Fishermen's Organisation sought funding from the FRDC to run a workshop involving spanner crab fishers and scientists, to examine the state of knowledge about alternative fishing apparatus, and identify opportunities to further this knowledge. Although the funding was made available by FRDC, for internal administrative reasons the project was not followed through, and the grant was subsequently relinquished.

In accordance with Objective 4(b) of this present project, we advised the Crab Fishery Management Advisory Committee (CrabMAC) of this situation, and recommended that the QCFO be encouraged (with the MAC's support) to re-apply to FRDC to have the grant re-instated. After consideration, the MAC and QFMA decided that (given the relatively modest probable cost), the Authority itself would take on the project as a minor research allocation. Project staff assisted QFMA personnel to re-formulate and update the proposal, identifying a substantial list of potential participants from Queensland and interstate (principally NSW). These included not only commercial spanner crab fishers and research personnel, but also fishery managers and manufacturers of crab fishing gear.

The main aims of the workshop were to similar to those in the QCFO's proposal, but it was expanded to include the implementation of a strategy developed primarily by the senior author for enabling the commercial fishery to develop and test alternative apparatus. As mentioned

above, present regulations inhibit the use of anything but specifically prescribed apparatus in the crab fishery. Our proposed strategy is to provide the commercial fishery with a framework in which gear development and testing can be done legitimately.

Individual spanner crab fishers would be invited to register their interest in such a programme, and submit details of the generic characteristics of their proposed apparatus (whether enclosed net or tangle-net modification, approx. size, general structure and number of units), and the locality where they intend to do the testing work. A Working Group nominated by the MAC would assess the expressions of interest and select a number for approval by the QFMA. The Authority would then issue these applicants with research permits to allow them to use and modify their various apparatus subject to stringent reporting requirements (e.g. special detailed logbooks) and notification of the Queensland Boating and Fisheries Patrol when using the experimental gear.

After a pre-determined period (say 6 months) the permits would expire, and the gear development programme would conclude. At that point any of the fishers involved who believed that they had made significant advances to the design of the gear (with respect to size-selectivity and/or post-discard mortality while maintaining catching efficiency) would be invited to submit their designs to the Working Group. The Group would then arrange for field trials of the apparatus using a team of independent research scientists (perhaps from QDPI and CSIRO) under strict experimental design protocols. The developer of the "best" apparatus would be awarded a cash prize, towards which both QCFO and QDPI have indicated a willingness to contribute in the past. That particular apparatus would then be considered by the MAC as a possible industry standard, and be incorporated into the regulations under the Spanner Crab Fishery Management Plan.

The Authority intended to hold the workshop in about mid-1998, but developments in the crab fishery management area have resulted in the process being put on hold. These included a Government requirement to "fast track" development plans for the mud crab and blue swimmer crab fisheries, and the need to deal with unforeseen aspects relating to the progress of the Spanner Crab Fishery Management Plan. Despite this, a workshop on the development of a non-damaging spanner crab catching apparatus remains a high priority both within industry and the various advisory bodies, and we are optimistic that it will take place soon after the Management Plan is gazetted.

9 GENERAL DISCUSSION

9.1 STOCK SIZE

9.1.1 Commercial catch statistics

Since 1988 all licenced commercial fishers in Queensland have been required to provide information on their daily catches. The data, including catch weights, relevant effort statistics and fishing location, are recorded in a fishery-specific logbook, whose sheets are supposed to be submitted monthly. In comparison to most of the State's fishery statistics, evidence suggests that the spanner crab data are relatively reliable.

The catch data are likely to be of reasonably high quality and reliability, although until recent years it is likely that the reported catches were mostly estimates rather than weighed catches. After the introduction of a TACC and daily catch limits the precision of the catch data probably improved (because of quota accounting requirements), although this gain may have been offset in some instances by the practice of transferring excess catch (over the allowed daily limit) to other boats.

In the early years of the logbook programme fishing effort was measured as 'fishing days', because there was some confusion amongst the fleet about the meaning of the alternative effort index – the 'net (or dilly) lift'. With the advent of daily catch limits the former index was replaced by the net-lift, as fishing days became variable in length depending on whether the catch limit had been reached. All commercial spanner crab data summarisations and analyses are now based on catch weight (kg) per net-lift. There is no specific procedure for a commercial crab fisher to accurately tally daily fishing effort, so the data are largely the result of recall after the event. In recent years this has probably been made more reliable by the use of GPS plotters to mark fishing locations, and the fact that nearly all of the fleet operates with three strings or trot-lines each with a maximum of 10 nets. Location data are reported at one of three levels of precision – the half-degree grid, the 6-minute square subgrid, or individual latitudes and longitudes. There is an increasing tendency towards reporting fishing location at finer spatial scales, but there are still many reporting and/or transcriptions errors in the database. The extent to which catch and effort data are mis-reported, either deliberately or unintentionally, is not known.

Annual catch, effort and CPUE trajectories over the period since the start of logbook recording generally reflect a fishery that expanded north and south from an initial focus around Brisbane and the Gold Coast, where commercial spanner crab fishing had been established during the previous decade. Over the 10-year logbook period catch rates in the established areas were relatively constant, at around 0.9 kg.net-lift^{-1}. As the fishery expanded into more northern areas catch rates were initially high, but decreased to what appears to be a stable level at a little over 1 kg.net-lift^{-1}.

Whether CPUE is a reliable index of spanner crab stock abundance is, however, debatable. It is possible that any of several factors may be contributing to maintaining catch rates at an artificially high level, thus potentially disguising a real decline in stock abundance. Such factors include 'effort creep' and the phenomenon of hyperstability. Increasing real but undocumented effort, referred to as effort creep, can result from increases in the fishing power of catching vessels. Hyperstability can occur where a fishery targets aggregations and maintains high CPUEs in the face of a declining total stock.

9.1.2 Effort standardisation

Through an effort standardisation analysis we identified several vessel characteristics that contributed to differences in fishing power within the fleet. These included the number of crew carried, the skipper's experience, and the vessel's size and cruising speed. However the effects of these factors was very small compared to the effects of fishing location (assessment region), year and month. Standardisation by individual vessel accounted for somewhat more of the variation in fishing power, suggesting that there were other significant factors which we had not identified. In any case, the standardised CPUE data were not greatly different from the 'raw' data and did not substantially alter the original interpretation. This is probably because of the high level of variability in spanner crab availability and catchability due to unquantified factors relating to the species' patchy distribution, behavioural characteristics with respect to passive fishing gear, and unknown effects of environmental factors on gear efficiency.

9.1.3 Population modelling

Our attempts to model the dynamics of the Queensland spanner crab fishery have been frustrated by uncertainty about the reliability of some elements of the commercial CPUE series, lack of contrast in the catch and effort data, and uncertainty about auxiliary population parameters such as growth rates. In collaboration with Dr André Punt (CSIRO, Hobart) we developed two versions of a comprehensive size-based model - an equilibrium and a dynamic version. The equilibrium version was designed to test how well the observed size-frequency distribution of the population early in the fishery (1980-81) provided by Brown (1986) matched the expected size distribution generated from growth parameter estimates from the Seychelles (de Moussac 1988) and NSW (Chen & Kennelly in ms.). It was also used in a slightly modified from to predict growth parameters (L_∞ and K) independently. The dynamic version of this length-based model (tuned to CPUE and current size-frequency data-sets described elsewhere in this report) has not yet been applied because of continuing uncertainty about the reliability of growth estimates. For completeness, we also fitted the observed commercial CPUE data series to a standard observation-error biomass-dynamic model of the Schaefer form.

The population size-frequency distributions predicted by the equilibrium size-based model given 'slow growth scenario' VBG parameters from Seychelles and NSW studies were seriously at variance with the observed 'early exploitation' data. If the 1980-81 length-frequency samples were truly representative of the population, and if the size-structure of the population at the time actually approximated that of a virgin stock, then there might be considerable doubt about the reliability of the growth parameters. However data from the present study highlights the huge variability in observed size and sex-composition of spanner crabs over relatively small spatial and temporal scales, suggesting that (even though the samples were quite large) they may not necessarily have been representative. Moreover, the amount of fishing that had been applied to that (small) section of the stock in previous years is impossible to estimate, and therefore the 1980-81 data may not have been typical of an unexploited spanner crab stock.

The equilibrium size-based model failed to find growth parameters that resulted in a good fit between predicted and observed length-frequency data. While the fit was reasonable for length classes up to about 125 mm, the model consistently estimated L_∞ values (for male crabs) in the range 124-132 mm, substantially below what would be considered biologically realistic for an unfished population. Natural mortality rate estimates were also suspiciously low (as little as 0.016 yr^{-1}). This inability of the model to home in on 'realistic' parameter values may also be a function of the non-representativeness of the sample data-set.

It was not anticipated that the Schaefer biomass-dynamic model would perform very much better than the size-based models, but for different reasons. In the absence of comprehensive

survey data the model was tuned to commercial CPUE trajectories for each Assessment Region separately. The reason for running the model separately for each region was because the regions in which the fishery had been established for the longest time showed very flat CPUE trajectories. Only in the more recently developed regions was there any appreciable contrast in the data-set, and even then it tended to be evident only when the fishery first began operating in the particular region. The model was run twice for each region, under two assumptions – that the initial biomass was, or was not, equal to the environment's carrying capacity. Under both conditions, however, the variation in parameter estimates between regions, combined with the huge variability in associated error estimates, means that the results are completely unreliable. It is likely that there are three main reasons for this lack of reliability: (i) the relative brevity of the CPUE data time-series, (ii) the lack of contrast in the data, and (iii) uncertainty as to the meaning of early CPUE trends in the developing regions. The former two issues are widely known to cause biomass-dynamic models to perform poorly. The latter relates to situations where (in regions where the fishery is starting to become established) CPUEs start at a low level, increase suddenly, then gradually decline. The initial rise in catch rate is interpreted by the model as the rapid recovery of a previously depleted stock. It may, however, actually be due to the fleet-learning process, where some time elapses while fishers explore the new grounds and gradually discover the best fishing locations. Unfortunately this sort of problem may not be able to be eliminated by standardisation, and can result in the model's arriving at quite erroneous conclusions about the dynamics of the stock.

We reiterate that the output from this model is included here for completeness, and should not be used in any way as an indication of the present status of the spanner crab stock in southern Queensland.

9.1.4 Population density estimation – depletion experiments

Apart from growth rates, one of the major issues in the assessment of spanner crab stocks is the lack of knowledge about how much of the stock is removed from a given area by fishing activity. If the baited dilly is very effective (i.e. if the crabs' catchability is high relative to that particular gear) the fishery must be removing a greater proportion of the available biomass than if the dilly is not so effective, and the species' catchability is low. Previous collaborative work between QDPI and CSIRO (Hill and Wassenberg, in ms.) using an underwater video camera indicated that the proportion of crabs retained by the baited dilly was quite low (in the order of 7%). However that study was unable to determine the total number of crabs in the dilly's area of influence, or effectively estimate the species' catchability coefficient in relation to the baited dilly.

We attempted to estimate the catchability coefficient of spanner crabs by using a standard population sampling technique – the depletion or 'fish-down' experiment. By repeatedly fishing a small known area and observing the decline in catch rate it is possible to estimate the initial population size. Catchability can then be calculated, from the amount of fishing effort that had been applied.

The success of this method depends upon certain assumptions being satisfied – principally the absence of movement of animals into or out of the experimental area, the absence of population change resulting from recruitment or natural mortality, and a strong relationship between catch rate and population density. The issue of changes due to recruitment and mortality can usually be accommodated by conducting the experiment over a short time-span, but the assumption of no migration is more difficult to satisfy. Nevertheless, the collective wisdom of the fishing fleet, in its strong perception about the patchiness of the stock and the capacity of a single operator to substantially fish down a patch of crabs over a period of a few days, suggested that this assumption could be approximated if not satisfied completely. The extent to which catch rate reflects population density is influenced by various behavioural

processes and undocumented micro-scale environmental effects, and in the case of this fishery the existence of a strong relationship between catch rate and population density remains an assumption.

We initially intended to involve several commercial vessels in the fish-down experiment, so that the greatest amount of fishing pressure could be applied per unit time, thereby maximising the chance of producing a measurable depletion effect. However the perceived logistic problems of having more than one vessel, each setting perhaps three 0.3 km groundlines in the one small area, resulted in our using just the one vessel (RV *Warrego*).

The results of the four separate depletion experiments were inconsistent. In one case there was a very rapid apparent depletion effect, producing an estimate of population density of 33 crabs.ha^{-1} and a catchability coefficient of 3.09 x 10^{-3}. In one case there was no significant change in CPUE over the 5-day experimental period, and in the other two cases CPUE actually increased. We conclude that these inconsistencies are the result of changing behavioural patterns, including significant but unquanitifiable movement across the boundary of the experimental area, and possible changes in susceptibility to capture. The former may have been due to the gradual attraction of crabs from well outside the experimental area by continuous deployment of large number of baits in a relatively small area. The latter could have been influenced by the time since individual crabs had last fed. Without actually erecting some sort of physical barrier around the depletion site, it is difficult to imagine how the ingress and egress of crabs could be prevented.

By tagging and releasing crabs caught during the depletion experiments we had hoped to be able to provide an independent estimate of population density in the experimental area. This procedure produced some evidence of reduced activity during the four days after release, but later recaptures allowed the calculation of a Peterson estimate of population density. This estimate (1,460 crabs ha^{-1}), was two orders of magnitude larger than that derived from the depletion experiment. While this figure may seem high, it does include crabs of all sizes susceptible to capture by baited dillies, and the methodology probably violates fewer assumptions than did that of the depletion experiment.

9.1.5 Surveys of potential new fishing grounds

In terms of investigating stock size, we undertook exploratory surveys to assess whether exploitable populations of spanner crabs exist at locations outside the currently-exploited areas. This follows on from previous survey work (Brown 1994) which failed to locate any spanner crabs in the 'lagoon' between the Great Barrier Reef and the mainland, from Cape Manifold to Mackay. We investigated claims by crab fishers that spanner crabs should be able to be found in the vicinity of the Duke and Percy Island group and in the Swain Reefs. No crabs were caught near the Duke and Percy Is., and only a very small number (mostly from one isolated area) were caught in the Swains. This indicates that there are unlikely to be any significant unexploited populations remaining in Queensland, at least in areas accessible to the sorts of vessels currently comprising the fleet. We have certainly found no evidence of large spawning populations to the immediate north that might be supplying recruits to the fishery further south. Populations of spanner crabs certainly do exist in other areas, and possibly throughout the entire length of the Great Barrier Reef. However the evidence to date suggest that these are unlikely to be anything more than isolated colonies, at best capable of supporting only a very small temporary fishery.

9.1.6 Stock structure – genetic analysis

It appears, from mitochondrial DNA analysis, that there are not likely to be any significant structural elements within the Queensland spanner crab stock that could require different

spatial management arrangements. While the numbers of crabs actually analysed from each sampling location were quite small, the mDNA technique is very sensitive, and the phyletic relationships within the total sample (including those from Hawaii) did not reveal any spatial pattern. However, the analysis did reveal the presence of a distinct group or 'clade', spread throughout the fishery. This is a very unusual situation, although it has been reported in the stone crab (*Menippe* sp.) and may occur in the redclaw crayfish (N. Baker, pers. comm.). Several possible explanations are discussed in the relevant section of this report, but the phenomenon (while possibly of great theoretical interest) seems unlikely to have any significant impact on the assessment or management of the spanner crab fishery. Because of the seasonal nature of the small spanner crab fishery in the Seychelles Is., samples from that area were not able to be collected until quite recently, and have not yet been analysed. Depending on the availability of funding in the near future, this material will be analysed and the results interpreted in the context of those referred to above.

9.2 ASSESSMENT OF SEASONAL CLOSURE

The timing of the existing seasonal (spawning) closure was set originally on the basis of reproductive chronology data from a previous FIRTA study (Brown 1986). Since that time there have often been concerns raised as to whether the dates (20 November – 20 December) are still appropriate, given that the fishery has expanded considerably further north in the intervening period. Sometimes ovigerous or 'berried' female crabs are caught outside the spawning closure, and it was thought that there might be a need to adjust the timing accordingly.

Our data showed some variation in reproductive chronology (i.e. in the timing of gonad development, as estimated by the gonosomatic index) between broad geographic areas. However there did not appear to be any overall latitudinal trend in the results, and the differences were not consistent from year to year. Very few (1.1%) of the female crabs observed during the tagging study in the period just prior to, or just after, the seasonal closure were carrying eggs, while over 88% of the females inspected during the closure were ovigerous.

While there is some theoretical validity in the argument against spawning closures, our lack of knowledge about so-called spawning aggregations and the possible physical impact of fishing activities on mating and post-copulatory behaviour suggests that the closure should remain, even if as a precautionary measure. The vast majority of adult spanner crab length-frequency samples measured aboard commercial vessels during this project showed sex ratios skewed very much in favour of males (2.97:1 in a sample of over 25,000 crabs). Similar findings were common among research samples taken over the same period in exploited areas of the fishery (2.14:1 in a sample of over 8,000 crabs). This seems to indicate a counter-intuitive numerical imbalance between the sexes which, at face value, would not support a relaxation of any management arrangement designed to protect female crabs.

In any case, there is strong community support for spawning closures (whatever their logical or scientific validity) in a number of Queensland fisheries, and this support frequently extends to the commercial catching sector. It would be highly unlikely that under the current ESD-oriented management climate any move to expunge the 1-month spanner crab closure, which has been in place for a decade and a half, would be viewed favourably. Our data confirm that the timing of the closure, over the entire Queensland fishery, is appropriate to minimise the capture of ovigerous female crabs.

9.3 AGE AND GROWTH

The growth rate of spanner crabs has proved to be a difficult parameter to estimate with confidence. The evidence is conflicting, and different interpretations of the available data from this project and the results of other (unpublished) studies have failed to resolve the issue satisfactorily.

Two previous studies (Brown, 1986 and Boullé, 1995) suggested that growth of spanner crabs is rapid ($K > 0.5$). On the other hand, work by de Moussac (1988) and Chen and Kennelly (1999), indicate a much slower growth rate in male crabs ($K = 0.3$ and 0.216 respectively). The evidence from the present study tends, at face value, to support the slow growth hypothesis. Apart from Brown (1986), there is a general consistency in the various studies that males grow faster than females, and all studies indicate that males reach a greater asymptotic length than females.

9.3.1 Slow growth hypothesis

Evidence for slow growth derives from length-frequency analyses of material from the Seychelles Is by de Moussac (1988), from tag recapture data obtained in northern NSW by Chen and Kennelly (1999), and from juvenile length-frequency data collected in southern Queensland waters during the present study.

Given that this evidence is based on analysis of stocks in three separate localities and using two completely independent methodologies, it is tempting to conclude that the growth of male spanner crabs is indeed quite slow, with a K of somewhere between 0.216 (Chen and Kennelly) and 0.30 (de Moussac). Our study, using an estimate of L_∞ (= 155.9) from the Powell-Wetherall plot, and length-frequency data on juvenile crabs from dredge-sampling operations, yielded an intermediate value of $K = 0.242$. The latter set of parameter estimates describes a male crab that takes four years to reach minimum legal size (100 mm RCL), nine years to attain 140 mm, and possibly 14-15 yr to attain asymptotic (population average maximum) size. It is possible that the difference in K between Queensland and NSW could relate to differences in latitude and consequently in ambient water temperature. However throughout the 6C° annual cycle in coastal water temperatures, the temperature difference between offshore Bundaberg (Qld) and Cape Byron (NSW) was little more than 1C°. Whether this could account for the estimate differences detailed above is debatable.

There are several generic problems with the interpretation of these results. They relate to (i) the subjectivity and unreliability of some of the length-based estimation models, (ii) the non-continuous mode of growth in crustaceans, (iii) the small size of the samples on which the estimates were based, and (iv) the probable adverse effects of tagging on growth in this species.

It is possible to read greater complexity than is warranted into small length-frequency data sets because of the artificial accentuation of peaks and troughs resulting purely from random variation in the samples. If the modal progression signal is weak, this may increase the risk (in a model such as ELEFAN or NORMSEP) of creating spurious age-classes. As a result the growth function K would be biased downward, suggesting slower growth than is actually the case. The growth estimates of de Moussac (1988) were based on quite small sample sizes, and may therefore have been biased by this effect.

While our juvenile length-frequency data (derived from dredge sampling) strongly suggest the presence of two distinct modal groups that could be easily interpreted as successive age-classes, we recognise that it is a particularly small data set. Even when the data from both years are pooled, the number of individuals represented in the second modal group only amounts to 15, spanning a range of sizes from 31 to 48 mm. The absence of any individuals

between 19 and 31 mm throughout the entire first six months of the year is a powerful argument for considering the modes to represent two legitimate age-classes. However we concede that monthly samples of merely three or four of the larger individuals of a single age-class is barely adequate for fixing the growth curve of this species.

Because crustaceans increase in size by moulting, their growth occurs in discrete steps rather than as a continuous process. Adult crabs may only moult once each year (and possibly not even every year (see Chen and Kennelly, 1999) with the result that age-class modes, if they exist in that sector of the population, may show no 'seasonal' movement throughout a given year. This may confuse a length-based analysis programme such as ELEFAN, which expects to see a temporal trend in the data. An animal that moults will flip from one age-class mode into the next one, with the result that modal lengths will remain static except for variations attributable to environmentally-mediated changes in average moult increment, or fishing mortality effects due to selective gear.

In some of the length-frequency data sets obtained from the present study it is possible to identify a number of indistinct modes, which, if interpreted as successive age-classes, are consistent with the 'slow growth' hypothesis. However we are not confident that these represent anything more than random variation, even though the samples were very large compared to those in previous studies. In fact it was precisely because of the lack of consistent modal resolution in the length-frequency data originally that we changed the project's methodological approach.

The estimates of Chen and Kennelly (1999) were not derived using length-frequency analysis methods, but from the actual changes in size of tagged animals between the times of release and recapture. By modelling estimates of moult frequency and moult increment, these authors were able to develop a picture of the stepwise (non-continuous) growth pattern in spanner crabs. However the picture was restricted to the adult sector of the population, as no crabs less than 65 mm OCL had been tagged, and the results were expressed in terms of relative age rather than absolute age. The authors recognised that juvenile growth (prior to maturity) might follow a quite different trajectory from that of the adults. Without knowledge of the growth pattern of juvenile crabs, the attribution of ages to the adult size-range might be biased one way or the other.

Moreover there is the question of the extent to which tagging may affect growth, either by interfering with the moulting process or modifying the animals' capacity to achieve maximum size increment between moults. Our aquarium experiments showed that tagging spanner crabs with T-bar anchor tags is likely to increase mortality and decrease body growth in weight, both of which effects may translate into a reduction in overall growth rate. For this reason the estimates of Chen and Kennelly (1999) should perhaps be regarded as minimum rather than typical. Our own tagging results yielded growth increments that were, on average, about 10% greater than those of equivalent premoult lengths predicted from the VBG function. The percentage differences between predicted and observed increments were, however, very variable, ranging from –49% to +75%. We believe the source of this experimental error is more likely to be related to the presence of a T-bar anchor tag than to differences in environmental factors such as water temperature or food availability.

Notwithstanding the reservations expressed above with respect to the dredge length-frequency data, it is significant that our estimate of K derived from a composite model based on the modal growth of juveniles and an independent estimate of $L\infty$ was very similar to that of another composite model utilising the NSW tagging data and the modal size-at-age data from our dredging operations.

9.3.2 Fast growth hypothesis

Evidence for fast growth derives from analysis of adult length-frequency data from southern Queensland by Brown (1986), from the Seychelles Is by Boullé (1995), and from the present study. Brown's (1986) estimate of K (=0.90) was the highest of any of the prior studies. Boullé (1995) estimated somewhat lower values of K from his own data and from re-analysis of de Moussac's (1988) previous data (0.55 and 0.58 respectively). Observations by Brown (1986) on juvenile exuvium (moult shell) size-frequencies, and visual interpretation of some adult length-frequency data-sets from the present study may also lend some support to the fast growth hypothesis.

The parameter estimates of Boullé describe the growth trajectory of a spanner crab that reaches minimum legal size in 18 months, 140 mm in about 4 yr, and attains asymptotic length in about 8-9 yr.

Evidence for fast growth is based solely on length-frequency information, and to a great extent on the use of length-based parameterisation and interpretational aids such as ELEFAN and NORMSEP. Due to the variable nature of the size-distributions from the present project, some frequency plots can be interpreted as having a large number of indistinct modes (thus supporting slow growth), while some others are characterised by clear bimodality. In these cases the primary mode was around 103-105 mm and the secondary mode around 120-127 mm. Assuming that the two modes represented successive age-classes, the 20 mm length increment from 104 mm RCL is consistent with the fast growth hypothesis. Boullé's parameterisation would put the first age-class mode (104 mm) at 1.9 yr and the second (123.5 mm) at 2.8 yr, a difference of almost exactly 1 year.

Additional evidence in support of the fast growth scenario has been presented in a previous FIRTA report (Brown 1986). This evidence comprises information about the inferred size-structure of a local population of post-settlement juvenile spanner crabs in the vicinity of the northern end of Fraser Island. On 12 and 13 December 1982 project staff collected 31 small live crabs (of both sexes) ranging from 38 to 58 mm RCL from the intertidal zone on the northern and north-western beaches. Nearly 180 intact carapaces between 14 and 57 mm RCL were collected from the tide-line at the same time. These carapaces, assumed to have been moult shells (exuviae), strongly suggested the presence of a local population of crabs in the process of moulting. This assumption was based on the fact that the exuviae showed no signs of deterioration, and those of appropriate size still retained their natural pigmentation. Brown (1986) concluded that the live crab sample could have been drawn from the same statistical population as that which produced the exuviae. The size-frequency plots suggested modes at about 16-17 mm, 25-26 mm, 33-35 mm and 45-50 mm. It would seem unlikely that these could represent different year-classes, as it would suggest that spanner crabs take 3 years to reach a length of 45 mm, an extraordinarily slow rate of growth for a subtropical crustacean. The alternative is that they represent the modal lengths of different juvenile developmental stages, which would suggest that the largest animals belonged to the same year-class as the smallest, and had undergone an increase in size of between 35 and 40 mm since settlement as 9 mm megalopae.

There are, however, as many caveats upon the various pieces of evidence for rapid growth as there were on the evidence for slow growth, and in some cases the caveats are the same. The use of length-based analysis routines on only data for adult crabs calls for exactly the same caution in interpretation as is referred to above. Because of non-continuous growth, routines such as ELEFAN are probably inappropriate and will produce unreliable growth estimates. Again, visual selection of modes in the adult length-frequency data is highly subjective and amenable to several different interpretations.

It seems certain that, whatever the growth rate of male spanner crabs may be, it is more rapid than that of female spanner crabs. Thus is it unfortunate that, because of small sample sizes, Boullé found it necessary to combine male and female length-frequency data prior to estimating the VBG parameters. The possible effect of such a procedure on the outcome of a length-based model is not easy to predict, and it may not necessarily result in an 'average' growth trajectory.

The length-frequency analyses lock in on modes present in the sample data. If there are two adjacent modes that remain more or less fixed from year to year the analysis may well assume that they are successive year-classes, and derive growth parameters accordingly. It may be argued, on the other hand, that the (relatively few) instances of bimodality in the data from the present study result from a missing year-class, due to recruitment failure or other reasons. This would then favour the slow growth hypothesis, which predicts that the relevant length increase would take a little over two years, rather than one.

At face value, the evidence from the Fraser Is moult shell size-frequencies seems clear. However even here there are major interpretational difficulties, which relate to our knowledge of reproductive chronology - particularly the timing of ovulation and the duration of embryonic and pre-settlement larval development. The earliest date on which ovigerous (berried) females were caught during the present study was 24 October. Brown (1986) found that embryonic development (under laboratory conditions) takes about 5 weeks, and the zoeal larval series (also *in aquaria*) takes another four weeks. Assuming that the Fraser Is juveniles had been the progeny of females which ovulated on 24 October 1982, our current chronology would have them hatching on 28 November and settling on 25 December. This latter date would have been two weeks *after* they had actually been collected (on 12 December), some already having attained a size of 45-50 mm. If all of the Fraser Is juveniles belonged to the same year-class, growth was not only exceptionally rapid, but some of the year-class must have settled (as megalopae) considerably earlier than would be suggested from our laboratory-based knowledge of the species' early life-history. Either ovulation can occur (in particular years and at particular locations) earlier than our data indicate, or the duration of embryonic/larval development is much shorter under natural than laboratory conditions.

The alternative explanation is that the moult shells were not produced at the same time. They would then represent a random sample of the moulting history, over an unknown time-span, of a local population that comprised perhaps two or more year-classes. If the largest of the Fraser Is juveniles had belonged to the previous (1991) year-class, this entire data-set would favour the 'slow growth' interpretation.

Although significant questions still remain about the growth rate of *Ranina ranina*, it would seem that, on balance, the best available evidence favours a slow-growth hypothesis.

9.4 POST-DISCARD MORTALITY

It could be argued that there is some justification to remove the minimum legal size regulation altogether, as the commercial gear is fairly selective, taking few very small crabs. However the catch of crabs in the 80-100 mm range can be quite substantial, and if there is a high level of mortality amongst this group resulting from poor handling practices (i.e. limb damage during extraction from the net), fishing mortality can be quite high. We have shown that if post-discard mortality relating to capture and handling exceeds 39% there is a risk that (under current management arrangements) the total fishing mortality will be greater with a minimum legal size than without it. We have also shown that the amount of damage inflicted on an undersized crab needs only to be minor to have a substantial effect on its chance of survival after release. While the effects of limb damage on survival *in aquaria* have been reported previously by Onizuka (1972) and Kennelly *et al.* (1990), our results represent the first time such experiments have been conducted under more or less natural conditions.

However, despite reports and statements from the crab fishers themselves, there is no effective way of estimating the level of limb damage caused to undersized spanner crabs over the entire fleet. Trustworthy sources maintain that, by and large, handling practices have improved in recent years, but there is still a significant element of concern in the industry about the extent of damage and mortality from this cause. Unless post-discard mortality can be quantified, and with some degree of accuracy, it may be counter-productive to pursue a policy of removing the size limit on spanner crabs. The minimum size limit was introduced originally to protect female crabs (which appeared to be far less numerous than males), to create a more orderly domestic marketing situation, and to discourage 'backyard' meat-extraction operations. For a time the export market was favouring smaller crabs, and was presumably sourcing these from fisheries outside Australia, but in the last year there has been a significant shift in market preference towards sizes above 100 mm (P. Packman, Ocean Pacific Seafoods, pers. comm.).

At present, when a crab fishing operation yields a particularly high proportion of undersized animals, the fisher is likely to move away from the area because of the amount of time required to clear the nets. If there were no minimum size limit, and assuming minimal price differential between small and large crabs, the fisher would probably opt to stay on the patch rather than move, with the result that a larger than usual number of small crabs would be captured. This effect may well negate the mortality 'advantage' of removing the minimum legal size.

During the course of the project we have actively promoted the need for greater care in handling undersized crabs, both through articles in the industry journal and via personal contact with numerous crab fishers. While there is probably a growing consciousness amongst the majority of fishers about the adverse consequences of damage to small crabs, there is undoubtedly a proportion of operators who have little regard for the long-term sustainability of the stock and treat their discards accordingly. Without an operational harvest-strategy model it is impossible to properly quantify the effects of varying levels of post-discard mortality on long-term yields and stock sustainability. For this reason it is considered important to persevere with the development of alternative catching apparatus that may reduce this mortality. A new 'pigeon-bar' trap or pot developed and trialled during this project was successful in capturing spanner crabs, but (like most of the apparatus tested in the past) it failed to come even close to matching the catch rate of the tangle-net or dilly. Senior project staff are cooperating with staff of the Queensland Fisheries Management Authority in planning a workshop for the dissemination of information on post-discard mortality and a strategy to allow commercial fishers themselves to (legally) develop and test their own trap designs.

10 BENEFITS

This Project was designed principally to develop a clearer understanding of the underlying dynamic processes of the spanner crab stock(s) in Queensland. The work will initially be of value to the stock assessment and monitoring process, from which management recommendations may be made to the ultimate benefit of the fishery as a whole.

Our attempts to estimate stock size (both relative and absolute) met with mixed success. The general linear regression analysis showed that standardisation of effort will be of advantage to the present stock assessment arrangements, by giving a picture of annual changes in commercial CPUE that are less influenced by differences in fishing power between vessels. This advantage should translate into an improvement in the reliability of annual total allowable catch recommendations, and greater confidence in the TAC/ITQ management process as a whole. Estimation of absolute stock density by depletion and mark-recapture experiments was hampered by either an unexpectedly high rate of localised movement amongst the crabs, or unpredictable behavioural patterns. While not providing a definitive value of the density or catchability of the crabs, the information gained will be particularly valuable to the design of the long-term monitoring programme.

Results of the exploratory surveys for new exploitable populations of spanner crabs will benefit industry by focussing attention away from the potential existence of new undiscovered grounds. This will reinforce the need for careful management of the known resources, and remove some of the uncertainty surrounding possible sources of recruitment into the northern part of the fishery. Likewise, the results of our work on the spawning closure should remove doubts amongst some spanner crab fishers about the appropriateness of its timing.

Our mitochondrial DNA analyses of material both from within the Queenland fishery and from remote locations suggests that there is little if any observable genetic structure, and there is no evidence of separate stocks or even sub-stocks. This information will be helpful to managers, as it will obviate the need for consideration of different regional management arrangements which might otherwise be required. It will also answer the question often raised by crab fishers as to whether differences in the appearance of crabs from different areas means that there are different spawning populations.

We have determined that modal discrimination even in very large length-frequency samples from the commercial catch are subject to multiple interpretations, and are thus of dubious value with regard to estimation of growth rates. We have also shown that tagging spanner crabs almost certainly has an adverse effect on their growth patterns, with the result that growth rates estimated from mark-recapture programmes are probably biased. Our data on the size-distribution of post-settlement juvenile crabs has provided previously unavailable evidence about a critical part of the species' life history. This has been very valuable in helping to interpret the conflicting evidence about whether spanner crabs grow quickly or slowly. While there is no definitive set of growth parameters yet available, our project results have contributed significantly to this important area of investigation.

Until accurate growth parameters are estimated, our size-structured fishery models will perform inadequately, and not be particularly useful to stock assessment. However the models are available and will be put to very good use as soon as the relevant data requirements are met. When this occurs, the model(s) will represent an integral part of the stock assessment process for spanner crabs.

Our experimental results on post-capture mortality highlight the need for great care to be taken by crab fishers while disentangling spanner crabs from the dillies. This knowledge builds upon previous work, and demonstrates that the effects of limb damage observed in laboratory

experiments also apply under natural conditions. It will be of great benefit in providing an impetus for continuing the search for a catching apparatus that is as effective as the dilly but less likely to result in limb damage to undersized crabs. If such a device can eventually be developed, it will reduce post-discard mortality rates and theoretically result in higher total allowable catches.

11 FURTHER DEVELOPMENT

- The major area in which further development needs to occur is in the estimation of growth rates. The lack of reliable growth parameters is one of the main reasons for the very poor performance of our size-based dynamic fishery model. There are significant problems associated with tagging methods, and length-frequency analysis is clearly not appropriate unless a more quantitative method can be devised for collecting samples across the animal's size range.

  Small samples of post-settlement juveniles obtained with the channel dredge showed considerable promise in the area of estimating pre-recruit growth, but a larger device is needed to make the sampling more cost-effective. We have developed what we believe to be a suitable dredge, but have been unable (within the time-frame of the project) to test and fine-tune it adequately.

  A second possible approach to the growth determination question is the use of novel techniques such as lipofuscin assay. This technique has been applied to some effect in research on rock lobsters and other crustaceans. However calibration of the method requires animals of known age, which may require long-term maintenance of a captive population.

  While not specifically providing a solution to the issue of growth, some knowledge of the moulting cycle would greatly enhance our understanding of the process. At present we don't have a clear idea of when or how frequently the crabs moult, or whether there is a terminal moult in the species. These issues could be addressed by conventional techniques, and would assist with the interpretation of other (and existing) data relating to age and growth.

- A better understanding of the causes of the extreme spatial and temporal variability in the size and sex structure of population samples is needed. Are they real, or an artefact of the sampling method? A strategy is required for minimising this variability so that more reliable and consistent size-frequency data can be obtained for the age-based population model. This would probably best be done through a fishery-independent sampling programme, which would provide a means of assessing the accuracy of commercial catch and effort statistics, and should ultimately be used to calibrate the commercial data, if not replace them altogether, in stock assessments. NSW Fisheries staff have been running a small-scale monitoring programme in northern NSW (the subject of an FRDC project) over the past three years. This is a repeat of a similar exercise carried out 10 yr ago by the same researcher (Dr S Kennelly), and the data (together with the earlier data set) are to be used in an assessment of the east coast spanner crab stock.

  As a result of the interaction between senior Project staff and the Queensland Fisheries Management Authority, the Crab Fishery Management Advisory Committee (CrabMAC) and the Spanner Crab Stock Assessment Group, the groundwork is already in place for such an on-going fishery-independent survey of the spanner crab stock in Queensland. The survey is to be funded partly by industry (it will be one of the first partial cost-recovery stock surveys in Queensland) and partly by the QDPI Monitoring Programme. Whether the same sampling design and protocols as are being used in NSW are

appropriate to the (much more geographically extensive) resource in Queensland has yet to be determined.

12 CONCLUSION

Trends in commercial fisheries catch-effort statistics indicate that the spanner crab stock in southern Queensland is currently being harvested at a sustainable level. However several questions remain with respect to the application of the commercial logbook data, possibly the most important of which is how well commercial catch-per-unit-effort represents stock abundance. The spatial distribution of spanner crabs is patchy, and the fishery operates such that patches are located, targeted and fished down. This can potentially lead to a situation of hyperstability, where the stock is actually declining despite catch rates remaining constant. This highlights the likely value of the fishery-independent monitoring programme currently being planned by QDPI with (in the case of the spanner crab fishery) a significant level of cost-recovery from industry.

Our length-based assessment model has not yet been successful in producing useful estimates of the relevant stock performance indicators for use by management, largely because of lack of contrast in the CPUE data, the relatively short data time-series, and the extreme spatial and temporal variability in population size-structure as represented in commercial catches and research samples. Whether this variability is due to the impact of localised fishing activity, or whether it is an artefact of the sampling/fishing method is not clear, and requires further investigation. Whatever the cause, it is an issue that does need to be taken into consideration in the design of any long-term monitoring programme for this species.

Our commercial catch sampling demonstrated that variability in the size-structure of even very large samples of adult crabs was so great that we are not able to place any confidence in growth estimates obtained from this type of data. In addition, we have found that growth parameters estimated from tag-recapture may be seriously in error because of adverse sublethal effects of tagging. On the other hand, significant new information has been obtained on the size structure of post-settlement juvenile crabs from sampling with a small channel dredge. These data have been incorporated into exploratory growth models, and (depending upon certain assumptions) favour a slow growth scenario. The evidence on growth in spanner crabs remains equivocal, and is a major impediment to the successful application of our mathematical models of the fishery. Resolving the issue of growth is the most important task for ongoing research into this species.

We conclude that the east-coast spanner crab fishery comprises a single unit stock, and there is no biological need for separate management arrangements in different geographic areas.

The timing of the current seasonal (spawning) closure is appropriate to the management aims of minimising mortality amongst egg-bearing female spanner crabs. While there may be theoretical arguments for removing the spawning closure, our knowledge of the potential effects of fishing on spawning aggregations of crabs is poorly understood. For this precautionary reason alone we recommend that the closure remain in place.

Poor handling practices in the fishery continue to cause limb damage to undersized crabs that are returned to the water. Such damage is a significant contributor to mortality amongst pre-recruits under natural environmental conditions as well as in captivity. We have shown that if the short-term survival rate amongst discards falls below a critical threshold level, fishing mortality amongst small crabs could theoretically be greater with the current minimum legal size than without it. Nevertheless, other considerations mitigate against the abolition or relaxation of the current 100 mm limit. It is important not only that the need for careful handling practices continue to be reinforced in the spanner crab fishery, but also that additional

work be done towards the development of a catching apparatus which will result in lower discard mortality rates. We believe that such an objective would be best addressed by the industry itself, and we are encouraging the development of appropriate arrangements.

13 ACKNOWLEDGMENTS

The involvement of a large number of people who contributed to various aspects of this Project is acknowledged with sincere gratitude. We apologise if we've inadvertently omitted any names from the list.

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As is usually the case with projects such as this, a good many Southern Fisheries Centre staff and associated workers have pitched in from time to time, providing assistance particularly in the field. These colleagues include Adam Butcher, Darren Cameron, Michael Cosgrove, Wayne Hagedoorn, Ian Halliday, Simon Hoyle, Stuart Jackson, Eddie Jebreen, Mathew Johnston, Kath Kelly, Jason McGilvray, Scott McKinnon, Michael O'Neill, Brian Pascoe, Claire Peterkin, Petra Ringeltaube, Jonathan Staunton-Smith, John Sutherland, and Kate Yeomans. Matthew Seese was of enormous assistance with the diving operations relating to the cage experiments, and Raewyn Street persevered with great equanimity in the Genetics Laboratory.

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15 APPENDICES

Appendix 1: Intellectual Property

There is no intellectual property (in the sense of patents or commercially marketable information) associated with this research work.

Appendix 2: Project Staff

Dr. John M. Kirkwood	(Project Leader)
Dr. Ian W. Brown	(Principal Investigator)
Mr. Brett G. Davidson *	(Master, *RV "Warrego"*)
Ms. Cathy M. Dichmont *	(Modelling)
Mr. Shane Gaddes *	(Fisheries Technician)
Dr. Jenny R. Ovenden *	(Genetics)
Ms. Raewyn Street *	(Genetics)

* = part time

APPENDIX 3

SPANNER CRAB FLEET SURVEY – 1998

IW Brown, K Yeomans, C Dichmont, S Gaddes and J Kirkwood

INTRODUCTION

In many fisheries throughout the world, undocumented changes to vessels, their crew and/or fishing gear have been shown to lead to significant changes in the fishing power or catching capacity of the fleet. If not detected, this can cause biases in the estimation of catch-per-unit-effort (CPUE), and may ultimately result in wrong conclusions about the status of the fishery. Statistical analyses capable of "factoring out" such changes in fishing power (which could result from the installation of advanced navigational aids such as GPS) are generally referred to as "effort standardisations", and have become standard tools in fisheries science.

Unfortunately the sort of information most valuable to effort standardisation is rarely captured by fishery logbook programmes. However, if it can be obtained, it may help determine exactly which of the wide range of possible factors is/are responsible for changes in fleet fishing power.

One of the objectives of our Spanner Crab research project (funded by the Fisheries Research and Development Corporation FR&DC) was to carry out an effort standardisation analysis of the commercial fisheries data. We had hoped initially to obtain the required information on vessel characteristics from the QFMA Licensing Database. However investigations showed that this would be very time-consuming and expensive – as the vessel data were not in a readily accessible form – and in any case some pieces of information vital to the analysis would be missing.

METHODS

We therefore decided that the best way to access the required information was by means of an industry-wide survey, aimed at all spanner crab licence-holders. The survey was carried out *via* a questionnaire which was mailed out between late December 1997 and early January 1998. Because we expected certain complexities to arise with regard to the effects of licence trading and the identification of the most appropriate person to answer the questionnaire (i.e. whether the vessel owner, licence-holder or the actual skipper), we invested considerable time in the structure of the questionnaire. Prior to the main mail-out we carried out a "dry run" with two long-time spanner crab fishers to ensure that the questions were intelligible and would provide answers in the form we desired.

In addition to information about the characteristics of the vessel and the history of improvements/changes to the vessel and gear, we also sought industry opinion about certain aspects of their fishery. These included data reporting procedures, perceptions about long-term changes in stock distribution, and perceptions about the reliability of

logbook data and changes in data quality over time. The reliability of the catch and (particularly) effort data in the logbooks can vary depending on how conscientious the recorder is at ensuring the data are accurate and precise. It can also vary if there is ambiguity in the way the logbook is set out, resulting in some operators recording data in one way while others record it differently. Both of these issues were addressed in the questionnaire.

Our original intention was to do a detailed "pre-view" analysis of the survey results for release as soon as possible to a sub-set of the respondents who indicated their wish to be part of this process. Following this, a more general and condensed summary, including some results of the effort standardisation process, would be released via the Queensland Fisherman. Although somewhat delayed in production, the document you are reading is the limited release "pre-view" analysis, in response to the fact that you signified your wish to be included.

RESULTS

1. Response rate

The questionnaire was mailed out in late December 1997, with explanatory covering letter, to the approx. 250 holders of Queensland spanner crab fishing licences. Over the next 3 months or so we received some 84 replies (33.6%), of which about half (44) indicated a willingness for their data to be included in the detailed "pre-view" process. It should be borne in mind, therefore, that the following analyses are based on about 50% of the responses, or a little over 17% of the fleet. Some random comparisons of the answers to particular questions between the "pre-view" group and the entire sample of responses indicated that there was probably little bias between the two. Most of the results in this section are presented as histogram charts showing the percentage of respondents who provided a particular answer to each question.

2. Vessel characteristics

2.1 Hull size

Vessels in the fleet sample ranged in size from 5 to 12 metres, but most were between 7 and 10 m in length (Fig. 1). More than 25% were in the 9.0 – 9.9 m range. To examine spatial differences in vessel size, nominal fishing areas north of Double Island Point were grouped and those south were

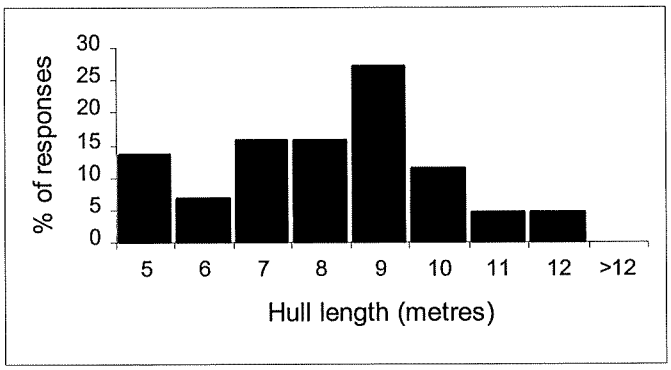

Figure 1 Frequency distribution of hull length (metres) in fleet sample.

grouped, and the data re-analysed. As expected, the sample results confirmed general belief that the larger vessels in the fleet tend to be based in the northern (Bundaberg-Gladstone) region (Fig. 2). Over 25% of the fleet sample was in the 9 metre length class, almost all of these being based in the northern region. South of DIP the vessels ranged fairly uniformly between 5 and 8 m, with no one length-class predominating (Fig. 2).

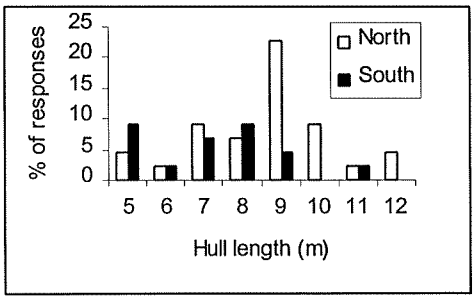

Figure 2 Comparison of size of vessels in fleet sample between northern and southern parts of the fishery. The "cut-off" point for this purpose was Double Island Point.

2.2 Hull Type.

Slightly more than 60% of the sampled licence-holders classed their vessels as having planing hulls (Fig. 3). About half as many reported having semi-planing hulls, while the remainder (5%) used displace-ment-hulled vessels in their crabbing operations (Fig. 3).

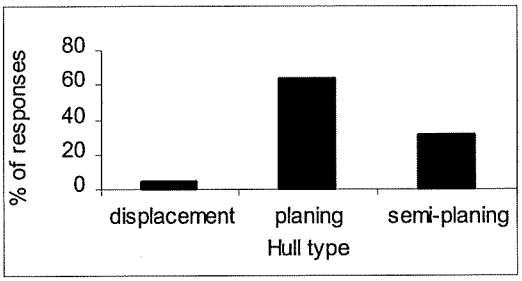

Figure 3. Fleet sample composition in terms of hull type.

2.3 Hull configuration

As estimated by the fleet sample, 75% of licenced spanner crab boats are monohulls and 25% are multihulls (presumably mostly catamarans) (Fig. 4).

All 11 multihulls in the sample were classsed as "planing". Of the 33 monohulls in the sample, 17 were classed as planing, 14 as semi-planing, and 2 as displacement hulls.

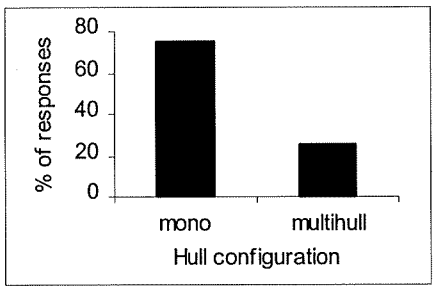

Figure 4 Fleet sample composition in terms of hull configuration.

2.4 Cruising Speed.

Apart from a small number of very high speed vessels (30 kt or more) and the displacement hulls with cruising speeds less than 10 kt., vessels in the spanner crab fleet tend to be of a configuration allowing cruising speeds of between 11 and 29 kt (Fig. 5). The average cruising speed of the three "hull types" were as follows: displacement = 10.6 kt, semi-planing = 13.3 kt, and planing = 20.2 kt.

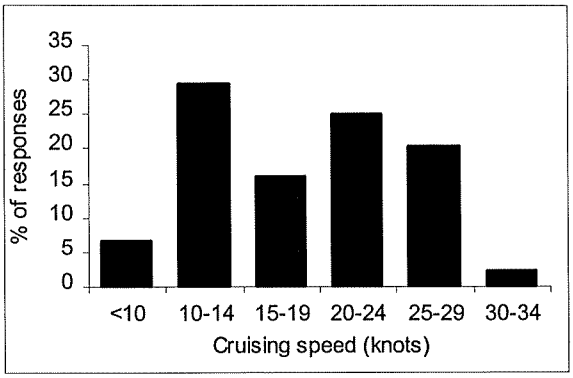

Figure 5 Frequency distribution of hull speed within the fleet sample of spanner crab boats.

2.5 Engine Manufacturer

Thirty-four percent of the fleet sample reported having Volvo motors (Fig. 6). Most (71%) of these were installed in planing or semi-planing mono-hulled vessels and the remainder in planing multi-hulls. The next most common manufacturers were Caterpillar and Cummins (11 and 9% respectively), installed in a mixture of planing and semi-planing mono and multi-hulled vessels. A broad range of other engines are also used within the fleet, each representing between 2 and 7% of the sample.

2.6 Engine Power

By far the majority of engines powering vessels in the spanner cab fleet were in the 200-249 hp class (Fig. 7). This group comprised 40% of the sample and was followed by motors ranging from 300 to 349 hp (Fig. 7). Together these two groups comprised 65% of the sample, and were thus by far the most "popular".

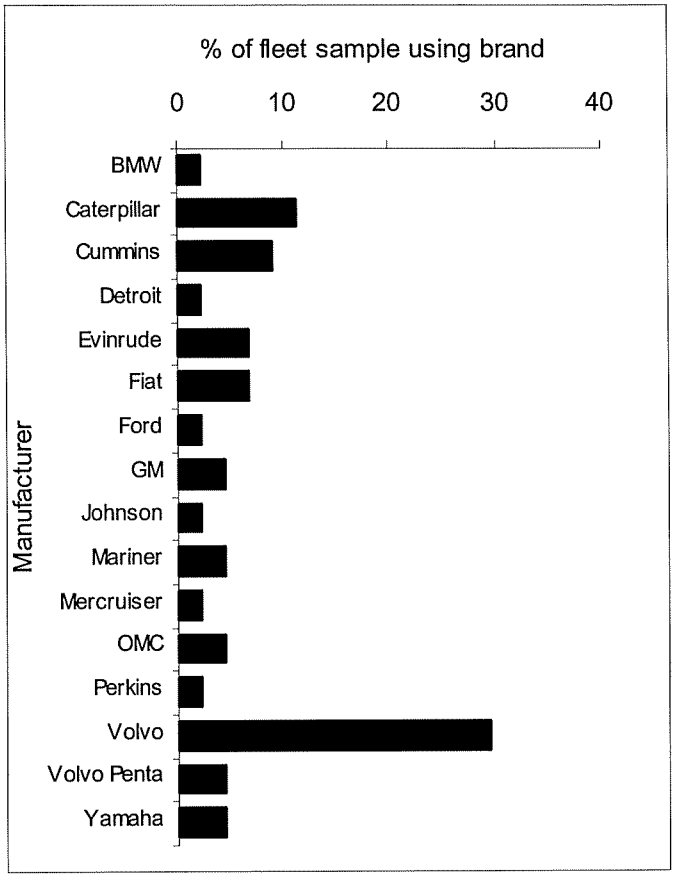

Figure 6 Frequency distribution of engine manufacturer within the sampled spanner crab fleet.

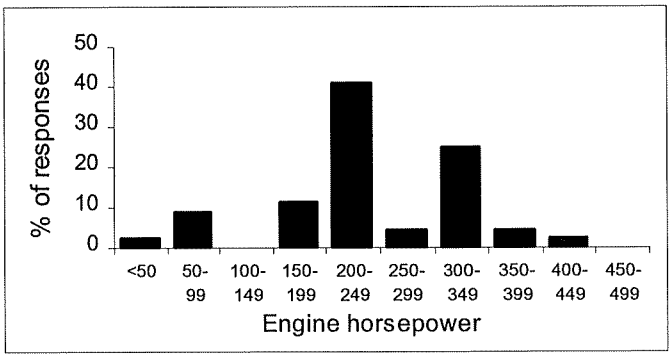

Figure 7. Proportional frequency distribution of engine horsepower (i.e. per engine) within the spanner crab fleet sample.

2.7 Number of Motors

Eighty percent of boats in the fleet sample were powered by a single motor, and the remainder (20%) by two (Fig. 8). Of the single-engine vessels, 32 (91%) were monohulls and 3 (9%) multihulls. In contrast, only one (11%) of the twin-engine vessels was a monohull, the remainder (89%) being planing multihulls.

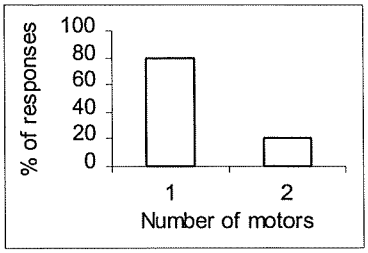

Figure 8 Percentages of vessels in the fleet with one and two motors.

2.8 Navigational Aids

Of the 44 vessels in the fleet sample, 10 (23%) utilise radar in the fishery. All radar units were installed since 1993. Five (11%) carry SatNav (installed since 1990). Four (9%) carry GPS without plotter (installed since 1990), and 40 (91%) carry GPS with plotter. By far the bulk of those vessels using GPS (either with or without plotter) came into the fishery or installed their GPS units during or since 1993 (Fig. 9). 80% of the 44 vessels in the fleet sample used GPS (either with or without plotter) when first entering the spanner crab fishery. Of the 20% that did not have GPS installed on entry, none had SatNav, and only one had radar. The latter represent operators who entered the fishery relatively early (mostly between 1980 and 1993, and primarily in the southern areas) and mainly used landmark sightings and depth soundings for navigation around the fishing grounds.

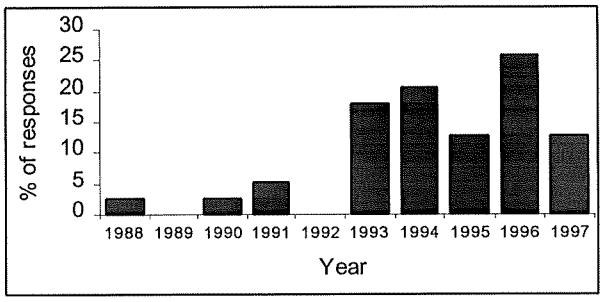

Figure 9 Frequency of installation of GPS (with or without plotter) or entry of vessel with GPS into the fishery, by year.

2.9 On-board Product Holding

23% of the pre-view sample either did not respond to the question about special on-board holding facilities, or answered "nothing" (Fig. 10). Nearly 40% use some sort of ice cooling arrangement, 18% use spray mist, and 23% use wet bags to cover baskets of crabs. A small number of respondents (4.5%) indicated that they use refrigerated boxes or holds in their vessels to hold product. As no

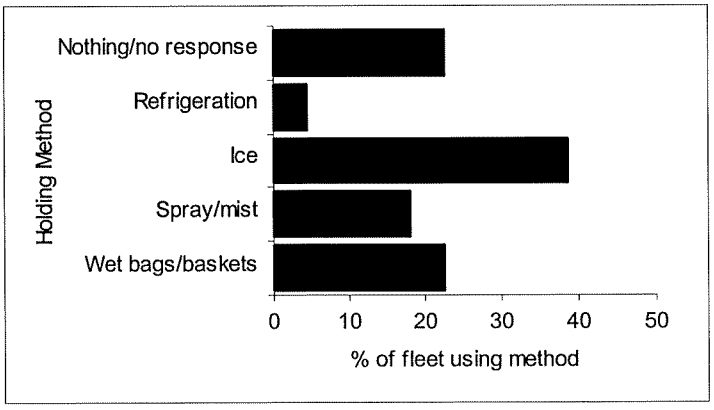

Figure 10 Percentage of boats in the fleet sample using different on-board holding methods (note that some boats use more than one method.

"prompting" options were provided in the questionnaire, it is possible that some of the respondents who omitted to answer this question may use the basic wet-sack holding method, but didn't consider it a "special" facility.

3. Gear Characteristics

3.1 Line-hauler

Not unexpectedly, line-haulers are a characteristic of spanner crab vessels. Only two respondents indicated that they do not use a line-hauler. We believe that they probably marked the wrong box in error, as both had also provided information on the date on which the line-hauler was installed.

3.2 Dilly characteristics

The majority of fishers use dilly mesh in the 31-35 mm size range (Fig. 11). Significant numbers used mesh between 26 and 30 mm, and some between 36 and 40 mm. It should be noted here that in many instances the mesh size was reported in inches and subsequently converted to the precise equivalent metric measurement.

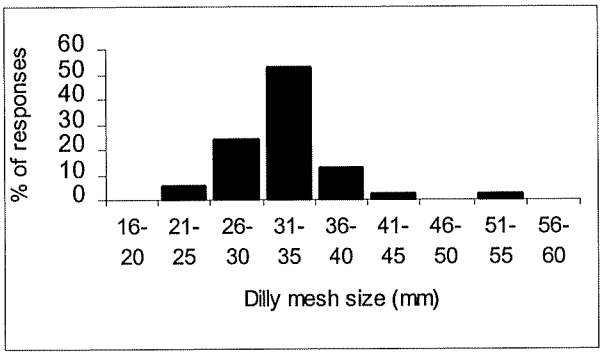

Figure 11 Proportion of fishers in the spanner crab fleet sample using mesh of a particular size in their dillies.

Of the 42 people who answered the question about their use of single and double layer mesh, 41 (98%) indicated that they use a single layer on their dillies (Fig. 12). Thirty-six of the 38 licence-holders who responded to the question about the thread-type used on their nets indicated that they used multifilament (Fig. 13).

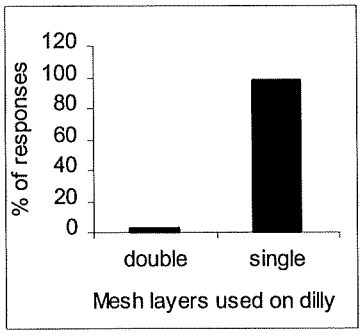

Figure 12 Relative use of single and double-layer mesh on spanner crab dillies.

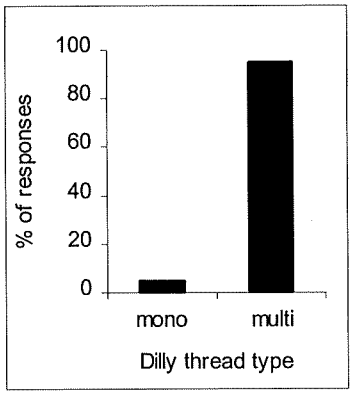

Figure 13 Relative use of monofilament and multi-filament thread in spanner crab dilly mesh.

4. Crewing and Fishing Experience

About 32% of the pre-view sample of the fleet indicated that they carry no crew apart from the skipper. Most boats (63%) carry one crew member, and the remainder (about 5%) carry two crew. None of the fleet sample carried more than two.

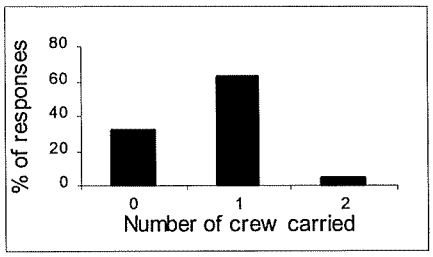

Figure 14 Proportion of boats in the fleet sample carrying different numbers of crew.

When asked the year in which the respondents started using their current vessels in the spanner crab fishery, most indicated that this occurred fairly recently. Fig. 15 shows that the bulk of the fleet sample entered the fishery in 1993 or later. However the wording of the question does not preclude the possibility that some of the boats may have been involved in the fishery previously, but under a different licence-holder.

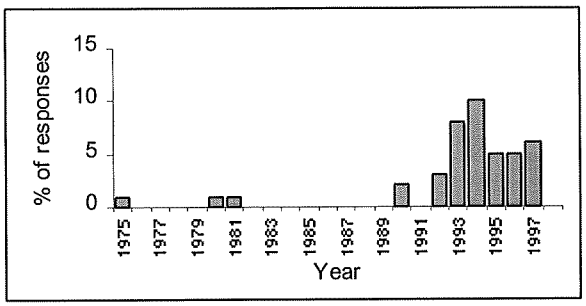

Figure 15 Proportion of vessels in the fleet sample entering the spanner crab fishery by year.

Most of the respondents indicated that they (or their skippers) had been involved in the spanner crab fishery for between 3 and 6 years (Fig. 16). There was an obvious peak in 1993/94 (4 years ago) when over a quarter of the existing skippers sampled came into the fishery. Few skippers had been in the fishery for more than 10 yr (i.e. prior to 1988).

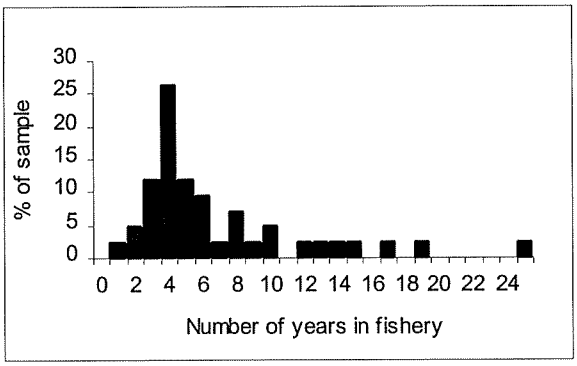

Figure 16 Proportion of skippers (of sampled vessels) who have been in the spanner crab fishery for different periods of time.

Nearly all respondents rated the experience level of their skipper as "moderate" or "high" (Fig. 17). It should be pointed out that 85% of the respondents actually were the skippers. It is therefore not really surprising that fewer than 5% of the pre-view sample ranked as having a low level of experience, particularly given that (according to Fig. 16) relatively few have had less than three years experience in the fishery.

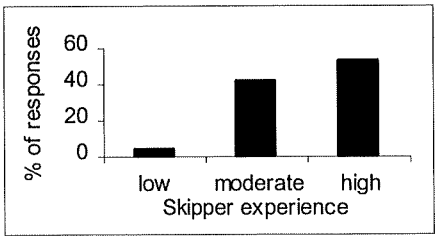

Figure 17 Proportion of skippers in sample rated as having a low, moderate or high level of experience in the spanner crab fishery.

Most (56%) of the respondents believed that the skill level of their vessel's skipper had improved very markedly since entering the spanner crab

fishery. About 42% believed that the skill level had increased moderately, and a mere 2% considered that their skipper's spanner crabbing skill had not increased at all.

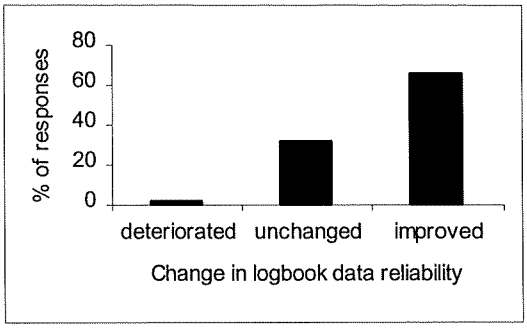

Figure 18 Perceptions amongst fleet sample as to changes in the reliability of logbook information over the past three or four years.

5. Logbook Data Reliability

When asked whether they believed the reliability of spanner crab logbook data had changed over the past three or four years, two-thirds of the respondents replied that they thought it had improved (Fig. 18). Almost all of the remainder considered that there had been little if any change in data reliability, and only one (2.4%) of the 41 people who answered this question were of the opinion that the data had actually decreased in reliability.

In the next section we sought opinions about the relative accuracy of the respondent's logbook data compared to that of the rest of the fleet. As there are several elements to the logbook data, we asked about each individually (i.e. catch, effort as pot-lifts, effort as fishing time, and location data), and asked the respondent to rank perceived accuracy as high, medium or low.

There was a general tendency for respondents to consider the accuracy of their own catch, effort and location data to be considerably superior to that of the rest of the fleet. Because catches are weighed accurately by the processors, it is not surprising that a very large proportion of the sample (nearly 90%) considered their catch figures very accurate

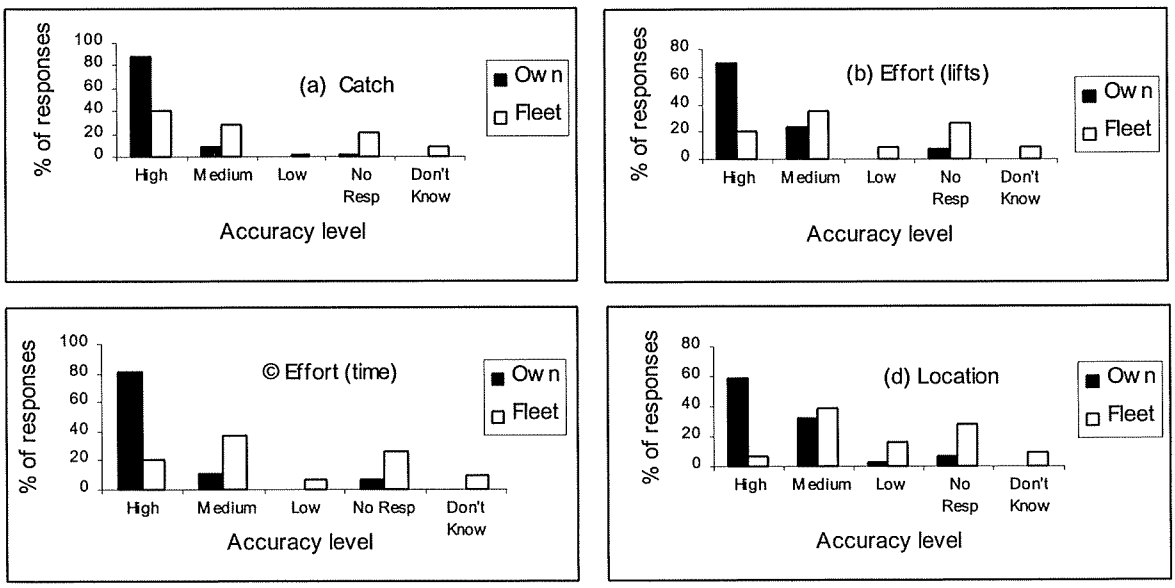

Figure 19 Perceived accuracy of respondent's own catch-effort data (as reported in the QFMA compulsory logbook system) compared to that of the fleet as a whole. This data set is based only on the pre-view subset of the questionnaire sample. No resp = no response.

(Fig. 19 (a)). Nearly all of the remainder classified the accuracy of their catch data as "medium". However over a quarter of the respondents classified the accuracy of the rest of the fleet's catch data as "medium". Similar trends were apparent with the effort data (Fig. 19 (b) and (c)), most respondents considering their data to be of high accuracy compared to the rest of the fleet. The situation was even more marked with respect to the location data (Fig. 19 (d)), where very few (7%) believed fleet accuracy to be high, and a considerable number (16%) actually thought it was low. Interestingly, there was a tendency here for respondents to be less optimistic about the accuracy of their own data than for the other three data types.

6. Resource Monitoring.

In this section of the questionnaire we asked for opinions relating to the use of logbook data for stock monitoring and assessment, and for information about observed changes in stock density and distribution.

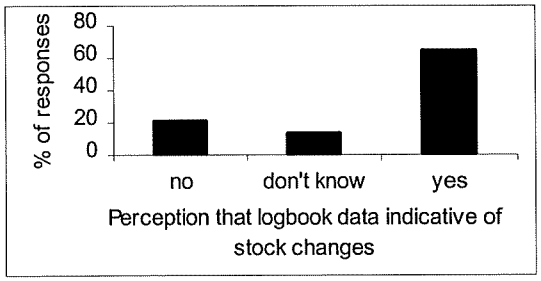

Figure 20 Opinions as to the ability of the spanner crab logbook data to reflect changes in stock abundance.

About 65% of the respondents in the "pre-view" sample believed that the logbook data are useful in tracking changes in stock abundance, through modelling and analysis of catch-per-unit-effort trends. Twenty percent thought that the data were presumably not sufficiently reliable for this application, and the remainder (15%) were not sure one way or the other.

Of those who answered "no" to this question, some offered ideas about alternative monitoring procedures. These included grid monitoring and tagging, size frequency analyses at wholesalers' and processors' premises, and sending more DPI staff out on "actual working boats". A cautionary note was added by one respondent who answered "yes" - that the data might not be of any use for another 20 years, by which time the stocks might be totally depleted. Other comments were included here, expressing concern about illegal trafficking of product between A and B management areas, the problem of stock patchiness in interpreting catch data, and the opinion that some skippers may not be providing good data because they don't have an interest in the long-term viability of the spanner crab fishery.

One of the difficulties in using catch-per-unit-effort data in any fishery for tracking changes in population size is patchiness in its geographic distribution. This is especially the case with schooling fish, where population density can be very high in one area and nil in surrounding areas. Like most animals, spanner crabs are not distributed evenly or uniformly throughout their range. Also, as with most animals, events such as mating and spawning can add a seasonal dimension to this patchiness. To get an idea as to how patchy the spanner crab stock is, and how this changes over time, we asked respondents to provide a rating (very patchy, fairly patchy, and evenly spread out) for each month of

the year. The results indicate a considerable variety of opinion, with significant numbers of people indicating all three levels of patchiness in each month (Fig. 21). This lack of consistency could be due partly to the criteria different people use to judge patchiness (it was a subjective individual decision). It is also very likely to have been influenced by differences in stock density between some of the areas fished. Despite this, however, there was a trend towards increasing patchiness towards the end of the year, with minimal levels of extreme patchiness being encountered in mid-winter (June-July).

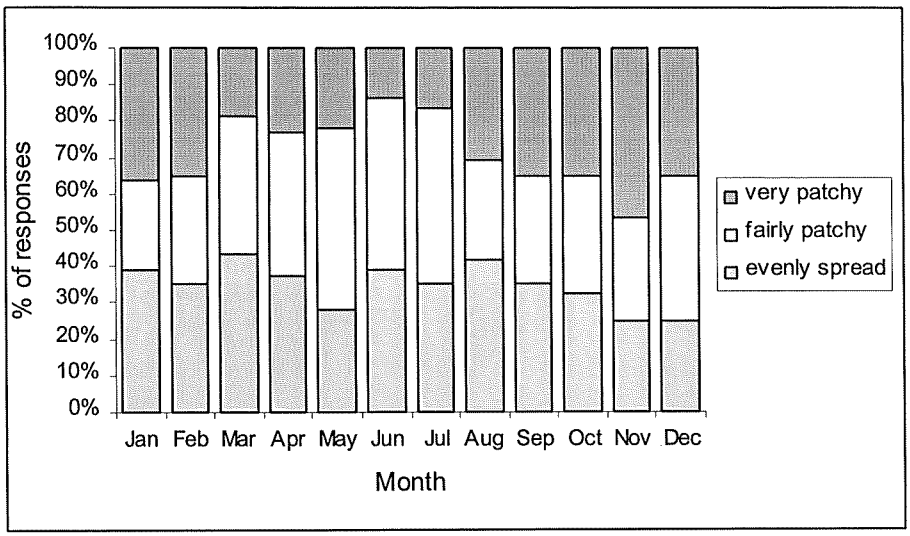

Figure 21 Perception amongst "pre-view" fleet sample of seasonal changes in patchiness of the spanner crab stock.

To determine whether all the main spanner crab fishing areas were represented among the those who responded to the questionnaire, we asked each respondent to indicate which area he/she normally fishes. As can be seen in Fig. 22, most of the "pre-view" respondents (28%) fish mainly in the Sunshine Coast area, followed by about 22% in the Bundaberg area. These were followed by the Gold Coast and Seventeen Seventy. If the pre-view group is representative of the fishery, Fig. 22 gives an indication of the geographical distribution of the fleet, at least in late 1997. However it does not necessarily reflect regional differences in catch or fishing effort.

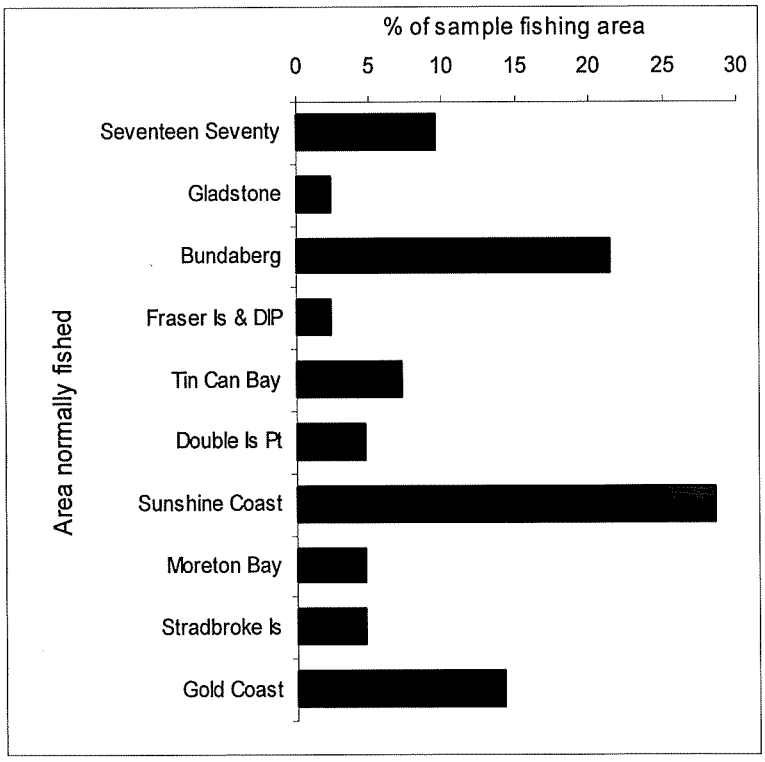

Figure 22 Proportion of crabbers in the sample fleet "normally" working in various areas of the fishery.

When asked whether they thought that the patchiness of the spanner

crab stock had changed appreciably over the past three or four years, nearly half felt that the stock had become more patchy (Fig. 23). Slightly fewer respondents believed that there had been no appreciable change, and a few (10%) felt that the stock had become more uniformly distributed. Again, the lack of unanimity between responses may be a function of geographical differences. This is because areas that have been fished heavily are likely to have become more patchy, with lower population densities between fishable patches.

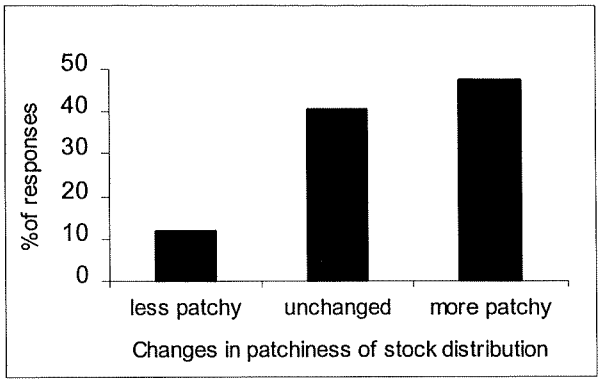

Figure 23 Fishers' perceptions about how the density distribution of the spanner crab population has changed over the past 3-4 years.

Also of interest in this context is whether the patches of crabs themselves have been reduced in size over time. Fig. 24 shows that most respondents in the pre-view group believe that the patches have become smaller. However a significant number evidently do not believe there has been a change, and a few suggest the patches have actually increased in size over the past 3-4 years.

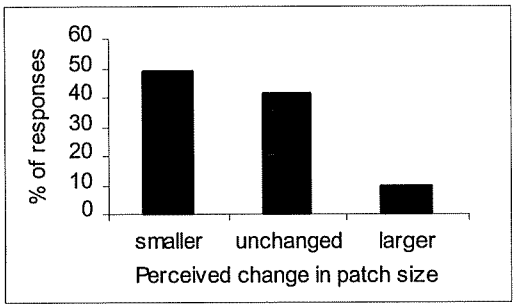

Figure 24 Fishers' perceptions as to changes in the size of spanner crab patches over time.

As researchers, we have an interest in the possible influence of environmental factors on catch rates, and consequently on our ability to make sense of temporal and spatial variation in CPUE. In this section of the questionnaire we asked fishers whether the speed and direction of water currents can influence the catch rates of spanner crabs on baited tangle nets. According to more than 80% of the fleet sample in the pre-view group, currents do have an effect on catch rates (Fig. 25). Fourteen percent disagreed, and the remainder (about 2%) did not offer an opinion.

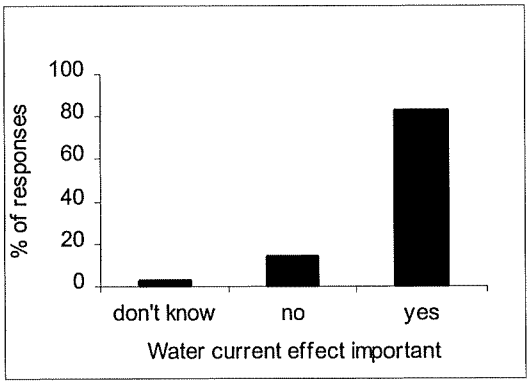

Figure 25 Proportion of fleet sample's opinion as to the effect on CPUE of water current speed and direction.

Thirty-six of the pre-view respondents offered opinions as to what other environmental factors may affect catch rates. The most commonly mentioned factors were swell size (22%), water temperature (14%), moon (11%) and weather in general (11%). A wide variety of other factors was mentioned, including currents, turtles, wind strength and direction, pollution and reduced water quality from river outflows, atmospheric pressure, tide height and time, cloud

cover, long-term climate changes including El niño events, and disruptions to the natural food chain.

ACKNOWLEDGMENTS

Our thanks are due to QFMA staff for helping identify spanner crab fishers and their current contact addresses, and to various members of the Southern Fisheries Centre staff who helped with the substantial job of mailing out the questionnaires and tagging information. However by far the greatest tribute must go to the 84 people (including yourself) who made their time available to work through the questionnaire and provide answers to the (often not very straightforward) questions. We hope after reading this you will consider it to have been time well spent.

Dr Ian Brown (Principal Fisheries Scientist, Coastal and Estuarine Fisheries Section)
Ms Kate Yeomans (Fisheries Biologist, Stock Assessment Section)
Ms Cathy Dichmont (Senior Fisheries Biologist, Stock Assessment Section)
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