Department of Agriculture, Fisheries and Forestry, Queensland

Harvest strategy evaluations and co-management for the Moreton Bay Trawl Fishery

Australian Seafood CRC Project 2009/774
October 2012

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AUSTRALIAN SEAFOOD COOPERATIVE RESEARCH CENTRE
Australian Government Fisheries Research and Development Corporation
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List of acronyms

ACPF	Australian Council of Prawn Fisheries
BOM	Bureau of Meteorology
BRD	bycatch reduction device
CFISH	The Queensland commercial fishery logbook database
CL	carapace length
CPUE	catch per unit effort
CRC	Cooperative Research Centre
CSIRO	Commonwealth Scientific Industrial Research Organisation
DAFF	Department of Agriculture, Fisheries and Forestry
DERM	Department of Environment and Resource Management
GLM	generalised linear model
GLMM	generalised linear mixed model
GPS	global positioning system
IMAS	Institute for Marine and Antarctic Studies
LMM	linear mixed model
LTMP	Fisheries Queensland Long-Term Monitoring Program
MVP	marginal value product
MBSIA	Moreton Bay Seafood Industry Association
MSY	maximum sustainable yield
NPF	Northern Prawn Fishery
QSIA	Queensland Seafood Industry Association
QSMA	Queensland Seafood Marketers Association
QECTF	Queensland east coast trawl fishery
s.e.	standard error
TAFI	Tasmanian Aquaculture and Fisheries Institute
TED	turtle excluder device

1 Non-Technical Summary

Seafood CRC Project 2009/774. Harvest strategy evaluations and co-management for the Moreton Bay Trawl Fishery

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Project objectives:

1. Review the literature and data (i.e., economic, biological and logbook) relevant to the Moreton Bay trawl fishery.
2. Identify and prioritise management objectives for the Moreton Bay trawl fishery, as identified by the trawl fishers.
3. Undertake an economic analysis of Moreton Bay trawl fishery.
4. Quantify long-term changes to fishing power for the Moreton Bay trawl fishery.
5. Assess priority harvest strategies identified in 2 (above). Present results to, and discuss results with, Moreton Bay Seafood Industry Association (MBSIA), fishers and Fisheries Queensland.

Note: Additional, specific objectives for 2 (above) were developed by fishers and the MBSIA after commencement of the project. These are presented in detail in section 5 (below).

The project was an initiative of the MBSIA, primarily in response to falling profitability in the Moreton Bay prawn trawl fishery. The analyses were undertaken by a consortium of DAFF, CSIRO and University of Queensland researchers. This report adopted the Australian Standard Fish Names (http://www.fishnames.com.au/).

Trends in catch and effort
The Moreton Bay otter trawl fishery is a multispecies fishery, with the majority of the catch composed of Greasyback Prawns (*Metapenaeus bennettae*), Brown Tiger Prawns (*Penaeus esculentus*), Eastern King Prawns (*Melicertus plebejus*), squid (*Uroteuthis* spp., *Sepioteuthis* spp.), Banana Prawns (*Fenneropenaeus merguiensis*), Endeavour Prawns (*Metapenaeus ensis, Metapenaeus endeavouri*) and Moreton Bay bugs (*Thenus parindicus*). Other commercially important byproduct includes blue swimmer crabs (*Portunus armatus*), three-spot crabs (*Portunus sanguinolentus*), cuttlefish (*Sepia* spp.) and mantis shrimp (*Oratosquilla* spp.). Logbook catch and effort data show that total annual reported catch of prawns from the Moreton Bay otter trawl fishery has declined to 315 t in 2008 from a maximum of 901 t in 1990. The number of active licensed vessels participating in the fishery has also declined from 207 in 1991 to 57 in 2010. Similarly, fishing effort has fallen from a peak of 13,312 boat-days in 1999 to 3817 boat-days in 2008 – a 71% reduction.

The declines in catch and effort are largely attributed to reduced profitability in the fishery due to increased operational costs and depressed prawn prices. The low prawn prices appear to be attributed to Australian aquacultured prawns and imported aquacultured vannamei prawns, displacing the markets for trawl-caught prawns, especially small species such as Greasyback Prawns which traditionally dominated landings in Moreton Bay. In recent years, the relatively high Australian dollar has resulted in reduced exports of Australian wild-caught prawns. This has increased supply on the domestic market which has also suppressed price increases.

Since 2002, Brown Tiger Prawns have dominated annual reported landings in the Moreton Bay fishery. While total catch and effort in the bay have declined to historically low levels, the annual catch and catch rates of Brown Tiger Prawns have been at record highs in recent years. This appears to be at least partially attributed to the tiger prawn stock having recovered from excessive effort in previous decades. The total annual value of the Moreton Bay trawl fishery catch, including byproduct, is about $5 million, of which Brown Tiger Prawns account for about $2 million. Eastern King Prawns make up about 10% of the catch and are mainly caught in the bay from October to December as they migrate to offshore waters outside the bay where they contribute to a large mono-specific trawl fishery. Some of the Eastern King Prawns harvested in Moreton Bay may be growth overfished (i.e., caught below the size required to maximise yield or value), although the optimum size-at-capture was not determined in this study. Banana Prawns typically make up about 5% of the catch, but can exceed 20%, particularly following heavy rainfall.

Economic analysis of the fishery

From the economic survey, cash profits were, on average, positive for both fleet segments in both years of the survey. However, after the opportunity cost of capital and depreciation were taken into account, the residual owner-operator income was relatively low, and substantially lower than the average share of revenue paid to employed skippers. Consequently, owner-operators were earning less than their opportunity cost of their labour, suggesting that the fleets were economically unviable in the longer term. The M2 licensed fleet were, on average, earning similar boat cash profits as the T1/M1 fleet, although after the higher capital costs were accounted for the T1/M1 boats were earning substantially lower returns to owner-operator labour.

The mean technical efficiency for the fleet as a whole was estimated to be 0.67. That is, on average, the boats were only catching 67 per cent of what was possible given their level of inputs (hours fished and hull units). Almost one-quarter of observations had efficiency scores above 0.8, suggesting a substantial proportion of the fleet are relatively efficient, but some are also relatively inefficient. Both fleets had similar efficiency distributions, with median technical efficiency score of 0.71 and 0.67 for the M2 and T1/M1 boats respectively. These scores are reasonably consistent with other studies of prawn trawl fleets in Australia, although higher average efficiency scores were found in the NSW prawn trawl fleet.

From the inefficiency model, several factors were found to significantly influence vessel efficiency. These included the number of years of experience as skipper, the number of generations that the skipper’s family had been fishing and the number of years schooling. Skippers with more schooling were significantly more efficient than skippers with lower levels of schooling, consistent with other studies. Skippers who had been fishing longer were, in fact, less efficient than newer skippers. However, this was mitigated in the case of skippers whose family had been involved in fishing for several generations, consistent with other studies and suggesting that skill was passed through by families over successive generations.

Both the linear and log-linear regression models of total fishing effort against the marginal profit per hour performed reasonably well, explaining between 70 and 84 per cent of the variation in fishing effort. As the models had different dependent variables (one logged and the other not logged) this is not a good basis for model choice. A better comparator is the square root of the mean square error (SMSE) expressed as a percentage of the mean total effort. On this criterion, both models performed very similarly. The linear model suggests that each additional dollar of average profits per hour in the fishery increases total effort by around 26 hours each month. From the log linear model, each percentage increase in profits per hour increases total fishing effort by 0.13 per cent. Both models indicate that economic performance is a key driver of fishing effort in the fishery.

The effect of removing the boat-replacement policy is to increase individual vessel profitability, catch and effort, but the overall increase in catch is less than that removed by the boats that must exit the fishery. That is, the smaller fleet (in terms of boat numbers) is more profitable but the overall catch is not expected to be greater than before. This assumes, however, that active boats are removed, and that these were also taking an average level of catch. If inactive boats are removed, then catch of the remaining group as a whole could increase by between 14 and 17 per cent depending on the degree to which costs are reduced with the new boats. This is still substantially lower than historical levels of catch by the fleet.

Fishing power analyses
An analysis of logbook from 1988 to 2010, and survey information on fishing gear, was performed to estimate the long-term variation in the fleet’s ability to catch prawns (known as fishing power) and to derive abundance estimates of the three most commercially important prawn species (i.e., Brown Tiger, Eastern King and Greasyback Prawns). Generalised linear models were used to explain the variation in catch as a function of effort (i.e., hours fished per day), vessel and gear characteristics, onboard technologies, population abundance and environmental factors. This analysis estimated that fishing power associated with Brown Tiger and Eastern King Prawns increased over the past 20 years by 10–30% and declined by approximately 10% for greasybacks. The density of tiger prawns was estimated to have almost tripled from around 0.5 kg per hectare in 1988 to 1.5 kg/ha in 2010. The density of Eastern King Prawns was estimated to have fluctuated between 1 and 2 kg per hectare over this time period, without any noticeable overall trend, while Greasyback Prawn densities were estimated to have fluctuated between 2 and 6 kg per hectare, also without any distinctive trend.

A model of tiger prawn catches was developed to evaluate the impact of fishing on prawn survival rates in Moreton Bay. The model was fitted to logbook data using the maximum-likelihood method to provide estimates of the natural mortality rate (0.038 and 0.062 per week) and catchability (which can be defined as the proportion of the fished population that is removed by one unit of effort, in this case, estimated to be 2.5 ± 0.4 E-04 per boat-day). This approach provided a method for industry and scientists to develop together a realistic model of the dynamics of the fishery. Several aspects need to be developed further to make this model acceptable to industry. Firstly, there is considerable evidence to suggest that temperature influences prawn catchability. This ecological effect should be incorporated before developing meaningful harvest strategies. Secondly, total effort has to be allocated between each species. Such allocation of effort could be included in the model by estimating several catchability coefficients. Nevertheless, the work presented in this report is a stepping stone towards estimating essential fishery parameters and developing representative mathematical models required to evaluate harvest strategies. Developing a method that allowed an effective discussion between industry, management and scientists took longer than anticipated. As a result, harvest strategy evaluations were preliminary and only included the most valuable species in the fishery, Brown Tiger Prawns. Additional analyses and data collection, including information on catch composition from field sampling, migration rates and recruitment, would improve the modelling.

Harvest strategy evaluations
As the harvest strategy evaluations are preliminary, the following results should not be adopted for management purposes until more thorough evaluations are performed. The effects, of closing the fishery for one calendar month, on the annual catch and value of Brown Tiger Prawns were investigated. Each of the 12 months (i.e., January to December) was evaluated. The results were compared against historical records to determine the magnitude of gain or loss associated with the closure. Uncertainty regarding the trawl selectivity was addressed using two selectivity curves, one with a weight at 50% selection ($S_{50\%}$) of 7 g, based on research data, and a second with $S_{50\%}$ of 14 g, put forward by industry. In both cases, it was concluded that any monthly closure after February would not be beneficial to the industry. The magnitude of the benefit of closing the fishery in either January or February was sensitive to which mesh selectivity curve that was assumed, with greater benefit achieved when the smaller selectivity curve (i.e., $S_{50\%}$ = 7 g) was assumed.

Using the smaller selectivity ($S_{50\%}$ = 7 g), the expected increase in catch value was 10–20% which equates to $200,000 to $400,000 annually, while the larger selectivity curve ($S_{50\%}$ = 14 g) suggested catch value would be improved by 5–10%, or $100,000 to $200,000. The harvest strategy evaluations showed that greater benefits, in the order of 30–60% increases in the tiger annual catch value, could have been obtained by closing the fishery early in the year when annual effort levels were high (i.e., > 10,000 boat-days). In recent years, as effort levels have declined (i.e., ~4000 boat-days annually), expected benefits from such closures are more modest. In essence, temporal closures offer greater benefit when fishing mortality rates are high.

A spatial analysis of Brown Tiger Prawn catch and effort was also undertaken to obtain a better understanding of the prawn population dynamics. This indicated that, to improve profitability of the fishery, fishers could consider closing the fishery in the period from June to October, which is already a period of low profitability. This would protect the Brown Tiger Prawn spawning stock, increase catch rates of all species in the lucrative pre-Christmas period (November–December), and provide fishers with time to do vessel maintenance, arrange markets for the next season's harvest, and, if they wish, work at other jobs. The analysis found that the instantaneous rate of total mortality (Z) for the March–June period did not vary significantly over the last two decades. As the Brown Tiger Prawn population in Moreton Bay has clearly increased over this time period, an interesting conclusion is that the instantaneous rate of natural mortality (M) must have increased, suggesting that tiger prawn natural mortality may be density-dependent at this time of year. Mortality rates of tiger prawns for June–October were found to have decreased over the last two decades, which has probably had a positive effect on spawning stocks in the October–November spawning period.

Abiotic effects on the prawns

The influence of air temperature, rainfall, freshwater flow, the southern oscillation index (SOI) and lunar phase on the catch rates of the four main prawn species were investigated. The analyses were based on over 200,000 daily logbook catch records over 23 years (i.e., 1988–2010). Freshwater flow was more influential than rainfall and SOI, and of the various sources of flow, the Brisbane River has the greatest volume and influence on Moreton Bay prawn catches. A number of time-lags were also considered.

Flow in the preceding month prior to catch (i.e., 30 days prior, Logflow1_30) and two months prior (31–60 days prior, Logflow31_60) had strong positive effects on Banana Prawn catch rates. Average air temperature in the preceding 4-6 months (Temp121_180) also had a large positive effect on Banana Prawn catch rates. Flow in the month immediately preceding catch (Logflow1_30) had a strong positive influence on Greasyback Prawn catch rates. Air temperature in the preceding two months prior to catch (Temp1_60) had a large positive effect on Brown Tiger Prawn catch rates. No obvious or marked effects were detected for Eastern King Prawns, although interestingly, catch rates declined with increasing air temperature 4–6 months prior to catch. As most Eastern King Prawn catches in Moreton Bay occur in October to December, the results suggest catch rates decline with increasing winter temperatures. In most cases, the prawn catch rates declined with the waxing lunar phase (high luminance/full moon), and increased with the waning moon (low luminance/new moon). The SOI explains little additional variation in prawn catch rates (~ <2%), although its influence was higher for Banana Prawns. Extrapolating findings of the analyses to long-term climate change effects should be interpreted with caution. That said, the results are consistent with likely increases in abundance in the region for the two tropical species, Banana Prawns and Brown Tiger Prawns, as coastal temperatures rise. Conversely, declines in abundance could be expected for the two temperate species, Greasyback and Eastern King Prawns.

Corporate management structures

An examination of alternative governance systems was requested by the industry at one of the early meetings, particularly systems that may give them greater autonomy in decision making as well as help improve the marketing of their product. Consequently, a review of alternative management systems was undertaken, with a particular focus on the potential for self-management of small fisheries (small in terms of number of participants) and corporate management. The review looks at systems that have been implemented or proposed for other small fisheries internationally, with a particular focus on self-management as well as the potential benefits and challenges for corporate management. This review also highlighted particular opportunities for the Moreton Bay prawn fishery.

Corporate management differs from other co-management and even self-management arrangements in that 'ownership' of the fishery is devolved to a company in which fishers and government are shareholders. The company manages the fishery as well as coordinates marketing to ensure that the best prices are received and that the catch taken meets the demands of the market. Coordinated harvesting will also result in increased profits, which are returned to fishers in the form of dividends. Corporate management offers many of the potential benefits of an individual quota system without formally implementing such a system. A corporate management model offers an advantage over a self-management model in that it can coordinate both marketing and management to take advantage of this unique geographical advantage.

For such a system to be successful, the fishery needs to be relatively small and self-contained. Small in this sense is in terms of number of operators. The Moreton Bay prawn fishery satisfies these key conditions for a successful self-management and potentially corporate management system. The fishery is small both in terms of number of participants and geography. Unlike other fisheries that have progressed down the self-management route, the key market for the product from the Moreton Bay fishery is right at its doorstep.

Corporate management also presents a number of challenges. First, it will require changes in the way fishers operate. In particular, the decision on when to fish and what to catch will be taken away from the individual and decided by the collective. Problems will develop if individuals do not join the corporation but continue to fish and market their own product separately. While this may seem an attractive option to fishers who believe they can do better independently, this is likely to be just a short-term advantage with an overall long-run cost to themselves as well as the rest of the industry. There are also a number of other areas that need further consideration, particularly in relation to the allocation of shares, including who should be allocated shares (e.g. just boat owners or also some employed skippers). Similarly, how harvesting activity is to be allocated by the corporation to the fishers. These are largely issues that cannot be answered without substantial consultation with those likely to be affected, and these groups cannot give these issues serious consideration until the point at which they are likely to become a reality.

Given the current structure and complexity of the fishery, it is unlikely that such a management structure will be feasible in the short term. However, the fishery is a prime candidate for such a model, and development of such a management structure in the future should be considered as an option for the longer term.

KEYWORDS: Moreton Bay trawl fishery, fishery economics, abiotic effects, temperature, freshwater flow, southern oscillation index, SOI, temporal closures, selectivity curve, fishing power, generalised linear model, linear mixed models, corporate governance models, harvest strategy evaluations.

2 Acknowledgements

Ms Linda Cupitt and Dr David Sterling (MBSIA) initiated the project and contributed to early versions of the proposal, assisted with the survey interviews and fishing power analyses, disseminated project results, and coordinated steering committee meetings. They were also members of the project steering committee.

Several fishers contributed to the project steering committee meetings, including Bernie Wilson, Bob Dallas, Brett Savage, Daryl Townsend, Evan Rees, Gary Radford, Grant Lewis, Hung Van Nguyen, Jim Dallas, Jo Lane, Kev Baker, Matt Quadrell, Mike Soady, Sam Anderson, Ted Woodham, V. Ferrington, Van Phuc Hoang and Wayne Till. Mike Woods contributed to the committee meetings and additional meetings about fishing power analyses, harvest strategies and gear selectivity. We would like to acknowledge the support and trust demonstrated by 49 T1/M1 and M2 Moreton Bay trawl fishery licence holders who patiently participated in the survey interviews.

Karen Hollamby (ACPF) participated in committee meetings, provided advice and assisted with the presentation of results to the ACPF in October 2011. John Kung, Eddie Jebreen, Darren Roy and David Byrom from Fisheries Queensland (DAFF) and Winston Harris and Eric Perez (QSIA) contributed to the steering committee meetings.

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3 Background

The project was an initiative of the Moreton Bay Seafood Industry Association (MBSIA) and developed from concerns over a number of issues. These included concern over declining profitability in the fishery, which is generally attributed to poor prawn prices, declining markets for small 'Bay prawns' (this is a local marketing name given to small prawns which have traditionally dominated catches from Moreton Bay, predominantly Greasyback Prawns, *Metapenaeus bennettae*), and increasing operational costs, including rising diesel fuel prices. The MBSIA and trawl fishers also expressed a desire to have a greater say over management of the fishery. This is partly attributed to frustration associated with the introduction of additional marine zoning areas in Moreton Bay, which prohibit fishing, by the Queensland Department of Environment and Resource Management (DERM) in 2009. Some fishers argue that buy-backs associated with the marine park closures failed to remove effective trawl effort, and that as a result, effort is now more concentrated on remaining fishing grounds. The relationship between the Moreton Bay commercial fishers and the Queensland Government remains strained. Fishers and the MBSIA are particularly interested in pursuing greater co-management of the fishery. Over many years, a number of fishers have also expressed dissatisfaction with the current boat-replacement policy for M2 licence holders in the Moreton Bay fishery. This is an important but highly contentious issue, as it involves addressing an effective trawl fishing effort limit in the fishery.

4 Need

The Moreton Bay trawl fishers and the MBSIA believe that immediate action is required to improve the economic viability of the fishery. Fishers argue that management measures have resulted in inefficiencies in harvesting and use of the resource, with examples reflected in restrictive fishing gear, poor harvest rules, unnecessary fuel consumption, over-capitalisation and environmental impacts. They argue that these inefficiencies have been exacerbated by the addition of the closed zoning areas in Moreton Bay in recent years. In summary, fishers believe the ecological, social and economic costs of fishing have increased and they hope to address these impacts by identifying and implementing harvest strategies that improve their profitability. At the time of writing, the Queensland East Coast Trawl Fishery (QECTF) Management Plan was undergoing a 10-year review. The project was therefore considered to be beneficial and timely, with the intention that findings and results be incorporated in the revised management plan.

5 Objectives

1. Review the literature and data (i.e., economic, biological and logbook) relevant to the Moreton Bay trawl fishery.
2. Identify and prioritise management objectives for the Moreton Bay trawl fishery, as identified by the trawl fishers.
3. Undertake an economic analysis of Moreton Bay trawl fishery.
4. Quantify long-term changes to fishing power for the Moreton Bay trawl fishery.

5. Assess priority harvest strategies identified in 2 (above). Present results to, and discuss results with, MBSIA, fishers and Fisheries Queensland.

<u>Specific objectives identified for 2</u> (above) were developed over several months (November 2010 to April 2011) after the project commenced by interviewing the Moreton Bay otter trawl fishery licence holders and through discussions with the project steering committee. Through this process, the following additional tasks were put forward in April 2011 for the research group to address:

Objective 5A. Develop optimal temporal and spatial harvesting patterns in the bay, considering a range of effort levels, to maximise the sustainable catch value for the four main prawn species (Greasybacks, Eastern King Prawns, Brown Tiger Prawns and Banana Prawns).

Objective 5B. For the four important prawn species in the bay, identify empirical evidence for the environmental factors driving the variable strength of prawn recruitment and the timing of seasonal prawn behaviour, which are both strongly evident in the bay. The predictive outcome of the work will allow dynamic-tuning of harvest/market strategies to better capture the opportunities presented by variable environmental conditions and also mitigate associated risks.

Objective 5C. Further development of the corporate governance model, including detail on how each licence holder type (i.e., T1/M1 and M2) could participate, likely locations for the business, initial operating cost estimates, and how each participating fisher could be paid.

Objective 5D. Collate all sampling information for the bay to provide clearest possible fine-scale picture of variable prawn recruitment and seasonal prawn behaviour (e.g. ‘Cleveland’ juvenile tiger study and Long-Term Monitoring Program work).

Objective 5E. Work-up a relationship between mesh size and the selectivity of MB prawns so that optimal mesh sizes can be estimated for harvest strategies involving the exclusion of small prawn from the gear whilst on the seabed.

6 Review the literature and data (i.e., economic, biological and logbook) relevant to the Moreton Bay trawl fishery (Objectives 1, 5D and 5E)

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In addition to addressing Objective 1, this section also addresses:
Objective 5D. Collate all sampling information for the bay to provide clearest possible fine-scale picture of variable prawn recruitment and seasonal prawn behaviour (e.g. Cleveland juvenile tiger study and Long-Term Monitoring Program work); and
Objective 5E. Work-up a relationship between mesh size and the selectivity of MB prawns so that optimal mesh sizes can be estimated for harvest strategies involving the exclusion of small prawn from the gear whilst on the seabed.

6.1 INTRODUCTION

This review of the literature and relevant data for the Moreton Bay trawl fishery includes a description of the region's physical properties, the biology of the main commercially important prawn species in the fishery, the Fisheries Queensland Long-Term Monitoring Program (LTMP), management of the fishery, gear selectivity, trends in logbook catch, effort and catch rates, and previous economic studies of the fishery.

6.2 PHYSICAL PROPERTIES OF MORETON BAY

Moreton Bay is approximately 100 km long and ranges in width from 1 km in the south to 30 km in the north. The bay has a maximum depth of about 35 m and was formed as a result of subsidence in the southern marginal continuation of the Maryborough Basin during Palaeozoic times (540–250 million years ago) (Maxwell 1970). Advances and retreats of glaciers and ice sheets during the Quarternary Period (i.e. last 2.5 million years) repeatedly filled and drained the bay (Hekel *et al.* 1979). As the sea level rose and fell it exposed large areas of the continental shelf that were covered in quartz sand. The sand is thought to be largely from materials eroded by rivers in the highlands of northern New South Wales and swept northwards by long-shore currents (Maxwell 1970). Strong south-easterly winds, likely to have been associated with the glacial climatic conditions of the period, heaped the sand into large dunes which now comprise the bulk of the sand dune barrier islands of North Stradbroke, South Stradbroke, Moreton and Fraser. The islands are a distinguishing physical feature of the southeast Queensland coast. Fraser Island is the largest sand dune island in the world. Over the last 6000 years, a build-up of land decreased the area of the bay itself. Quartz sand is also the main sedimentary component in Moreton Bay, although terrestrial sediments in the form of mud deposited by rivers and creeks dominate the western side. Prevailing southeast trade winds continue to transport fine uniform sand from the high dune systems into the bay (Figure 6-7).

Newel (1971) described Moreton Bay as an estuary but Milford and Church (1977) concluded it was not possible to classify the bay adequately under one of the standard schemes because it has several quite different hydrological characteristics. Except for the northern opening, which is about 17 km wide, and three narrow (< 2 km wide) openings between the eastern barrier islands, the bay's 1300 km^2 of water is enclosed. About 1% of its freshwater content is exchanged during each tidal cycle (Newell 1971). The flood tide is southerly in direction and the ebb tide northerly. Most of the water exchange and currents are due to tidal flux in the north. Tidal velocity peaks at approximately 1.1 m s^{-1} in the east and decreases to approximately 0.3 m s^{-1} in the west. Salinity varies widely depending on the area and season (Blaber and Blaber 1980; Hyland 1987). Chlorinity is highest in the north-east and east and declines with depth, suggesting vertical transport of freshwater is slow, especially in depths greater than 9 m (Newell 1971). March is normally associated with the highest rainfall while September has the minimum (Table 6-1). Surface water temperatures range from approximately 16^{o}C in August to 28^{o}C in February. Air temperatures follow a similar seasonal pattern but are generally a few degrees lower (see Figure 13-5 for long-term trends in air temperature).

Table 6-1. Monthly rainfall and air temperature in southeast Queensland. Data are based upon 121 years of records from the Bureau of Meteorology, Cape Moreton Lighthouse weather station.

	Jan	**Feb**	**Mar**	**Apl**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
Mean Rainfall (mm)	160	165	192	155	176	138	120	81	70	84	96	129	1566
Mean Number Raindays	13	14	16	15	14	12	10	10	9	10	10	11	144
Mean Daily Temperature (^{o}C)	21.8	21.9	21.1	19.3	16.5	14.0	13.0	13.7	15.7	17.7	19.3	20.9	23.1

6.3 BIOLOGY OF THE COMMERCIALLY IMPORTANT PRAWNS IN MORETON BAY

The relatively sheltered conditions which prevail in Moreton Bay have added establishment of a variety of littoral wetland habitats (Hyland and Butler 1989; Hyland *et al.* 1989; Kirkman 1978; Roelfsema *et al.* 2009; Young 1975; Young and Kirkman 1975). The wetlands provide nursery habitats for many species and are particularly important for penaeid prawns, which are among the most abundant of the benthic fauna in the riverine (Hyland 1987), littoral (Young 1978; Young and Carpenter 1977) and sub-littoral (Stephenson *et al.* 1982) environments. The penaeid prawn fauna is diverse, as well as abundant: Hyland (1987) recorded 12 species in Moreton Bay.

The three main commercially important species are the greentail or inshore Greasyback Prawn (*Metapenaeus bennettae*), the Eastern King Prawn (*Melicertus plebejus*) and the Brown Tiger Prawn (*Penaeus esculentus*). These species display similar Type 2 (Dall *et al.* 1990) life cycle characteristics of most *Penaeus* and *Metapenaeus* species, which generally include a seaward migration of sub-adults to mature and spawning of benthic eggs by adult females, a pelagic larval stage, shoreward migration and settlement of post-larvae in shallow estuarine nurseries, and a benthic juvenile phase which precedes the seaward migration of sub-adults. A review of the biology of each of the three species follows.

6.4 GREASYBACK PRAWNS *METAPENAEUS BENNETTAE*

The Greasyback Prawn (*M. bennettae*) is endemic to the east coast of Australia from northern Queensland (15°S) to Victoria (38°S) (Racek and Dall 1965). It is the smallest and most numerous of the commercially important species in Moreton Bay and the most estuarine-dependent—a characteristic of the genus (Kutkuhn 1966). *Metapenaeus bennettae* is one of the few penaeids capable of breeding in enclosed brackish waters (Morris and Bennett 1952), although most large populations occur in open estuaries. All life cycle stages have been found in estuarine and inshore waters (Kirkegaard and Walker 1970b).

Significant genetic heterogeneity for populations from different locations has been demonstrated (Mulley and Latter 1981a; Salini 1987). Mulley and Latter (1981) attributed the major isolating mechanism responsible for these discrete populations to *M. bennettae's* ability to reproduce in estuaries and lakes, but Salini (1987) suggested it was more likely due to the limited dispersal ability of spawning females and planktonic larval stages.

Young (1975; 1978) and Young and Carpenter (1977) studied the distribution of epibenthic post-larval prawns in the littoral and infralittoral habitats in Moreton Bay and found *M. bennettae* was more abundant in areas that were subjected to a freshwater influence. Riverine studies have shown juveniles can be found up to 35 km upstream (Coles and Greenwood 1983; Dall 1958), while adults can be found up to 15 km from the mouth, and to sea in depths that generally do not exceed 20 m (Grey *et al.* 1983). Laboratory studies demonstrated juvenile *M. bennettae* could tolerate a wide range of salinities (1.0-62 ppt, (Aziz and Greenwood 1981)) and prefer very fine (62.5–125μm) and fine (125–250μm) sand substrates (Aziz and Greenwood 1982).

Dall (1958) attempted to describe juvenile growth rates by measuring change in sample length-frequencies over time, but concluded that there were no consistent results. Hyland (1987) identified a pattern of progressively larger mean sizes from monthly samples obtained from Moreton Bay, however, robust growth rate estimates have yet to be published for *M. bennettae*. Monthly length-frequency samples (Figure 6-1) collected from nine sites in Moreton Bay from 1988 to 1990 show that male Greasyback Prawns can grow to a maximum size of about 21 mm carapace length (CL) (Courtney *et al.* 1995a), with a maximum weight of about 8 grams (Figure 6-2). This equates to a commercial market size category of about 60 count per pound. Females can attain considerably larger sizes than males (Figure 6-1), with a small proportion reaching 25–30 mm CL, weighing about 10 and 17 grams, respectively. These sizes equate to 50 count per pound and 30 count per pound, respectively.

Recruitment of small *M. bennettae* to otter trawl fishing grounds in Moreton Bay was found to extend over several months, September to October and February to March, and likely to be bi-annual (Figure 6-1). Catch rates fall to a minimum in the cooler months from May to July but it is unclear whether this represents an annual decline in abundance, or reduced catchability due to the cooler winter water, or both.

Maturation and spawning of *M. bennettae* in periodically enclosed coastal lakes of New South Wales was reported by Morris and Bennett (1952). In open river systems, studies by Dall (1958) and Hyland (1987) indicated that females moved downstream as they grew and while some mating may have occurred downstream, maturation and spawning occurred outside of rivers in adjacent coastal embayments. Laboratory experiments indicated *M. bennettae* was capable of spawning and hatching in both oceanic and brackish salinities (Preston 1985).

Courtney and Masel (1997) examined the temporal and spatial reproductive dynamics of *M. bennettae* in Moreton Bay and found that spawning occurred over an extended period of 7–8 months, with egg production peaking in February–March (late summer to early autumn). The incidence of females with vitellogenic ovaries increased markedly from 9% at 14 mm CL to about 52% at 25 mm CL. Trends in size classes larger than about 27 mm CL were less reliable due to their relatively low abundance (Figure 6-1).

Figure 6-1. Length-frequency distributions for Greasyback Prawns *M. bennettae* sampled from nine sites in Moreton Bay each month from August 1988 to July 1990. Data are from Courtney *et al.* (1995a). Note the small maximum size that males attain.

Mortality rates (i.e. total mortality, fishing mortality and natural mortality) have not been investigated for *M. bennettae*, but assuming their mortality rates are similar to other penaeid prawns, it is likely that most individuals die from natural causes or fishing mortality within about one year of hatching. Understanding mortality rates is important for developing harvest strategies that maximise value in the fishery and sustain the stock. The fishing mortality of Greasyback Prawns in the Moreton region can be broken into two components. The first can be attributed to the river and inshore commercial beam trawl fishery which predominantly harvests small, sub-adult Greasyback Prawns for the bait prawn market. The second component is from otter trawling in the bay which targets larger, older stages, mainly for human consumption.

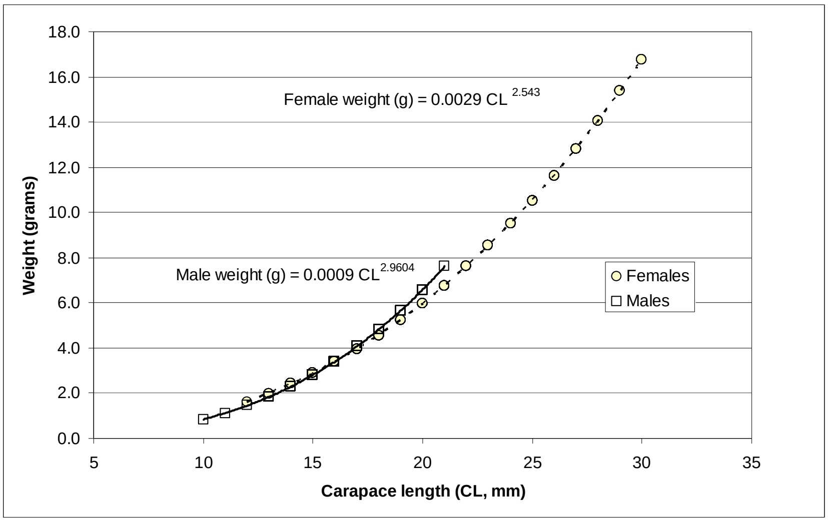

Figure 6-2. The length-weight relationships for male and female Greasyback Prawns *M. bennettae*. Note the maximum attainable size of males is about 21 mm CL, which weigh about 7.5 grams. Females grow considerably longer, but even the largest female weighs only about 17 grams.

6.5 EASTERN KING PRAWNS (EKP) *MELICERTUS PLEBEJUS*

The biology of Eastern King Prawns (*M. plebejus*) differs markedly from that of the Greasyback Prawns. Eastern King Prawns are endemic to the east coast of Australia from Central Queensland (20°S) to north-eastern Tasmania (42°S) (Kirkegaard and Walker 1970a; Ruello 1975b). They are the largest of Australia's endemic prawns in the Penaeidae family. Females can reach 300 mm total length and exceed 180 g (Grey *et al.* 1983), which equates to a market category of about 3 prawns per pound.

Adults are oceanic and among the most migratory of the Crustacea (Glaister *et al.* 1987; Montgomery 1981; 1990; Ruello 1975b). Based on tag-recapture data, Ruello (1975b) found that *M. plebejus* migrated northward from estuaries along the New South Wales coast, and that there was mixing of individuals from different estuaries. He hypothesised that there was a single adult population consisting of prawns from many estuarine habitats. This was independently supported by the enzyme polymorphism work of Mulley and Latter (1981a) that showed genetic homogeneity for samples from southeast Queensland (27°S) to Victoria (38°S). Montgomery (1990) undertook further tag-release experiments which confirmed the northward migration and mixing of prawns, supporting Ruello's single stock hypothesis.

Glaister *et al*. (1987) acknowledged some mixing of adults occurred but suggested that, for stock assessment purposes, two substocks existed, based on the origin of recruits. These were referred to as the Moreton Bay–Mooloolaba substock, which had recruits principally from Moreton Bay, and the New South Wales–Southport–Mooloolaba substock which derived recruits principally from New South Wales estuaries. The existence of a Moreton Bay–Mooloolaba substock was supported by the earlier work of Lucas (1974) who estimated population parameters for *M. plebejus* and considered the fisheries in Moreton Bay and adjacent waters as a single-unit stock. Potter (1975) also contributed towards the two-substock hypothesis by suggesting that a physical 'boundary between stocks', comprised of a system of sand bars, existed north of Moreton Island. Potter's work was based on recaptured prawns that were released in southeast Queensland. Understanding of the stock size and structure was complicated further when additional trawl grounds for Eastern King Prawns were established further north and offshore, near the Swain Reefs (22^{o}S) (Dredge and Gardiner 1984).

Examination of mitochondrial DNA of Banana Prawns *Fenneropenaeus merguiensis,* Brown Tiger Prawns *P. esculentus* and Eastern King Prawns *M. plebejus* from Australian coastal waters (Lavery and Keenan 1995), including the Swain Reefs, indicated *M. plebejus* had low genetic variation compared with the other two species and no clear spatial pattern of genetic differentiation. Lavery and Keenan (1995) suggested the results were consistent with the highly migratory behaviour of *M. plebejus*.

Barber and Lee (1975) and Rothlisberg *et al.* (1995) showed planktonic larval stages of *M. plebejus* entered Moreton Bay with the flood tide during both day and night. Post-larvae settle on seagrass and bare substrates, but fewer settle in areas with a freshwater influence (Young and Carpenter 1977). Although Young and Carpenter (1977) concluded abundance peaked between July and September in Moreton Bay, post-larvae were abundant year-round and seasonal trends in the data were weak. The aversion *M. plebejus* exhibits for areas with a freshwater influence was supported by Coles and Greenwood (1983) who found that, in the Noosa River, approximately 150 km north of Moreton Bay, post-larvae settled only at sites near the river mouth, and only for brief periods. Skilleter *et al.* (2005) examined the distribution of post-larval and juvenile *M. bennettae*, *M. plebejus* and *P. esculentus* in Moreton Bay in relation to seagrass density and distance from mangroves. They found abundance of *M. bennettae* and *M. plebejus* was consistently higher in dense seagrass closer to mangroves, while abundance of *P. esculentus* was higher in sparse seagrass that was further away from mangroves.

Masel and Smallwood (2000b) repeated the earlier post-larval and juvenile sampling program undertaken by Young and Carpenter (1977). They found the species compositions had changed between 1972–73 and 1990–93, with a relative increase in *M. bennettae* at two of the three locations. Reasons for the change remain unknown, but the authors discussed possible influences, including heavier rainfall in the 1970s compared to the 1990s and the effects of salinity of the species' distributions, changes in nursery habitats and impacts on spawning stocks.

Growth rates for *M. plebejus* were described by Ruello (1975a), Somers (1975), Lucas (1974) and Glaister *et al.* (1987). Lucas (1974) and Glaister *et al.* (1987) fitted von

Bertalanffy growth curves to data obtained from tag-release experiments. Lucas's estimates of the growth coefficient (K) for males were higher than those of Glaister *et al*., possibly because he tagged smaller, faster-growing individuals. Ruello (1975a) also used tagging data from experiments conducted on the New South Wales coast. He found growth rates were similar to those of Lucas (1974) but could not produce a growth curve due to insufficient data. Somers (1975) used both monthly length-frequency distributions of post-larvae and juveniles (2.5–11.0 mm CL), and tag-release data from prawns larger than 19 mm CL. He concluded that growth of post-larvae and juveniles could be described exponentially, but that the von Bertalanffy curve adequately described growth in the larger prawns.

Lloyd-Jones *et al.* (2012) estimated latitudinal and seasonal variation in growth rates of *M. plebejus*, by analysing recent and previous tag-recapture data from the studies mentioned above. This approach used data from a very broad latitudinal range. They found that the growth rate peaked in summer and fell to a minimum in winter, and that K declines by 0.0236 and 0.0556 for every one degree increase in latitude for males and females respectively (i.e., growth rate slows the further south the species occurs).

Lucas (1974; 1975) and Glaister *et al.* (1990) measured instantaneous rates of natural mortality (M), emigration (E) and fishing mortality (F) for *M. plebejus.* Lucas (1974) found the emigration rate for *M. plebejus* migrating from Moreton Bay to adjacent offshore waters was high ($E = 0.17$ week^{-1}), about 4 times the fishing mortality rate ($F = 0.04$ week^{-1}). He estimated M for *M. plebejus* in Moreton Bay was ≤ 0.22 week^{-1}. When the combined effects of emigration and mortality were considered, Lucas (1974) calculated that an initial population in the bay was reduced to about half in two weeks. Both fishing mortality (F) and natural mortality (M) were significantly lower in the adjacent offshore area; $F = 0.02$ week^{-1} and $M = 0.05$ week^{-1}. Similar rates were derived by Glaister *et al*. (1990). These studies and those of Coles and Greenwood (1983) suggest that *M. plebejus* utilise nursery areas and estuarine embayments for only a few weeks before migrating to deeper, oceanic waters. These are important considerations for management of Eastern King Prawns in Moreton Bay, and specifically with respect to designing closures for maximising catch value.

Dakin (1938) and Racek (1959) used field observations of the distribution of inseminated adult females, eggs, and larval stages to infer reproductive activity. Racek (1959) observed the population between 27^{o}S and 36^{o}S and suggested the 'period of maturity' was from March to June and that breeding grounds were in depths of 50–70 fathoms (~90–130 m), but warned his results were inconclusive due to difficulties in identifying larvae to species level. Laboratory experiments indicated spawning and maximum hatching success for *M. plebejus* were likely to occur in oceanic salinities (30–34 ppt). Based on the recapture of tagged prawns, Ruello (1975a) suggested the coastal area between Fraser Island and Southport was the most important spawning area for the species. However, this was prior to the establishment of additional trawling grounds for this species north of about 26^{o}S and in greater depths than previously trawled.

Courtney (1995b) and Montgomery *et al.* (2007) examined the size at maturity and temporal-spatial distribution of spawning in *M. plebejus* from the central New South Wales coast to the Swain Reefs in Queensland. The size of females, the proportion of females in spawning condition, and population egg production, were all higher at lower latitudes. Egg production was highest in autumn. There were also marked patterns in reproductive condition, behaviour and catchability of adult *M. plebejus* between lunar phases (Courtney *et al.* 1996). These patterns differ between the sexes, resulting in variation in size classes and sex ratios in the catch composition between lunar phases.

The peak in egg production generally results in a single pulse of recruitment of eastern kings in Moreton Bay in October to November each year (Figure 6-3). Eastern King Prawns move rapidly through the bay as they migrate seaward to continue to grow, mature and reproduce in deeper, oceanic waters. Abundance in the bay falls to a minimum in March to May (Figure 6-3).

Figure 6-3. Length-frequency distributions for Eastern King Prawns *M. plebejus* sampled from nine sites in Moreton Bay each month from August 1988 to July 1990. Data are from Courtney *et al.*(1995a). Catch rates in Moreton Bay are highly seasonal. There is a marked peak in abundance in October to November. By the time they reach about 30 mm CL most have migrated outside the bay to deeper waters where they mature and reproduce.

Although they can attain relatively large sizes (i.e. > 50 mm CL), the incidence of Eastern King Prawns larger than 35 mm CL in Moreton Bay is uncommon (Figure 6-4). This is mainly due to their migratory behaviour which results in the great majority of individuals emigrating from the bay by this size. At 35 mm CL Eastern King Prawns weigh about 25 g which equates to a market size category of 20 prawns per pound. Males can reach a maximum size of about 50 mm CL, or 65 g, which equates to about 8 per pound. Females can reach very large size classes—occasionally, females larger than 70 mm CL can be found weighing around 190 g, or around 3 per pound (Figure 6-4).

In addition to their migratory behaviour, the behaviour of adult *M. plebejus* in relatively deep (~160 m) offshore waters varies with lunar phase (Courtney *et al.* 1996). Catchability of adults increases leading up to the full moon phase, and shortly after, and declines to a minimum around the new moon. Offshore trawler operators are aware of this and plan their trips to coincide with these phases. On examination of the catches, the variation appears to be attributed, in part, to differences in behaviour between males and females. In general, females dominate catches in the greater depths, but during certain lunar phases, male catch rates increase markedly and the catch-sex ratio approaches 1:1. Female ovary weight and histological condition also vary with lunar phase, possibly as a strategy to maximise egg and larval survival and dispersal. The behaviour and catch rates of juveniles and sub-adults in the relatively shallow waters of Moreton Bay (< 20 m) do not appear to vary significantly with lunar phase (Courtney *et al.* 2002).

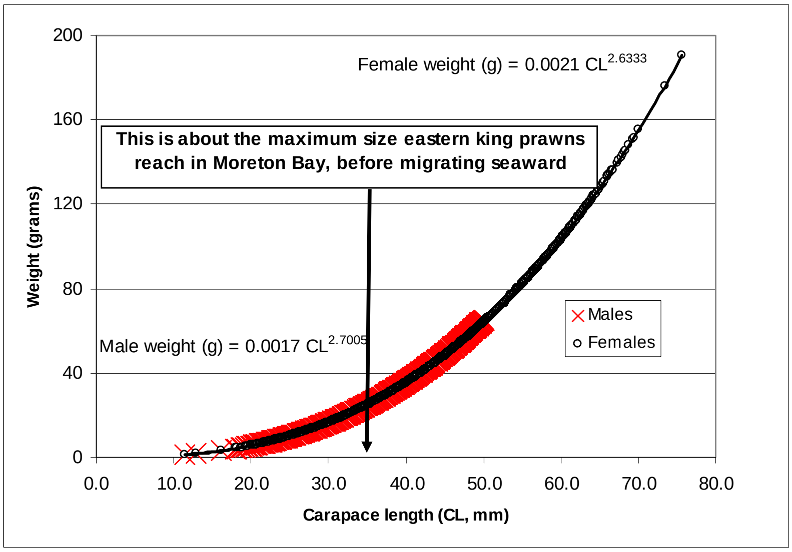

Figure 6-4. The length-weight relationships for male and female Eastern King Prawns *M. plebejus*. The maximum attainable size of males is about 50 mm CL or 65 g. Females can grow larger than 70 mm CL and weigh just under 200 g. The maximum size of Eastern King Prawns caught in Moreton Bay is about 35 mm CL, or about 25 g, which equates to a market category of 20 count per pound.

6.5.1 Long-term fishery-independent monitoring of Eastern King Prawns

A large trawl fishery exists for EKP in estuarine and offshore waters on the New South Wales and Queensland coasts (Ives and Scandol 2007; O'Neill *et al.* 2003). As noted above, *M. plebejus* inhabit inshore bays and estuaries for only relatively brief periods before undertaking an offshore, northerly migration. About 2000 tonnes of EKP are caught by trawlers in Queensland annually, with about 90% of the catch taken outside Moreton Bay (Braccini *et al.* 2012; O'Neill *et al.* 2003). The total landed value of EKP in Queensland is around $30 million (assuming an average of $15 per kg), and as such, they are one of the most valuable commercially fished species in the state.

In the 1990s, an FRDC-funded research project developed a fishery-independent recruitment monitoring program for EKP, based on a stratified survey of major recruitment areas (Courtney *et al.* 2002). The program focused solely on *M. plebejus* due to its economic importance, and was in addition to the mandatory fishery-dependent commercial logbook program. In 2006 the program was adopted and funded by the Fisheries Queensland Long-Term Monitoring Program (LTMP) and has been implemented annually since. The survey deploys a 5 m beam trawl to sample approximately 400 0.5 nautical mile (nm) transects or sites in southeast Queensland. Areas sampled include east of Moreton and Stradbroke Islands, the Wide Bay region near Fraser Island, and Moreton Bay (Table 6-2). The survey is undertaken in two legs, the first in November with the second leg in December, as abundance of recruits is generally at its maximum in southeast Queensland’s shallow coastal waters at this time. During each leg, approximately half of the sites in each area are sampled. A two-staged sampling design was deemed more likely to provide a reliable estimate of recruit abundance for *M. plebejus*, given their mobile and migratory nature.

Between 2006 and 2010, a total of 565 0.5 nm trawls were undertaken in Moreton Bay. The data collected include the size-frequency distribution and relative abundance of prawns at each site. The size of prawns sampled in the bay has ranged from 6 mm CL to 41 mm CL, with the mode at 20 mm CL (Figure 6-5). At 20 mm CL, EKP weigh about 6 g.

Table 6-2. The number of 0.5 nm sites sampled in Moreton Bay from 2006 to 2010 as part of the Eastern King Prawn recruitment monitoring program, conducted by Fisheries Queensland.

			Year		
Area (sampling strata)	**2006**	**2007**	**2008**	**2009**	**2010**
Moreton Bay	45	120	132	179	180
Moreton Island	44	40	25	37	40
Stradbroke Island	44	40	17	51	74
Wide Bay	20	20	39	0	53

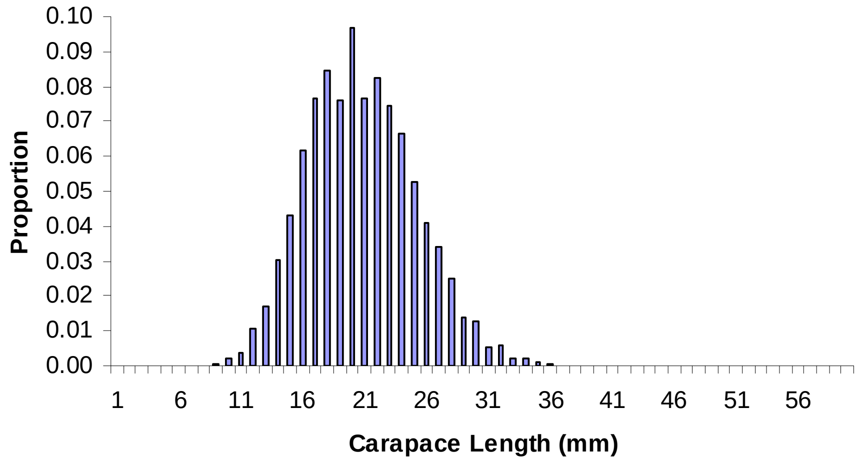

Figure 6-5. Size-frequency distribution of Eastern King Prawns *Melicertus plebejus* sampled in Moreton Bay between 2006 and 2010, as part of the monitoring program.

The data provide information on the likely strength of recruitment in the upcoming season (i.e., November to August) and are used to tune stock assessment models of the fishery. Survey catch rates in Moreton Bay have varied from a low of 63 prawns per hectare (ha^{-1}) in 2007 to a high of 121 ha^{-1} in 2010 (Figure 6-6). The survey catch rates from all areas (i.e., Moreton Bay, Moreton Island, Stradbroke Island and the Wide Bay) correlate well with the commercial logbook catch rates.

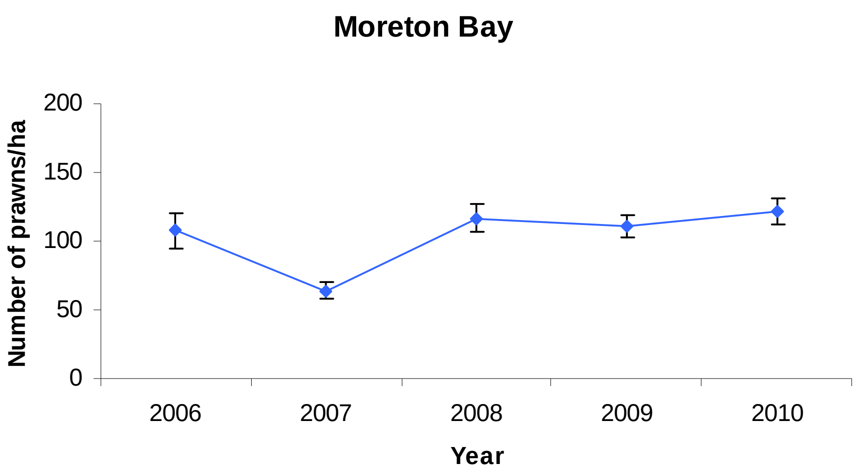

Figure 6-6. Catch rates of Eastern King Prawn recruits (all size classes) in Moreton Bay, from the monitoring prawn. Vertical bars represent one standard error above and below the mean.

The survey data indicate that Eastern King Prawns are generally more abundant on the western side of the bay (Figure 6-7). At the time of writing, the monitoring program was undertaking the 2011 survey.

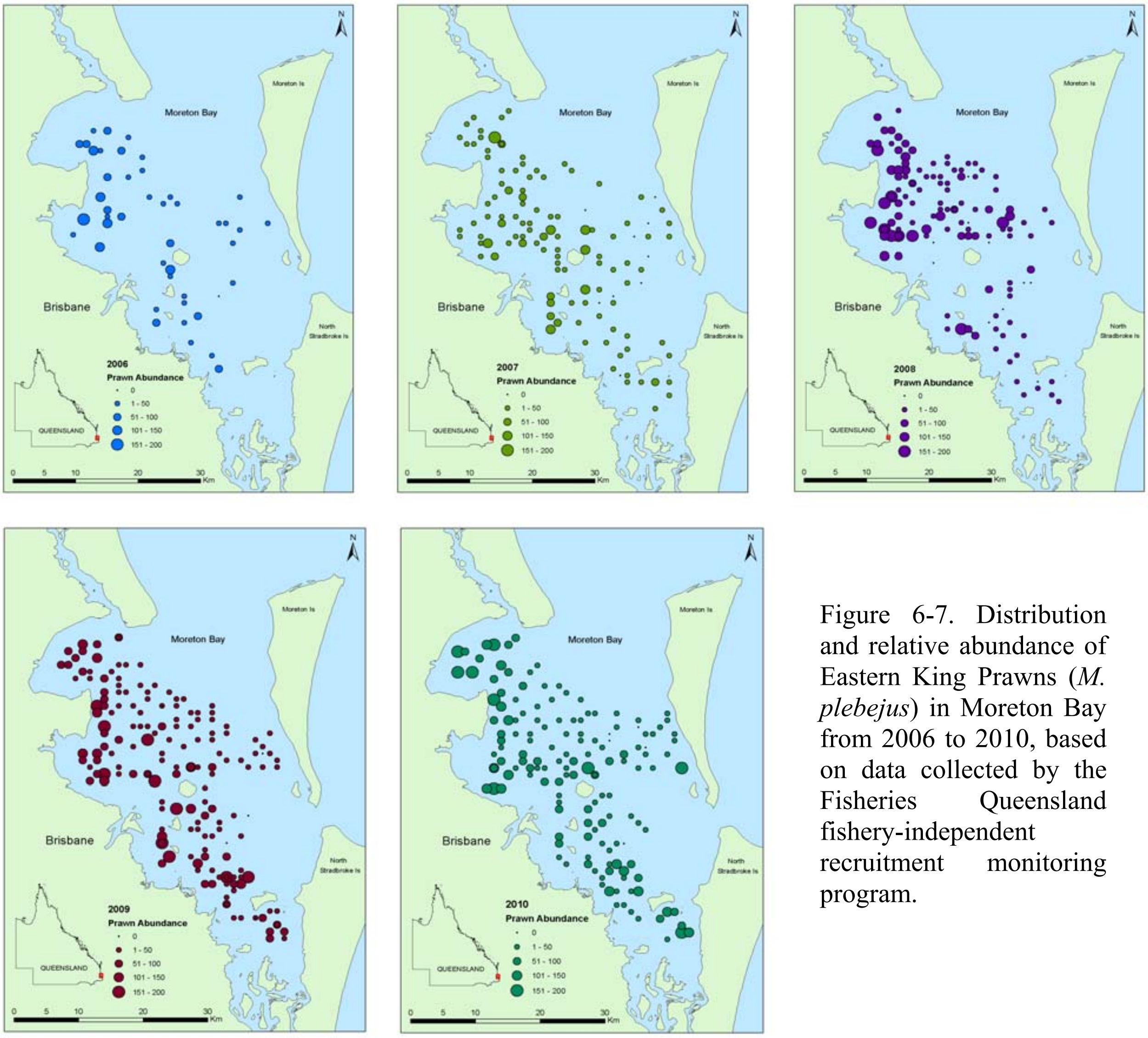

Figure 6-7. Distribution and relative abundance of Eastern King Prawns (*M. plebejus*) in Moreton Bay from 2006 to 2010, based on data collected by the Fisheries Queensland fishery-independent recruitment monitoring program.

6.6 BROWN TIGER PRAWNS *PENAEUS ESCULENTUS*

Although two specimens have been recorded from South Borneo, *Penaeus esculentus* is generally considered endemic to the warm tropical and sub-tropical coastal waters of Australia, to depths of 50 m (Kirkegaard and Walker 1969; Racek and Dall 1965). Mulley and Latter (1981b) used electrophoretic techniques to examine genetic differences in *P. esculentus* throughout its range, but despite the large distances between the areas sampled, no significant differences in gene-frequencies were found. Mitochondrial DNA examination (Lavery and Keenan 1994), however, has confirmed genetic differences between east and west Australian coast populations, and the possibility of differences between populations on the east coast.

In the Gulf of Carpentaria, *P. esculentus* larvae were found in depths less than 50 m and in waters with a relatively narrow salinity range (30.1–34.2 ppt) and mean temperature of about 28°C (Rothlisberg and Jackson 1987). Benthic post-larvae and juveniles prefer shallow water seagrass habitats (Coles and Lee Long 1985; Coles *et al.* 1987; Loneragan *et al.* 1994; O'Brien 1994; Staples *et al.* 1985; Young 1978; Young and Carpenter 1977). Factors affecting the catchability and sampling of juveniles were investigated by Vance and Staples (1992). Staples *et al.* (1985) showed that the distribution of commercial fishing for tiger prawns (includes both *P. esculentus* and *Penaeus semisulcatus*) in the Gulf of Carpentaria was limited to areas adjacent to seagrass beds and that catches within a region were directly related to the area of seagrass within the region. This association appears to be a major factor limiting the distribution of *P. esculentus* landings in southeast Queensland; extensive seagrass beds (Hyland *et al.* 1989; Young and Kirkman 1975) and the bulk of the catch are restricted to Hervey Bay and Moreton Bay. Preferred habitats of adults are less clearly understood, although Somers (1987) and Somers *et al.* (1987) found adults preferred sediments with high (50–80%) mud content.

The population dynamics of juvenile *P. esculentus* were investigated in the western Gulf of Carpentaria (Loneragan *et al.* 1994) and Moreton Bay (Masel and Smallwood 2000a; Masel and Smallwood 2000b; O'Brien 1994). O'Brien (1994) quantified the growth and mortality rates of juvenile tiger prawns in seagrass nursery habitats in Toondah Harbour, southern Moreton Bay. Growth rates increased from 0.03 and 2.1 mm CL week^{-1} with increasing water temperature. Instantaneous rates of natural mortality (*M*) ranged from 0.06 to 0.29 per week (or about 5.8 to 25.2%). Estimates of the von Bertalanffy growth parameters *K* and L_∞ for *P. esculentus* are provided in Table 6-3. Estimates of the instantaneous rate of natural mortality (*M*) for Brown Tiger Prawns in Moreton Bay have not been quantified. Somers (1990) used a value $M = 0.20$ month^{-1} (or 0.05 week^{-1}) to simulate the fishery in the Gulf of Carpentaria.

Table 6-3. von Bertalanffy growth parameters for Brown Tiger Prawns *P. esculentus*.

Female L_∞ (mm CL)	**Female *K* per week**	**Male L_∞ (mm CL)**	**Male *K* per week**	**Source**	**Comment**
45.4	0.0556	36.7	0.0536	Gribble and Dredge (1994)	Queensland east coast 1989 tagging data
46.3	0.0436	37.8	0.0528	Gribble and Dredge (1994)	Queensland east coast 1990 tagging data
44.80	0.041	37.49	0.034	Kirkwood and Somers (1984)	Gulf of Carpentaria 1981 tagging data
40.9	0.05	32.6	0.05	White (1975b)	Exmouth Gulf, W.A.

Movements and growth rates of sub-adults and adults were examined using tag-release methods in the western Gulf of Carpentaria (Kirkwood and Somers 1984; Somers and Kirkwood 1984), Torres Strait (Derbyshire *et al.* 1990; Watson and Turnbull 1993), Exmouth Gulf, Western Australia (White 1975b), North Queensland (Derbyshire *et al.* 1992) and Central Queensland (Gribble and Dredge 1994). Movements of *P. esculentus* in these studies were similar in that recaptures were generally less than 30 km from the point of release. Derbyshire *et al.* (1992) reported a maximum distance moved of 246 km, but this was based on a single observation and is likely to be erroneous. Unpublished results from a 1973 joint CSIRO–Queensland Department of Primary Industries tagging study suggest that few (i.e., < 5%) tiger prawns emigrate from Moreton Bay (M. Potter pers. comm., Figure 6-8). The majority of Moreton Bay trawl fishers believe that a significant proportion of the Moreton Bay Brown Tiger Prawns migrate northwards, typically a distance of 90 km (D. Sterling pers. comm.). Using Francis' (1988) maximum-likelihood method to analyse these data, estimates of the von Bertalanffy growth parameter L_∞ were found to be similar to previous studies (42.7 ± 2.1 mm for females and 37.9 ± 1.2 for males, Table 6-3). However, the growth coefficient K estimates were approximately 2.5 times larger (0.08 ± 0.01 for females and 0.10 ± 0.01 for males).

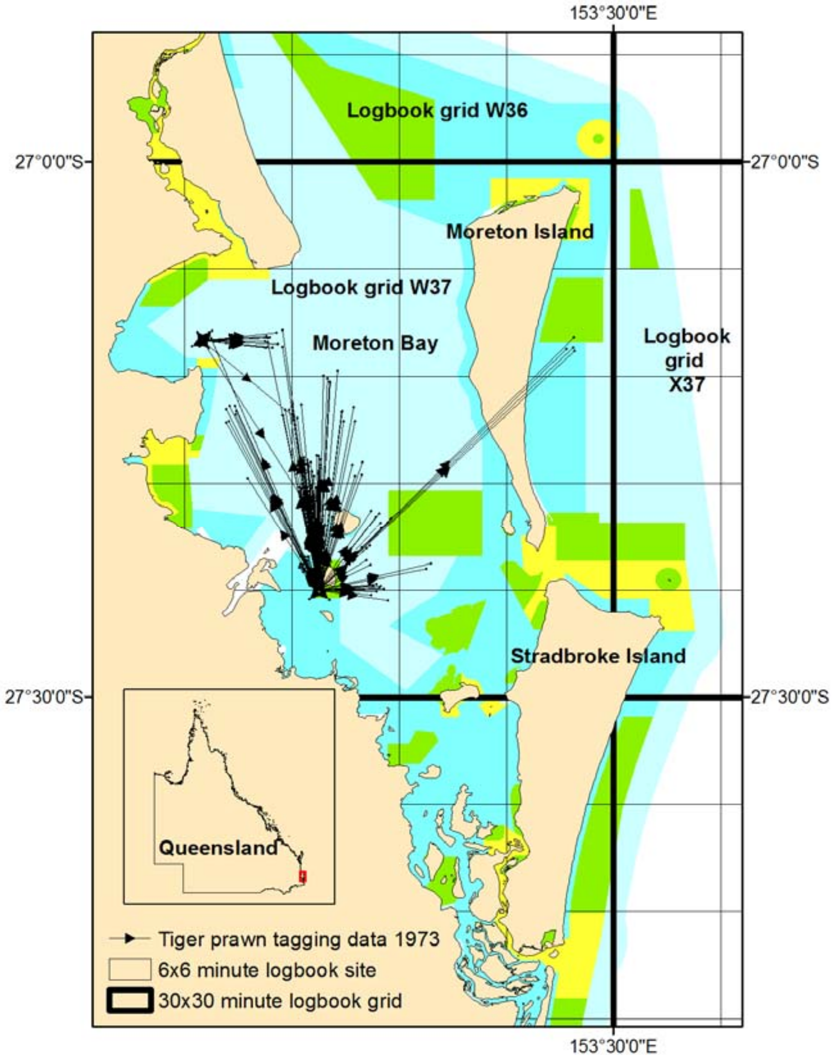

Figure 6-8. Movement pattern of tiger prawns (*P. esculentus*) in Moreton Bay based on an unpublished tagging study in 1973. Arrows indicate general direction of movement between release and recapture. The precise coordinates were not provided with these data, but rather each release and recapture was reported to a lower 'area' spatial resolution. Coordinates used in this figure were therefore estimated and are accurate to within a radius of approximately ±2 km. Also shown is the 30-minute logbook grid W37 where most of the Moreton Bay trawl catch and effort data are reported from. W37 includes some smaller six-minute grid sites that are located outside the bay. Trawling is permitted in areas shaded light blue.

Several studies have examined the reproductive dynamics of *P. esculentus*. O'Connor (1979) used a gono-somatic index to examine monthly spawning activity over three years in north Queensland. Buckworth (1985), Robertson *et al.* (1985) and Crocos (Crocos 1987) described spawning activity in the Gulf of Carpentaria. Somers *et al.* (1987), Keating *et al.* (1990) and Restrepo and Watson (1991) described the reproductive dynamics of *P. esculentus* in Torres Strait. In Western Australia, White (1975a) determined the major spawning period for *P. esculentus,* based on a combination of histological and macroscopic methods. Crocos (1985) investigated possible lunar periodicity in spawning for *P. esculentus* in Moreton Bay, but found it to be continuous over the lunar month and asynchronous among individuals.

The distribution of larval stages was used to infer temporal and spatial spawning activity of *P. esculentus* from the New South Wales–southeast Queensland coasts (Racek 1959) and the Gulf of Carpentaria (Rothlisberg *et al.* 1983; 1987). While Racek's early work was inconclusive due to difficulties identifying larvae, Rothlisberg *et al*. (1983) reared larvae for reference material. Rothlisberg *et al.* (1987) found larval abundance of *P. esculentus* was relatively low in the Gulf of Carpentaria and generally restricted to coastal areas in the north and south-west. Highest abundance occurred in January, well outside the main spawning period put forward by Buckworth (1985), Robertson *et al.* (1985) and Crocos (1987).

Courtney and Masel (1997) examined the spawning stock dynamics of *P. esculentus* in Moreton Bay. They sampled nine sites each month for two years and found that spawning occurred in a clearly defined peak in October (spring), although some egg production continued to March (early autumn) each year. The seasonal onset in ovarian development was rapid, and generally, population egg production increased with depth. The October spawning of Brown Tiger Prawns in Moreton Bay results in recruitment of small prawns entering the fished population from around February to May (Figure 6-9). Abundance peaks at this time and declines to a minimum in August to November. Brown Tiger Prawns do not undertake migrations that are as extensive as those of Eastern King Prawns, and to a greater extent remain in the bay. Hence, the length-frequency data include adult size classes that exceed 40 mm CL (Figure 6-9).

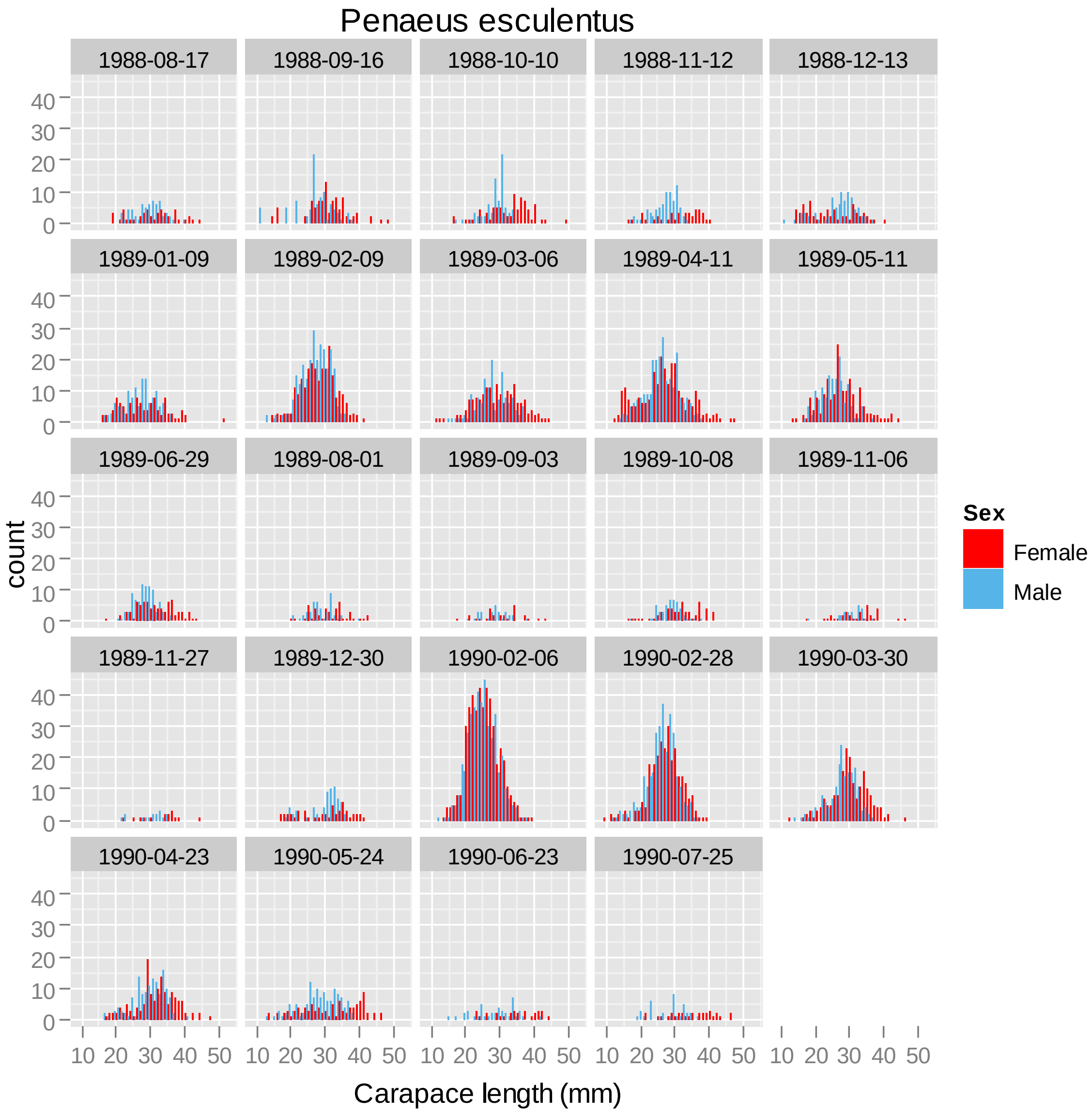

Figure 6-9. Length-frequency distributions for Brown Tiger Prawns *P. esculentus* sampled from nine sites in Moreton Bay each month from August 1988 to July 1990. Data are from Courtney *et al.* (1995a).

Like most penaeid prawns, females attain larger sizes than males and can reach 50 mm CL or about 100 g, a market size grade of about 5 count per pound (Figure 6-10). Males rarely grow larger than about 40 mm CL, which weigh about 57 g or 9 count per pound.

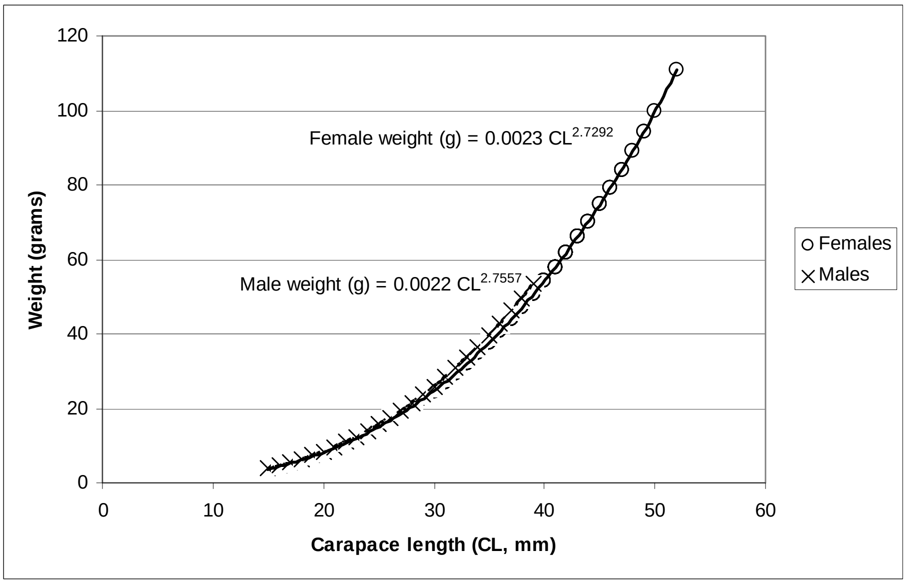

Figure 6-10. The length-weight relationships for male and female Brown Tiger Prawns *P. esculentus*. The maximum attainable size of males is about 40 mm CL or 57 g. Females can grow to about 50 mm CL and weigh about 100 g.

6.7 Development of the Moreton Bay trawl fishery

According to Ruello's (1975b) review of the development of penaeid prawn trawl fisheries in Australia, commercial prawn fishing in Queensland probably commenced in the Brisbane River in the 1840s. Methods were unsophisticated and included using hand-held scoop and scissor nets near the river bank. Nets were hauled by hand while drifting in small boats in the river channel. The industry soon spread to other rivers in southeast Queensland coast, but further development was slow. The main species exploited were Greasyback Prawns *M. bennettae*, school prawns *Metapenaeus macleayi* and Banana Prawns *F. merguiensis*. Ruello (1975b) noted that while the Queensland fishery was limited to 18 fishers working in the Brisbane River by 1895, over 100 vessels were working in New South Wales in 1886. He suggested the slow development was due to the arduous nature of the work, limited catches and an absence of a metropolitan fish market in southeast Queensland.

The fishery diversified in the 1900s, incorporating beam trawling, as well as seine, pocket, and stripe netting. In 1907 the Queensland Government established a fish market which promoted the sale and distribution of seafood and by 1942 an official annual catch of approximately 46 t was recorded by the Queensland Marine Department.

Although chartered trawl surveys indicated large ‘sea’ prawns could be trawled in the more open waters of Moreton Bay as early as the 1880s, development of a fishery in Moreton Bay and adjacent waters was also slow. Ruello (1975b) attributed this to Queensland Government restrictions on the length and power of beam trawlers, and the prohibition on otter trawling. Following experimental otter trawling in the bay by New South Wales vessels in 1950, the prohibition was abandoned and the fishery grew rapidly over the next decade. The 1952–53 official catch for Moreton Bay was 136 tonnes and by the following year was 225 tonnes.

By the mid 1950s trawling for Banana Prawns developed in central Queensland coastal waters. 'Gold rush' type media reports in New South Wales and Queensland attracted more fishers which resulted in up to 100 vessels participating in the new fishery. Another important factor in the fishery's development was the Federal Government-sponsored *Challenge* survey which identified significant catches of Eastern King Prawns *M. plebejus* off Fraser Island in 1957 and off Moreton Island in 1959. By the early 1960s offshore otter trawling had spread to North Queensland. Additional trawl grounds for *M. plebejus* and other deepwater prawns were identified from surveys conducted off the central and southern Queensland coasts between 1982 and 1984 (Dredge and Gardiner 1984; Potter and Dredge 1985).

Management of the Queensland trawl fishery has been discussed by Haysom (1975), Hill and Pashen (1986), Glaister (1991) and Glaister *et al.* (1993). The fishery was the last open-access otter trawl fishery in Australia and as a result attracted vessels that had been removed from other fisheries (Hill and Pashen 1986). Between June 1970 and July 1982, the number of trawlers licensed to operate in Queensland waters increased from about 500 to 1400. A freeze on the number of vessels was implemented in 1979. However, numbers continued to increase until 1981 due to a provision which allowed those who had evidence of prior contractual arrangements to purchase or build vessels to also participate. In 1993, 952 vessels were licensed to trawl the Queensland east coast (Glaister *et al*. 1993). Following the implementation of the Queensland Trawl Fishery Management Plan in 2000, which implemented a new fishing effort unitisation system, the number of licensed vessels declined further and by 2009 there were approximately 450 otter trawl vessels in the Queensland fleet.

Early management measures focused on southeast Queensland, and particularly Moreton Bay, as this was the centre of the fishery's development and where most issues of contention arose. In the late 1960s, concern about declining catches and the increasing number of large offshore vessels fishing in the bay led to the introduction of a permit system in 1970 (Haysom 1975). The objectives of the system were to limit fishing effort in the bay by allowing only those with a three-year history of participation to remain. However, without a logbook system to record the temporal and spatial fishing activity of individual vessels, such a permit system was open to abuse, and it is generally agreed the system failed.

Hill and Pashen (1986) noted the difficulty of analysing and assessing the fishery without a logbook system. They also discussed several options for reducing overcapitalisation and managing fishing effort. These included maximising economic rent, quotas, closed seasons, gear and power restrictions, licence limitations, removal of latent fishing effort, buy-back and licence leasing. Some of these were pursued with varying degrees of success, but arguably the most important was the introduction of the compulsory logbook program in 1988.

The 1979 freeze on vessel numbers was relatively successful. However, it became apparent in the early 1980s that retiring vessels were being replaced by others that were more powerful and efficient. The fishing power of the fleet therefore continued to rise. In an attempt to prevent this, a vessel size unitisation policy was introduced in 1985. This was aimed at quantifying, and controlling, the catching capacity of the fleet by allocating each vessel hull units. The number of units allocated was determined by the under-deck hull size and the power of the main engine. Fishers were still able to upgrade and increase their catching capacity, but in order to do so they also had to purchase additional units (from other fishers) and surrender them.

Although the unitisation policy led to a reduction in vessel numbers, it was unsuccessful in reducing fishing effort (Glaister *et al.* 1993). In 1990 a more stringent ‘two-for-one’ (licence/units) replacement policy was introduced. This required fishers who were considering upgrading their vessels to purchase and surrender twice as many units and an additional licence, before their upgrade was permitted. The number of vessel upgrades in the late 1990s suggested that this policy had the desired effect of limiting the fleet's catching capacity (Glaister *et al.* 1993).

In the Moreton Bay otter trawl fishery there are two licence types or symbols: T1/M1 and M2. T1/M1 licence holders are permitted to trawl in areas outside of Moreton Bay (i.e., the T1 symbol) as well as inside (i.e., the M1 symbol), while the M2 licence holders are only permitted to trawl inside the bay. Otter trawling in the bay is prohibited on weekends (i.e., there is no trawling on Friday and Saturday nights) and all vessels are limited to a maximum length of 14 m. Other management measures for the Moreton Bay fishery include a total net head rope length restriction of eight fathoms per vessel (approximately 16 m) and temporal and spatial closures.

In 2000, the Queensland Government implemented the Trawl Fishery Management Plan, a major initiative of which was the allocation of effort units to each otter trawl licence holder throughout the state, with the exception of M2 licences. Effort was allocated based on each vessel’s logbook effort history, and effort units were defined as the product of the number of nights fished and the vessel’s hull units. Licence holders can buy and sell effort units from each another. As M2 vessels are not allocated effort units, each M2 licence holder is permitted to trawl a maximum of 260 days per year (i.e., 52 weeks x 5 days per week).

While the effort unitisation program capped trawl effort throughout the state, including the T1/M1 operators in Moreton Bay, the two-for-one boat-replacement policy was continued as the management method for limiting effort in the M2 fleet. In 2012, there were a total of 72 licence holders who were permitted to trawl in Moreton Bay – 47 T1/M1 and 25 M2 licences.

The increases in fishing power for those vessels operating outside Moreton Bay in the other Queensland trawl sectors, including the Eastern King Prawn, scallop, and Tiger/Endeavour prawn sectors, have been quantified and used to standardise catch rate time-series (O'Neill *et al.* 2005; O'Neill and Leigh 2007), mainly for stock assessment. Variations in the fishing power of the Moreton Bay fleet have not been quantified, possibly because the M2 component of the fleet do not trade effort units.

6.8 LOGBOOK CATCH AND EFFORT DATA

The Queensland mandatory commercial logbook database, which was introduced in 1988, partitions coastal waters into 30-minute (i.e., half degree) spatial grids. In recent years, fishers have been required to provide higher spatial resolution on their daily catches to six-minute grid sites, and some fishers have provided actual latitudinal and longitudinal coordinates for individual trawls. The 30-minute grid which captures Moreton Bay catch and effort data is W37 (Figure 6-8), and includes some six-minute grid sites (and hence some catch and effort) from outside the bay east of Moreton Island. For this reason, the reported statistics below may include a small component of the catch and trawl effort from outside the bay. Because these sites are located just outside the bay, the catch and effort are predominately associated with Eastern King Prawns. Where fishers reported their data to six-minute grid site resolution, and the sites were located outside the bay, these data were omitted from the catch and effort summaries.

The logbook data used in the analysis are for the period from January 1988 to December 2010 and were provided by Fisheries Queensland. Decision rules used to define catch and effort data for the Moreton Bay trawl fishery (developed by K. Yeomans and A. Courtney, DAFF) are summarised in Table 6-4. Only catch and effort data for the otter trawl fishery (fishing method = 7) were used (i.e., the analysis excludes beam trawl fishery data, as this fishery mainly takes place in rivers adjacent to Moreton Bay, although some beam trawl catch and effort occurs in the bay). Where fishers recorded their spatial resolution to six-minute resolution and these sites included areas outside of Moreton Bay (i.e., grid sites 5, 10, 15, 20 and 25), these data were omitted from the analyses.

Table 6-4. Decision rules used to retrieve and define the Moreton Bay trawl fishery logbook data.

Logbook database field code	Explanation/Comment
Logbook type	OT or MI. OT is the otter trawl fishery logbook. MI is an older 'mixed' logbook for net, line, pot and beam trawl fisheries which ceased in 1999. The analyses included data from both types.
Fishing method	7 or 8
Latitude derived	>-28 and <=-26.5
Longitude derived	>=153 and <154
Rules from 'fishery symbol list inferred'	
(I) T5	Beam trawl licence symbol - data excluded
(II) T2 only	Concessional Zone otter trawl licence (used to differentiate from bay catch as T2 not allowed in bay)
(III) T1 only	Otter trawl licence
(IV) M2 only	Otter trawl licence restricted to Moreton Bay
(V) M2 and T5 fishing method 7	M2 vessel with additional beam trawl licence, likely to be otter trawling in bay - data included
(VI) M2 and T5 fishing method 8	M2 vessel with beam trawl licence likely to be beam trawling in the bay - data excluded
(VII) T1 and T5 only fishing method 7	Vessel with both otter and beam trawl licence, likely to be otter trawling - data included
(VIII) T1 and T5 only fishing method 8	Vessel with both otter and beam trawl licence, likely to be beam trawling – data excluded
(IX) Where no method specified inferred symbol, fishing method 7	Method assumed to be otter trawl - data included.
(X) Use the Grid W88 and the sites in W37 and W38 to get more precise inside-bay data	Grid W37 six-minute sites 5, 10, 15, 20 and 25 excluded as these occur predominantly outside the bay
(XI) Gear description included	'MB' can be used to further define Moreton Bay data.

Annual reported catch of all prawns from W37 varied between a minimum of 315 tonnes (t) in 2008 and a maximum of 901 t in 1990 (Figure 6-11). The pawn catch has declined markedly from 822 t in 1999. Much of the decline can be attributed to a large decline in the number of vessels, and hence, significantly reduced fishing effort, since the introduction of the Queensland Trawl Fishery Management Plan in 2000. The prawn catch increased to 444 t in 2009.

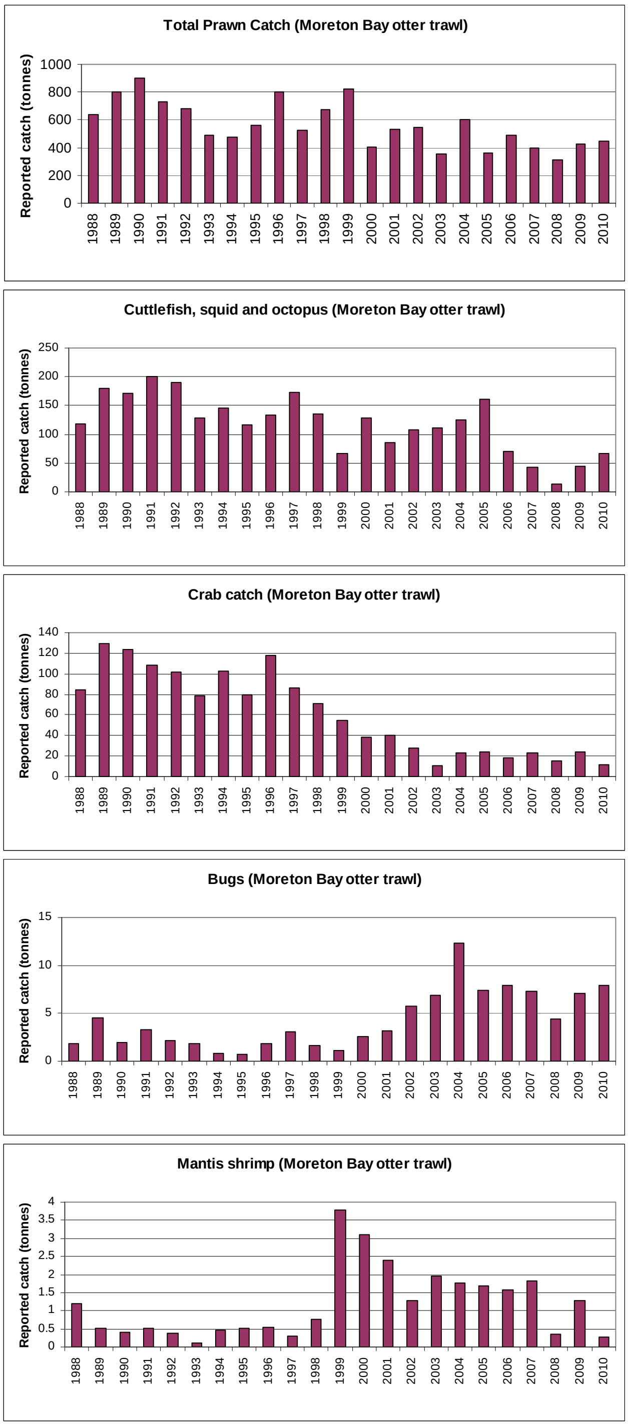

Figure 6-11. Reported annual catch from the Moreton Bay otter trawl fishery. Queensland commercial logbook data for grid W37.

Significant catches of cuttlefish, squid and octopus are also reported from Moreton Bay (Figure 6-11). While squid are classed in the Management Plan as principal target species (and can therefore be targeted with no restrictions on their catch), cuttlefish and octopus are classed as permitted species and as such are not permitted to be targeted. Non-targeting is policed by way of fishing trip catch limits for cuttlefish and octopus. In general, it is difficult to quantify targeted effort in the Moreton Bay trawl fishery which complicates analyses of catch rates (i.e., catch per unit effort) and stock assessment.

The maximum reported catch of cuttlefish, squid and octopus was 200 t in 1991, while the minimum was 14 t in 2008. Reported crab catches, which are predominantly blue swimmer crabs, *Portunus armatus,* with a smaller component of three-spot crabs, *P. sanguinolentus*, declined from a peak of 130 t in 1989 to a minimum of 11 t in 2003 (Figure 6-11). The crab catch from 2002 to 2010 has been particularly low at about 20 t annually. This may be attributed to trip limits for sand crabs which were introduced in the early 2000s as part of the Trawl Management Plan. The reported catch of Moreton Bay bugs has varied between about 1 and 12 t annually. Reported catches of mantis shrimps from the bay average about 1 to 2 t annually. Collectively, the results indicate a marked decline in total reported catch of about 60% since 2000 in the Moreton Bay trawl fishery. The estimated total catch value for the fishery, including prawns and byproduct, in recent years is approximately $5 million annually.

Monthly reported landings for the main commercially important prawn species for each year since the mandatory logbook program commenced in 1988 are provided in Figure 6-12.

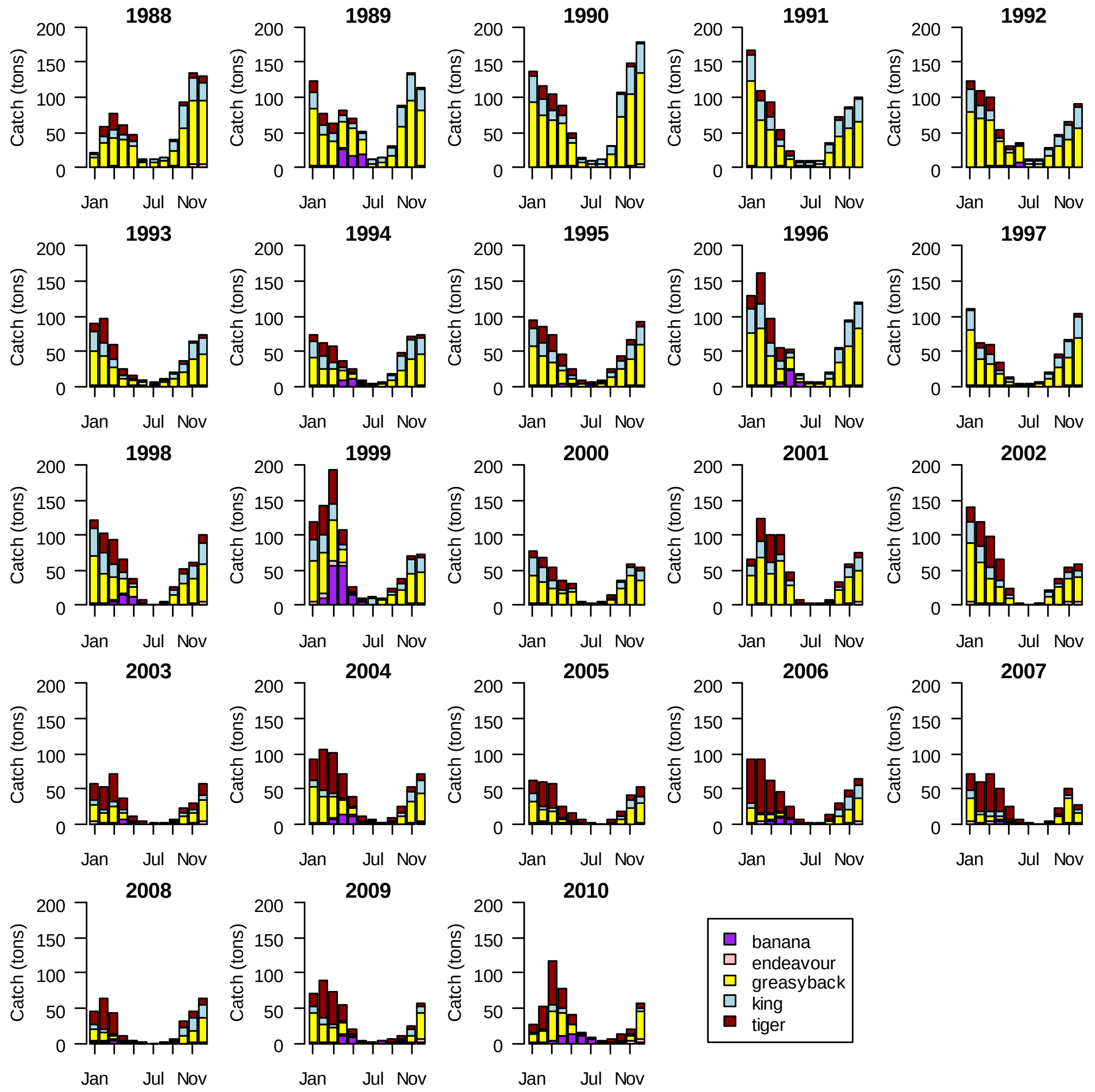

Figure 6-12. Annual reported landings of the main commercially important prawn species in the Moreton Bay otter trawl fishery, based on logbook data.

The seasonal trend in prawn catches is consistent over the 23-year data series (Figure 6-12) and characterised by troughs in winter (i.e., June, July, August) and peaks in summer (i.e., December to March). Reported landings were dominated by Greasyback Prawns from 1988 to 2002, but in more recent years Brown Tiger Prawns have dominated landings. Reasons for this change are unknown but likely attributed to the increase in cheap imported aquacultured vannamei prawns displacing demand for greasybacks. Australian trawl fisheries for small prawns appear to have been particularly adversely affected by vannamei prawns displacing their markets, and it is noteworthy that greasybacks are one of the smallest commercial prawn species in the country. Brown Tiger Prawns are the largest prawn species caught in Moreton Bay (Note: Eastern King Prawns grow to a larger size than Brown Tiger Prawns, but they are only present in Moreton Bay as juveniles and sub-adults, before they migrate offshore). The relatively high catch of Brown Tiger Prawns, combined with their relatively high price (~$15 per kilogram), suggest that this species is the most valuable component of the catch, valued at about $2 million annually. The contribution of Eastern King Prawns to the reported catch has also declined to around 10% over the 23 years. Banana Prawns contribute about 5% of the annual prawn catch, although landings can reach about 20% in some years, usually following heavy rainfall. Long-term trends in catch rates for each species are not provided, due to the difficulty in allocating targeted effort to each species.

Otter trawl fishing effort in Moreton Bay has declined markedly from a peak of 13,312 boat-days in 1999 to a minimum of 3817 boat-days in 2008 (Figure 6-13) – a 71% reduction. Effort declined significantly after 2000. Similarly, the number of licensed trawlers operating in the fishery each year has declined from a peak of 207 in 1991 to 57 in 2010. Effort in the fishery increased slightly in 2010 to 4071 boat-days. In 2012, there were a total of 72 Moreton Bay otter trawl licences (47 T1/M1 and 25 M2).

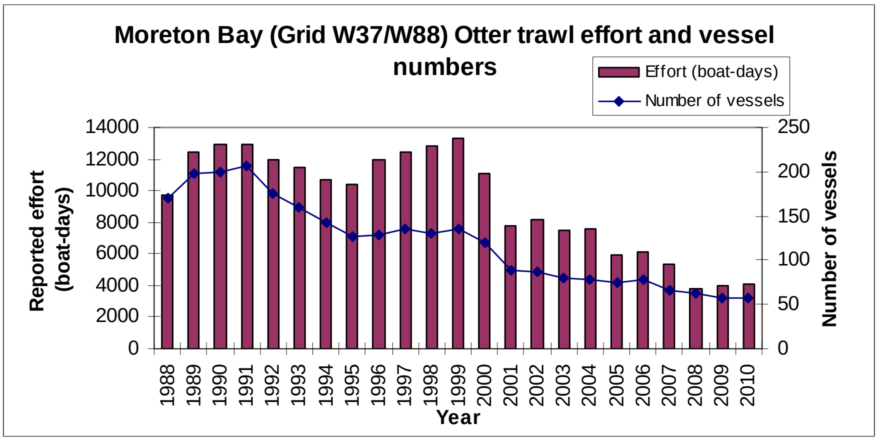

Figure 6-13. Annual trends in the number of vessels operating in Moreton Bay and trawl fishing effort since 1988. Data are from the Queensland logbook database program.

Trawl fishing effort in Moreton Bay is highly seasonal, peaking in January and falling to a minimum in July (Figure 6-14).

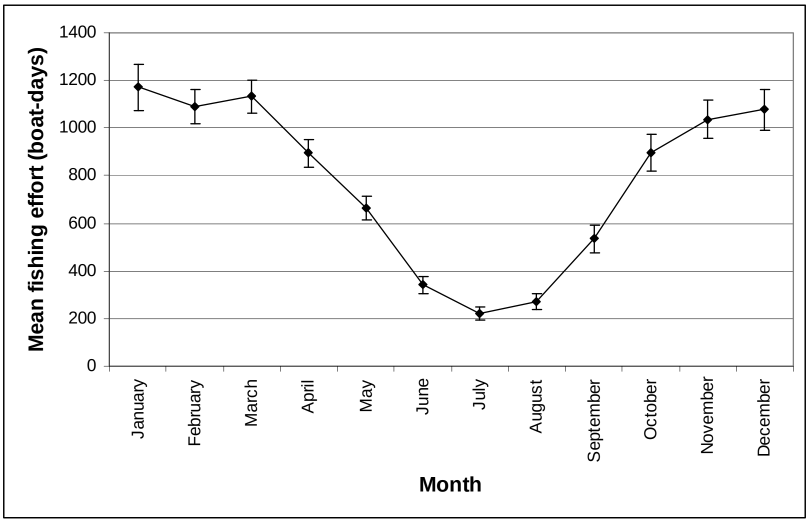

Figure 6-14. Seasonal trends in average trawl fishing effort in Moreton Bay 1988–2010. Vertical bars are one standard error either side of the mean.

Monthly catch rates also display a marked seasonal trend each year (Figure 6-15) and generally peak in December to January and fall to a minimum in July to August. Since 2002, monthly catch rates have increased, with notable peaks exceeding 160 kg per boat-night in February 2009 and March 2010.

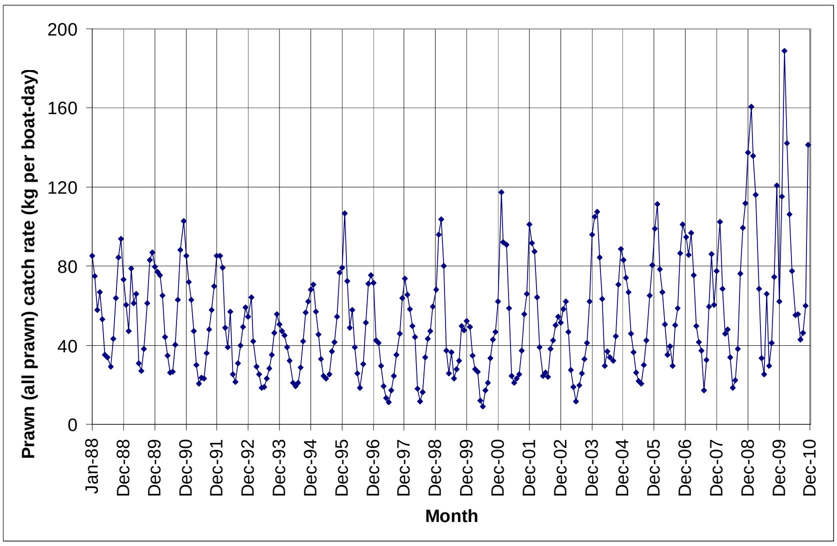

Figure 6-15. Monthly prawn catch rates (kg per boat-day) for the Moreton Bay otter trawl fishery 1988–2010.

It is noteworthy that the Brown Tiger Prawn catch in Moreton Bay has doubled over the last 15 years (Figure 6-12) as effort levels have fallen concurrently by about 71%. Catch rates of tiger prawns have also increased markedly, reaching record peaks in recent years, although it is difficult to precisely quantify tiger prawn effort. Brown Tiger Prawns have been recruitment overfished in other Australian trawl fisheries, including the Northern Prawn Fisheries (NPF) in the Gulf of Carpentaria (Dichmont *et al.* 2006) and Exmouth Gulf, Western Australia (Penn and Caputi 1986; Penn *et al.* 1995). Of all the prawn species fished in Australia, it is arguably the most prone to recruitment overfishing and therefore requires close monitoring and scrutiny. Logbook grid W37, which essentially encompasses Moreton Bay, has consistently received the highest annual trawl fishing effort of all 400+ logbooks grids distributed along the Queensland coast. It is therefore possible that the increased annual catch and increased catch rates of Brown Tiger Prawns in the bay are due to the significant declines in effort that have occurred, resulting in the stock recovering and the population size increasing. Alternatively, they may also be attributed to change in one or more environmental factors (abiotic factors affecting Brown Tiger Prawn abundance, and abundance of other prawn species in the bay, are investigated in section 13). Effort in the fishery is currently at historically low levels of about 4000 boat-days annually (Figure 6-13). If it is concluded that the tiger prawn stock has recovered from excessive effort levels in the previous decades, then it would be prudent to ensure that effort levels experienced by this species do not increase to previous levels, which peaked at 13,312 boat-days in 1999.

6.9 CODEND MESH SELECTIVITY

Pope (1966) described experimental techniques for determining codend mesh selectivity. Generally, data used in estimating selectivity curves come from two types of experiments. The first is the covered codend experiment in which the codend whose selectivity is being determined is surrounded by a much finer meshed net. In this type of experiment the proportion captured at each length can be simply computed. The second type of experiment is the alternate haul or parallel haul method in which two codend mesh sizes are deployed alternately, or simultaneously if the vessel is capable of towing multiple nets. Here we present selectivity curves for the three main species caught in Moreton Bay, *M. bennettae, M. melicertus* and *P. esculentus,* based on a sampling program undertaken in the bay that towed two nets with different codend mesh sizes.

The data were obtained by sampling nine stations in the bay from August 1988 to July 1990 each lunar month for two years (Courtney *et al.* 1991; Courtney *et al.* 1995a). Two four-fathom (7.3 m) nets were towed simultaneously during each monthly trip. One net had a codend mesh size of 1 5/8" (41.3 mm), which is the most commonly used mesh by Moreton Bay fishers, while a smaller 1 1/4" (31.8 mm) mesh codend was used in the second net. The selectivity curve for each codend was calculated using a method described by Kimura (1978) which incorporates a logistic, non-linear least squares model and is suitable for calculating selectivity from codends whose curves overlap. One advantage of the Kimura (1978) method is that it can calculate the curves for both mesh sizes.

For the 1 5/8" (41.3 mm) mesh codend, the size at which the probability of retention is 50% (L_{50}) was similar for all three species (Table 6-5). The results indicate that this mesh size retains a broad range of size classes, including very small prawns (i.e., prawns weighing less than 10 g) that are likely to have little or no market value. For example, the L_{50} for Greasyback Prawns was 19.5 mm CL which equates to an individual prawn weight of about 6 g (Figure 6-2). Similarly, the L_{50} for Eastern King Prawns was 20.4 mm CL which equates to about 5 g (Figure 6-4). Brown Tiger Prawns weigh about 10 g at their L_{50} of 20.7 mm CL (Figure 6-10). Selectivity approaches 100% at about 25 mm CL, 27 mm CL and 22 mm CL for Greasybacks, Eastern King and Tiger prawns, respectively (Figure 6-16).

Table 6-5. Lengths at 50% probability of retention (L_{50}) and 90% selectivity range for two codend meshes sizes for the most commercially important prawn species in Moreton Bay. Note the L_{50} is slightly smaller for the smaller mesh, although there is considerable overlap in selectivity range for two mesh sizes.

Prawn species	**Small mesh codend 1 1/4" (31.8 mm) L_{50} (90% selectivity range)**	**Commercial mesh codend 1 5/8" (41.3 mm) L_{50} (90% selectivity range)**
Greasyback Prawn *M. bennettae*	18.1 (13.1, 23.2)	19.5 (14.5, 24.6)
Eastern King Prawn *M. melicertus*	18.2 (11.98, 24.48)	20.4 (14.18, 26.68)
Brown Tiger Prawn *P. esculentus*	20.5 (19.36, 21.72)	20.7 (19.55, 21.90)

There was very little difference in the selectivity curves for the Brown Tiger Prawns (Table 6-5). The reason for this appears to be due to very few tiger prawns smaller than about 17 mm CL in the samples. This suggests that the tiger prawns recruit to the fishing grounds at much larger sizes than the Greasybacks and Eastern King Prawns. Furthermore, the relatively narrow range over which the tiger prawns are selected by the gear (i.e., 19.55–21.90 mm CL) is indicative of 'knife-edged' selectivity (Figure 6-16).

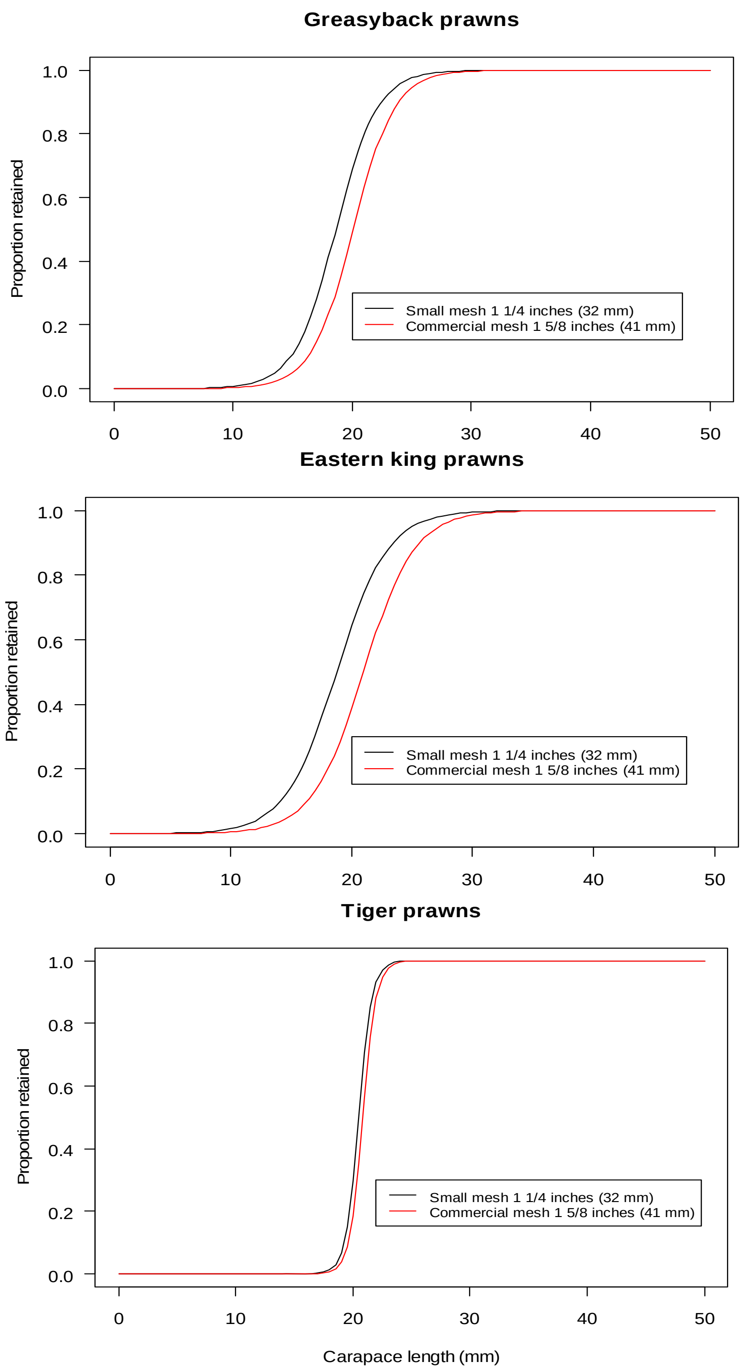

Figure 6-16. Logistic selectivity curves for small 1 1/4" (31.8 mm) and commercial mesh 1 5/8" (41.3 mm) codends for the main commercially important prawns in the Moreton Bay trawl fishery.

Broadhurst *et al.* (2004) examined the selectivity of 40 mm diamond mesh and 20 mm square mesh codends on prawns and fish in Lake Woolooweyah, New South Wales, in depths from one to three metres. The size range of the prawns was significantly smaller than those sampled in Moreton Bay. The L_{50} obtained for Eastern King Prawns was 10.3 mm CL, which differs markedly from the L_{50} obtained for Moreton Bay herein. Reasons for this may be due to the abundance of small size classes of Eastern King Prawns in the lake and to a lesser degree, the slightly smaller mesh size used, and the heavy twine in the codend compared to that used in the body of the net, which means that for a given mesh size the hole through which the prawn escapes is much bigger for trawl-body netting compared to codend netting.

In an attempt to produce a more realistic selectivity curve for tiger prawns, further curves of the same form as Kimura (1978) were fitted to the Moreton Bay data, although the fitting process allowed a greater flexibility of the logistic curves in order for them to more tightly fit the data and potentially identify more precisely the selectivity information of interest. The first approach was to fit completely free logistic equations to the data and the second approach was to logically control some of the freedom by applying the condition of geometric similitude to the two trawl net scenarios.

For the free-results on the left in Figure 6-17 the logistic curves for each species case were allowed to asymptote to different upper values, if the data required. This allowed for a situation where different amounts of large prawns were retained in the two codends, despite the large prawns being fully size-selected by the meshes in the trawls. This situation would exist, for example, if the lateral spans of the two trawls were different during the surveys and they therefore consistently covered different swept areas within each haul. Additionally for those same curves on the left in Figure 6-17, the logistic equations in each species case were allowed to have their own independent steepness, whereas the curves of Figure 6-16 produced by the Kimura method were constrained to have a single common steepness for the two logistic curves for each species.

The free logistic model-fits displayed on the left of Figure 6-17 were somewhat unstable, particularly for tiger prawns where the distribution of prawn sizes in the samples did not extend over the whole selectivity range. For all fitting tasks, residuals were weighted by the number of prawns in the respective size category. This stopped the highly variable results in the tails of the prawn distribution from overly influencing the model-fits. This improved the strength of convergence to a 'bestglobal' solution in each species case. For tiger prawns additional constraints needed to be applied, which were that L_{50} for the 1 1/4" (31.8 mm) net could not be larger than L_{50} for the 1 5/8" (41.3 mm) net and the steepness for the 1 1/4" (31.8 mm) net could not be smaller than the steepness for the 1 5/8" (41.3 mm) net.

For Eastern King and Brown Tiger Prawns, the data quite clearly produced curves from the free-model approach where the predicted catch of large prawns was about 10–20% higher for the 1 5/8" (41.3 mm) mesh compared to the 1 1/4" (31.8 mm) mesh. This general conclusion cannot be extended to the Greasyback Prawns because there were very few larger Greasyback Prawns in the 'fully selected' zone to produce a firm guide to the fitting process, and no trend for more large prawns in the 1 5/8" (41.3 mm) mesh net was indicated in this instance. For Greasyback and Eastern King

Prawns the data supported the view that the two trialled mesh sizes have well-separated selectivity curves. For the Brown Tiger Prawns though, this was not the case since the best model-fit still unrealistically indicated that the two selectivity curves are almost identical. Like the Kimura method, this appears to be because most of the tiger prawns in the samples were of a size that could not escape through either of the meshes, and the prawn-size range was insufficient to guide the fitting process to produce a model trend that was logical when extrapolated beyond the data to smaller prawn sizes. Note the sharp kick of the Predicted Relative Catch curve to the left in Figure 6-17.

Selectivty curves for free logistic models. $L_{50\,(32mm)}$, $L_{50\,(41mm)}$, Steepness $_{(32mm)}$, Steepness $_{(41mm)}$, and upper asymptote were all estimated.	Selectivity curves for semi-free logistic models due to geometric similitude condition. $L_{50\,(32mm)} = L_{50\,(41mm)} \times 32/41$

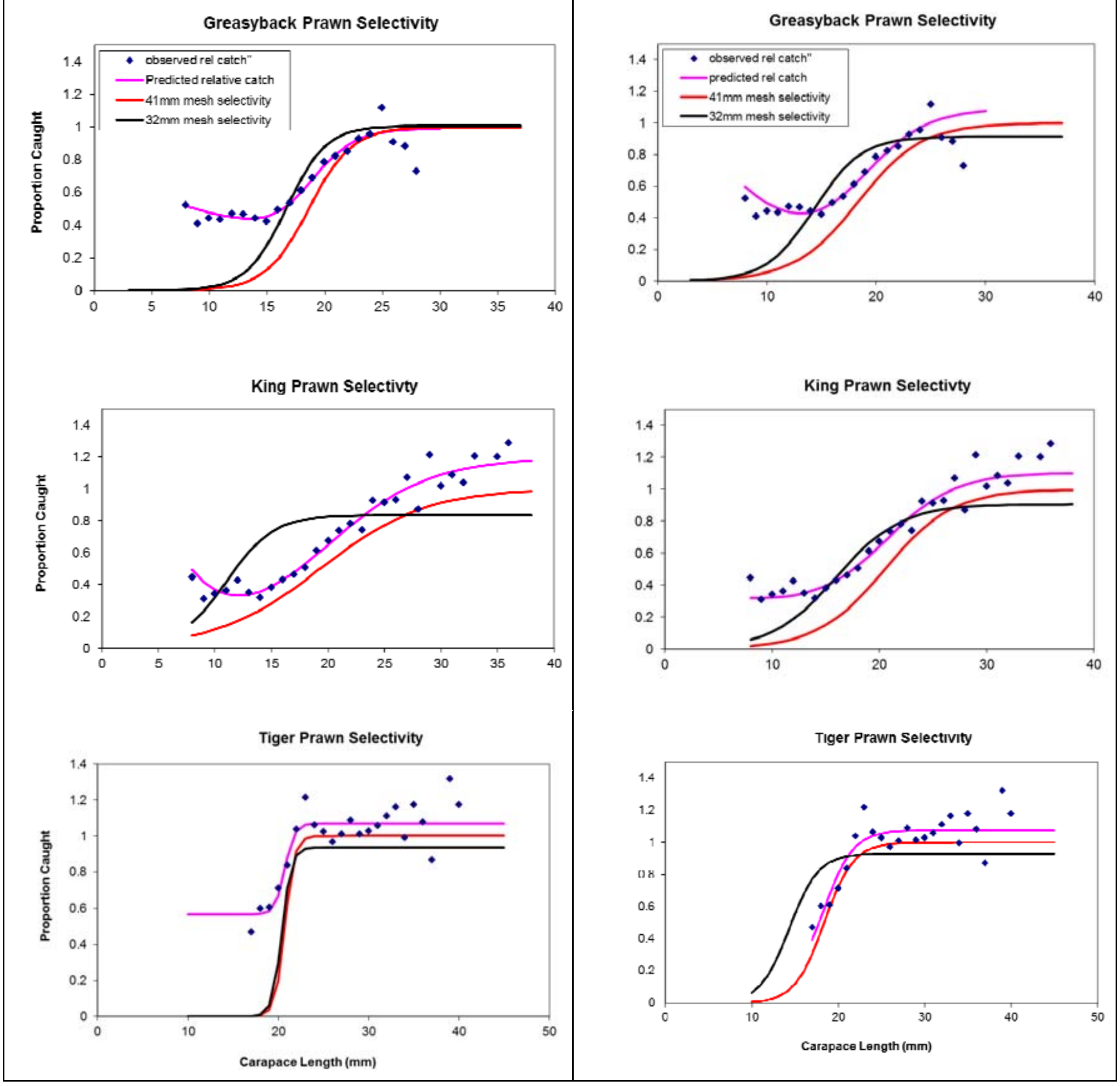

Figure 6-17. Logistic selectivity curves for small 1 1/4" (31.8 mm) and commercial mesh 1 5/8" (41.3 mm) for the main commercially important prawns in the Moreton Bay trawl fishery. These curves were obtained when more parameters in the model, than allowed in the Kimura (1978) method, were freed so that the logistic curve could more tightly fit the data.

In order to get firmer estimates of the selectivity curves it is necessary to add more information to the model-fitting process. In lieu of being able to collect more field data, another option is to constrain the logistic equations in a way that inherently produces realistic results. For the Kimura method the asymptotes were constrained to assume the catch of large prawns was equal for each trawl. However, exploration of the data indicates that this is not a suitable assumption in this instance due to the unequal catches of large prawns. If we assume geometric similitude exists between the two mesh sizes with respect to a given species then L_{50} for each netting should be in proportion to mesh size. For the selectivity curves fitted to the Moreton Bay data and displayed in Figure 6-17 on the right, the condition of geometric similitude has been applied, while the proportionality constant for the relationship between L_{50} and mesh size, the relative upper asymptote, and the steepness of curves for each prawn species are still freely determined by the data. Once again a solution constraint was applied that the steepness of the selectivity for the 31.8 mm net must not be less than the selectivity steepness for the 41.3 mm net. This constraint needed to be enforced for the tiger prawn model-fit.

Qualitatively, the selectivity curves for Greasyback and Eastern King Prawns containing the condition of geometric similitude agree with the respective curves on the left, and there is only a very small decrease in the quality of the fit as measured by the proportion of variance explained by the model that is provided in Table 6-6. For Greasyback Prawns the similitude condition produced selectivity curves that predicted the catch of large Greasyback Prawn in the 41.3 mm net would be higher than for the 31.8 mm net. For tiger prawns the condition of geometric similitude produced, as expected, two well-spaced selectivity curves for the two mesh sizes. The imposition of the similitude condition in the tiger prawn case did not cause the quality of the fit to decrease markedly and produced a logical trend in the prediction of relative catch for prawn sizes smaller than that contained in the data.

Table 6-6. Lengths at 50% probability of retention (L_{50}) and steepness of selectivity curves for two mesh sizes for the most commercially important prawn species in Moreton Bay, as estimated by fitting three logistic models with various parameter freedoms.

	1 1/4" (31.8 mm) L_{50}, steepness	**1 5/8" (41.3 mm) L_{50}, steepness**	**% of variance explained**
Greasyback Prawn			
Kimura method	18.1, 0.598	19.5, 0.598	97.5
Free logistic model	16.7, 0.582	18.6, 0.536	97.9
With geom. similitude	14.3, 0.465	18.3, 0.344	97.4
Eastern King Prawn			
Kimura method	18.2, 0.487	20.4, 0.487	95.0
Free logistic model	11.0, 0.475	19.4, 0.216	96.1
With geom. similitude	16.0, 0.322	20.5, 0.316	95.8
Brown Tiger Prawn			
Kimura method	20.5, 2.09	20.7, 2.09	42.2
Free logistic model	20.4, 1.90	20.7, 1.90	58.4
With geom. similitude	14.3, 0.597	18.4, 0.597	54.4

Given the difficulty at times in obtaining a suitable range of prawn size to properly evaluate the selectivity characteristics of netting, it may be advantageous to pool data from different species. It is expected that the different morphologies of prawn species would make this approach risky. However, the investigation of 'equivalent size' between species with respect to mesh selectivity, starting with the cube-root-of-weight, might lead to a workable methodology for pooling selectivity data across species in order to establish reasonably accurate selectivity performance indicators for netting materials used in commercial fishing.

6.10 PREVIOUS ECONOMIC ANALYSES IN MORETON BAY

In 2005 (the latest year for which data are publically available), the fishing industry in Moreton Bay produced around $13 million worth of seafood, around half of which was produced by trawlers (Table 6-7). More recent estimates of catch suggest that the value of catch from the commercial fishery in the order of $24 to $30 million per annum (McPhee *et al.* 2008).[1] Over two-thirds of the value of catch caught by the trawl fleet was derived from prawn species, with tiger prawns being the single most valuable species to the fleet (Figure 6-18). In 2007, 202 vessels were active in the fishery. The capital invested in the fleet in terms of vessels, associated fishing gear and onshore facilities was estimated to be around $77 million, $65 million of which was capital invested in vessels (McPhee *et al.* 2008).

Relatively few economic analyses have been undertaken on the fishing industry in Moreton Bay. A bioeconomic model of the beam trawl fishery was developed in the mid 1990s, primarily aimed at examining interactions between the beam trawl fleet, recreational fisheries and also the otter trawl fleet working in the area (Campbell and Reid 2000; Reid and Campbell 1998). The study concluded that the costs imposed by the beam trawl fishery on the recreational fishery (through bycatch of target recreational species, habitat disturbance and loss of natural bait) were relatively minor (around $10/day in 1997 dollars). Similarly, the cost imposed on the otter trawl fishery (through bycatch of juvenile target prawn species) was also found to be minor, and in the order of around $200/vessel over the year (Reid and Campbell 1998).

Table 6-7. Value and volume of catch from Moreton Bay, 2005

Fishery	Tonnes	Boats	Days	GVP (AUS $)
Trawl - Otter	548.7	73	5872	4.93
Trawl - Beam	193.5	30	3518	1.21
Pot - Crab	349.2	98	9002	3.01
Net	984	96	4554	3.51
Line	21.6	32	457	0.12
Total	2097.4	235	22453	12.78

Source: (Department of Employment Economic Development and Innovation 2010)

Several economic surveys of the fishery have been undertaken in the past (Moxon and Quinn 1984; Reid and Campbell 1998; Taylor-Moore 2000), however the fleet did not participate in the 2010 survey. The cost structure of the fishery was estimated as part

[1] This report was produced with an explicit objective of influencing the development of the Moreton Bay Marine Park so it is possible that the estimated values have been inflated.

of the Moreton Bay Marine Park study (McPhee *et al.* 2008), although the data were only presented as a percentage of expenditure (Figure 6-19) so profitability cannot be assessed. However, from this it can be seen that the dominant expense items in the fishery are fuel and repairs and maintenance (both boat and gear).

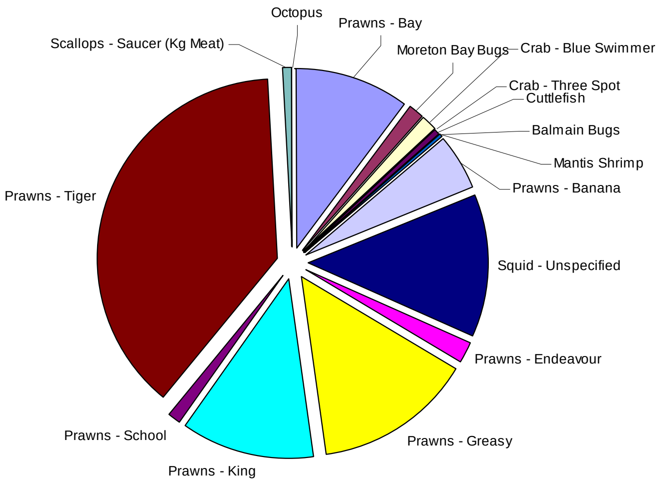

Figure 6-18. Relative trawl fleet catch value by species from Moreton Bay, 2005.
Source: (Department of Employment Economic Development and Innovation 2010)

Some analyses have been undertaken about the impact of the marine park designation on the fishery. The marine park was initially estimated to reduce the gross value of product of the fishery by $4.1 million (Sen 2010), a reduction of around one-third based on the 2005 estimated GVP. The structural adjustment package introduced to compensate the industry removed 119 active licences (over half the active fleet) at a cost of $15.1 million, and was estimated to have a short-term impact of reducing GVP by $6.2 million—higher than initially targeted (Sen 2010). The actual GVP post-adjustment has not yet been assessed.

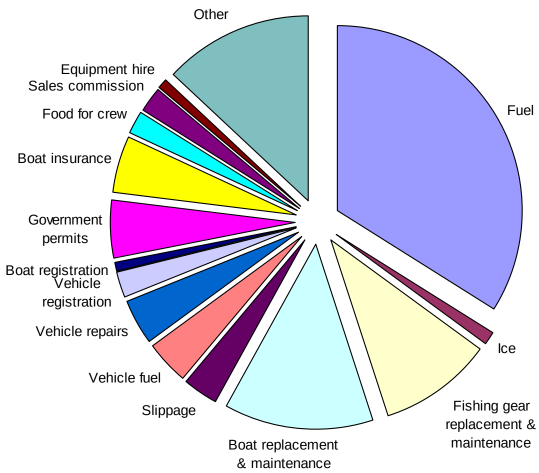

Figure 6-19. Cost items as a share of total expenditure, Moreton Bay fishing vessels.
Source: (McPhee *et al.* 2008)

While little economic analysis has been done on the commercial fishing fleet, considerable attention has been paid to the economic analysis of recreational fisheries and other activities in the bay (Clouston 2002; Driml and McBride 1982; McPhee *et al.* 2008; Properjohn and Tisdell 2010; Reid and Campbell 1998). Estimates of the economic value of recreational fishing range from \$194 million (Henry and Lyle 2003) to \$265 million (McPhee *et al.* 2008).

7 Identify and prioritise management objectives for the Moreton Bay trawl fishery, as identified by the trawl fishers (Objective 2)

By A. Courtney, J. Larkin and M. Landers

7.1 INTRODUCTION

To obtain an understanding of the issues that Moreton Bay trawl fishers considered to be important and assist with identifying harvest strategies for evaluation, the project developed a survey (Appendix 3 section 22) and interviewed fishers between November 2010 and April 2011. The survey was also designed to obtain detailed information on the fishery's economics (section 8) and factors affecting fishing power (section 9) for effort standardisation purposes (also known as effort creep). The section of the survey dealing with management and harvest strategies included nine questions that sought responses from fishers ranging from 'strongly support' to 'strongly disagree'. It also included the provision for fishers to raise and discuss any other issues that they felt were important to the fishery. This section of the report summarises the survey findings pertaining to management issues and harvest strategies.

7.2 RESULTS

During the project, 71 Moreton Bay licence holders were identified, including both T1/M1 and M2 licence holders. Attempts were made by project staff to contact each licence holder, seeking their participation in the survey and to make an appointment for the interview, preferably in person. Of the 71 licence holders, 49 were interviewed. The remaining 22 were not interviewed for the following reasons: 1) despite the licence to trawl in Moreton Bay being purchased and owned by the current licence holder, it has not been used by the current licence holder (i.e., unused or latent effort and licence); 2) either the owner and/or skipper associated with the licence was not willing to participate; 3) the licence holder was not available for interview (i.e., some were overseas); 4) licence holder did not respond to repeated phone contacts; and 5) despite possessing a licence that permits trawling in Moreton Bay, some T1/M1 licence holders do not work in the bay (i.e., they trawl other areas on the Queensland coast) or they trawled in Moreton Bay only rarely. Given this range of reasons, it was concluded that the project surveyed the great majority of fishers who were willing and available for interview, including those who are responsible for about 95% of the trawl effort and catch in the fishery. The majority of interviews were conducted in person (i.e., face to face), with the remainder over the phone.

With respect to the nine survey statements (Table 7-1), the majority of licence holders had a poor opinion of the fishery's management, although 17% neither agreed nor disagreed with the statement. Seventy-nine percent thought that there were not excessive licence holders in the fishery, while 17% thought there were. Eighty-two percent thought that the level of effort in the fishery was not excessive. Sixty-three percent thought that the M2 vessels should not have effort allocations, while 27% thought they should. Seventy-six percent thought the prawns were harvested at appropriate size classes, while 17% thought they were harvested too small. Eighty-two percent thought that increasing the mesh size would not increase the value of the catch. Similarly, 83% thought that the value of the catch could not be increased through additional seasonal or spatial closures. Most licence holders (63%) thought the fishery could not compete against the imported aquacultured prawns. Ninety-six percent disagreed that the main market of the fishery was for bait prawns.

In summary, the responses indicated that despite the majority of fishers believing that management needed to be improved, they did not support a reduction in the number of licensed vessels, or a reduction in effort. Nor were they supportive of additional closures, or changes to mesh size, aimed at increasing the size at which the prawns are harvested.

Table 7-1. Responses from 49 Moreton Bay trawl fishery licence holders to specific survey statements. Numbers are in percentages.

Statement	**Strongly agree**	**Agree**	**Neither Disagree or Agree**	**Disagree**	**Strongly disagree**	**Total**
1) Current management of the Moreton Bay prawn trawl fishery is very good.	0	15	17	39	28	100
2) There are too many trawlers in Moreton Bay prawn trawl fishery.	4	13	4	57	22	100
3) There is too much trawl fishing effort in Moreton Bay.	0	11	7	54	28	100
4) The M2 vessels should have effort units.	7	20	11	43	20	100
5) The size of the prawns that are being harvested is too small and well below the size needed to maximise value from the fishery.	4	13	7	61	15	100
6) The value of the prawn catch could be improved by using larger mesh.	2	13	2	54	28	100
7) Additional seasonal or spatial closures could increase the value of the prawn catch.	7	11	0	50	33	100
8) The Moreton Bay prawn trawl fishery cannot compete against imported vannamei prawns.	33	30	0	28	9	100
9) The main market for the Moreton Bay prawn trawl fishery should be the supply of bait-prawns.	2	0	2	59	37	100

Project staff recorded the issues raised by fishers during the interviews that fishers felt were important. These were grouped and summarised in Table 7-2. The most common issue raised by fishers was in regard to permission to retain and market additional bycatch species, specifically winter whiting. Currently Queensland trawl fishers cannot retain or market this species.

Table 7-2. Summary of the issues raised by 49 Moreton Bay otter trawl fishers during the survey interviews.

Percentage of fishers that raised the issue	**Issue raised by fishers during interview**
8%	**1. Bycatch.** Fishers said extra income generated retaining and selling bycatch helps with fuel and crew costs. Fishers argue they need to sell bycatch to survive financially.
53%	**1a. Winter whiting.** The prohibition on whiting bycatch was the top issue raised by fishers. Whiting is not targeted and catches are reduced with BRDs. Whiting bycatch is thrown back dead. Closures already exist in Moreton Bay to protect the species. Suggestions included a percentage of catch or a quota on weight basis for whiting bycatch.
31%	**1b. Crab Quota.** Blue swimmer crabs caught as bycatch currently have a quota of 100 on vessel. Fishers believe that crab bycatch caught should be kept. Crabs are not targeted but when caught fishers want to utilise them. Suggestions include no quota or an increased quota.
12%	**1c. Female Moreton Bay Bugs.** Female Moreton Bay Bugs that are berried shouldn't be allowed to be kept.
46%	**2.Vannamei Prawns.** Fishers are struggling to compete with cheap imported prawns that are ruining wild local prawn industry. Moreton Bay fisher costs are high and continue to increase however prawn has low market value. The import of prawns is flooding the market and keeping prices low. Suggestion is to increase the value of Moreton Bay prawn catch, include limiting importation of prawns with strict regulations and government testing of the product. Needs to follow same Australian Standards for production. Possibly introduce a tariff. Educate public about vannamei prawns.
29%	**3. Fuel Cost.** Increasing cost of fuel is a major issue. Most couldn't continue to fish without rebate. Suggestions include increased fuel subsidy and a rebate for primary producers.
	4. Marketing
23%	**4a. Marketing.** Moreton Bay is a small prawn fishery. Marketing is needed to increase prawn value. Local wild-caught prawn industry needs to compete with imported prawns. Fishers need a higher price or set minimum from wholesalers to cover costs. One wholesaler has monopoly on market due to closure of Sandgate Fisherman's co-op. With little competition low prawn prices are set for the industry. Wholesale price of prawn hasn't increased. Suggestions to establish a new market based on success of Southport fishery. A direct supply chain to the public is needed.
10%	**4b. Labelling and education.** Labelling for 'imported', 'farmed' and 'wild-caught' prawns at place of purchase for consumers. Educate retailers on how to display and keep 'wild prawns' to maintain quality.
12%	**4c. Advertising.** Raise awareness with an advertising campaign for wild-caught, local fresh prawns to compete with other primary industry and fast food. Generate good publicity for the industry to counteract negative image on the health of Moreton Bay after the floods.
	5. Closures
25%	**5a. Oppose all closures in Moreton Bay.** Fishers think there are currently too many permanent closures and zones in Moreton Bay. Closures restrict catch for the short period each year that the prawn is available. Green zone closures have only had a small or no impact or and are inconvenient. If more closures are introduced then the trawl effort will be concentrated into a smaller area of the bay. Large areas of the bay are unproductive and not commercially viable. Suggested a lift of closure to capture Banana Prawn.
14%	**5b. Support current and future closures.** Current closures are adequate for conservation. Closures would help if the prawn size is too small and are good to keep production high. Introduction of smart green closures in all brood stock areas. Introduce zones (not permanent closures) that switch on/off during certain years depending on conditions. Possibly close bay for 2-3 weeks to increase demand and size of product. Reduce the number of nights fished to four per week.
21%	**6. Buy-back scheme.** Fishers want another buy-back scheme so they can leave the industry or retire. Would like to be paid correctly for the vessel and licence as previous (DERM-funded) buy-back was mismanaged. A lot of fishers in the industry want to get out. Ineffective removal of licences that were not being used. There are currently many M2 and M1/T1 licenses being held for future investment. There are fewer vessels in the fishery now so licences should be worth more.
14%	**7. TEDs.** It is thought that current size of TEDs is too big. Need more towing power. No obvious change from smaller ones. The rebate for the recent change to the size of TEDs wasn't enough to cover costs.
	8.VMS for M2 Vessels
12%	**8a. Support VMS on M2 Vessels.** Help to monitor closures and to stop illegal fishing. Keep smaller vessels out of closed areas so prevent catching small prawn. M2 vessels are often seen in these areas. VMS on M2 would stop this.
12%	**8b. Oppose VMS on M2 vessels.** VMS not needed on M2 vessels. It is seen to be an extra expense. M2 License allows 52 weeks trawling per year and there is no effective limit on the number of nights M2 vessels can work (unlike T1/M1 vessels which have effort units that are monitored by VMS).
	9. Management issues
10%	**9a. Over-managed.** Moreton Bay is over-regulated and needs to reduce management. Stocks can't be overfished due to reductions in effort in winter months and if there is no prawn around no one trawls. Regulations on TEDs, nets and board sizes.
12%	**9b. Self-managed.** Industry needs fishers working together to market product. Increasing the price and size of product with a fixed price for the product. Industry needs to be run by fishers. Needs successful fishers for management, not investors.
10%	**9c. Lack of management.** The unregulated industry makes it harder for fishers to unite. There is a lack of management in Moreton Bay. Fishers don't work together, if one leaves the prawns to grow, another fisher will catch it. Management needs to be separated from the East Coast Trawl Fishery. Fishers competing with each other to sell product at Sandgate. Co-operation is needed in the management of fishery with stronger communication between managers and fishers. Have observers on vessels to understand industry, do surveys to talk to fishers about industry and educate fishers on new technology.
8%	**10. Licences for Moreton Bay - M1/T1 and M2.** Change M1 licenses to M2, as the bay should only be fished by M2 licenses. Smaller vessels will be a benefit to bay. Smaller vessels don't catch as much as the large ones. M1 licensed vessels work inside the bay when the weather is rough when smaller M2 boats can't.
8%	**11. Logbooks.** Logbook entries and compliance of logbook data should be monitored more closely. Large fines for not having information filled in and sent away. Majority of logbook data is falsified and no research or decisions should be made based on logbook data.

Fishers also expressed a desire to increase the number of blue swimmer crabs they are permitted to retain and market. Both the whiting and blue swimmer crab issues are highly political. A high proportion of fishers complained about the detrimental effects of imported aquacultured vannamei prawns on their market for wild-caught bay prawns. They also put forward ideas they considered might be useful for reducing these impacts, including tariffs, public education and more-stringent application of seafood health standards (some fishers perceive imported product to have lower health and safety standards). Other issues included government-funded assistance with fuel costs and a buy-back scheme. There was strong support for improving the marketing of Moreton Bay trawl-caught prawns, which included advertising initiatives, pursuing other wholesalers/buyers and improved labelling. There was limited support for closures or other effort-management measures aimed at increasing catch value.

In summary, while these issues were considered to be high priority for the fishers, the subject matter was considered to be largely political and beyond the fields of expertise of the project research consortium.

The interview results provided in Table 7-1 and Table 7-2 were presented to fishers at the fourth project steering committee meeting on 1 April 2011. At this meeting the project objectives and survey results were discussed in detail. Although no obvious harvest strategies were identified by the fishers through the survey interviews, the committee discussed all of the interview results at length, and eventually identified five tasks for the research consortium to address. These are listed below (as well as in section 5 Objectives).

A. Develop optimal temporal and spatial harvesting patterns in the bay, considering a range of effort levels, to maximise the sustainable catch value for the four main prawn species (Greasybacks, Eastern King Prawns, Brown Tiger Prawns and Banana Prawns).
B. For the four important prawn species in the bay, identify empirical evidence for the environmental factors driving the variable strength of prawn recruitment and the timing of seasonal prawn behaviour, which are both strongly evident in the bay. The predictive outcome of the work will allow dynamic-tuning of harvest/market strategies to better capture the opportunities presented by variable environmental conditions and also mitigate associated risks.
C. Further development of the corporate governance model, including detail on how each licence holder type (i.e., T1/M1 and M2) could participate, likely locations for the business, initial operating cost estimates, and how each participating fisher could be paid.
D. Collate all sampling information for the bay to provide clearest possible fine-scale picture of variable prawn recruitment and seasonal prawn behaviour (e.g. 'Cleveland' juvenile tiger study and Long-Term Monitoring Program work).
E. Work-up a relationship between mesh size and the selectivity of MB prawns so that optimal mesh sizes can be estimated for harvest strategies involving the exclusion of small prawn from the gear whilst on the seabed.

8 Economic analysis of Moreton Bay trawl fishery (Objective 3)

By S. Pascoe and J. Innes

8.1 ABSTRACT

The Moreton Bay prawn trawl fishery is one of Queensland's oldest commercial fisheries. Despite this, and its proximity to the main population centre in the State, little economic analysis has been undertaken on the fishery. In this section, we present the results of an economic survey of the fishery which provides a snapshot of its current economic performance. The results suggest that the current economic performance in the fishery is relatively poor, with incomes lower than might be achieved elsewhere. Hence, the fishery is economically unsustainable in the longer term and unlikely to attract new entrants or investment. In addition, logbook data were used to estimate a translog production frontier, from which the level and distribution of technical efficiency in the fishery was determined. The level of efficiency in the fleet was found to be comparable with those of other Australian prawn fisheries on average, with the only statistically significant driver of technical efficiency being the level of education of the skipper. The survey data and production frontier were combined to estimate the marginal profit per hour over the season, which was compared with the distribution of fishing effort. As would be expected, the results indicate that economic performance is a key driver of effort in the fishery. Finally, the production frontier model and economic survey data are used to estimate the potential impact of removing the existing M2 boat-replacement policy on total fishery catch and effort levels.

8.2 INTRODUCTION

The Moreton Bay prawn fishery has a particularly significant place in history in terms of the development of the Queensland fishing industry. In the early 1950s, a prawn fishery using otter trawl developed in Moreton Bay. By the mid 1950s, fishing had quickly spread up the coast, initially targeting Banana Prawns in inshore and estuarine areas, as well as diversifying into the scallop fishery and eventually into the more offshore areas targeting King, Endeavour and Tiger prawns (OECD 2006). This larger fishery has since become known as the Queensland East Coast Trawl Fishery (ECTF), a multispecies fishery based on several prawns species, Moreton Bay bugs and scallops, and Queensland's largest commercial fishery, with about 600 licensed vessels catching product valued at approximately $100 million in 2008–09 (ABARES 2010).

Several different commercial fisheries exist in Moreton Bay, of which the prawn trawl fishery is the most valuable. In 2010, the gross value of production of the prawn trawl fleet was estimated from logbook data to be roughly $4.6m, with 57 vessels actively fishing in the bay at least once over the year. The fishery is based on four main prawn species – Greasyback (generally referred to as Bay prawn), Banana, Tiger and King prawn – caught using otter trawl. Other species such as cuttlefish, Moreton Bay bugs and squid are caught as byproduct, although these represent roughly only 2% of the total value of landings.

Falling prawn prices over much of the last decade (Figure 8-1) has almost certainly contributed to a substantial reduction in fishing effort in both Moreton Bay (Figure 8-2) and the broader ECTF. Concerns have been raised by the industry about the continuing economic viability of the fishery in the face of potential future prawn price reductions.

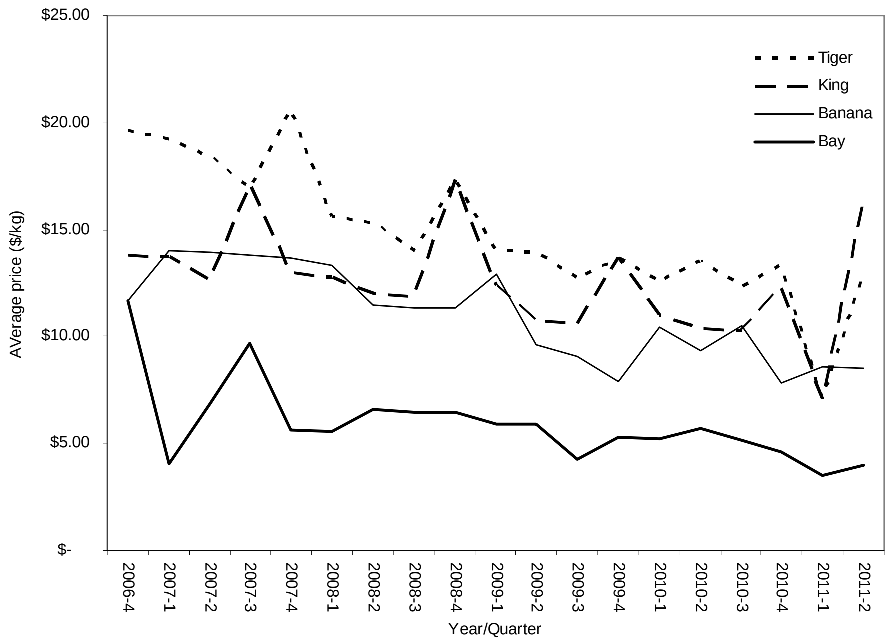

Figure 8-1. Price trends of the main species by quarter, 2006–2011.

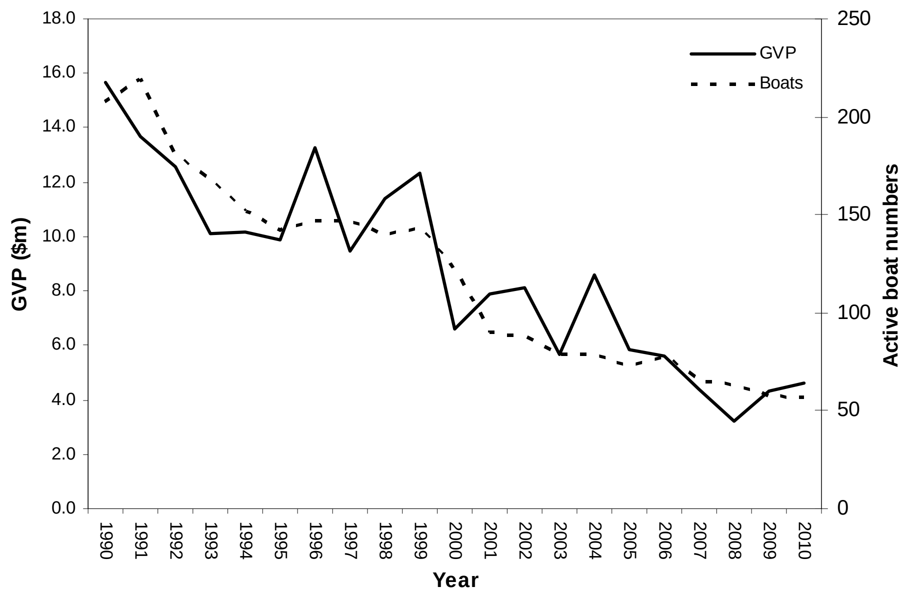

Figure 8-2. Change in real gross value of production and active vessel numbers since 1990 (2010 values).

While still part of the larger Queensland ECTF, the Moreton Bay trawl fishery remains partially independent in terms of management arrangements. Fishers who operate in the fishery need a separate endorsement to that required for the ECTF. Two forms of this endorsement exist: a 'T1/M1', which allows vessels to operate both outside the bay (the T1 component) as well as inside (the M1 component), and an M2 endorsement that allows fishers to operate only within the bay. In 2012 there were a total of 72 vessels holding endorsements (known as 'symbols') to operate in the bay; 47 T1/M1 symbols and 25 M2 symbols. All Moreton Bay-endorsed vessels are limited in size to a maximum of 14 metres.

The T1/M1 vessels are subject to a transferable effort quota system, and utilise effort units when fishing either inside or outside the bay. The effort units place a limit on the total number of days a vessel can operate, although as they are transferable, vessels can buy more effort units if required. In contrast, the M2 vessels are not subject to effort restrictions, other than a ban on daylight and weekend fishing (applicable also to T1/M1 vessels) – primarily to reduce conflicts with recreational fishers and other recreational users of the bay. The M2 vessels are also subject to other boat replacement restrictions, namely, that another M2 licence needs to be surrendered if an existing M2 vessel is modified or replaced (*Fisheries (East Coast Trawl) Management Plan 2010*, §99). Moreton Bay M2 holders have expressed concerns that the current boat replacement cost is preventing them from adjusting their fishing activities to achieve cost savings in light of the decline in prawn prices.

Despite its proximity to the major population centre in Queensland (i.e. Brisbane), relatively little economic analysis has previously been undertaken on the fishery. Several economic surveys of the fishery have been undertaken in the past (Moxon and Quinn 1984; Reid and Campbell 1998; Taylor-Moore 2000), although these have been fairly sporadic. A bioeconomic model of the beam trawl fishery was developed in the mid 1990s, primarily aimed at examining interactions between the beam trawl fleet (which operates in the rivers and creeks targeting juvenile prawns for the bait market), recreational fisheries and also the otter trawl prawn fleet working in the bay (Campbell and Reid 2000; Reid and Campbell 1998). The study concluded that the externalities imposed by the beam trawl fishery on the recreational and otter trawl prawn fishery were minor.

The fishery's available area to fish has decreased. In 2009, the Moreton Bay Marine Park expanded from 0.5% of the total Bay area to 16%, with prohibitions on trawling in this expanded area. A structural adjustment package was introduced to compensate the industry (Sen 2010), although this removed only four active prawn trawl licences. Total catches in the bay have remained relatively constant for most species despite the falling effort, resulting in increasing catch rates for the key species.

The aim of this component of the study was to determine the current economic status of the fishery, including its economic performance and level and distribution of technical efficiency within the fleet. Further, the relationship between economic performance and effort levels in the fishery is also assessed. Finally, at the request of industry, the potential impacts of relaxing the existing 'two-for-one' boat-replacement policy on catch and effort was examined.

8.3 METHODS AND DATA

The analysis involved four stages. First, an economic survey of fishers was undertaken to collect baseline information to assess current economic performance. These data were also used in the subsequent parts of the economic analysis. Second, technical efficiency was estimated through the estimation of stochastic production frontiers. These provided information on the distribution and drivers of technical efficiency in the fishery. Information developed in the first two stages of the study was used to examine the responsiveness of effort production to economic performance of the fleet. Finally, the potential impact of removal of the boat-replacement policy on effort production and catch was assessed.

8.3.1 Economic survey of the fleet

A survey of the fleet was conducted between December 2010 and March 2011 to obtain information on, amongst other things, the costs and earnings of the vessels. The survey (Appendix 3 section 22) was part of the broader project that was also concerned with fisher opinions on key issues in the fishery as well as changes in technology employed (used for estimating changes in the fishing power of the fleet, building on previous similar surveys in earlier years). The survey frame was the entire licensed fleet, with 49 vessels responding to the overall survey, and about 17 giving full economic information.

The key economic indicators examined included revenue, fuel costs, crew costs, other running costs, repairs and maintenance and fixed costs. Information on the capital value of the vessel and also the licence value was also collected. Most skippers interviewed were owner operators. For consistency, where skippers were employed, these costs were excluded to give an overall representation of the costs and earnings of an owner-operated vessel. Non-cash costs were also imputed. Depreciation was taken as 2 per cent of the capital value (Pascoe *et al.* 2011a), while an opportunity cost of capital was estimated as 5 per cent of vessel capital value. Owner-operator returns (the cash profits less the non-cash costs) were estimated as an overall indicator of vessel profitability, representing the residual return on the owner-operator/skipper labour after allowances for capital costs had been made. A combined cash profit and owner-operator income is considered a more appropriate indicator for small-vessel fleets compared to other measures traditionally estimated (e.g. rates of return to capital) (Boncoeur *et al.* 2000).

8.3.2 Technical Efficiency (TE) of the fleet

Economic efficiency is a function of several components, including allocative efficiency (are the vessels using the right combination of inputs and producing the right combination of outputs?), and technical efficiency (are the vessels producing the maximum possible outputs given their level of inputs?). Assessing allocative efficiency requires the estimation of profit functions, which include information on individual input and output process as well as individual vessel profitability. Relatively few such studies have been undertaken in fisheries primarily due to the lack of adequate appropriate economics data (Pascoe *et al.* 2011b). This was the case also for the Moreton Bay study, as the economic data collected in the survey were not sufficient to allow the estimation of a profit function. Technical efficiency, on the other hand, is estimated using a stochastic production frontier, which requires information only on inputs and outputs. Technical efficiency is a necessary (but not sufficient) condition for profit maximisation (Coelli *et al.* 1998), and provides an indication as to how much more output could be produced by fishers with the given level of inputs if they operated fully efficiently.

Numerous studies of technical efficiency have been undertaken in fisheries (Herrero and Pascoe 2003; Kirkley *et al.* 1998; Kirkley *et al.* 1995; Pascoe and Coglan 2002; Sharma and Leung 1999), including other Australian prawn fisheries (Greenville *et al.* 2006; Kompas *et al.* 2004; Pascoe *et al.* 2010a). Several studies have attempted to estimate drivers of technical efficiency, and generally concluded that individual skipper characteristics were the main driver of differences between vessels in a given year (Coglan and Pascoe 2007; Pascoe and Coglan 2002; Tingley *et al.* 2005), although management may also play a large role in changing average efficiency over time (Kompas *et al.* 2004; Pascoe *et al.* 2001; Pascoe *et al.* 2010a).

The estimation of technical efficiency requires, first, the estimation of the efficient production frontier, representing the efficient level of catch given a set of inputs. A range of potential stochastic production frontier functional forms exist, including the translog (Christensen *et al.* 1973), Cobb-Douglas and constant elasticity of substitution (CES), where the last two are effectively special cases of the translog. As the fishery is multispecies, ideally a translog multi-output distance function should be estimated. These allow for the possibility of output substitution (i.e. differences in targeting behaviour) of fishers. While several examples of the use of output distance functions in fisheries exists (Fousekis 2002; Huang and Leung 2007; Pascoe *et al.* 2007; Pascoe *et al.* 2010b), the more common approach is to use an aggregated output measure, with the total value of the catch (i.e. revenue) generally being an appropriate measure (Herrero and Pascoe 2003).

The translog production frontier (Aigner *et al.* 1977; Meeusen and Van den Broeck 1977) is given by:

$$\ln y_i = \beta_0 + \sum_k \beta_k \ln x_{k,i} + 0.5 \sum_k \sum_l \beta_{k,l} \ln x_{k,i} \ln x_{l,i} - u_i + \varepsilon_i \qquad (1)$$

where y is the quantity of output produced, x is a vector of inputs, u is a one-sided error term ($u \geq 0$) representing the level of inefficiency of the vessel and ε is a random error term. The TE of the i-*th* sample farm, denoted by TE_i is given by $TE_i = exp\ (-u_i)$. Alternative functional forms (e.g. the Cobb-Douglas production frontier, given by restricting the $\beta_{k,l}$ terms to zero) can be tested against the translog using the likelihood ratio test and accepted if found to be more appropriate.

Inefficiency can be modelled as a fixed effect for each vessel, a time-varying effect or a function of the characteristics of the vessel and/or skipper (Battese and Coelli 1995). Several fisheries studies have adopted the latter approach as this provides information not only on the level of efficiency but also factors that may be contributing to this efficiency level (Coglan and Pascoe 2007; Pascoe *et al.* 2001; Pascoe *et al.* 2010a; Sharma and Leung 1999; Tingley *et al.* 2005). In this study, inefficiency is modelled explicitly as a function of known characteristics and exogenous effects, such that:

$$u_i = \delta_0 + \sum_j \delta_j Z_{ij} + w_i \qquad (2)$$

where Z is a set of $j = 1,\ldots,J$ firm-specific variables which may influence the firm's efficiency, δ_l is the associated inefficiency parameter coefficient, and w_i is an iid random error term (Battese and Coelli, 1995).

Logbook data over the period 2005 to 2010 were used in the analysis. The daily logbook records were aggregated to the monthly level. Revenue of each vessel in each month was estimated using a common set of prices (average prices over 2010) to remove the effects of changes in prices on apparent efficiency measures. Data on engine power, headrope length, hull units, and the number of days and hours fished each month were also available, although complete data were available only for 35 vessels. A key input into the production function is the resource stock itself. Stock estimates for the key species were unavailable, but a proxy stock measure was derived as the average value per unit effort each month from all boats operating in the fishery (including those not included in the final model due to having missing characteristics data).[2] This approach has been applied elsewhere (Kirkley *et al.* 1995; Pascoe and Coglan 2002) but is less than ideal as it is only a valid indicator if the 'stock' elasticity is one (1), which can only be tested retrospectively. Crowding pressures have also been seen to affect catch rates in other trawl fisheries (Pascoe *et al.* 2001; Pascoe *et al.* 2010a), so the total number of days fished each month was also included in the analysis.

Some information was also collected on skipper characteristics and the level and types of technology employed in the survey described previously. Nearly all vessels used similar types of technologies (e.g. some form of GPS, radar, echo sounder etc.) so these were excluded from the analysis. Skipper characteristics included number of years experience in fishing, number of years as skipper, age of the skipper, number of years of schooling, and number of generations of the family that had been involved in commercial fishing. Vessel characteristics used only included the age of the vessel.

A summary of the key data available is presented in Table 8-1. The input and output data were logged and normalised[3] such that $\ln \bar{y} = \ln \bar{x} = 0$. The variables (other than the dummy variables) in the inefficiency model were logged (but not normalised).

8.3.3 Relationship between effort production and economic performance

The production frontier and associated efficiency scores provide other useful information relevant to fisheries management, especially when combined with cost data from an economic survey. From an economic perspective, fishers should operate only to the point where their marginal revenue equals their marginal cost. Fishing beyond this point would result in a net reduction in fishing profits. This point can be determined for each vessel, given that information on costs, prices, and marginal productivity can be assessed. Cost information has been collected in the survey, price

[2] The use of month and annual dummy variables was also tested, but substantial differences between years in the seasonal pattern resulted in these being poor proxy measures for changes in stock conditions.

[3] Normalisation was undertaken primarily to satisfy theoretical consistency issues associated with the translog production function, namely, that it is a second order Taylor series expansion of a generalised production function centred on zero. Barnett W. A., Lee Y. W., Wolfe M. D. (1985). The three-dimensional global properties of the minflex laurent, generalized leontief, and translog flexible functional forms. *Journal of Econometrics* **30**, 3-31.

data have been collected from prawn buyers and logbook and data collected in the survey are sufficient to estimate the production function from which marginal value product can be estimated.

Table 8-1. Summary of key data available for the analysis.

Variable	**Min.**	**1st Qu.**	**Median**	**Mean**	**3rd Qu.**	**Max.**
Production frontier						
Revenue ($)	63	3551	7974	10340	14520	55540
Hull units	6	12	18	18	24	29
Engine (kW)	80	140	170	173	188	700
Days fished	1	7	12	11	16	23
Hours fished	2	70	127	127	183	305
Headrope (m)	6	13	15	14	15	29
Stock index	0.08	0.71	0.92	1.00	1.14	2.17
Total days fished (crowding)	1	143	202	191	241	344
Inefficiency model						
Years fishing	6	18	23	25	29	57
Years as skipper	1	11	19	19	25	57
Skipper age	29	40	48	48	56	81
Years of schooling	1	8	10	9	10	15
Number of generations	1	1	2	2	3	5
Age of vessel in 2010	16	33	37	38	47	57

Marginal value product (MVP) is the additional revenue derived from one additional unit of input. As hull units are fixed in the short term and individual fishers have no direct control over the stock at any one point in time, the only input relevant for MVP estimation in the short term is hours fished. Changes in MVP due to price changes can therefore provide information on the incentives for fishers to increase or decrease their fishing effort.

Marginal value product is derived from multiplying the marginal product (the additional production from one unit increase in inputs) by the price received. As our production data have already been converted to revenue, then the MVP is the first derivative of the production frontier, given by

$$MVP_i = \frac{\partial V_i}{\partial x_i} = \frac{\partial \ln(V_i)}{\partial \ln(x_i)} \frac{V_i \cdot TE_i}{x_i} \tag{3}$$

where V_i is the value of the output from the frontier for boat i, x_i is the input level used by boat *i* for which MVP is being assessed, and TE_i is the technical efficiency of the boat. Rather than estimate the frontier level of output (V_i) then reduce this by the efficiency score, the observed value of output can be used directly.

An adjustment was also made to allow for prices change over the season. Prices generally peak in December (leading up to Christmas) and April (leading up to Easter), and are lowest during the winter months. The quarterly price information shown in Figure 8-1 is too aggregated to pick up the key monthly peaks and troughs.

Information provided by industry members was used to derive more-appropriate seasonal price changes (Figure 8-3). The weighted average of the seasonal price index over the year is 1.

As noted above, the profit-maximising condition is that MVP equals the marginal cost (MC) of fishing. An appropriate indicator therefore is MVP-MC, representing the marginal profit per hour. If this is positive, then there are incentives for fishers to try to increase their fishing effort. Conversely, if it is negative, then fishers should decrease their fishing effort.

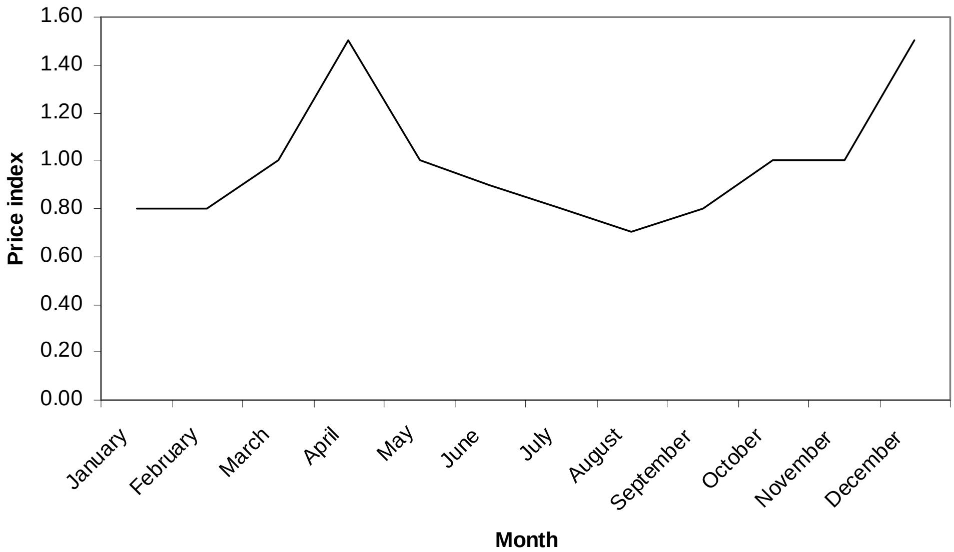

Figure 8-3. Assumed seasonal price index based in industry discussion.

Marginal cost was estimated from the survey information, assuming marginal costs are equal to average costs (a common assumption in fisheries economics data due to lack of data).[4] Average fuel and other variable costs per day were estimated for the T2 and T1/M1 fleets, and adjusted for the average number of hours fished by the vessels to produce an estimated hourly cost. As the decision to continue to fish (or not) also includes an implicit and/or explicit value of labour time, average crew cost share plus an allowance for owner-operator labour based on employed skipper shares was also included in the marginal cost calculation.

The marginal profit per hour for a boat *i* of licence type *t* was estimated as:

$$M\pi_{i\in t} = pMVP_i(1-c) - vc_t,\ t = \text{M2, T1/M1} \quad (4)$$

where *p* is the relative price index, MVP is the marginal value product for each boat (estimated in equation 3), *c* is the labour share including the value of the owner operator's labour, and *vc* is the average variable cost per hour for a vessel in each of

[4] With more individual cost data and over a longer time period, it may have been feasible to estimate cost functions which would allow better estimates of marginal cost to be made. This was not feasible with the cost data available.

the two licence types. The estimate of the marginal profit per hour excludes the fixed costs as these are effectively 'sunk' for a vessel once it is operating at any point of the year. However, over the year it would be expected that the vessel revenues should cover both fixed and variable costs for the fisher to remain economically viable.

The average marginal profit was regressed against effort levels to determine how these influenced the total fishing activity at any point in time. Both linear and log linear model formulations were examined. Month dummy variables were also included to pick up any effects not accounted for by the profitability alone.

8.3.4 Impact of change in the M2 vessel replacement policy

At the request of industry, the potential impact of a change in the M2 boat-replacement policy (to remove the 'two-for-one' licence requirement) on potential output was also examined. The key issue is whether or not a hull-unit-based capacity management system would be sufficient to constrain catch if the existing boat-replacement policy was removed.

While numerous potential outcomes exist under such a policy change, a hypothetical scenario was developed in which a group of M2 vessels increase their size to 18 hull units from the average of 14 hull units. Under this scenario, two boats must exit the fishery for every seven boats replaced. It is assumed that all the average catch of the boats that upgrade is equal to the average catch in the fleet segment. The average revenue is assumed to be equal to 1 (for simplification, but also the estimation of the models used a normalised set of variables with a mean of 1). The initial catch of the fleet is hence 9 (i.e. 7 boats that upgrade and 2 boats that exit).

The hull unit production elasticity from the production frontier was used to estimate the impact of a change in hull units on catch. The MVP analysis was then used to estimate the effects of this on per-hour profitability, and the derived impact of this on effort production. Scenarios were also considered where the new vessel was more cost efficient (variable costs were reduced by 10 and 20 per cent respectively), and a further scenario was run assuming effort response would be substantially greater than estimated using the model (i.e. effort was assumed to increase by 20 per cent).

8.4 RESULTS

8.4.1 Economic performance of the fleet

In total, 49 fishers participated in the survey; however 10 of these did not provide any economic data. A further 12 vessels did not operate in the bay in the two financial years collected (2008–09 and 2009–10). A further 10 vessels only provided cost data without revenue. Only 17 vessel owners gave complete economic data, although 7 of these vessels trawled in only one year (2008–09 or 2009–10). Logbook book data were available from which estimates of revenue could have been derived for the 10 vessels that provided only cost data. However, a comparison of logbook-based estimates and those from the survey for the vessels that provided full data suggested that logbook-based estimates were generally unreliable, particularly at the higher end (Figure 8-4). This may be due to a common price being applied to the catch in the logbooks, whereas prices received by fishers may vary considerably (with higher revenues reflecting higher average prices rather than higher catches).

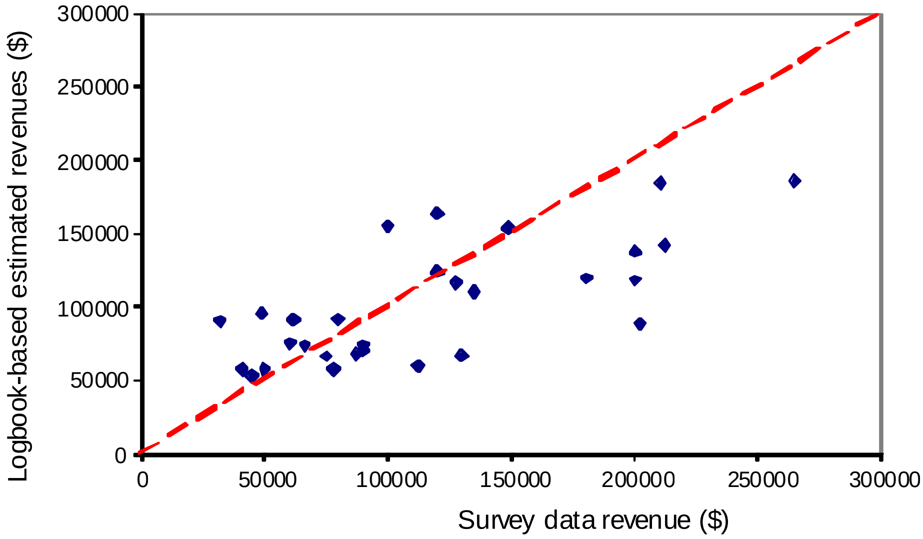

Figure 8-4. Comparison of logbook-estimated revenue and survey data over the two years of data.

The average characteristics of the vessels that participated in the survey are presented in Table 8-2, and the main economic performance indicators are given in Table 8-3. The sample was not the same in both years, with larger, on average, M2 vessels and smaller T1/M1 vessels in 2009–10 than 2008–09.

As in most fisheries (McConnell and Price 2006), crew were generally paid a share of the (gross) revenue. The share proportion ranged from 10 to 25 percent, depending on the number of crew, with an average of 17 per cent. A small number of vessels paid a wage to the crew rather than a share. While some vessels employed skippers, most were owner-operated. For consistency, skipper payments were removed from the crew cost values where they appeared. Where skippers were paid, these were paid between 20 and 35 per cent of the revenue (under a share arrangement), with an average of 26 per cent. Rather than imputing an owner-operator allowance (or skipper income), a combined cash profit and owner-operator income was estimated as this is considered a more appropriate indicator for small-vessel fleets (Boncoeur *et al.* 2000).

Table 8-2. Vessel characteristics.

	M2				T1/M1			
	2008-09		2009-10		2008-09		2009-10	
	Average	RSE	Average	RSE	Average	RSE	Average	RSE
Number of vessels	10		10		5		6	
Year built	1972	0%	1971	0%	1971	0%	1971	0%
Hull units	14	16%	14.9	15%	25.4	3%	21.5	13%
Value of licence & symbol	$89,000	12%	$90,444	12%	$163,360	38%	$139,466	40%
Replacement value of boat	$126,000	25%	$151,111	20%	$291,000	8%	$210,833	26%
Effort (days fished)	135	20%	134	19%	129	35%	177	17%

RSE is the relative standard error.

From the survey, cash profits were, on average, positive for both fleet segments in both years of the survey. However, after the opportunity cost of capital and depreciation were taken into account, the residual owner-operator income was relatively low, and substantially lower than the average 26 per cent of revenue paid to employed skippers. Consequently, owner-operators were earning less than their opportunity cost of their labour, suggesting that the fleet were economically unviable in the longer term.

Table 8-3. Economic performance indicators.

	M2				T1/M1			
	2008-09		2009-10		2008-09		2009-10	
	Average	RSE	Average	RSE	Average	RSE	Average	RSE
Revenue	$96,738	19%	$101,337	24%	$146,888	16%	$130,618	15%
Fuel	$38,012	19%	$32,220	20%	$49,326	23%	$47,664	10%
Crew (excluding skipper)	$13,306	23%	$16,016	21%	$17,115	13%	$16,628	16%
Other variable costs	$7,267	26%	$6,486	21%	$9,359	29%	$14,995	32%
Repairs/maintenance	$6,484	35%	$15,843	28%	$30,740	29%	$22,363	29%
Fixed costs	$7,578	18%	$10,485	19%	$13,684	16%	$11,803	9%
Cash profit	$24,091	46%	$20,287	92%	$26,664	74%	$19,116	104%
Derived non-cash costs								
• Depreciation (2%)	$2,520		$3,022		$5,820		$4,217	
• Normal return to capital (5%)	$6,300		$7,556		$14,550		$10,542	
Owner-operator return	$15,271		$9,709		$6,294		$2,406	

RSE is the relative standard error.

Variability (indicated by the relative standard errors) around the average cash costs was high. While on average cash profits were relatively low, a number of fishers were earning substantially higher profits, while others were earning negative cash profits (Figure 8-5). Twenty percent of boats in 2008–09 and 38% in 2009–10 were earning negative cash profits.

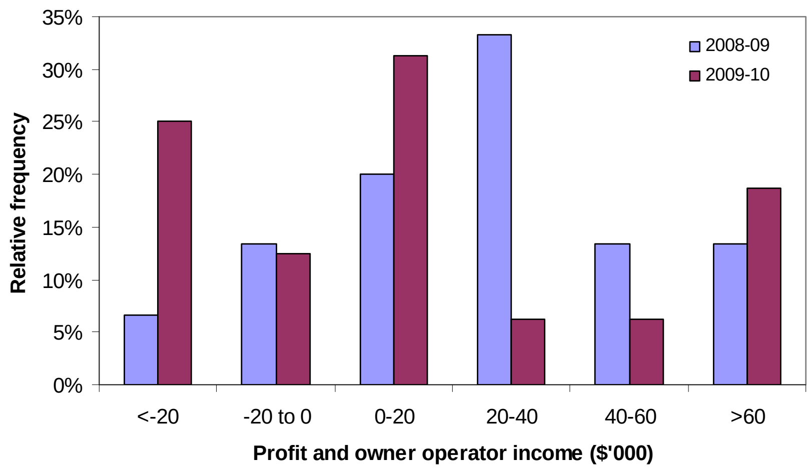

Figure 8-5. Distribution of cash profits (including the owner-operator income).

8.4.2 Distribution and drivers of technical efficiency in the fleet

Several variants of the model were estimated as a translog production frontier and compared based on the log likelihood value. Engine power, headrope length and hull units were all highly correlated, causing problems of multicollinearity in the model if all applied simultaneously. The best model was that which included only hull units and hours fished in the main interaction part of the model, with crowding and the stock index as shift variables (Table 8-4). As all of the individual vessel dummy variables in the inefficiency model were not significant, the model was also estimated excluding these variables. While the restricted model was not significantly different to the base model (χ_{34DF}=31.43), the restricted model did not satisfy the convexity conditions that are usually required for a translog production frontier, so the base model was considered the more appropriate. Finally, both models were also tested for the presence of inefficiency, which was found to be significant in all cases.

Table 8-4. Maximum-likelihood results for the production frontiers.

	Baseline model			**Without boat dummy variables**		
	Estimate	**Std. Error**		**Estimate**	**Std. Error**	
Production frontier						
Constant	0.423	0.076	***	0.421	0.066	***
Ln(Hull units)	0.387	0.039	***	0.415	0.037	***
Ln(Hours)	1.051	0.026	***	1.048	0.026	***
Ln2(Hull units)	0.114	0.150		0.257	0.145	.
Ln(Hull)*Ln(Hours)	-0.099	0.044	*	-0.099	0.044	*
Ln2(Hours)	0.044	0.033		0.042	0.032	
Ln(Stock)	0.973	0.052	***	0.975	0.052	***
Ln(Crowd)	-0.022	0.028		-0.022	0.029	
Inefficiency model						
Constant	-0.243	0.661		-0.357	0.661	
Ln(vessel age in 2010)	0.081	0.112		0.083	0.119	
Ln(years as skipper)	0.246	0.086	**	0.249	0.083	**
Ln(generations of fishers)	-0.158	0.072	*	-0.143	0.072	*
Ln(years of school)	-0.172	0.058	**	-0.155	0.052	**
Model diagnostics						
σ^2	0.263	0.052	***	0.258	0.057	**
γ	0.661	0.051	***	0.698	0.068	***
Log likelihood	-518.404			-534.123		
Mean efficiency	0.671			0.664		
Motonicity						
Hull units	100%			100%		
Hours	100%			100%		
Convexity	100%			90%		

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1 a) the 34 individual vessel dummy variable coefficients in the inefficiency model are not reported to save space. None were individually significant.

From the model, the parameter relating to hours was not statistically significant from 1, suggesting constant catch per unit of effort over a month. The parameter values in the Cobb-Douglas function form directly represent the production elasticities. That is, the percentage change in output given a one per cent change in input. A value of 1 indicates that a one per cent increase in hours fished would lead to a 1 per cent increase in catch (or, in this case, revenue). Similarly, the stock parameter was also not significantly different from 1, a necessary condition if the 'stock' measure (average revenue per unit effort in each month) was to be considered a reasonable stock indicator. The effect of boat numbers operating each month was negative, as would be expected if crowding was affecting catch rates, although this value was not statistically significant. Given that the stock indicator was based on observed catch per unit effort, then crowding effects may already have been captured in this. The production elasticity for hull units was 0.39, indicating that a one percent increase in hull units results in a substantially less than proportional increase in catch.

The mean efficiency for the fleet as a whole was estimated to be 0.67. That is, on average, the boats were catching only 67 per cent of what was possible given their level of inputs (hours fished and hull units). However, the average values are biased downwards by the presence of a number of observations with relatively low efficiency scores (Figure 8-6). From Figure 8-6, almost one-quarter of observations had efficiency scores above 0.8, suggesting a substantial proportion of the fleet are relatively efficient, but some are also relatively inefficient. The distribution for M2 and T1/M1 boats separately is illustrated in Figure 8-7. Both groups had similar distributions, with median technical efficiency score of 0.71 and 0.67 for the M2 and T1/M1 boats respectively. These scores are reasonably consistent with other studies of prawn trawl fleets in Australia. For example, median efficiency in the Commonwealth northern prawn fishery fleet has been estimated to be around 0.77 to 0.79 (Kompas *et al.* 2004; Pascoe *et al.* 2010a), although higher average efficiency scores (around 0.9) have been found in the NSW prawn trawl fleet (Greenville *et al.* 2006).

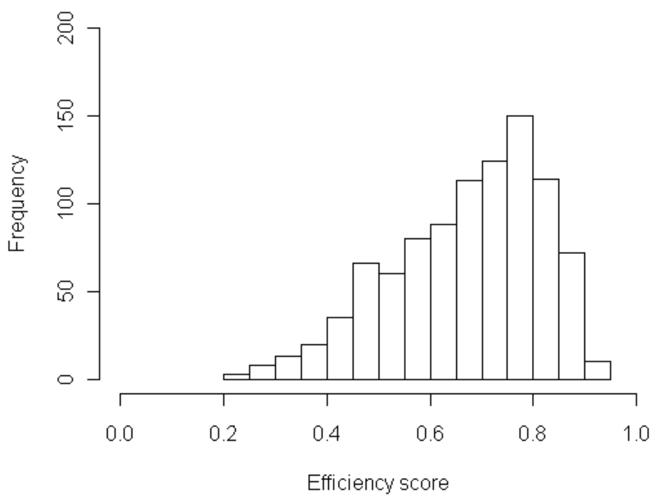

Figure 8-6. Overall distribution of technical efficiency.

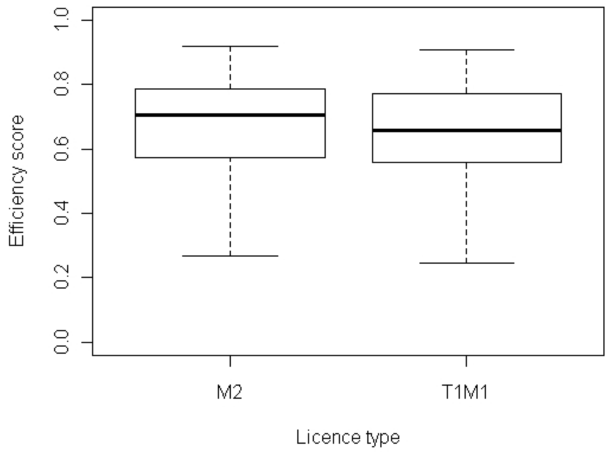

Figure 8-7. Distribution of technical efficiency by licence type.

The distribution of the efficiency scores over the year is illustrated in Figure 8-8. The median efficiency score was relatively constant over the year, although increased slightly during August.

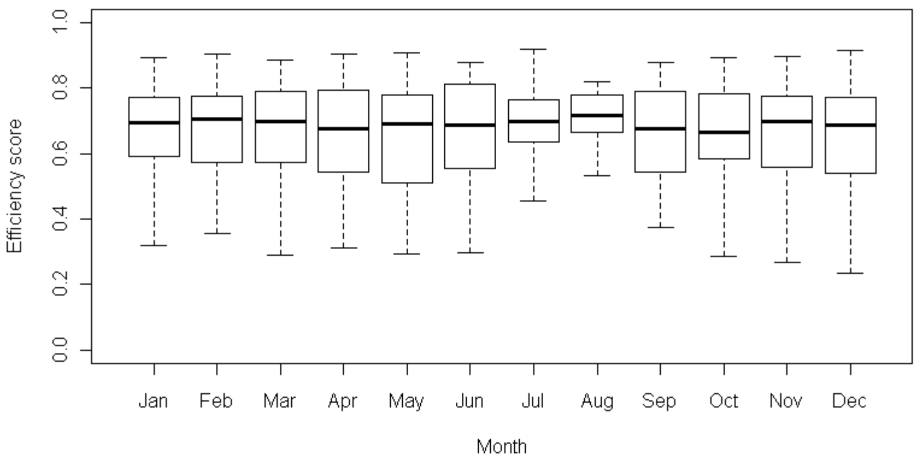

Figure 8-8. Distribution of technical efficiency over the year.

From the inefficiency model, several factors were found to significantly influence vessel efficiency. These included the number of years of experience as skipper, the number of generations that the skipper's family had been fishing and the number of years schooling. As this is an inefficiency model (rather than efficiency model), a negative sign indicates a decrease in inefficiency, which in turn indicates an increase in efficiency. Hence, skippers with more schooling were significantly more efficient than skippers with lower levels of schooling, consistent with other studies (Coglan and Pascoe 2007; Sharma and Leung 1999; Tingley *et al.* 2005). Skipper experience had a positive sign, suggesting that skippers who had been fishing longer were, in fact, less efficient than newer skippers. However, this was mitigated in the case of skippers whose family had been involved in fishing for several generations, consistent with other studies (Coglan and Pascoe 2007; Tingley *et al.* 2005) and suggesting that skill was passed through by families over successive generations.

8.4.3 Relationship between marginal value product and effort production

The distribution of the marginal profit per hour between the two main licence types and over the year is shown in Figure 8-9. For most vessels in both fleets, the marginal profit per hour was above zero. Over the year, the marginal profit per hour was positive during the late summer and autumn months, but the median value was zero (or close to zero) over the winter and spring months.

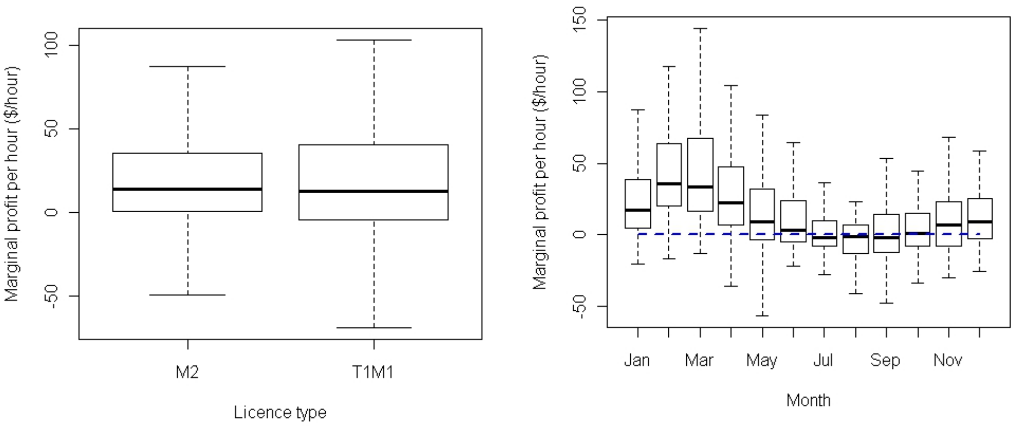

Figure 8-9. Distribution of the marginal profit per hour: a) for each licence type; and b) over the year.

A potential difficulty arising by using the observed data for the analysis is that participation decreases in the winter months and the potential exists for only the most efficient boats to remain, possibly distorting the MVP estimate. From Figure 8-8, there were fewer boats with low efficiency scores during the winter months, as might be expected given that their MVP would be lowest also during this period and lower than that of their more efficient counterparts. Given this, it is likely that the average MVP for the winter months is slightly overestimated relative to what might have been observed if all boats were operating.

The results of the two regression models of fishing effort against the marginal profit per hour are presented in Table 8-5. Both models performed reasonably well, with the $\overline{R}^2$ representing the amount of variation explained by the models. While the linear model appeared the better model based on the $\overline{R}^2$, this is not a valid comparison as the models have different dependent variables (one logged and the other not logged). A better comparator is the square root of the mean square error (SMSE) expressed as a percentage of the mean total effort. On this criterion, both models performed very similarly. The estimated level of effort from each model is also shown with the actual effort over the period of the data in Figure 8-10.

In most cases, the month dummy variables were not significant, suggesting that profitability is the main driver of effort in these months. For the winter months, there was a significant effect. This may reflect the 'self-selection' bias in the data as more efficient (and more profitable) boats tended to operate in these months, so a lower level of effort might be expected if profitability could be observed for all vessels (not just those who fished).

Table 8-5. Estimated fishing effort models.

	Linear model		**Log linear model**	
	Estimate	**Std. Error**	**Estimate**	**Std. Error**
Intercept	1810.90	179.37***	7.39	0.29 ***
Average profitability	26.18	3.98***	0.13	0.04 **
Month dummy variables				
• January	106.82	236.32	0.02	0.40
• February	-427.43	260.84	-0.05	0.40
• March	-126.11	252.94	0.02	0.40
• April	-239.78	236.93	-0.17	0.40
• May	-564.65	233.76*	-0.37	0.40
• June	-1215.59	237.44***	-1.36	0.40 ***
• July	-1430.31	245.57***	-2.00	0.43 ***
• August	-1515.77	246.57***	-2.12	0.43 ***
• September	-1079.49	241.37***	-0.73	0.41 .
• October	-251.28	237.05	-0.08	0.40
• November	85.45	234.80	-0.01	0.40
Model diagnostics				
$\bar{R}^2$	0.84		0.67	
F	32.68	***	13.34	***
SMSE(%)	22%		24%	

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

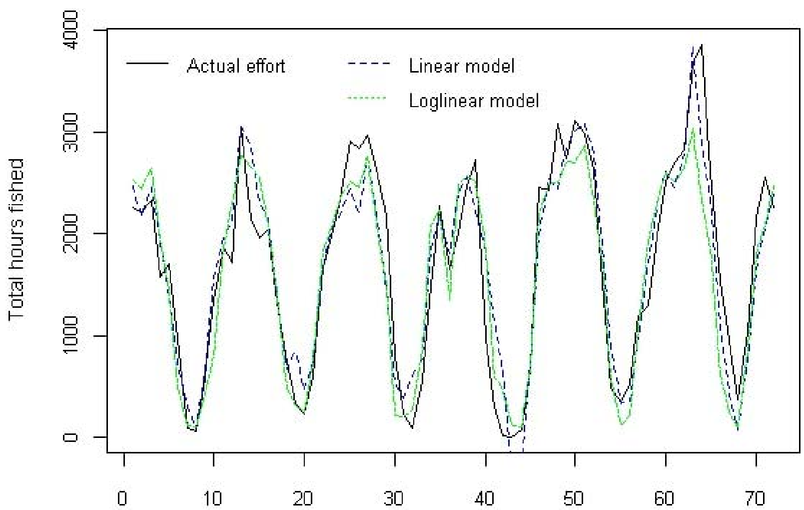

Figure 8-10. Actual and estimated fishing effort over the 72-month period of the data.

The linear model suggests that each additional dollar of average profits per hour in the fishery increases effort by around 26 hours each month. From the log linear model, each percentage increase in profits per hour increases total fishing effort by 0.13 per cent. This equates to around 2 hours a month per vessel on average, although most of the effort changes in the past have been supplied by vessels becoming either active in the fishery (i.e. T1/M1 entering the fishery or M2s not active starting to fish), or inactive (e.g. T1/M1 move to the ECTF) when profitability decreases.

At the individual vessel level, only a linear model could be reliably estimated given the existence of negative marginal profit estimates. Vessel size (hull units), seasonality and licence type (representing the potential for opportunities elsewhere) were also considered in the model as these are also likely to influence the level of effort expended by a vessel in any given month. From the regression results, each hull unit added an additional hour to the average number of hours fished, while T1/M1 vessels fished, on average, around 60 hours a month less than the M2 vessels (Table 8-6). Each dollar increase in vessel marginal profits per hour also increased the number of hours by almost 1. However, the significant negative interaction terms between profitability and hull size suggest that this increase with profitability decreases with vessel size. Overall, the model was able to explain only around 22 per cent of the variation in individual vessel effort production.

Table 8-6. Estimated vessel level fishing effort model.

	Estimate	**Std. Error**
Intercept	137.09	9.49***
Marginal profitability per hour	0.94	0.21***
Hull units	1.08	0.48*
T1/M1 dummy	-60.44	16.76***
Hull*profitability	-0.03	0.01***
Hull*T1/M1	1.04	0.82
Profitability*T1/M1	-1.29	0.44**
Hull*profitability*T1/M1	0.065	0.02**
Month dummy variables		
• February	-9.92	8.55
• March	-2.06	8.50
• April	-16.15	8.53.
• May	-40.72	8.78***
• June	-62.00	10.31***
• July	-65.95	13.30***
• August	-83.74	13.97***
• September	-59.54	10.27***
• October	-19.03	9.08*
• November	-4.06	8.78
• December	22.24	8.37*
Model diagnostics		
$\overline{R}^2$	0.218	
F	15.82	***

Significance codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

8.4.4 Impact of a change in the M2 vessel replacement policy on fishing effort

Assuming initially that the new boats do not expend any more effort than the original vessels, then the increase in revenue from the increase in hull units can be derived from the hull unit elasticity in Table 8-4 (i.e. 0.387). An increase from 14 to 18 units is an increase of 28 per cent. Given the hull unit elasticity, this is likely to result in an 11 per cent increase in revenue each month (Table 8-7). The total catch of the fleet segment is 7.77 (i.e. 7 times 1.11), less than the total catch of the original group (i.e., 9).

Table 8-7. Simulated changes in catch due to increasing hull units from 14 to 18 on average for M2 vessels.

	current	Base assumptions	Lower running costs 10%	Lower running costs 20%	20% effort increase
Initial catch change		11%	11%	11%	11%
MVP ($/hour)	80.5	89.3	89.1	89.1	
Variable cost per hour ($)	26.9	26.9	24.2	21.5	
Profit per hour ($)	23.8	29.4	31.9	34.6	
Increase profit per hour		24%	34%	46%	
Induced effort increase					20%
• Profit induced		4%	6%	8%	
• Hull unit ‘induced’		3%	3%	3%	
Total (individual) catch change		19%	21%	23%	33%
Group catch change		-8%	-6%	-4%	4%

Effort is likely to increase as the MVP of the vessels would also be higher than in the initial analysis (Table 8-7). The percentage MVP increase will be equivalent to the percentage revenue increase, but the percentage profit increase will be greater than the percentage revenue increase as costs per hour do not vary. From the data, a 10 per cent increase in revenue due to the use of a greater number of hull units results in an average increase in profit per hour of 24 per cent for the M2 fleet segment. From the model results in Table 8-6, this is expected to lead to an increase in effort of 4 per cent for each vessel, while the larger hull itself is likely to result in an increase in effort of around 3%.[5] With an effort elasticity of revenue (catch) of 1.05 from Table 8-4, this in turn is likely to lead to a further 8 per cent increase in revenue (catch). Taking this into consideration also, the catch of the remaining 9 boats is likely to be roughly equivalent to 8 of the original boats, but less than the catch of the whole 9 original boats.

[5] This is likely to produce an overestimate of the effort response, as we ignore the negative interaction term between hull units and profitability.

A range of other scenarios are also possible.[6] From the inefficiency model, there is not likely to be any technical efficiency increase through introducing new boats. However, there may be other economic efficiencies in terms of lower costs of fishing. The above analysis was also conducted assuming that variable costs in the new boats were 10 or 20 per cent lower than the existing boats. In both instances, the overall group catch was less than the original catch due to the removal of two vessels to allow the remaining 7 to increase. Finally, the induced effort response component was ignored and it was assumed that fishing effort of the new boats would increase by 20 per cent (effectively an extra day a week). In this case, the smaller group of new boats could potentially take more than the original set of boats, although this increase is still relatively small and requires a level of response beyond that observed in the data.

A caveat to this analysis is that the assumption is made that active boats are removed, and that the boats removed were also taking the average level of catch. In the above example, if two inactive boats (rather than active boats) are removed, then the increase in catch of the group will be equal to the change in individual catch. That is, catch for the group could increase by between 14 and 17 per cent based on the degree to which costs are reduced with the new boats.[7]

The analysis also considered one main scenario, namely, upgrading from 14 to 18 hull units. Individuals could potentially upgrade to a higher number of units, although this would also require the removal of more vessels to allow a substantial number of vessels to upgrade. As the relationship between hull units and catch is substantially less than 1 (i.e. 0.377), upgrading to a larger number of units will result in a less than proportional increase in catch. Consequently, it is likely that the overall changes in catches would not be too dissimilar to those in the scenarios considered.

8.5 DISCUSSION

The Moreton Bay prawn trawl fleet is, on average, operating at an economically unsustainable level in the longer term as owner-operator incomes are below their opportunity cost levels. This is largely due to the decline in prawn prices over recent years, due in turn to the increased imports of prawns as well as the shift of other major prawn fisheries from the export to the domestic market. Managers are unable to control this factor directly, but can ensure that the conditions under which the fishers operate allow them to optimise their own returns.

The average level of technical efficiency in the fishery is comparable with that in other prawn fisheries in Australia. The only factor that was found to have a significant impact on efficiency in the fishery was the education level of the skipper, with higher levels of schooling being related to higher technical efficiency. The age of the skipper appeared to have some impact on the level of efficiency (with older

[6] For example, the analysis was also undertaken assuming the vessels doubled in size (i.e. 14 to 28 hull units) such that the fleet halved in size. Individual catches increased by around 73% once the profit and hull-induced effort increases were also factored in, but the overall group catch was still 14% lower than the pre-adjustment fleet.

[7] Again, this increase is for the group that adjusts, so averaged over the whole fleet this increase may be relative small. The overall increase will depend on the proportion of the fleet that upgrades. At most, only half the vessels could potentially upgrade, and relatively few inactive vessels are available, so potential catch increases are likely to be low, even in pessimistic scenarios.

skippers being less efficient than younger fishers), although this was not statistically significant. Nearly all boats in the data had similar levels of technology so the effects of technology on efficiency could not be determined.

The level of fishing effort expended in any given month was largely dependent on the average profitability per hour in that month. This suggests that the fishery is very much driven by economic incentives, with the observed low levels of fishing effort in the winter months consistent with profit-maximising behaviour. The decline in fishing effort over the last two decades, corresponding to price declines, is further evidence that the fishery is driven by economic incentives (i.e. responds to changes in prices).

Industry members with M2 licences have requested that the existing boat-replacement policy of a 'two-for-one' licence surrender be removed, with hull units being the main constraining capacity management option. A concern by managers is that this may lead to a substantial increase in fishing effort in the fishery as the number of days is relatively unconstrained.[8] The analysis suggests that, if active vessels are removed through selling their hull units to other fishers, then the overall net change in catch is likely to be negative (although the profitability to the individuals remaining is likely to improve), or at most relatively small (if extreme assumptions about effort increases are made). However, if inactive vessels are 'removed' from the fishery, then there is likely to be a net increase in catch.

[8] There is an overall constraint on the number of days fished being 5 nights a week for 52 weeks (i.e. 260 days), although vessels are operating well within this constraint.

9 Quantify long-term changes to fishing power in the Moreton Bay trawl fishery (Objective 4)

By M. Kienzle, M. O'Neill, D. Sterling, J. Larkin and M. Landers

9.1 ABSTRACT

An analysis of logbook and vessel survey data, collected between 1988 and 2010, was performed to estimate the variation of fishing power and abundance of three prawn species caught in Moreton Bay (Brown Tiger Prawn, *Penaeus esculentus*; Eastern King Prawn, *Melicertus plebejus*; Greasyback Prawn, *Metapenaeus bennettae*). Generalised Linear Models were used to explain the variation of catch as a function of effort, vessel and gear characteristics, onboard technologies, population abundance and environmental factors. This analysis estimated that fishing power on Brown Tiger and Eastern King Prawns has increased over the past 20 years by 10–30% and declined by approximately 10% for greasybacks. Abundance of all three species was estimated to have remained constant or increased during that period.

9.2 INTRODUCTION

In many commercial fisheries, stock abundance is assessed using catch and effort data. The ratio of catch over effort (i.e., catch per unit of effort, CPUE) is not considered to provide a reliable index of abundance as it is often more stable than abundance because catchability of the targeted species tends to improve over time while the effort used to locate and exploit it decreases as improvements in fishing technology are adopted (Harley *et al.* 2001). Providing information that quantifies technological changes in a fleet exists, CPUE can be adjusted over long time periods for factors other than abundance (Maunder and Punt 2004). This change in the fleet's fishing ability is often referred to as fishing power—a relative measure of the variation over time of the ability of a fleet to catch fish. Generalised Linear Modelling (GLM) provides a statistical method that is suitable for estimating both: (a) an index of abundance; and (b) a fishing power time-series using commercial catch and effort data (Venables and Dichmont 2004).

In many instances, the quality of commercial data is considered to be poor by fishers and scientists alike, and their analyses are often thought to lead to an unrealistic representation of stock abundance (Petitgas *et al.* 2009). Therefore, part of the scientific community has developed and implemented fishery-independent methods to estimate fish population abundance (Simmonds and MacLennan 2005), pushing this approach to the extent whereby stock assessments may exclude fishery data altogether (Petitgas *et al.* 2009). For benthic species, scientific surveys are often performed using a trawl whose dimensions and speed are carefully monitored in order to determine the area swept, allowing for the calculation of a density for each species present in an area (Quinn and Deriso 1999).

This swept area approach was applied to standardise logbook records for the Moreton Bay otter trawl fishery between 1988 and 2010. The fishing fleet was surveyed (Appendix 3 section 22) to collect vessel and gear measurements required to estimate a swept area rate (SAR) for each vessel. A GLM was applied to individual catch from three prawn species as a function of changes in technology, SAR and effort. The problem of multicollinearity between covariates, which is often encountered in such analyses of catch and effort data, was explicitly dealt with. The resulting estimates of density were validated with abundance indices collected using a fishery-independent survey of the Moreton Bay (DPI&F 2006) (see section 6.5.1 for further details).

9.3 MATERIALS AND METHODS

9.3.1 Data

9.3.1.1 Logbooks

Trawler operators in Moreton Bay use a relatively large number of categories to record their prawn catches. Logbook data show that from 1988–2010, 20 categories were used, with 98% of total prawn landings represented by eight categories which were associated with a particular species or a mixture of species (Table 9-1). Catches were negligible for about half of the categories. The most abundant species (i.e., Brown Tiger Prawn, *Penaeus esculentus;* Eastern King Prawn, *Melicertus plebejus* and Greasyback Prawn, *Metapenaeus bennettae*) were considered for further analysis.

Table 9-1. Percentage of prawn catch reported from 1988 to 2010 in the logbook database by commercial categories and species.

Commercial category	Percentage of catch	Common name
‘Prawn - bay’	37	Greasyback
‘Prawn - tiger’	24	Brown Tiger
‘Prawn - king’	17	Eastern King
‘Prawn - unspecified’	5	mixture
‘Prawn - banana’	5	Banana
‘Prawn - eastern king’	4	Eastern King
‘Prawn - greasy’	4	Greasyback
‘Prawn - endeavour’	2	Endeavour
‘Prawn - blue leg king’	< 1	not used
‘Prawn - coral’	< 1	not used
‘Prawn - red spot & blue leg k’	< 1	not used
‘Prawn - clicker’	< 1	not used
‘Prawn - school’	< 1	not used
‘Prawn - mixed bait’	< 1	mixture
‘Prawn - hardback’	< 1	not used
‘Prawn - red spot king’	< 1	not used
‘Greasy and school prawn’	< 1	mixture
‘Prawn - leader’	< 1	not used
‘Prawn - Japanese king’	< 1	not used
‘Prawn - scarlet’	< 1	not used

9.3.1.2 Vessel survey

In the 1990s and 2000s, Queensland trawler operators in the main trawl fishery sectors (i.e., North Queensland Tiger/Endeavour prawn, scallop and Eastern King Prawn sectors) were surveyed to determine the types of fishing nets and onboard equipment that have been adopted over time and how these affect the fleet’s fishing power (O'Neill *et al.* 2005; O'Neill and Leigh 2007). As only very few Moreton Bay vessels were included in these earlier surveys, another survey was undertaken in late

2010 and early 2011 of the entire Moreton Bay fleet (see section 22 Appendix 3, and Table 9-2).

The number of nets, total head-rope length, mesh size, type and size of the otter-boards, steaming speed, engine power, propeller diameter, presence/absence of kort nozzle, maximum trawling speed and fishing operation revolution per minute were combined using the Prawn Trawl Prediction Model (PTPM) (Sterling 2005) to estimate a swept area rate (SAR, in hectares per hours) for each vessel/net configuration available (134 in total). The PTPM mathematically describes the physics of multi-net trawl system used in Australian prawn fisheries and predicts the swept area performance and operating dimensions of the fishing gear. This model is currently used to assess other prawn trawl fisheries in Australia (Bishop *et al.* 2008). Swept area rate was estimated using the number of nets, the total head-rope length, the dimension (height and length) and types of otter-boards, mesh size, steaming speed, rated horse power, the maximum revolution per minutes (RPM) of the engine while trawling, the rated RPM, the operational RPM, the propeller diameter and the presence of a kort nozzle. SARs multiplied by the number of hours trawled reported in the logbook provided an estimated area swept (SA, in hectares) during each specific fishing event to be used in the analysis of catch per unit of effort described in the following section.

Table 9-2. Summary of the dataset used for fishing power analysis. Numbers represent the number of boat-days when the combination of licence holder and vessel had the technology on board. For example, in 2010, of the 1789 boat-days represented in the survey sample data, 37 had no radar and 1752 had radar. 0= technology absent, 1=technology present.

	No. of record	No. of vessels	radar(0)	radar(1)	satnav(0)	satnav(1)	GPS(0)	GPS(1)	DGPS(0)	DGPS(1)	plotter(0)	plotter(1)	autopilot(0)	autopilot(1)	GPS Coupled autopilot(0)	GPS Coupled autopilot(1)	GPS Coupled radar(0)	GPS Coupled radar(1)	Computer mapping(0)	Computer mapping(1)
1988	32	2	0	32	32	0	32	0	32	0	32	0	0	32	32	0	32	0	32	0
1989	111	2	0	111	111	0	111	0	111	0	111	0	0	111	111	0	111	0	111	0
1990	94	3	0	94	94	0	94	0	94	0	94	0	0	94	94	0	94	0	94	0
1991	90	2	0	90	90	0	90	0	90	0	90	0	0	90	90	0	90	0	90	0
1992	58	2	0	58	58	0	58	0	58	0	58	0	0	58	58	0	58	0	58	0
1993	52	2	0	52	52	0	52	0	52	0	52	0	0	52	52	0	52	0	52	0
1994	24	2	0	24	24	0	24	0	24	0	24	0	0	24	24	0	24	0	24	0
1995	132	3	0	132	132	0	36	96	132	0	36	96	0	132	132	0	132	0	132	0
1996	241	6	0	241	241	0	45	196	241	0	11	230	0	241	192	49	227	14	206	35
1997	298	7	0	298	298	0	38	260	298	0	4	294	0	298	202	96	256	42	244	54
1998	474	9	0	474	474	0	18	456	474	0	0	474	0	474	254	220	394	80	325	149
1999	797	19	10	787	797	0	43	754	786	11	10	787	46	751	566	231	769	28	496	301
2000	933	20	0	933	933	0	150	783	923	10	37	896	207	726	657	276	892	41	520	413
2001	1188	20	0	1188	1175	13	178	1010	1175	13	151	1037	175	1013	875	313	1105	83	688	500
2002	1256	21	0	1256	1223	33	285	971	1171	85	217	1039	188	1068	857	399	1183	73	739	517
2003	1465	25	0	1465	1444	21	254	1211	1363	102	317	1148	191	1274	891	574	1378	87	754	711
2004	1122	26	0	1122	992	130	62	1060	1051	71	275	847	187	935	640	482	1055	67	581	541
2005	1218	17	0	1218	1033	185	61	1157	1076	142	316	902	218	1000	634	584	1146	72	541	677
2006	1035	17	0	1035	875	160	144	891	928	107	285	750	288	747	581	454	994	41	493	542
2007	1124	18	42	1082	936	188	136	988	1048	76	216	908	208	916	738	386	1124	0	468	656
2008	1148	19	0	1148	994	154	74	1074	1048	100	159	989	148	1000	767	381	1148	0	551	597
2009	1502	26	1	1501	1335	167	188	1314	1403	99	342	1160	190	1312	1223	279	1502	0	778	724
2010	1789	33	37	1752	1571	218	218	1571	1682	107	332	1457	153	1636	1294	495	1789	0	791	998

9.3.2 Statistical analyses

9.3.2.1 Model of catch and effort

In fisheries, catch (*C*, in units of mass) of a given species is often found to vary according to the product of its abundance (*N*), effort involved in fishing activity (*E*), and fishers' capacity to capture that particular species (referred to as catchability, *q*) (Hilborn and Walters 1992):

$$C = q\ N\ E$$

This model was used to analyse catch and effort data from the Moreton Bay prawn trawl fishery using the swept area approach (Quinn and Deriso 1999) which related catch (C, in kg) caught per vessel per day[9] to the product of effort (E, in hours); catchability represented by the product of swept area rate (S, in ha/hr); several binary variables representing presence/absence of particular technologies (T_i, dimensionless) and lunar phase (L, expressed in percentage of full-moon, dimensionless); and abundance in year *y* and month *m* ($N_{y,m}$). An analysis of the physical dimension of variables involved in this equation showed that abundance was expressed in kg/ha.

$$C_j = L_j \times \prod_i T_{i,j} \times S_j \times N_{y,m} \times E_j$$, where j denotes a particular logbook record.

Inclusion of 8 devices (T_i, $1 \le i \le 8$) that potentially affected prawn catchability was considered: colour echo-sounder, satellite navigation (satnav), global positioning system (GPS), plotter, auto-pilot, GPS coupled with autopilot, bycatch reduction devices (BRD) and turtle excluding devices (TED). Moreover, an attempt was made to capture a 'vessel effect' using an identifier for each vessel.

Multicollinearity occurs when two explanatory variables are correlated and there is no way to distinguish their effects separately (Graham 2003). It results in individual parameter estimates that vary erratically when: (a) the number of covariates in the model changes; and/or (b) the size of the dataset changes. Collinear variables in our dataset were identified and treated using a method inspired by Legendre and Legendre's (1998) approach to multiple regression and variance partitioning: first, explanatory variables were taken in pairs and regressed one against the other to calculate how much of each variability (R^2) was explained by the other; second, above the threshold value of 5%, only one variable was chosen to be included as a covariate in the catch per unit of effort model.

The parameters of catch per unit of effort model (β) were estimated using both a linear regression on log-transform values of catch and effort using the linear regression or a generalised linear model (GLM) assuming the distribution of catch was represented by the quasi family with log-link function and variance proportional to the mean or the square of the mean (Venables and Ripley 1999).

[9] Catch by a vessel in a given day reported in the logbook is often referred to as a fishing event later in the text.

$$\log(C_j) = \beta_1 L_j + \underbrace{\beta_2 + \ldots + \beta_{2+i}}_{\text{a coefficient of each technology } T_{i,j}} + \underbrace{\beta_{2+i+1}}_{\substack{\text{Density estimate} \\ \text{in year } y \text{ and month } m}} + \beta_{2+i+2} \times \log(S_j \times E_j)$$

All statistical analyses were coded in R (2005) and are available upon M. Kienzle.

To evaluate the effect of technological changes on CPUE over the period 1988–2010, the average catch per hour trawled was calculated using the linear model of CPUE with a fixed value of abundance. The estimates of the variation of fishing power through time were expressed relative to the value at the beginning of the time-series. Standard error on fishing power estimates were obtained by propagating the uncertainties of the GLM predictions (Bevington and Robinson 2003).

9.3.2.2 Targeting

Analysis of catch per unit of effort using linear models assumes a linear relationship between catch and effort on the log-scale where catch increases as a function of effort. In multispecies fisheries such as the Moreton Bay fishery, the fleet exploits different species opportunistically through the year as they become available. An indiscriminate analysis of catch as a function of effort will certainly include fishing events (*i.e.* logbook records) with very low catch rates, not because this particular species was present at low abundances in these particular conditions but because it was not targeted. Therefore, a rule that determines which logbook record was targeted at which species was developed to reduce ‘noise’ in the fishing power analysis.

We assumed that during fishing events, non-target species are caught at random or are present on the fishing ground together with the target species but at a lower abundance. In the former case, catches of a species during fishing events not targeted at it will not be related to fishing effort, while in the second case, the linear relationship that might exist between catch and effort (on the log-scale) will depict lower catch rates than those from targeted species (Figure 9-1).

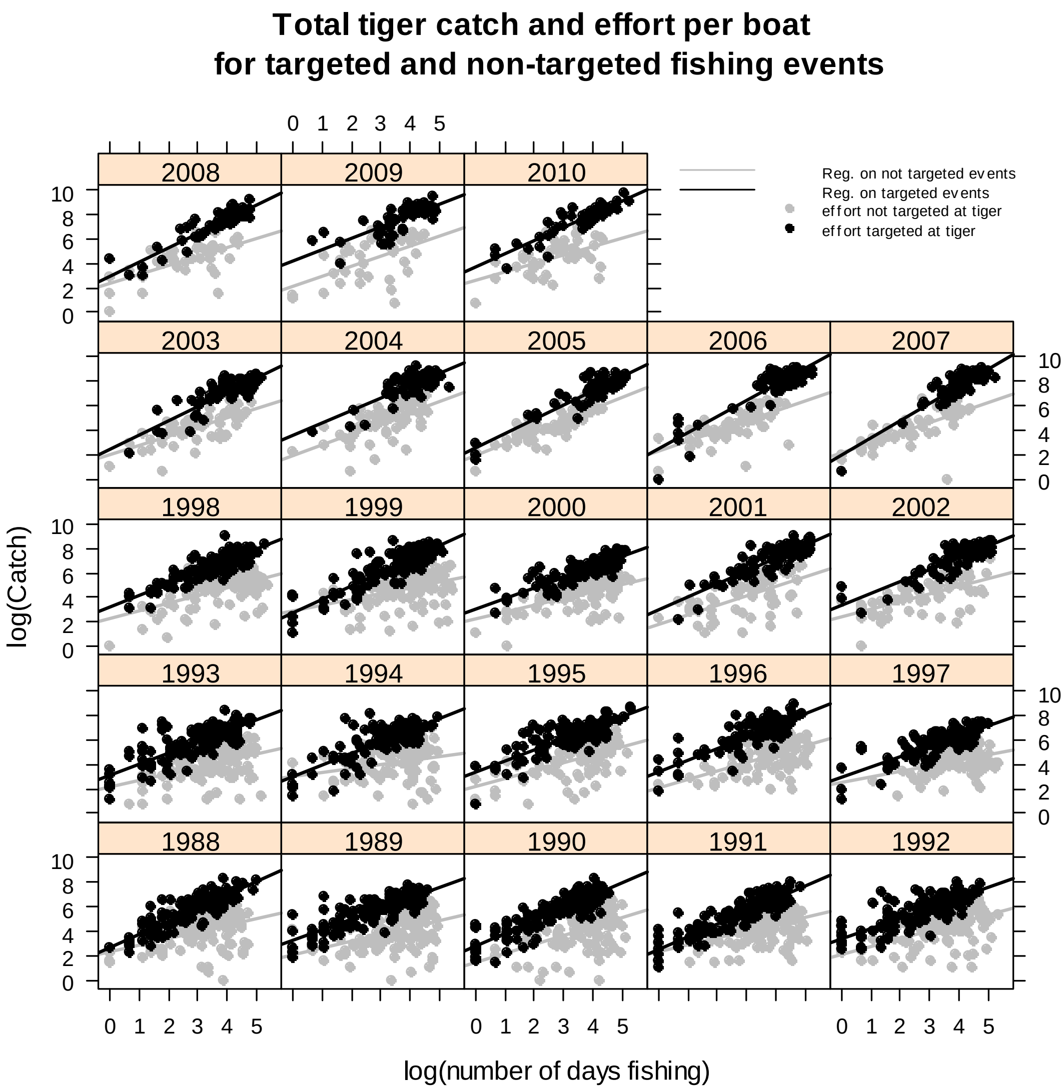

Figure 9-1. Relationship between total Brown Tiger Prawn catch and effort (on the log-scale) by boat and year for fishing events targeted at Brown Tiger Prawn or not.

Several rules were defined to decide whether each fishing event was targeted at a particular species or not. Since we assumed that both targeted and non-targeted catch were linearly related to effort on the log-scale, the residual sum of square of an analysis of covariance (ANCOVA) was used to determine which rule provided the best data to fit this model.

9.4 RESULTS

9.4.1 Allocating targeted effort

Several rules were applied to logbook records to determine which fishing events were targeted at Brown Tiger Prawns. These rules were compared using the residual sum of square of an ANCOVA (Table 9-3, Table 9-4 and Figure 9-1) to determine which explained the largest portion of the variability observed. For example, the ANCOVA sum of the squares was minimised (i.e., indicating the best model for defining tiger prawn effort) when logbook records reported that tiger prawns made up 20% or more of the fisher's daily catch (Figure 9-4).

Table 9-3. Example of ANCOVA applied to assess the effect of applying a targeting rule to each logbook record.

	Df	Sum Sq	Mean Sq	F value	Pr(> F)
target:Year	46	200548.4	4359.75	6500.73	0.000
target:Year:log(SAR * hourstrawled)	46	1905.88	41.43	61.78	0.000
Residuals	25626	17186.21	0.67		

Table 9-4. Comparison of the residual sum of squares of ANCOVAs applied to the Brown Tiger Prawn logbook catch. Several definitions of targeted effort were considered, based on the proportion of the fisher's total daily catch that was comprised of tiger prawns (i.e., >0.1 to >0.9 of the total daily catch). The sum of the squares was minimised (i.e., the best model) when the tiger prawn catch was >0.2 of the total daily prawn catch.

Targeting definition	ANCOVA resid. SSQ
(tiger / (tiger + banana + greasyback + king)) > 0.1	18451
(tiger / (tiger + banana + greasyback + king)) > 0.2	17186
(tiger / (tiger + banana + greasyback + king)) > 0.3	17264
(tiger / (tiger + banana + greasyback + king)) > 0.4	17704
(tiger / (tiger + banana + greasyback + king)) > 0.5	18399
(tiger / (tiger + banana + greasyback + king)) > 0.6	19232
(tiger / (tiger + banana + greasyback + king)) > 0.7	20006
(tiger / (tiger + banana + greasyback + king)) > 0.8	21316
(tiger / (tiger + banana + greasyback + king)) > 0.9	22617
tiger > banana & tiger > greasyback & tiger > king	18014
banana ==0 & king == 0	22558

Using this rule for targeting, 90% of tiger catch was associated with effort targeted at tiger prawns (Figure 9-2). Note that this rule removed zeroes from catch data associated with targeting tiger prawns, resolving a potential problem often encountered in statistical analysis of catch per unit of effort data involving their log-transformation.

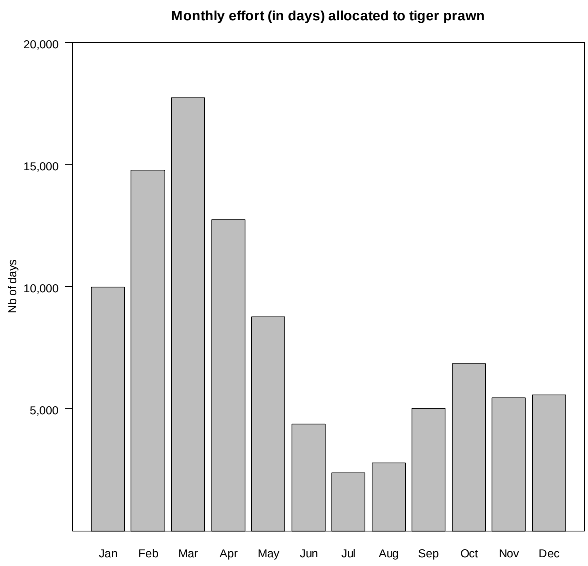

Figure 9-2. Seasonal distribution of effort targeted at Brown Tiger Prawns in Moreton Bay (for all years between 1988 and 2010) resulting from the definition of targeting.

The same approach was applied for determining Eastern King Prawn targeted effort. The sum of the squares was minimised, indicating the best targeted effort model, when logbook catch data was comprised of 20% or more of Eastern King Prawns (Table 9-5).

Table 9-5. Comparison of several definitions of targeting applied to Eastern King Prawn logbook records. The sum of the squares was minimised (i.e., the best model) when the Eastern King Prawn catch was >0.2 of the total daily prawn catch.

Targeting definition	ANCOVA resid. SSQ
(king / (tiger + banana + greasyback + king)) > 0.1	11048
(king / (tiger + banana + greasyback + king)) > 0.2	9940
(king / (tiger + banana + greasyback + king)) > 0.3	10218
(king / (tiger + banana + greasyback + king)) > 0.4	10821
(king / (tiger + banana + greasyback + king)) > 0.5	11550
(king / (tiger + banana + greasyback + king)) > 0.6	12337
(king / (tiger + banana + greasyback + king)) > 0.7	13018
(king / (tiger + banana + greasyback + king)) > 0.8	13638
(king / (tiger + banana + greasyback + king)) > 0.9	14011
king > banana & king > tiger & king > greasyback	11215
banana ==0 & tiger == 0	13781

Using this model, the seasonal trend in effort applied to Eastern King Prawns in Moreton Bay is provided in Figure 9-3. This pattern reflects the relatively high abundance from October to January, in contrast to the Brown Tiger Prawns which generally peak in abundance earlier in the year (i.e., February, March and April).

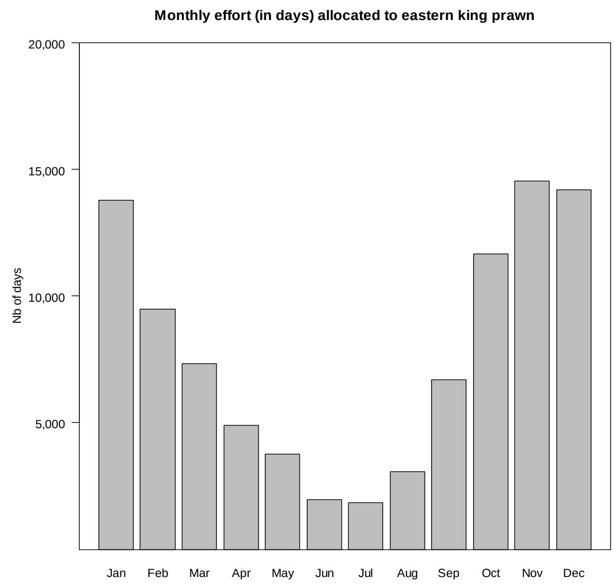

Figure 9-3. Seasonal distribution of effort targeted at Eastern King Prawns in Moreton Bay (for all years between 1988 and 2010) resulting from the definition of targeting.

Using the same method, effort was defined as targeted at Greasyback Prawns when the Greasyback Prawn catch was greater than 0.4 of the fisher's daily catch (Table 9-6).

Table 9-6. Comparison of several definitions of targeting applied to Greasyback Prawn logbook records. The sum of the squares was minimised (indicating the best model) when daily Greasyback Prawn catches comprised >0.4 of the catch, hence indicating targeted effort.

Targeting definition	ANCOVA resid. SSQ
(greasyback / (tiger + banana + greasyback + king)) > 0.1	19445
(greasyback / (tiger + banana + greasyback + king)) > 0.2	16027
(greasyback / (tiger + banana + greasyback + king)) > 0.3	14944
(greasyback / (tiger + banana + greasyback + king)) > 0.4	14492
(greasyback / (tiger + banana + greasyback + king)) > 0.5	14860
(greasyback / (tiger + banana + greasyback + king)) > 0.6	16139
(greasyback / (tiger + banana + greasyback + king)) > 0.7	17934
(greasyback / (tiger + banana + greasyback + king)) > 0.8	20111
(greasyback / (tiger + banana + greasyback + king)) > 0.9	22408
greasyback > banana & greasyback > tiger & greasyback > king	14575
banana ==0 & king == 0	23882

Using this model, fishing effort is applied to Greasyback Prawns over several months of the year, possibly reflecting their extended recruitment (Courtney *et al.* 1995b) (Figure 9-4). Effort targeted on Greasyback Prawns falls to a minimum in June, July and August.

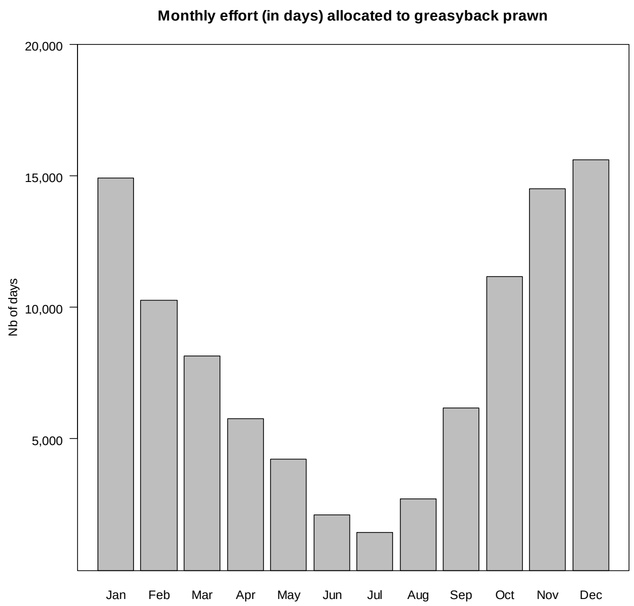

Figure 9-4. Seasonal distribution of effort targeted at Greasyback Prawns in Moreton Bay (for all years between 1988 and 2010) resulting from the definition of targeting.

9.4.2 Collinear covariates

Collinearities between potential candidate-variables to be incorporated into the linear model of catch were investigated by fitting a linear regression to pairs of variables to determine what percentage of the variability of one covariate (*i.e.* R^2) was explained by the other (Table 9-7). The vessel identifier (record number) was strongly confounded with most other covariates ($R^2 > 0.35$) and therefore eliminated from the analysis. SatNav, plotter, autopilot, GPS coupled with autopilot, GPS coupled with radar, and computer mapping were also eliminated from the analysis because they explained 5% or more of the variability of one of the covariates retained in the model. As a result of this selection process, the model fitted to catch was:

E[Catch] ~ Year:Month + colour echo-sounder + GPS+ DGPS + BRD + TED +
Lunar + Lunar _adv7 + log(SAR * hours_trawled)

9.4.3 GLM using Brown Tiger Prawn catch and effort data

Tiger prawn catch was fitted as a function of vessel characteristics and fishing effort using a linear model on the log-scale as well as a GLM using family quasi with log-link and variance proportional to the square of the mean. Comparisons of diagnostics from these two modelling approaches to fit catch using all covariates identified from the analysis described in the previous section (Figure 9-5 and Figure 9-6) showed that a better fit was achieved using the GLM. Residuals from the GLM showed less deviation from a normal distribution than those from the linear model.

Using the deviance as a measure of the discrepancy between several nested models, Table 9-8 showed that the SA term, the log of the product of SAR and hours trawled accounted for the largest drop in residual deviance (98%), followed by the abundance term (interaction between year and month), BRD, colour echo-sounder, differential GPS (i.e., DGPS), TED, lunar phase advanced by 7 days and lunar phase, respectively, in decreasing order of importance. GPS was found to have a positive effect on Brown Tiger catch, increasing catch by about 6% compared to a vessel without GPS, all other things being equal (Table 9-9). DGPS was estimated to improve catch by approximately 18%. TEDs were found to have no significant effect on catches while BRDs had a positive effect of the same order of magnitude than GPS.

Table 9-7. R^2 from a linear regression between pairs of variables using each variable appearing in the table rows as the dependent variable and each variable in the columns as the independent variable.

	Record Number	SA	Lunar Quarters	Colour Echo sounder	satnav	GPS	DGPS	plotter	autopilot	GPS Coupled autopilot	GPS Coupled radar	Computer mapping	BRD	TED
record.number	1													
SA	0.35	1												
LunarQuarters	NA	NA	1											
colour.echo.sounder	0.95	0.01	0	1										
satnav	1	0.04	0	0.01	1									
GPS	0.79	0.02	0	0	0	1								
DGPS	0.93	0	0	0.01	0.01	0	1							
plotter	0.92	0.02	0	0.01	0.01	0.19	0.02	1						
autopilot	0.95	0.02	0	0.42	0	0	0.01	0.03	1					
GPSCoupledautopilot	0.93	0.09	0	0	0.11	0.05	0	0	0.03	1				
GPSCoupledradar	0.62	0	0	0.01	0	0.01	0	0.01	0.01	0.09	1			
computer.mapping	0.93	0.02	0	0.1	0.07	0.1	0.06	0	0.05	0.18	0.02	1		
BRD	0.55	0	0	0.01	0.03	0.04	0.01	0	0	0.01	0	0.07	1	
TED	0.54	0	0	0	0	0	0	0	0	0.01	0	0.02	0.02	1

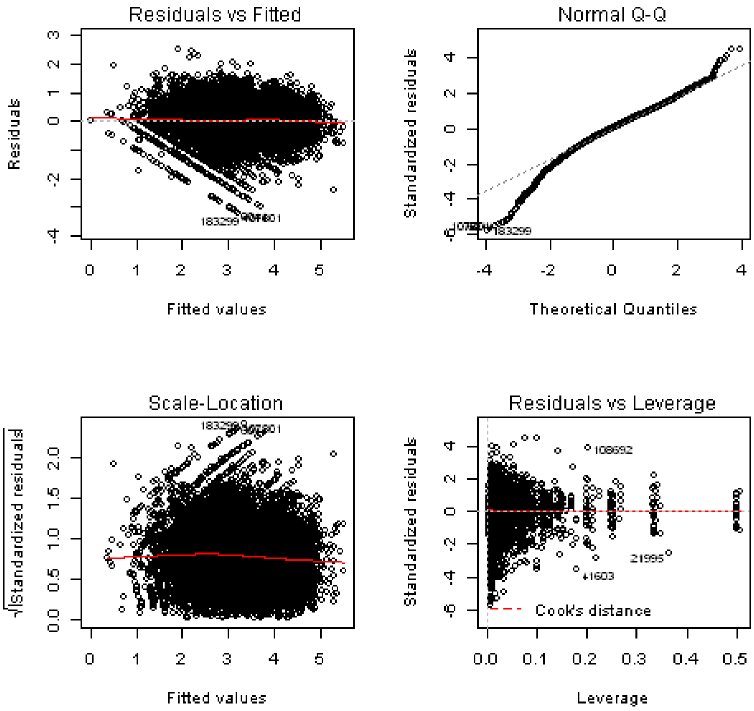

Figure 9-5. Diagnostic plots of the linear model of Brown Tiger catch as a function of effort on the log-scale for Brown Tiger Prawn.

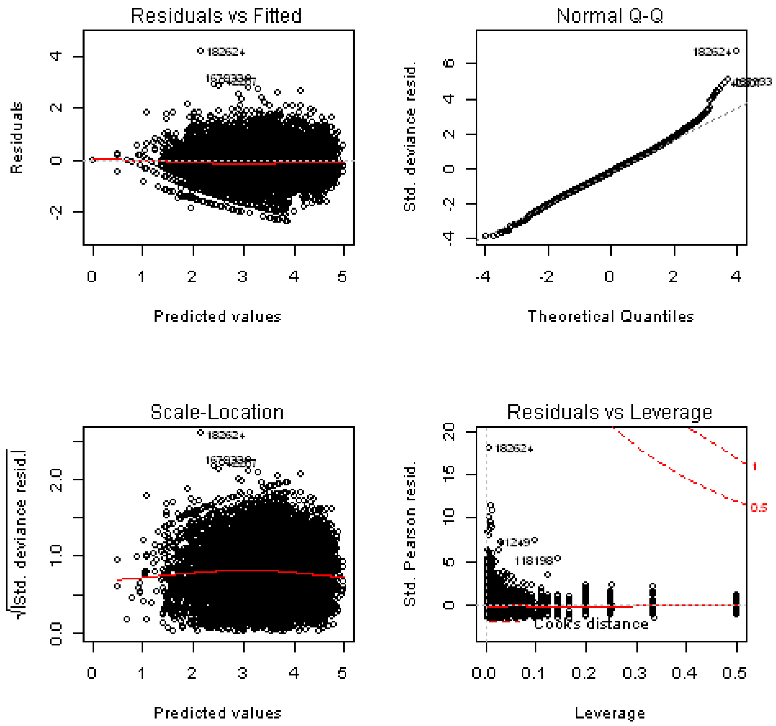

Figure 9-6. Diagnostic plots of a GLM of Brown Tiger catch using quasi family with log-link and variance varying as the square of the mean.

Table 9-8. Analysis of deviance table of the GLM for Brown Tiger Prawn catch per unit of effort.

	Df	Deviance	Resid. Df	Resid. Dev
NULL			15075	941866.6
log(SAR * hours_trawled)	1	929661.5	15074	12205.11
Lunar_phase	1	1.14	15073	12203.96
lunar_adv_7_days	1	5.77	15072	12198.19
colour.echo.sounder	1	272.03	15071	11926.16
GPS	1	77.23	15070	11848.92
DGPS	1	157.52	15069	11691.41
BRD	1	1020.06	15068	10671.35
TED	1	8.37	15067	10662.98
Year:Month	244	5085.32	14823	5577.66

Table 9-9. Parameter estimates from the GLM of Brown Tiger Prawn catch per unit of effort.

	Estimate	Std. Error	t value	Pr(> |t|)
log(SAR * hourstrawled)	0.7091	0.017	41.73	0.0000
Lunar_phase	-0.0466	0.0148	-3.14	0.0017
lunar_adv_7_days	0.0211	0.0148	1.43	0.1536
colour.echo.sounder	0.2208	0.0165	13.35	0.0000
GPS	0.0647	0.0175	3.7	0.0002
DGPS	0.1823	0.0224	8.13	0.0000
BRD	0.0819	0.0304	2.69	0.0072
TED	0.0053	0.0368	0.14	0.8855
Year1990:Month01	-1.3713	0.6321	-2.17	0.0301
Year1992:Month01	0.104	0.2917	0.36	0.7215

Fishing power was estimated to have increased by 20-30% for Brown Tiger Prawns from 1988 and 2010 (Figure 9-11). Brown Tiger Prawn densities in the bay were estimated to have increased by a factor of three over this period, from approximately 0.5 kg/ha to 1.4 kg/ha (Figure 9-12). Uncertainties associated with both of these time-series have declined throughout the time period as the number of vessels with relevant fishing power information has increased.

9.4.4 GLM using Eastern King Prawn catch and effort data

The same modelling approach was applied to fit Eastern King Prawn catch as a function of effort. Comparisons of diagnostics from these two models (Figure 9-7 and Figure 9-8) showed that a better fit was achieved using the GLM.

This model was found to fit the data as well as the Brown Tiger Prawn data. Ninety-eight percent of the Eastern King Prawn catch null deviance was explained by effort (Table 9-10). The effect of GPS and DGPS were not significant while echo-sounder, BRD and TED were found to have a positive effect, increasing catches by about 12 to 16% (Table 9-11). Lunar phase had no significant effect on Eastern King Prawn catch rates in the bay, although it does have a marked effect on the larger, older stages further offshore (Courtney *et al.* 1996) of this species in offshore waters.

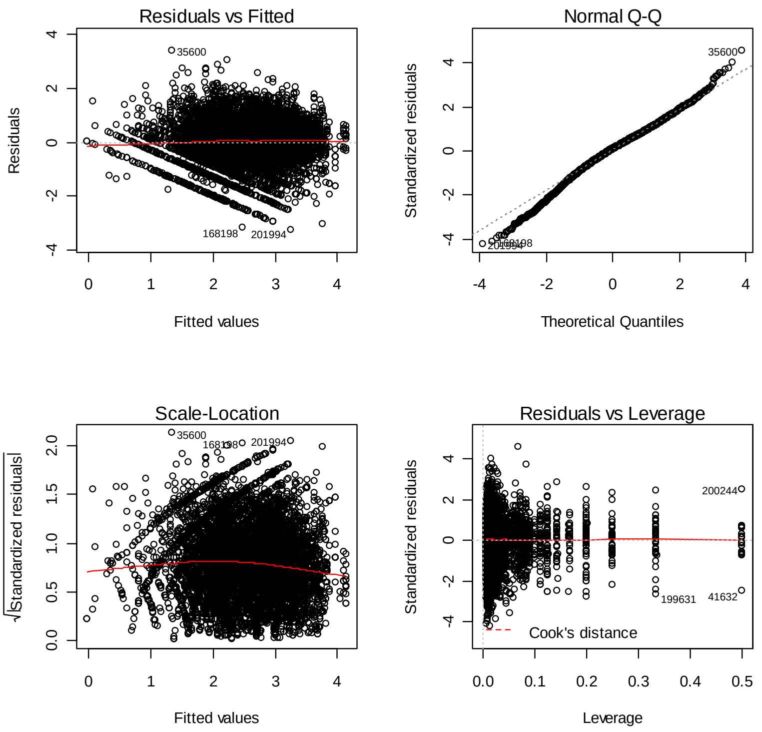

Figure 9-7. Diagnostic plots of the linear model of Eastern King Prawn catch as a function of effort on the log-scale.

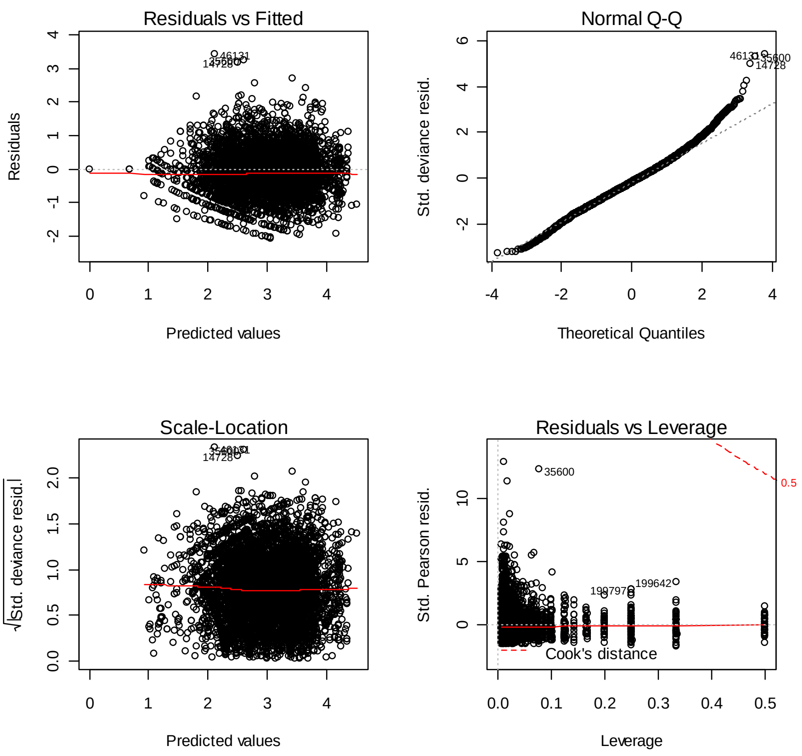

Figure 9-8. Diagnostic plots of a GLM of Eastern King Prawn catch using quasi family with log-link and variance varying as the square of the mean.

Table 9-10. Analysis of deviance table of the GLM for Eastern King Prawn catch per unit of effort.

	Df	Deviance	Resid. Df	Resid. Dev
NULL			7297	281566
log(I((SAR * 3600/10000) * hourstrawled))	1	277294	7296	4272.22
lunar	1	0.69	7295	4271.53
lunar_adv_7_days	1	0.1	7294	4271.43
colour.echo.sounder	1	12.22	7293	4259.21
GPS	1	0.84	7292	4258.37
DGPSs	1	4.73	7291	4253.63
BRD	1	235.76	7290	4017.87
TED	1	45.46	7289	3972.41
Year:Month	220	1416.6	7069	2555.81

Table 9-11. Parameter estimates from the GLM of Eastern King Prawn catch per unit of effort.

	Estimate	Std. Error	t value	Pr(> |t|)
log(SAR * hourstrawled)	0.5554	0.025	22.22	0.0000
Lunar_phase	-0.0281	0.0217	-1.29	0.1957
lunar_adv_7_days	-0.0041	0.0217	-0.19	0.8492
colour.echo.sounder	0.1348	0.0377	3.57	0.0004
GPS	-0.0348	0.0233	-1.49	0.1356
DGPS	0.0734	0.0438	1.68	0.0936
BRD	0.1531	0.0281	5.44	0.0000
TED	0.1253	0.0452	2.77	0.0056
Year1989:Month01	0.8361	0.6474	1.29	0.1966
Year1991:Month01	0.8138	0.6473	1.26	0.2087

Fishing power for Eastern King Prawns in Moreton Bay was estimated to have increased by approximately 20% from 1988 and 2010 (Figure 9-13). Over the same period, the density of Eastern King Prawns in the bay was estimated to have fluctuated between 1 and 2 kg/ha, decreasing in the first six years of this time-series, a stable density around 1.2 kg/ha between the early 1990s and early 2000s and increasing in recent years to around 2 kg/ha (Figure 9-14).

9.4.5 GLM using Greasyback Prawn catch and effort data

GLMs applied to Greasyback Prawn catch and effort data showed that the variance of the residuals increased with predicted catch (Figure 9-9) while the residuals of a GLM where the variance was set to vary as the cube of the mean showed a better fit (Figure 9-10). The latter model was used in subsequent analysis.

Almost all (i.e., 99%) of the null deviance of greasyback catch was explained by effort (Table 9-12). The effect of GPS, DGPS and TEDs were not significant. Instead, echo-sounder and BRD were found to have a strong negative effect, decreasing catches by approximately 15–20% (Table 9-13). Lunar phase was not significant while the 7-days advanced lunar phase was shown to have a negative effect: overall the deviance explained by these two variables was close to zero.

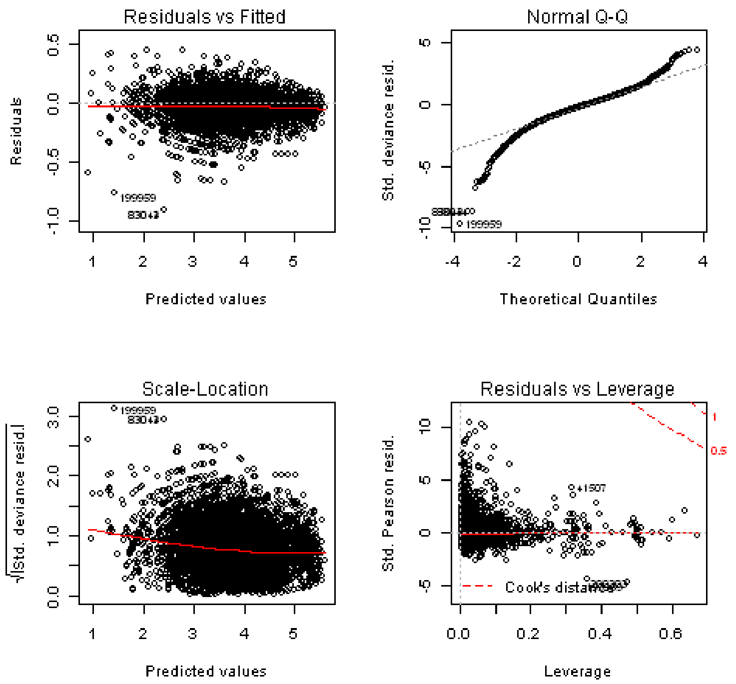

Figure 9-9. Diagnostic plots of a GLM of greasyback catch using quasi family with log-link and variance varying as the square of the mean.

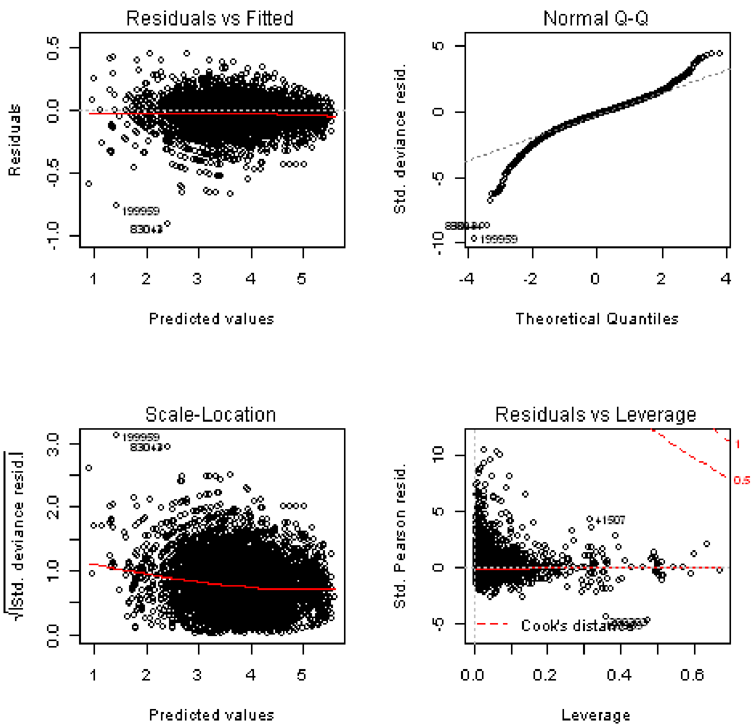

Figure 9-10. Diagnostic plots of a GLM of greasyback catch using quasi family with log-link and variance varying as the cube of the mean.

In contrast to the Brown Tiger and Eastern King Prawns, fishing power associated with Greasyback Prawn catches decreased slightly over the period (i.e. 1988–2010) studied (Figure 9-15). Greasyback Prawn density was the highest of the three species studied and varied between 2 and 5 kg/ha over most of the time-series, initially declining, and then increasing, similar to Eastern King Prawn densities (Figure 9-16). In recent years, densities have been about 5 kg/ha.

Table 9-12. Analysis of deviance table of the GLM for Greasyback Prawn catch per unit of effort.

	Df	Deviance	Resid. Df	Resid. Dev
NULL			7357	383284
log(I((SAR * 3600/10000) * hourstrawled))	1	383108	7356	175.81
lunar	1	0.01	7355	175.8
lunar_adv_7_days	1	0.13	7354	175.67
Colour.echo.sounder	1	1.85	7353	173.82
GPS	1	0.1	7352	173.72
DGPS	1	0.57	7351	173.15
BRD	1	5.36	7350	167.79
TED	1	3.64	7349	164.14
Year:Month	247	73.51	7102	90.63

Table 9-13. Parameter estimates from the GLM of Greasyback Prawn catch per unit of effort.

	Estimate	Std. Error	t value	Pr(> |t|)
log(SAR * hourstrawled)	0.6372	0.0248	25.72	0
Lunar_phase	0.0013	0.0214	0.06	0.9497
lunar_adv_7_days	-0.0797	0.0216	-3.69	0.0002
colour.echo.sounder	-0.1413	0.0223	-6.33	0.0000
GPS	0.0335	0.0269	1.25	0.2127
DGPS	0.0667	0.0557	1.2	0.2316
BRD	-0.2018	0.0321	-6.29	0.0000
TED	-0.0093	0.0485	-0.19	0.8476
Year1988:Month01	2.473	1.169	2.12	0.0344
Year1989:Month01	1.949	0.2458	7.93	0.0000

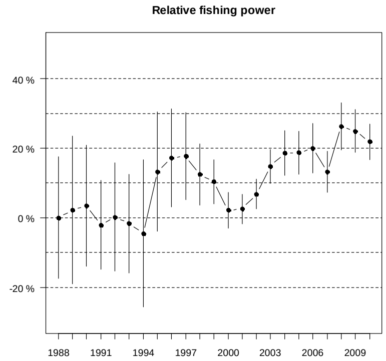

Figure 9-11. Estimated trends in relative fishing power using Brown Tiger Prawn catch and effort data. The vertical bars indicate 2 standard errors from the mean that were derived by propagating the uncertainty estimated by the GLM.

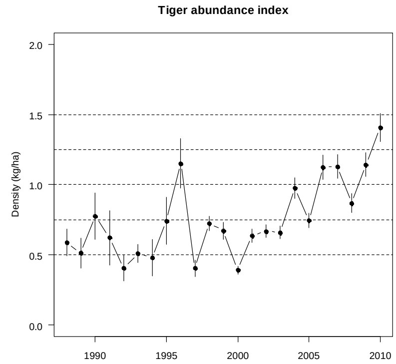

Figure 9-12. Estimated trend in tiger prawn densities. The vertical bars represent 2 standard errors that were derived by propagating the uncertainty estimated by the GLM.

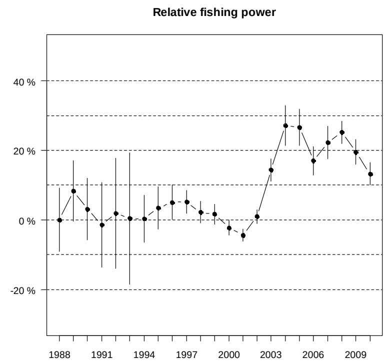

Figure 9-13. Estimated trends in relative fishing power using Eastern King Prawn catch and effort data. The vertical bars indicate 2 standard errors from the mean that were derived by propagating the uncertainty estimated by the GLM.

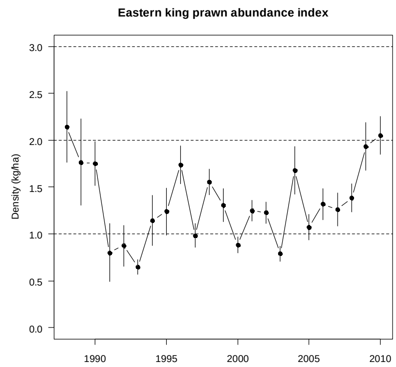

Figure 9-14. Estimated trend in Eastern King Prawn densities. The vertical bars represent 2 standard errors that were derived by propagating the uncertainty estimated by the GLM.

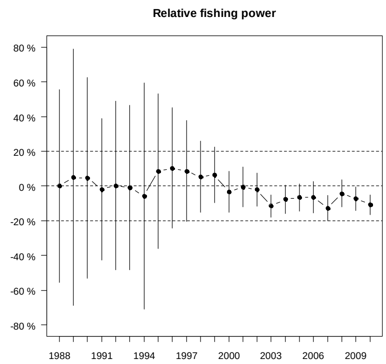

Figure 9-15. Estimated trends in relative fishing power using Greasyback Prawn catch and effort data. The vertical bars indicate 2 standard errors from the mean that were derived by propagating the uncertainty estimated by the GLM.

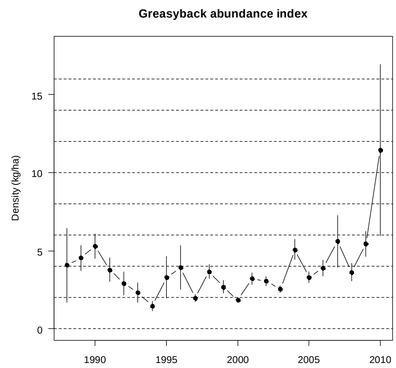

Figure 9-16. Estimated trend in Greasyback Prawn densities. The vertical bars represent 2 standard errors that were derived by propagating the uncertainty estimated by the GLM.

9.4.6 Comparison between commercial and survey indices of abundance

King prawn densities estimated using GLMs were compared to those collected by the long-term monitoring program (LTMP) fishery-independent survey which sampled in Moreton Bay annually from 2006 to 2010 (DPI&F 2006). (For further details of the LTMP, see section 6.5.1. Long-term fishery-independent monitoring of Eastern King Prawns) Although the time-series available for comparison was relatively small, the correlation between these two estimates was quite high at 0.75. Logbook-based estimates were approximately three times larger than the survey estimates (Figure 9-17).

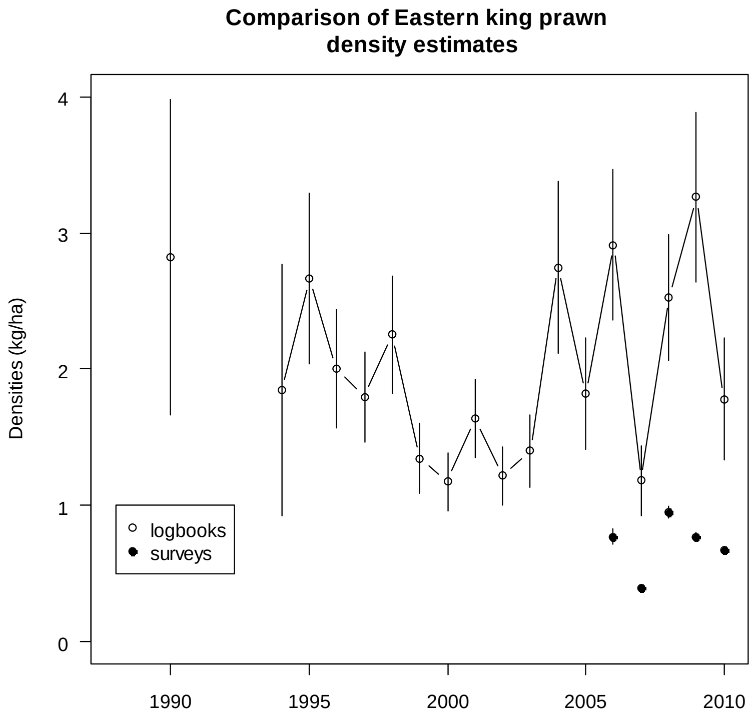

Figure 9-17. Comparison of survey and logbook-based estimates of Eastern King Prawn densities in Moreton Bay. The vertical bars represent 2 standard errors.

9.5 DISCUSSION

Benthic species such as those targeted by the Moreton Bay prawn trawl fishery (i.e., Eastern King Prawn, Tiger Prawn and Greasyback Prawn) essentially occupy the surface of the seabed. Their abundance in a region can be calculated as the product of their density and area. Therefore, estimates of prawn densities provide a relative measure of prawn abundance. Nevertheless, the swept area approach applied to commercial data (Quinn and Deriso 1999), which is often used to estimate density using scientific surveys, provides larger estimates of density than would be found at random due to the fishers' preferences to operate at locations that yield the largest possible catch per unit of effort. Comparison between density estimates from logbooks and survey data suggested that: (1) the abundance trends estimated by both methods were consistent; and (2) the densities estimated from commercial data were three times larger than those from the scientific survey.

The definition of targeting was found to be necessary because preliminary analyses on all data showed no relationship between catch and effort on the log-scale: in particular years, records with low catches at high levels of effort effectively constrained the slope of the relationship to be null. In this multispecies fishery, it seemed reasonable that small amounts of a particular species were incidentally caught with the targeted species. This non-targeted prawn catch had to be removed from the analysis aimed at estimating the relative abundance of each species because these data were collected in areas where, and at times when, they were less abundant and therefore less representative of the total abundance. Rather than eliminating these records, a stratification of the dataset, according to whether the species was targeted or not, might provide a more general approach to deal with the fact that some fishing was performed in high-density spatial/temporal units, while some effort was applied in low-density units.

Nevertheless, we approached this problem by discriminating between many targeting definitions which best fitted an ANCOVA (Table 9-4, Table 9-5 and Table 9-6). An analysis of the seasonal pattern of tiger prawn fishing between 1988 and 2010 resulting from this definition was consistent with empirical knowledge of the Moreton Bay fishery where tiger prawns were mostly targeted at the beginning of the year (January to May) and, to a lesser extent, towards the end of the year (September to November, Figure 9-2). Abundances of Brown Tiger, Eastern King and Greasyback Prawns were estimated to have increased in the past ten years. For example between 2000 and 2010, Brown Tiger Prawn densities were estimated to have increased threefold from 0.5 to 1.5 $kg.ha^{-1}$. This biomass increase is believed to be related to the concomitant drop of fishing effort observed during that same period of time which declined from 11,000 to 4000 boat-days (Figure 6-13). Further investigation of the response of this species to varying effort levels should be pursued to determine, within the large range of effort level observed, the level of effort associated with optimal catch.

The estimate of SA associated with each logbook record is likely to be biased because: (a) logbook information, specifically hours trawled, is inaccurate according to fishers; and (b) in this particular application, the PTP model most probably only provided a relative measure (i.e., not an absolute measure) of the SAR because important information regarding the netting material used by each vessel (i.e. twine diameter and ply) was not recorded during the gear survey or in the logbook data. Hence, the density estimates are likely to be relative measures of abundance.

This analysis showed that the estimated trends in prawn densities were robust to a wide variety of model specification (comparison not shown here) while fishing power time-series were very sensitive to the same model uncertainty. The latter were showing unexpected decreasing trends such as those reported by Mahévas *et al.* (2004): decreasing trends in fishing power time-series were not expected, in particular during a period when several electronic technologies, such as GPS and plotters, were quickly adopted by the fleet and were shown to have a positive effect on catches (Bishop *et al.* 2008; Robins *et al.* 1998). This model uncertainty was shown to be induced by multicollinearity in our dataset and needed to be explicitly dealt with. Our work suggested that regressing pairs of explanatory variables against each other and using R^2 values provided a method for identifying collinear variables. This approach was used to decide which covariate to include in the catch per unit of effort model. The threshold value for inclusion was chosen arbitrarily and a more stringent criteria, such as $R^2 > 1\%$, could have been applied but would have certainly resulted in eliminating variables that appeared to be collinear by chance as well as retaining fewer covariates.

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10 A maximum-likelihood method for estimating natural mortality and catchability from catch and effort data, with application to Moreton Bay Brown Tiger Prawn trawl fishery (Objective 5A)

By M. Kienzle

Estimation of natural mortality and catchability is required to evaluate harvest strategies reported in section 11. As such, this section is a fundamental step in addressing:
Objective 5A. Develop optimal temporal and spatial harvesting patterns in the bay, considering a range of effort levels, to maximise the sustainable catch value for the four main prawn species (Greasybacks, Eastern King Prawns, Brown Tiger Prawns and Banana Prawns).

10.1 ABSTRACT

Catchability and natural mortality are key quantities needed to evaluate the impact of fishing on prawn survival. A maximum-likelihood method is proposed to estimate these two quantities using the time-series of catch and effort. This method was applied to estimate natural mortality and catchability of Brown Tiger Prawns (*Penaeus esculentus*) in Moreton Bay using logbook data collected between 1988 and 2010. A range of assumptions was investigated to determine which model best fitted the data based on likelihood-ratio tests. Natural mortality was estimated to range between 0.038 and 0.062 per week and catchability per boat was estimated to be equal to 2.5 ± 0.4 E-04.

10.2 INTRODUCTION

Assessing the status of exploited aquatic resources involves estimating mortality rates to determine whether the current level of exploitation is sustainable and investigating management actions that could increase stock production. Relating fishing mortality to fishing effort using a coefficient of catchability is a key aspect of this evaluation (Arreguin-Sanchez 1996), as is the estimation of the magnitude of natural mortality. Simultaneous estimation of these two quantities is notoriously difficult using only fishery catch and effort data (Lee *et al.* 2011; Wang 1999; Zhou *et al.* 2011).

A new maximum-likelihood method derived from the combination of survival analysis (Cox and Oakes 1984) and quantitative fisheries stock assessment (Hilborn and Walters 1992; Quinn and Deriso 1999) is proposed to simultaneously estimate catchability and natural mortality using catch and effort data. This method was developed to relate the entire time-series of Brown Tiger Prawn (*P. esculentus*) catch to effort in the Moreton Bay trawl fishery using logbook data collected between 1988 and 2010. This section of the report describes how the method was used to compare a range of hypotheses concerning the dynamics of the fishery to determine the model that was best supported by logbook data.

10.3 MATERIALS AND METHODS

10.3.1 Estimation method

The purpose of this maximum-likelihood method is to estimate both natural and fishing mortality rates from landing data. Consider a single cohort of prawns where individual survival depends on a constant natural mortality rate (*M*) as well as a time-dependent fishing mortality rate (*F(t)*) according to the survival function *S*(*t*):

$$S(t) = \exp\left\{-\int_0^t (M + F(u))\, du\right\}, \text{ for } t > 0 \qquad \text{(Eq. 1)}$$

Fishing mortality was assumed to be proportional to effort ($E(t)$) standardised by a year specific fishing power coefficient (r_y):

$$F(t) = q\, r_y\, E(t) \qquad \text{(Eq. 2)}$$

Assuming that weight at age (t) in the population is given by a length-based von Bertalanffy growth function:

$$W(t) = W_\infty \left[1 - \exp\{-k(t - t_0)\}\right]^3 \qquad \text{(Eq. 3)}$$

and that trawl selectivity ($s(t)$) is a function of weight,

$$s(t) = \frac{1}{1 + \exp(a - b \times W(t))} \qquad \text{(Eq. 4)}$$

then the exploitable biomass of the cohort at time *t*, *Q*(*t*), can be written as:

$$Q(t) = N(0)S(t)\int_0^\infty W\, \phi(\mu = W(t), \sigma = \alpha\, W(t))\, s(W)\, dW \qquad \text{(Eq. 5)}$$

where $\phi(\mu = W(t), \sigma = \alpha\, W(t))$ is the probability-density function of a Gaussian distribution with mean μ and standard deviation σ.

Given that the differential of catch is given by $dC/dt = F(t)Q(t)$ (Quinn and Deriso 1999), catch over an interval of time $[t; t + \Delta t]$ is:

$$C_{[t;t+\Delta t]} = \int_t^{t+\Delta t} F(t)Q(t)\, dt \qquad \text{(Eq. 6)}$$

A numerical application of these equations (Figure 10-1) illustrates these concepts.

To estimate mortality rates by maximum likelihood, we used this expression of catch as a probability-density function (PDF) to express the probability of catching a given weight of prawns between particular time intervals: $[t; t + \Delta t]$

$$P(C_{[t;t+\Delta t]}) = \frac{\int_t^{t+\Delta t} F(t)Q(t)\,dt}{\int_0^{+\infty} F(t)Q(t)\,dt} = \frac{\int_t^{t+\Delta t} qE(t)S(t)W(t)\,dt}{\int_0^{+\infty} qE(t)S(t)W(t)\,dt} \quad \text{(Eq. 7)}$$

And expressed the likelihood of q, M and t_0 given catch and effort grouped into n monthly intervals and growth parameters (W_∞, k, a, b and α) as

$$L(q,M,t_0 \mid C_i,E_i,W_\infty,k,a,b,\alpha) = \prod_{i=1}^{n} P(C_i)^{C_i} \quad \text{(Eq. 8)}$$

The hessian resulting from minimising the negative log-likelihood function derived from Eq. 8 provided unrealistically small uncertainties associated with the parameter estimates. These were attributed to the very large variation in catch data, in the order of 10-100,000 kg. A more realistic measure of uncertainty was obtained by replacing the exponent in Eq. 8 (C_i) with the proportion (p_i) of total catch on a cohort ($\sum_i C_i$) that occurred at each particular time step i ($p_i = C_i \big/ \sum_i C_i$) multiplied by an effective sample size fixed to (for lack of better suggestion) to the number of vessels operating in every corresponding year. This modification was found to substantially increase the uncertainty on parameters and provide more realistic estimates than previously obtained.

The likelihood function is independent of recruitment to the fishery ($N(0)$). An estimate of recruitment was calculated as follows:

$$\hat{N}(0) = \frac{C_{[0;\infty]}}{\int_0^{\infty} F(t)S(t)W(t)dt} \quad \text{(Eq. 9)}$$

The Spawning Stock Biomass (SSB) was estimated using the number of individuals that survived the spawning season expressed as the interval of time between t_1 and t_2:

$$SSB = N(0)\int_{t_1}^{t_2} S(t)W(t)dt \quad \text{(Eq. 10)}$$

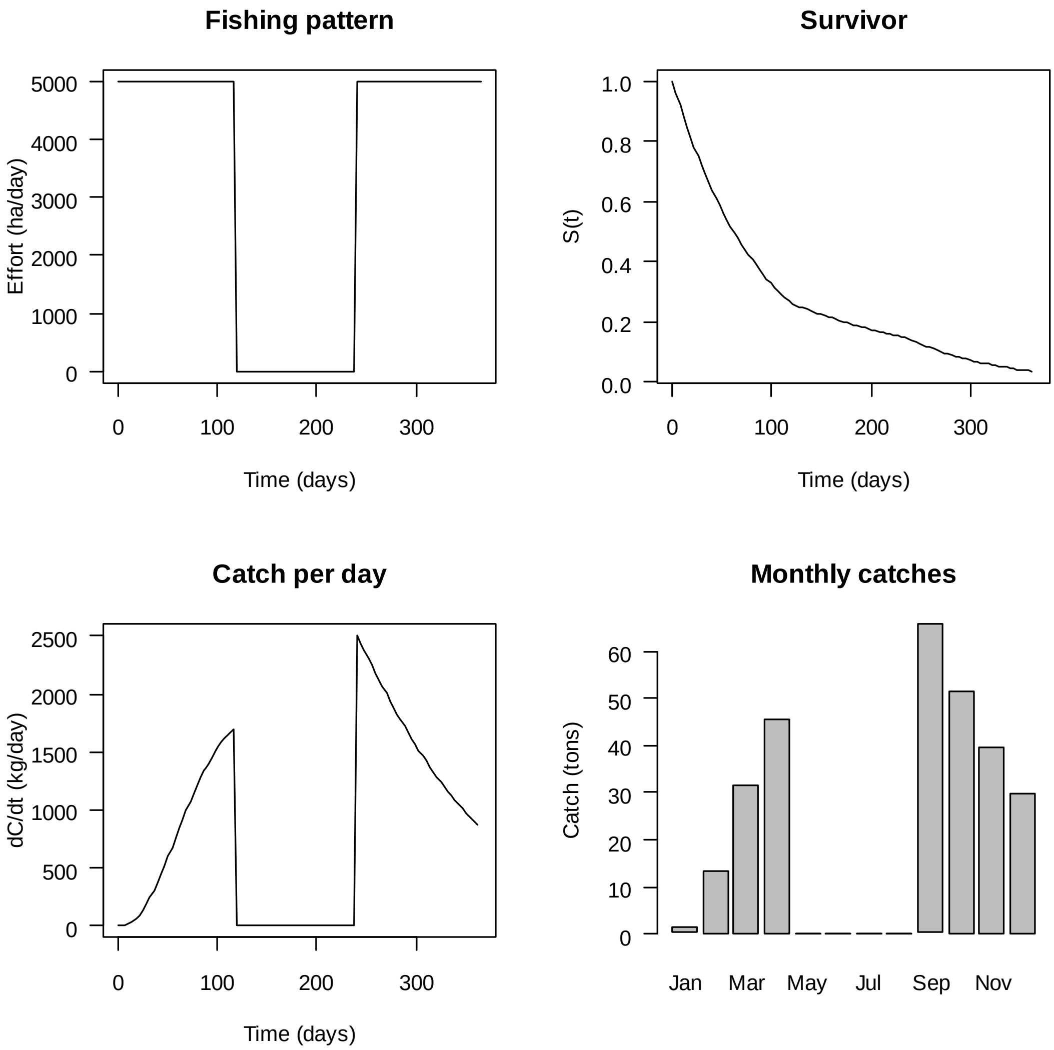

Figure 10-1. Illustration of the concepts with a numerical application using: (top left) a constant fishing effort through the year with a 4-month closure between May and August; (top right) a coefficient of proportionality between effort and fishing mortality of q=1.25E-5 and a fixed natural mortality rate of 0.005 per day to calculate the survival through the first year of life of the cohort; (bottom left) showing how catch per day would vary had the cohort size been 100 million individuals at t=0; and (bottom right) showing the sum of the hypothetical catches over monthly periods.

10.3.2 Data

The Moreton Bay trawl fishery is a multispecies fishery that mainly catches four species of prawn: Brown Tiger Prawn, Banana Prawn, Eastern King Prawn and Greasyback Prawn. Catch (in kg) and effort (in number of boat-days) recorded in logbooks between 1988 and 2010 were summed over 276 monthly intervals of time. The peak of spawning season was assumed to occur as a single, instantaneous pulse (modelled by the parameter t_0) in October (Courtney and Masel 1997). Following preliminary analyses and consultations with the industry, each cohort was assumed to recruit to the fishery in January and modelled through to December. The size of the cohort after 12 months was assumed to be negligible.

Effort ($E(t)$) was expressed in the number of boats fishing each day and integrated over time by daily time-steps[10]. Two time-series of effort were used to model catch: total effort and effort allocated to tiger prawns. Allocated effort was calculated according to the relative species prices (Tiger Prawn = 1; King Prawn = 0.71; Banana Prawn = 0.63, Greasyback Prawn = 0.27 and Endeavour Prawn = 0.69). The fishing effort (1 boat-day) was allocated to tiger if it represented the largest value in that record. In both cases, the number of boat-days fished each month was divided by 30 to obtain the effort-variable in the model. Note: this is an approximation of reality because Moreton Bay trawl fishing is allowed during week-days (i.e., Sunday to Thursday) and prohibited on weekends (Friday and Saturday). In some cases, effort was standardised using a year-specific coefficient (r_y) that provided an estimate of fishing power variation of the order of magnitude of 22 ± 5 % (relative to 1988). This accounted for all significant changes in fishing technology over the period considered (i.e., 1988-2010) (see section 9).

Growth was assumed to be known and described by the von Bertalanffy growth function parameterised using values for k and L_∞ intermediate between values provided by Kirkwood and Somers (1984) for male and female tiger prawns ($L_\infty = 41.2$ CL in mm and $k = 0.0375$ week^{-1}); t_0 was either fixed to -90 (locating spawning peak at the 1 October) or estimated. L_∞ was converted into W_∞ using a length-weight relationship (Quinn and Deriso 1999) with $\alpha = 2.2E-03$ and $\beta = 2.76$ (unpublished analysis). The parameter α (Eq. 5) that fixed the relationship between mean weight and S.D. (standard deviation) at time t was set arbitrarily to 0.20 due to the lack of data for this part of the model.

The trawl selectivity function (Eq. 4) was parameterised using external information. On one hand, survey data collected by Courtney *et al.* (1991) in 1989–90 indicated that this function should be parameterised using $a = 7$ and $b = 0.7$ (Figure 6-16). On the other hand, the fishing industry argued that survey data were not representative of fishers' observations and insisted on setting the selectivity parameters (a and b) at the values of 28 and 2 respectively, effectively setting the weight at 50% retention ($S_{50\%}$) at 14 g rather than 5g. The effect of these different settings is discussed in the Results.

10.3.3 Model selection

Three models were compared using likelihood ratio to determine the hypothesis that best representeded the observed catches. These models were of increasing levels of complexity in terms of the number of parameters to be estimated: the simplest (model 1) was used to estimate only one parameter (q, catchability) having all the others fixed at specific values; a more complicated model (model 2) was used to estimate both catchability (q) and natural mortality (M); the most complex model (model 3) estimated M, q and a cohort specific t_0 (23 parameters). The likelihood value of the catch according to the different models was also used to test these hypotheses:

[10] Other measures of effort, in particular those representing targeted effort at each species (derived from catch data), were tried but they did not provide as good a fit (according to the negative log-likelihood) as total effort.

1. Total effort explains the catch data better than allocated effort to single-species
2. Fishing power improves the fit to the catch data.
3. No particular combination of gear selectivity parameters and t_0 best explains the catch data.

10.4 RESULTS

10.4.1 Which assumptions best represent the data?

The entire time-series of tiger prawn catch, recorded between 1988 and 2010, were fitted with models that used either the total effort or the effort allocated to tiger prawns in proportion of their value. A likelihood-ratio test (Table 10-1, $Q = 2.8e-92$) suggested that total effort provided a better fit to total catch of tiger prawns in Moreton Bay.

The inclusion of fishing power time-series did not improve the model's fit to the catch: the likelihood-ratio tests ($Q = 0.61$) indicated that not accounting for fishing power variation provided a slightly better fit of tiger prawn catches.

Allowing the cohort recruitment to the fishery to change from year to year (variable t_0) improved the fit of the models to the data ($Q = \frac{\exp[-5642.4]}{\exp[-5759.8]} = 9.7e+50$ and $Q = \frac{\exp[-5661.1]}{\exp[-5701.2]} = 2.6e+17$).

The 50% selectivity ($S_{50\%}$) and t_0 are negatively correlated in the estimation process: models with large values of $S_{50\%}$ and small values of t_0 (cohort born earlier) explained the data equally well compared to models with small values of $S_{50\%}$ and large values of t_0 (cohort born later). Cohorts were estimated to be born between July and September when $S_{50\%}$ was fixed at 14 g. In contrast, cohorts were estimated to be born between September and November, with an average in October, when $S_{50\%}$ was fixed at 7 g. The latter assumptions provide a model that is more consistent with current knowledge of the biology of tiger prawn in Moreton Bay. The likelihood-ratio tests suggested that all but the most complex model favoured $S_{50\%}$ having a value of 7 g over 14 g.

10.4.2 Mortality estimates for tiger prawn in the Moreton Bay fishery

Natural and fishing mortalities for Brown Tiger Prawns in Moreton Bay were estimated using the assumptions that were best supported by the fishery data and most consistent with current knowledge on the biology of the species in Moreton Bay using the most complex model which estimates 25 parameters. This model captures the observed seasonal variation of catches through each year (Figure 10-2). Analysis of the residuals indicated this model tended to underestimate large catches and overestimate small catches (Figure 10-3).

Table 10-1. Summary of likelihood-ratio tests of hypotheses using 3 models with increasing complexity.

	Hypotheses tested		
	Total effort provides a better fit to the data than allocated effort, based on economical values	**Inclusion of a fishing power time-series improves the fit to the catch data**	**An** $S_{50\%}$ **value of 14 g explains the catch better than a value of** 7 g
Model 1 (only catchability was estimated)	$\frac{L_{Allocated\ effort}}{L_{Total\ effort}} = \frac{\exp[-5886.3]}{\exp[-5675.5]} = 2.8e-92$	$\frac{L_{fishing\ power\ TS}}{L_{no\ fishing\ power\ TS}} = \frac{\exp[-5675.6]}{\exp[-5675.1]} = 0.61$	$\frac{L_{S_{50\%}=14g}}{L_{S_{50\%}=7g}} = \frac{\exp[-5760.1]}{\exp[-5702.8]} = 1.3e-25$
Model 2 (catchability and natural mortality were estimated)	**NA**	$\frac{L_{fishing\ power\ TS}}{L_{no\ fishing\ power\ TS}} = \frac{\exp[-5675.1]}{\exp[-5674.6]} = 0.61$	$\frac{L_{S_{50\%}=14g}}{L_{S_{50\%}=7g}} = \frac{\exp[-5759.8]}{\exp[-5701.2]} = 3.6e-26$
Model 3 (catchability, natural mortality and cohort specific t_0 were estimated)	**NA**	**NA**	$\frac{L_{S_{50\%}=14g}}{L_{S_{50\%}=7g}} = \frac{\exp[-5642.4]}{\exp[-5661.1]} = 2.4e+08$

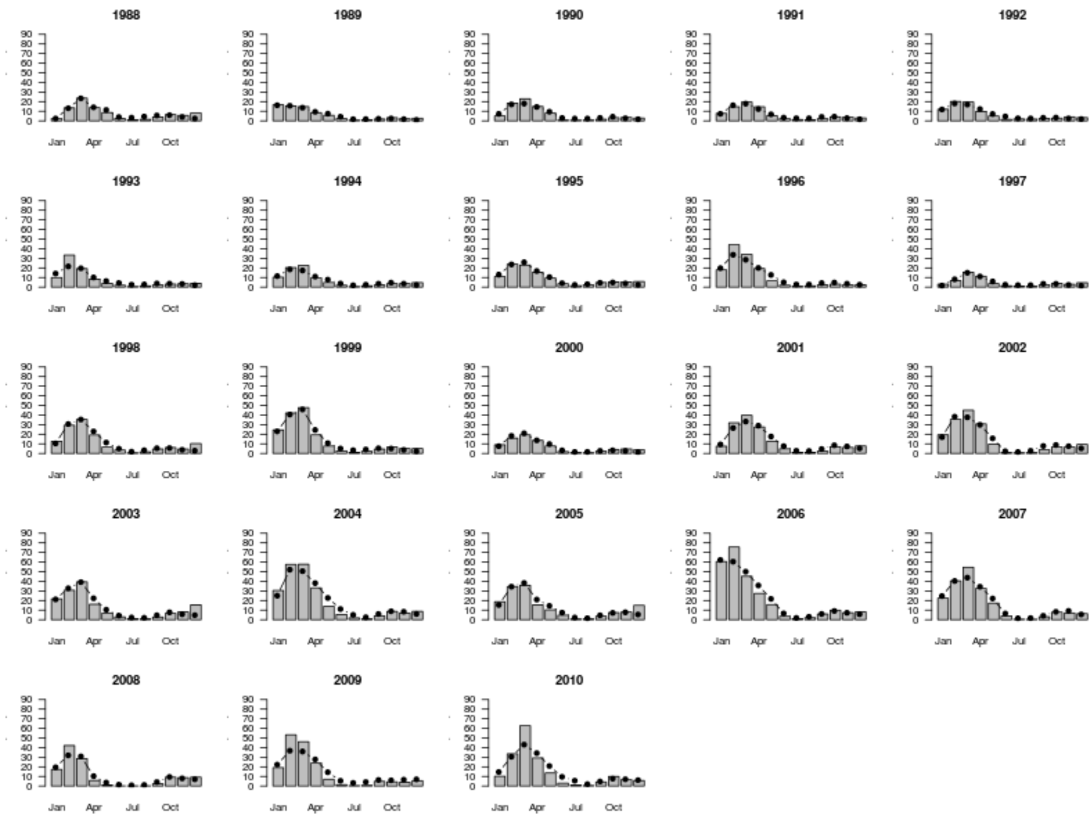

Figure 10-2. Observed (bars) and predicted (dots) Brown Tiger Prawn catches from the Moreton Bay trawl fishery, grouped by year and month.

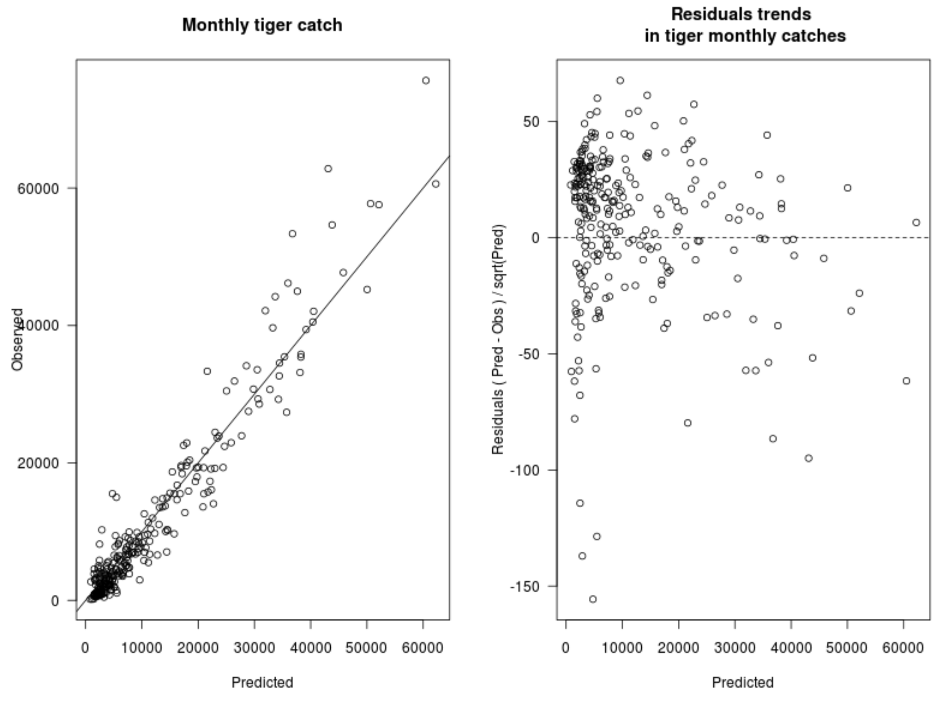

Figure 10-3. Diagnostic plots of the model of monthly tiger prawn catch.

Natural mortality was estimated to be equal to 7.1 ± 0.87 E-03 per day, equivalent to 5.0 ± 0.60 E-02 per week or 2.6 ± 0.32 per year. Fishing mortalities, calculated using estimates of catchability ($\hat{q}$ =2.53 ± 0.43 E-04), were estimated to have varied between 0.96 and 3.4 per year, declining in proportion to the effort during the past two decades (Figure 10-4).

Figure 10-4. Estimated trends in tiger prawn fishing mortality in Moreton Bay from 1988 and 2010. The horizontal dotted line represents the natural mortality rate estimated from logbook data (2.6 per year).

10.5 DISCUSSION

The method described herein facilitates calibration of a single-cohort dynamic model of the fishery to the tiger prawn catch and effort data. The purpose of this calibration was to establish the relationship between catches and effort in order to investigate how a variation of the seasonal pattern of effort would affect total catch. The assumption that monthly catches from January to December were composed of a single cohort depends on whether survival of tiger prawn from one year to another can be neglected. Estimates of the mortality rate from this model indicated that total mortality was at least equal to 3.6 per year which would result in fewer than 3% of prawns surviving after one year. Moreover, the lack of data about the age composition of the catch prevented any modelling of overlapping cohorts.

Effort is the most influential variable on catch in this model. As fishing mortality is assumed to be proportional to effort, the estimated fishing mortality trends simply followed total effort trends. As the fleet operating in Moreton Bay catches multiple species, the allocation of targeted effort to each species is very challenging. This is partly because fishers do not target any one species but rather on each night of fishing all fishers try to maximise the value of their catch. In the present modelling approach, total effort was used. This is a poor proxy for tiger prawn fishing mortality because much of the effort is not directed at tiger prawns. More work is required to derive targeted effort for the main prawn species in the Moreton Bay fishery. It would be beneficial to compare models that incorporate different effort time-series and determine which is most supported by the data. In particular, it would be instructive to compare the performance of models that include definitions of targeted and non-targeted effort and compare these against models that use total effort.

It is important to note that this method assumes a single pulse of recruitment to the fishery on 1 January. However, a previous two-year monthly sampling program showed that recruitment for Brown Tiger Prawns in Moreton Bay occurred over 2–3 months (Courtney *et al.* 1995a). Developing a model that includes staggered recruitment is likely to provide a more realistic representation of the fishery.

Natural mortality estimated with this method was 5.0 ± 0.60 E-02 wk^{-1}, which is comparable to previous studies. For example, it is lower or at the lower boundary of the natural mortality estimate by O'Brien (1994) for juvenile tiger prawns in Moreton Bay (0.06–0.29 wk^{-1}) and consistent with the maximum-likelihood estimate from Wang (1999) who concluded that natural mortality was more likely to be less than 0.065 wk^{-1} and more than 0.03 wk^{-1}, based on an analysis of the Northern Prawn Fishery.

To overcome the uncertainty about size composition of the tiger prawn catch, two distinct selectivity curves were implemented, one using $S_{50\%}$ = 14 g and a second using $S_{50\%}$ = 7 g. The best fit to the data was obtained using the larger value and by estimating a cohort-specific t_0 positioning birth between July and September. This was inconsistent with previous work on the biology of tiger prawn in Moreton Bay (Courtney and Masel 1997). There is evidence that tiger prawns recruit to the fishery at a carapace length of around 27 mm (Courtney *et al.* 1995a) which supports the use of the larger $S_{50\%}$ value Therefore the shift of t_0 outside the possible biological domain might indicate that a better model of total catch could be achieved using growth curves that provide larger weight-at-age, such as a seasonal growth model that is dependent on temperature (O'Brien 1994).

The likelihood function (Eq. 8) provided estimates of catchability and natural mortality that depended on a set of fixed parameters $(W_\infty, k, a, b, \alpha)$. It has been suggested that the estimate of natural mortality depended on the growth function parameters used in the model which were borrowed from Kirkwood and Somers (1984) for tiger prawns from the Western Gulf of Carpentaria. Future analyses on tiger prawn growth in Moreton Bay might reveal a different growth pattern, as well as different mortality rates.

11 Assessing the effect of temporal closures on tiger prawn catch and value in the Moreton Bay prawn trawl fishery (Objective 5A)

By M. Kienzle, M. O'Neill and A. Courtney

This section of the report addresses:
Objective 5A. Develop optimal temporal and spatial harvesting patterns in the bay, considering a range of effort levels, to maximise the sustainable catch value for the four main prawn species (Greasybacks, Eastern King Prawns, Brown Tiger Prawns and Banana Prawns).

11.1 ABSTRACT

A bio-economical analysis of the effect of effort redistribution through the year on catch and value of tiger prawn was performed using a model of the tiger prawns population dynamics. Evaluation of the effects of removing effort altogether in each month showed that such harvest strategy would only be beneficial if applied at a time when individuals were still growing fast (January or February), effectively optimising the size at first capture.

11.2 INTRODUCTION

The size of the Moreton Bay prawn trawl fleet has declined by approximately 70% over the past 20 years (Figure 6-13), largely as a result of increased marketing competition with aquacultured prawns and reduced exports of other Australian wild-caught prawns. This has resulted in reduced fishing effort and reduced fishing mortality for all prawn species caught in the bay. The reduction in effort is likely to have had a positive effect on biomass, spawning stock and recruitment, especially for the Brown Tiger Prawns, and the current level of exploitation on this stock is considered to be sustainable.

In this context, an economical analysis of the relationship between tiger prawn catch value and effort was performed to determine whether the seasonal distribution of effort could be modified to optimise the total revenue of the fleet. The option of removing fishing mortality on Brown Tiger Prawns for one month, using monthly closures, was investigated to evaluate the costs and benefits of catching prawns at larger, more valuable sizes.

11.3 MATERIALS AND METHODS

The model representing the dynamics of a single cohort of Brown Tiger Prawns over each year between 1988 and 2010 was calibrated to total catch and effort data in order to estimate catchability, natural mortality and the von Bertalanffy's adjustment parameter (t_0) for each cohort (see section 10, describing a maximum-likelihood method to estimate natural mortality and catchability). Two models using different trawl selectivity parameters (Figure 11-1) were fitted to the data to address uncertainty. One model used a selectivity curve based on Kimura's (1978) method which was applied to data collected from Moreton Bay (Courtney *et al.* 1991; Courtney *et al.* 1995a) in 1989–90 (see Figure 6-16). This selectivity curve was deemed as unrepresentative of current practice by the industry who argued that a second parameterisation was more consistent with their observations of the sizes of the prawns they catch.

Monthly catches were converted into their corresponding economic value using a weight-dependent price per kilo for prawns and a seasonal index representing the variation of prices according to demand (Figure 11-2). Prices per kg increase asymptotically as a function of their size: the largest category (U20) commands $16 to $18 per kg. Values varied seasonally according to consumer demand, with prices peaking at Christmas. The difference in price between high and low seasons was as high as 60%.

The model calculated monthly catches of Brown Tiger Prawns using the distribution of logbook effort each year between 1988 and 2010. It also calculated what would have been monthly catches had the pattern of effort been different. The model was used to evaluate monthly closures (i.e., one month-long cessation of trawl effort) that were applied to each calendar month in succession each year. Effects on the total annual catch and value of tiger prawns were derived.

The analyses were coded in R (2005) and are available from M. Kienzle.

11.4 RESULTS

The effects of the monthly closures for each year from 1988 to 2010 on total catch and value of Brown Tiger Prawns using the two selectivity curves, are shown in Figure 11-3, Figure 11-4, Figure 11-5 and Figure 11-6, respectively. The results indicate that significant benefits could have been obtained by closing the fishery in January in the 1980s, 1990s and early 2000s when effort levels were high (i.e., > 10,000 boat-days annually). Figure 11-6 indicates that the value of the tiger prawn catch could have been increased by up to 60% at this time. As effort has declined markedly since 2000, benefits from closing the fishery have diminished. When effort levels from recent years are considered (i.e., effort levels that are < 5000 boat-days annually), potential benefits from monthly closures are more modest. The results indicate that benefits from closures are greater when effort levels, and hence fishing mortality levels, are high, and that there is less benefit when effort and fishing mortality levels are low.

Results for recent years indicate that a one-month closure implemented in any month between March and December would produce a loss of revenue to the industry as letting prawns grow larger does not compensate for the loss in catch at that time. On the other hand, the magnitude of the effect of a closure in January or February depends on the selectivity curve used in the analysis:

- assuming 50% weight selectivity ($S_{50\%}$) = 14 g, catch would not have improved with a fishing closure in January or February but value could have improved by 5–10% in recent years by closing the fishery in January.

- assuming 50% weight selectivity($S_{50\%}$) = 7 g indicated a potential increase in catch by 8–10% and a concurrent increase in value of 10–20% if the fishery was closed in January.

The benefit achieved by these closures implied a reduction of effort in the order 10–15% of total effort (Table 11-1 and Table 11-2). The corresponding reduction in fishing costs would be an additional benefit associated with these monthly closures.

Table 11-1. Assessment of the effect on tiger prawn catch and value from a one-month closure compared to predicted catch using observed effort. Based on the selectivity curve described in Courtney *et al.* (1991).

Closed month	Year	% change of total catch	% change in value of catch	% change of total effort
Jan	2008	10	20	-15
Feb	2008	-8	11	-16
Mar	2008	-17	-4	-16
Apr	2008	-7	-4	-6
May	2008	-2	-2	-2
Jun	2008	-1	-1	-1
Jul	2008	-1	-1	-1
Aug	2008	-1	-1	-1
Sep	2008	-3	-4	-4
Oct	2008	-7	-12	-11
Nov	2008	-6	-13	-12
Dec	2008	-6	-17	-15
Jan	2009	10	18	-13
Feb	2009	-5	10	-14
Mar	2009	-12	-3	-14
Apr	2009	-12	-8	-12
May	2009	-7	-6	-7
Jun	2009	-3	-3	-3
Jul	2009	-2	-2	-2
Aug	2009	-2	-3	-3
Sep	2009	-3	-5	-5
Oct	2009	-3	-6	-6
Nov	2009	-4	-8	-9
Dec	2009	-5	-12	-12
Jan	2010	8	14	-11
Feb	2010	-3	8	-11
Mar	2010	-12	-3	-15
Apr	2010	-13	-8	-14
May	2010	-9	-7	-10
Jun	2010	-4	-4	-5
Jul	2010	-3	-3	-3
Aug	2010	-1	-1	-1
Sep	2010	-2	-3	-4
Oct	2010	-4	-7	-7
Nov	2010	-4	-8	-9
Dec	2010	-3	-9	-10

Table 11-2. Assessment of the effect on Brown Tiger Prawn catch and value from a one-month closure compared to predicted catch using observed effort. Based on an industry-derived selectivity curve.

Closed month	Year	% change of total catch	% change in value of catch	% change of total effort
Jan	2008	-1	9	-15
Feb	2008	-17	-9	-16
Mar	2008	-21	-17	-16
Apr	2008	-7	-6	-6
May	2008	-2	-2	-2
Jun	2008	-1	-1	-1
Jul	2008	-1	0	-1
Aug	2008	-1	-1	-1
Sep	2008	-2	-3	-4
Oct	2008	-6	-9	-11
Nov	2008	-6	-10	-12
Dec	2008	-6	-12	-15
Jan	2009	0	8	-13
Feb	2009	-13	-7	-14
Mar	2009	-16	-13	-14
Apr	2009	-13	-12	-12
May	2009	-7	-7	-7
Jun	2009	-3	-3	-3
Jul	2009	-2	-2	-2
Aug	2009	-2	-2	-3
Sep	2009	-3	-4	-5
Oct	2009	-3	-5	-6
Nov	2009	-3	-6	-9
Dec	2009	-4	-9	-12
Jan	2010	1	7	-11
Feb	2010	-10	-5	-11
Mar	2010	-17	-14	-15
Apr	2010	-15	-13	-14
May	2010	-9	-8	-10
Jun	2010	-4	-4	-5
Jul	2010	-2	-3	-3
Aug	2010	-1	-1	-1
Sep	2010	-2	-3	-4
Oct	2010	-3	-5	-7
Nov	2010	-3	-6	-9
Dec	2010	-3	-7	-10

11.5 DISCUSSION

The analysis was based on a single-cohort model that investigated the effect of one-monthly closures on total tiger catch and value. This stock is currently perceived to be exploited at a sustainable level and additional effort reductions are not necessary to preserve the stock from overfishing. In this context, our purpose in using closures was to illustrate how the model can be used to compare different effort patterns to increase yield and value, and to reduce operational costs: we do not recommend the use of these results for management purposes. The population dynamic model needs further development to provide a realistic representation of the dynamic of this stock. In particular, the decrease in CPUE in winter induced by temperature (Arreguin-Sanchez 1996; Hill 1985) should be taken into account in the assessment of the profitability of a unit of effort at a different time during the year.

Positive effects on catch and value were found using closures in January and February, which are equivalent to increasing the size of prawns at first capture. The magnitude of these benefits depended on the selectivity of the mesh: the smaller the weight at 50% selectivity ($S_{50\%}$), the larger the benefit from reducing growth overfishing. Given that the parameterisation of the selectivity function is uncertain, it would be advantageous to collect tiger catch size-composition data to reduce the uncertainty on the outcome of implementing such a change in harvest strategy. Currently, adopting the industry position on selectivity, the economical benefit of avoiding catching small prawns in January is in the order of magnitude of 10%, corresponding approximately to an increase in revenue in the order of $150,000.

The assumption that the tiger prawn catch was composed of a single cohort might have overestimated the effect of a monthly closure: the simulation study by Watson *et al.* (1995) concluded that wrongly representing a multi-cohorts population by a single-one exaggerated the benefit of seasonal closures. Thes modelling presented here was essentially a yield-per-recruit analysis which altered the size and age at which the prawns were harvested. Given the historical trends in the fishery, it seems possible that further improvements in yield, value and profitability might also be achieved by way of manipulating effort levels, in addition to or instead of temporal closures.

There is a risk associated with implementing temporal closures at fixed dates because the timing of recruitment varies from year to year. Both the cohort dynamic analysis and fishers indicated that recruitment to the fishery varies by approximately 15 days around its mean: recruitment from an early year can occur up to one month before that of a late year. Therefore implementing a temporal closure on specific dates each year would prevent industry from exploiting an early recruitment cohort of prawns. In such a situation, growth-overfishing may be more efficiently dealt with by modifying the selectivity of the gear, rather than a closure.

Yield-per-recruit analysis often assumes that fishing mortality is constant throughout the year. This assumption is not consistent with the effort pattern observed in Moreton Bay which was found to be highly correlated with water temperature. Sea temperature is known to affect the duration of emergence of tiger prawns (Hill 1985) and is thought to influence catchability. Incorporating this biological constraint into this fishery model would certainly improve the description of past observations and the predictions of catch resulting from varying effort distribution.

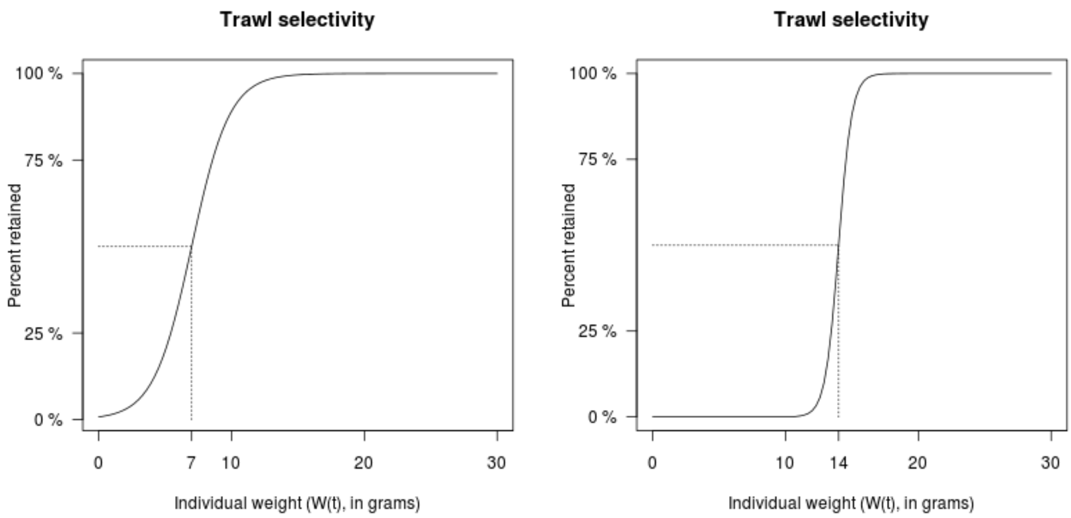

Figure 11-1. The two-gear selectivity curves used in the model. Left curve is based on Kimura's method applied to research data ($S_{50\%}$ = 7 g). Graph on the right side is according to fishers ($S_{50\%}$ = 14 g).

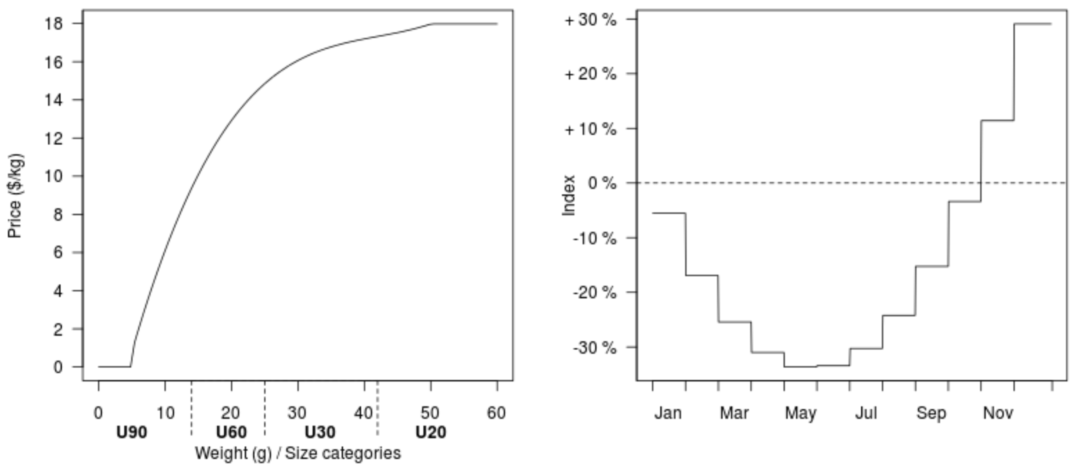

Figure 11-2. Economic input to the tiger prawn model: price per kg (left panel) and seasonal price index (right panel).

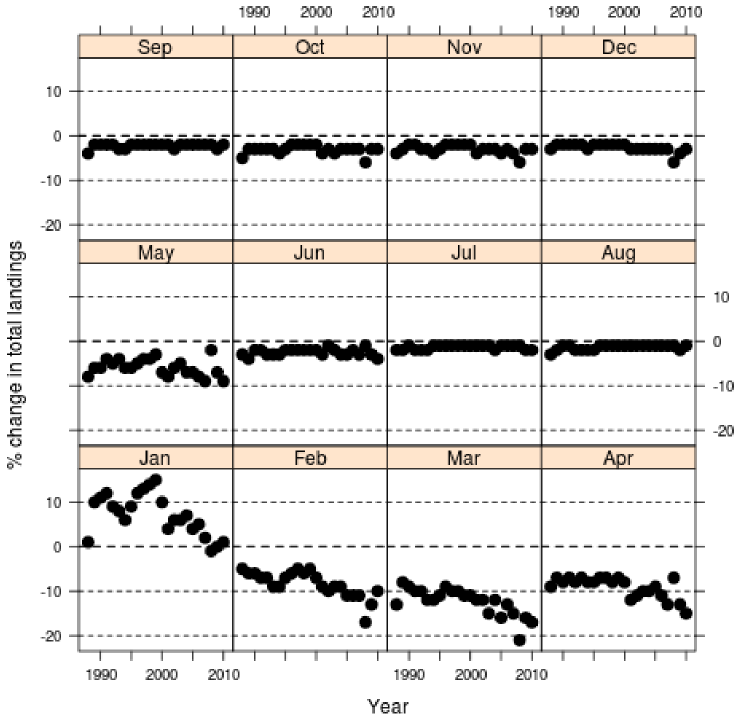

Figure 11-3. Effect on total tiger prawn catch from a one-month fishing closure (each panel) for each year between 1988 and 2010, assuming $S_{50\%}$ = 14 g.

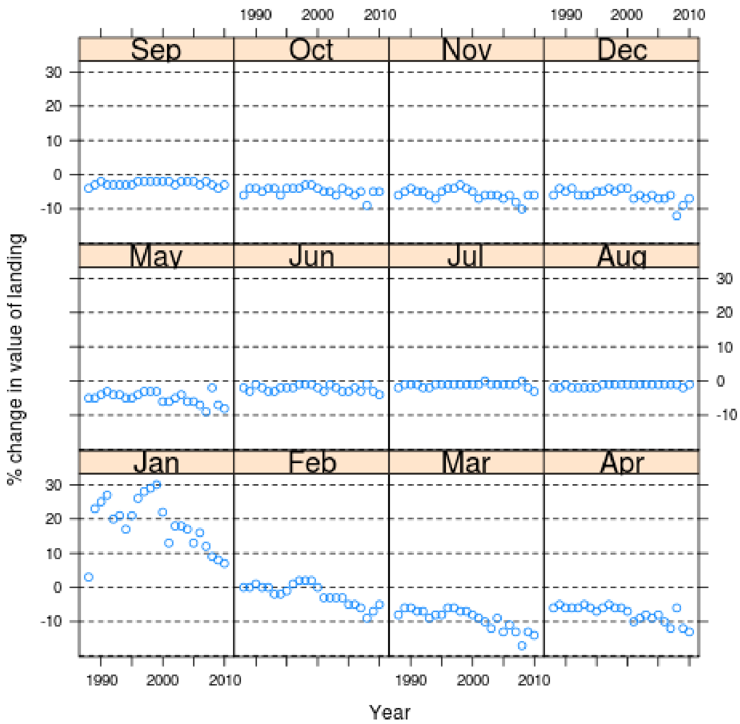

Figure 11-4. Effect on total tiger prawn catch value from a one-month fishing closure (each panel) for each year between 1988 and 2010, assuming $S_{50\%}$ = 14 g.

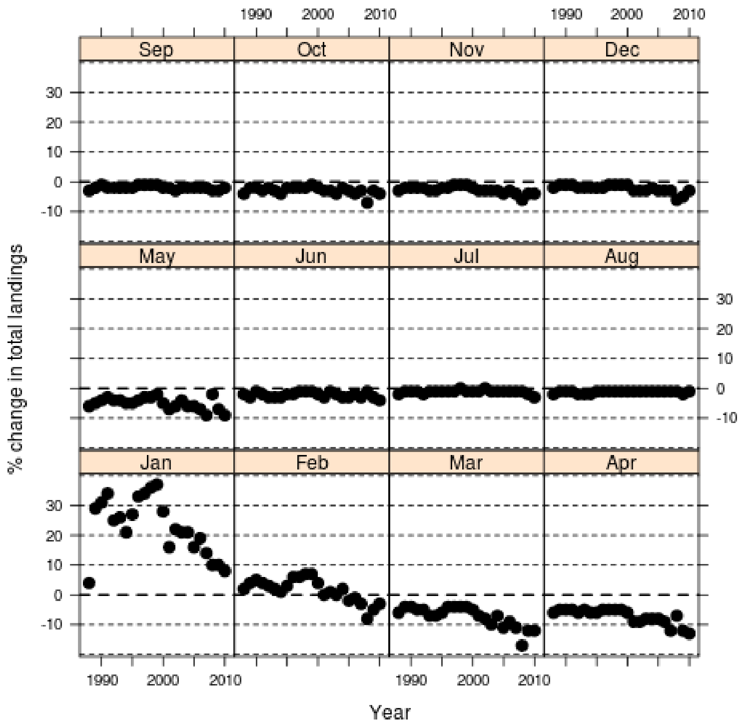

Figure 11-5. Effect on total tiger prawn catch from a one-month fishing closure (each panel) for each year between 1988 and 2010, assuming $S_{50\%}$ = 7 g.

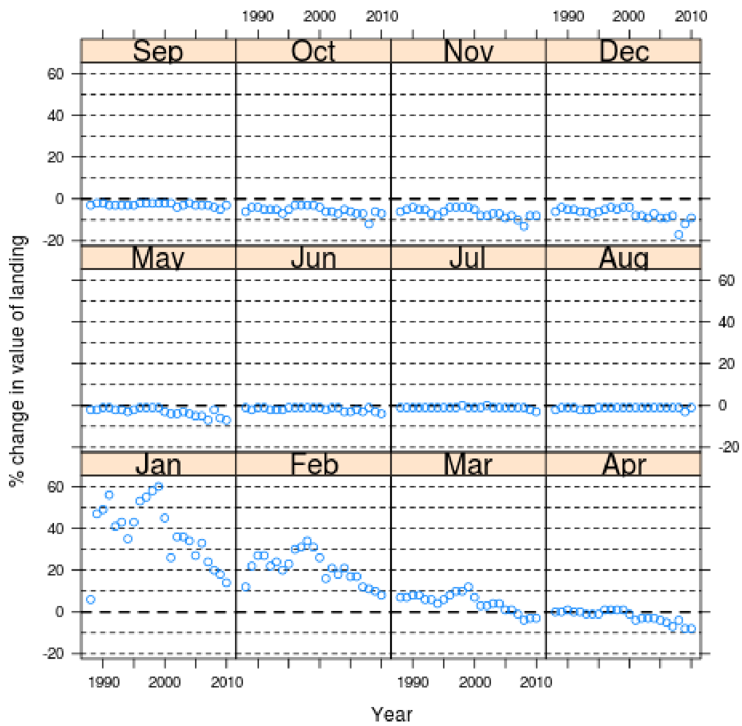

Figure 11-6. Effect on total tiger prawn catch value from one-month fishing ban (each panel) for each year between 1988 and 2010, assuming $S_{50\%}$ = 7 g.

12 Spatial population dynamics of Brown Tiger Prawns in Moreton Bay (Objectives 5A and 5D)

By G. Leigh and M. O'Neill

This section of the report addresses:
Objective 5A. Develop optimal temporal and spatial harvesting patterns in the bay, considering a range of effort levels, to maximise the sustainable catch value for the four main prawn species (Greasybacks, Eastern King Prawns, Brown Tiger Prawns and Banana Prawns), and
Objective 5D. Collate all sampling information for the bay to provide clearest possible fine-scale picture of variable prawn recruitment and seasonal prawn behaviour (e.g. 'Cleveland' juvenile tiger study and Long-Term Monitoring Program work).

12.1 ABSTRACT

This section of the report presents an alternative analysis of the Brown Tiger Prawn population dynamics in Moreton Bay, using generalised linear models and spatial data on the six-minute by six-minute logbook grid site scale. To improve profitability of the fishery, it is suggested that fishers consider closing the fishery from June to October, which is already a period of low profitability. This would protect the spawning stock of Brown Tiger Prawns, increase the catch rates in the lucrative pre-Christmas period (November–December), and provide fishers with time to do vessel maintenance, arrange markets for the next season's harvest, and, if they wish, work at other jobs. Currently, effort in the fishery is low and spawning stock closures are not required, but a closure for some or all of the June–October period would help to protect spawning stock in the future, if the level of effort increases beyond that corresponding to maximum sustainable yield. The analysis provides a different view of the population from the model presented in sections 10 and 11. It shows that the instantaneous total mortality rate (Z) for Brown Tiger Prawns, measured over the March–June period, has not changed significantly since 1990, despite a large decline in fishing effort. This result is ascribed to density-dependent natural mortality (M), whereby the increase in the Brown Tiger Prawn population over the years has had the consequence of increasing the natural mortality rate. In contrast, the mortality rate of prawns over the June–October period has decreased significantly over the years, in line with the decrease in fishing effort. This is consistent with a fall in instantaneous fishing mortality rate (F) for the June–October period from about 0.15 month^{-1} to about 0.05 month^{-1}, and with a non-density-dependent instantaneous natural mortality rate (M) for the June–October period. This increase in survival rate of Brown Tiger Prawns leading up to the main spawning period (October–November) may explain, in part, the observed increase in annual catches and catch rates of tiger prawns in the bay in recent years.

12.2 INTRODUCTION

Moreton Bay approximates the most southerly location for commercially exploited populations of Brown Tiger Prawns (*P. esculentus*) on Australia's east coast (Grey *et al.* 1983). As such, aspects of the species' population dynamics, particularly growth, spawning and recruitment are more seasonal than in the more tropical waters of North

Queensland and the Gulf of Carpentaria. Egg production and spawning in Brown Tiger Prawns in Moreton Bay is relatively succinct and peaks in October–November, with some egg production occurring through to May (Courtney and Masel 1997). Juveniles grow quickly over the summer (O'Brien 1994) and are highly attractive to fishers by autumn. They are inactive and difficult to catch over the winter, and grow very little during this time. Prawns spawned late in the season are not recruited to the fishery until the following spring. These prawns can be considered to be a second, smaller, cohort.

In addition to trawling, the tiger prawn population in Moreton Bay is also affected by the environmental conditions. Some of these abiotic influences are discussed in section 13. Air and sea surface temperatures, rainfall, freshwater flow, the condition and availability of Brown Tiger Prawn habitats, particularly seagrass, and chemical pollutants affect population size.

A spatial analysis of the commercial catch and effort data in Moreton Bay is presented below, to try to gain an insight into the population dynamics and especially the mortality rates of tiger prawns over the period from 1988 to 2010 (i.e., the period for which logbook data are available). It would be desirable to analyse the data more thoroughly at a later date, to include factors that could not be considered here due to time limitations. The analysis presented here does not take into account the changes in fishing gear over the years, and does not quantify how the average weight of a tiger prawn changes with time of year. It has also not attempted to model whether tiger prawns were targeted in particular catch records, but has taken the view that fishers catch whatever happens to be there at the time and place that they fished. The analysis was performed in the software *R*, and the important code is listed in Appendix 4 of this report (section 23).

12.3 MATERIALS AND METHODS

12.3.1 Data preparation

Catch records from the CFISH database maintained by Fisheries Queensland were restricted to those Moreton Bay records in which catch from the six-minute by six-minute grid sites had been recorded, and years between 1988 and 2010 inclusive. The raw fields were used; these are the names used in the *R* code for the analysis (see Table 12-1). To these were added fields derived from the above fields (Table 12-2).

Data were condensed to ensure that there was no more than one record per fisher per night. Where a fisher fished in multiple grid sites on one night, all the resulting catch was allocated to the grid site with the greatest catch weight for that fisher on that night. Grid sites with less than 20 tonnes total catch were excluded from further analysis. The number of grid sites in the analysis was thereby reduced from 24 to 12. The number of fishers was also reduced from 383 to 120 by excluding records from fishers who fished in only one year, had ten records or less in total, or caught less than 200 kg of tiger prawns in total (over all years).

Table 12-1. Raw data fields used to derive catch, effort and catch rates for Brown Tiger Prawns. Fields marked * are factors (categorical variables); the other fields are continuous variables.

Field name	Meaning
`Auth`*	Boat identifier (= Authority chain number from CFISH database)
`Date`	Date of catch
`GridSq`*	Grid square (30 minute, code as in CFISH database)
`Site`	Grid-site within `GridSq` (6 minute, as in CFISH database)
`Tiger`	Catch weight of tiger prawns (kg)

Table 12-2. Derived variables used in calculation of catch, effort and catch rates for Brown Tiger Prawns. Fields marked * are factors (categorical variables); the other fields are continuous variables.

Field name	Meaning
`Lat`	Latitude (decimal degrees)
`Long`	Longitude (decimal degrees)
`Cell`*	Combination of `Lat` and `Long`, to produce a single field that uniquely identifies the 30-min by 30-min grid and the six-minute by six-minute grid site
`Year`	Year of catch
`Month`	Month of catch
`Day`	Day of catch, within `Month`
`MonthSeq`	Sequential month, beginning from 1 in January 1988 and proceeding up to 276 in December 2010
`fYear`*	`Year` expressed as a factor
`fMonth`*	`Month` expressed as a factor
`fMonthSeq`*	`MonthSeq` expressed as a factor
`CatchId`*	Combination of `Auth`, `Year`, `Month` and `Day`, to produce a unique identifier for each catch record

12.3.2 GLM to calculate effective fishing effort

A generalised linear model (GLM) was used to estimate the relative effectiveness of each boat in the Moreton Bay otter trawl fishery. The analysis was applied to all catch records, even those with zero catches of tiger prawns. No judgment was made as to whether fishers were targeting Brown Tiger Prawns.

The boat coefficients from the GLM provided the effective fishing effort expended by each boat.

Ideally, it would be desirable to make the vessel identifier (`Auth`) a random effect rather than a fixed effect, allow for the increase in fishing power due to gear upgrades on the boats, and examine the model-fit in detail, but time did not permit.

After fitting the GLM, catch data were aggregated to produce a single record for each year-month-cell combination. This record includes a field for effective fishing effort, which was the sum of boat coefficients for all boat-nights for which catches were reported in that year, month and cell.

12.3.3 Catch curves

A 'catch curve' was defined from March to June in each year; a period of seasonally declining catch rates. Catch curves are used to estimate the instantaneous total mortality rate (Z) in a population, which is the sum of the instantaneous fishing mortality rate (F) and the natural mortality rate (M) (Sparre and Venema 1998). Ideally, catch-curve analysis should be applied to population abundance measured in numbers (not weight), and there should be no recruitment, migration or change in catchability over the study period.

The above conditions were not fully met in this case; however, the aim of the present analysis was to compare different years. The comparison of years should still be valid, provided that there has not been any major change in the patterns of growth and migration over the years. Nevertheless, grid sites that appeared to be affected by migration were excluded from catch-curve analysis (see below).

The catch-curve method works by assuming that the logarithm of catch rate follows a straight line over time. A separate catch curve was fitted to the March–June period for each year, using a generalised linear model. The *R* code is listed in section 23 (Appendix 4: *R* code for analysis in section 12).

12.3.4 Survival from June to October

The survival rate of prawns from June to October was analysed by another generalised linear model, using catch rate data from June and October. That is, survival was based on the adjusted catch rate in October divided by the adjusted catch rate in June. This analysis did not produce a usable estimate of the absolute survival rate each year, because the catchability of prawns was higher in October than in June. However, it did allow comparisons between different years, to see whether the survival rate had changed over the years.

12.4 Results

12.4.1 Catch records by six-minute grid site

Numbers of data records by six-minute grid site are provided in Table 12-3. The corresponding total recorded catch in tonnes for each grid site over all years is provided in Table 12-4.

Table 12-3. Number of data records used in the analysis.

Latitude (°S)	**Longitude (°E)**			
	153.05	153.15	153.25	153.35
27.05	124	180	130	216
27.15	2068	8577	1504	238
27.25	126	18313	10377	8319
27.35	294	5414	7866	1687
27.45	65	320	1797	1133
27.55	0	1	4	403

Table 12-4. Catch weight (tonnes) of tiger prawns summed over all years, by latitude and longitude.

Latitude (°S)	**Longitude (°E)**			
	153.05	153.15	153.25	153.35
27.05	1.535	2.375	0.709	11.423
27.15	59.475	170.327	32.184	4.544
27.25	1.958	234.262	226.585	183.162
27.35	1.138	93.164	193.889	36.267
27.45	0.227	0.132	123.961	62.921
27.55	0	0.050	0.396	26.104

12.4.2 Catches by location and month

The catch weight of Brown Tiger Prawns by grid site and month, totalled over all years, is provided in Table 12-5. The `Site` field is, by chance, unique to each cell, despite providing no information about `GridSq`.

The highest proportion of Brown Tiger Prawns caught late in the year (when the prawns are largest) occurs at site 13, which is in the middle of Moreton Bay. This supports scientific opinion that there is minimal migration out through the north of Moreton Bay.

Table 12-5. The catch weight (tonnes) for tiger prawns caught in each six-minute grid site, summed for each month over all years.

Site	**Cell lat & long (°S, °E)**	**Calendar month number**											
		1	2	3	4	5	6	7	8	9	10	11	12
6	27.15, 153.05	11.4	16.3	14.0	11.1	3.4	0.4	0.1	0.1	0.1	0.4	0.7	1.5
7	27.15, 153.15	19.7	46.0	50.3	22.4	9.2	3.7	1.2	1.6	3.3	4.6	4.1	4.2
8	27.15, 153.25	2.8	4.9	8.5	2.9	2.2	0.6	0.1	0.2	1.4	2.5	2.7	3.5
12	27.25, 153.15	18.9	39.4	58.9	36.1	22.7	7.0	2.3	3.3	10.3	16.1	9.3	10.0
13	27.25, 153.25	20.7	33.9	45.5	30.6	24.0	6.4	2.4	1.3	9.6	19.3	18.1	14.8
14	27.25, 153.35	21.7	32.2	39.8	24.8	11.9	4.7	1.6	1.6	3.7	12.3	13.8	15.0
17	27.35, 153.15	10.5	20.1	30.8	14.0	4.3	1.0	0.3	0.4	1.5	1.8	2.7	5.7
18	27.35, 153.25	32.3	51.9	49.0	27.8	8.5	2.1	0.4	0.2	1.2	5.2	5.8	9.3
19	27.35, 153.35	3.3	5.9	6.0	6.9	3.7	2.4	0.4	0.2	1.3	2.2	1.9	2.1
23	27.45, 153.25	22.9	60.6	31.8	5.6	0.2	0.0	0.0	0.0	0.3	0.2	0.1	2.3
24	27.45, 153.35	5.6	22.4	24.5	7.2	0.7	0.2	0.0	0.0	0.0	0.0	0.1	2.2
4	27.55, 153.35	4.0	7.8	8.0	4.3	0.6	0.0	0.0	0.0	0.0	0.0	0.2	1.2

In the southern part of Moreton Bay (sites 23, 24 and 4), the catch weight declined more sharply in April, May and June than it does in the rest of the bay. This observation supports anecdotal information from fishers that the southern bay is a nursery area for young tiger prawns, which migrate into deeper water from April onwards. Sites 23, 24 and 4 are therefore omitted from the analysis of mortality rates presented below. If included, they would have made the estimates of monthly mortality too high.

12.4.3 GLM to calculate effective fishing effort

Total annual raw (i.e., unstandardised) trawl fishing effort in Moreton Bay was presented earlier in Figure 6-13. This effort covers all logbook records, including those for which the six-minute grid square was not recorded. The figure shows that effort declined by about a factor of three over the study period (1988–2010). Further analysis of this data used only a subset defined by the restrictions discussed above.

The boat coefficients from the GLM for effective fishing effort are plotted as a histogram in Figure 12-1.

12.4.4 Summary plots of effort and catch rate

The average fishing efficiency of boats in the fishery is plotted in Figure 12-2 (by sequential month) and Figure 12-3 (by calendar month averaged over all years). These figures show the relative effect of a day's fishing.

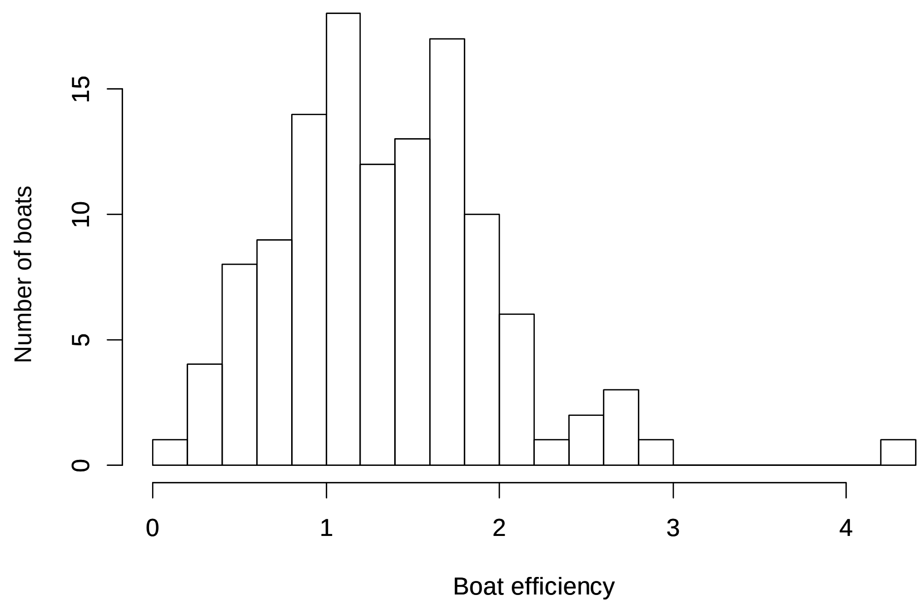

Figure 12-1. Histogram of boat efficiency (relative units), showing the range of efficiency of different boats at catching Brown Tiger Prawns.

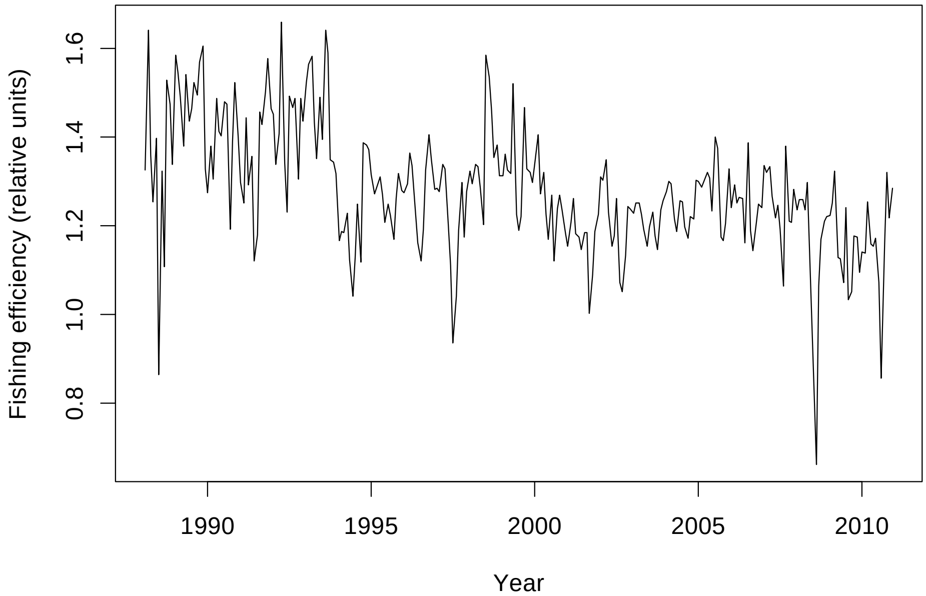

Figure 12-2. Average fishing efficiency of vessels for catches of tiger prawns, by sequential month.

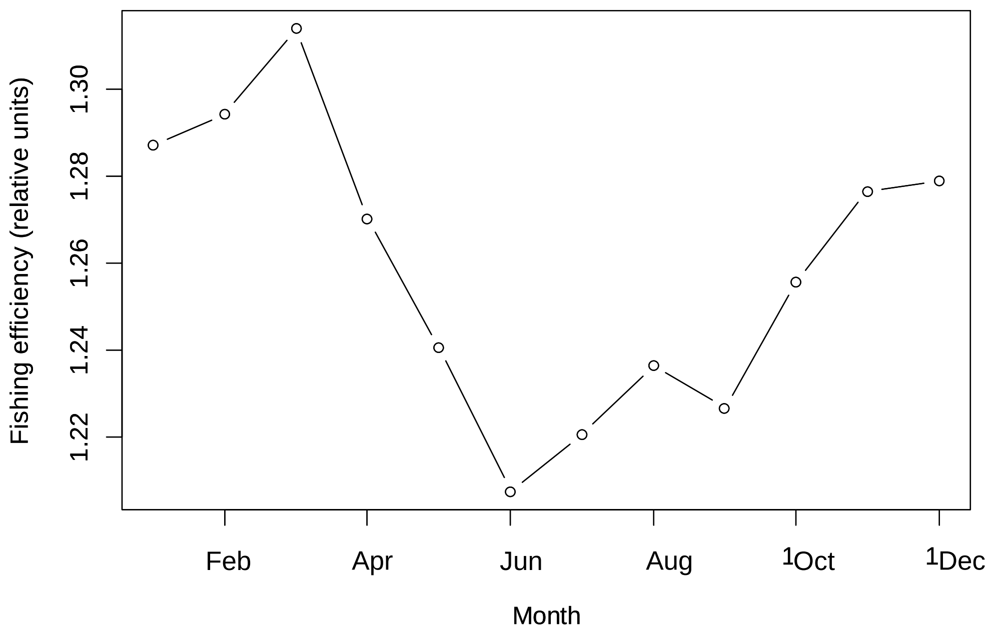

Figure 12-3. Average fishing efficiency of vessels for tiger prawn catches, by calendar month.

A remarkable feature of Figure 12-2 is that the efficiency gradually *decreases* over time, giving the impression that the contribution of fleet composition to fishing power has gone down since 1988. One sensible explanation for this trend is that reporting of six-minute grid sites may have been adopted only by efficient operators in the early years, and spread to less-efficient operators only gradually over the years, thereby dragging down the average. As explained in the data preparation (above), records that didn't provide the six-minute grid sites were excluded from analysis. Another possible explanation is that some efficient boats or operators had moved to other sectors of the QECTF, such as the offshore Eastern King Prawn fishery.

Figure 12-3 shows a peak in March and a trough in June. It indicates that between May and October the fishing tends to be undertaken by boats that are less efficient in catching tiger prawns, and which may specialise in other species.

The seasonal pattern of fishing effort (total amount of effective effort by month, summed over all years) is plotted in Figure 12-4. Effort is high from November to March and falls in the winter when the available biomass of tiger prawns is low and the prawns are harder to catch. This pattern is similar to trend in total trawl effort (i.e. all sites) in Moreton Bay (Figure 6-14).

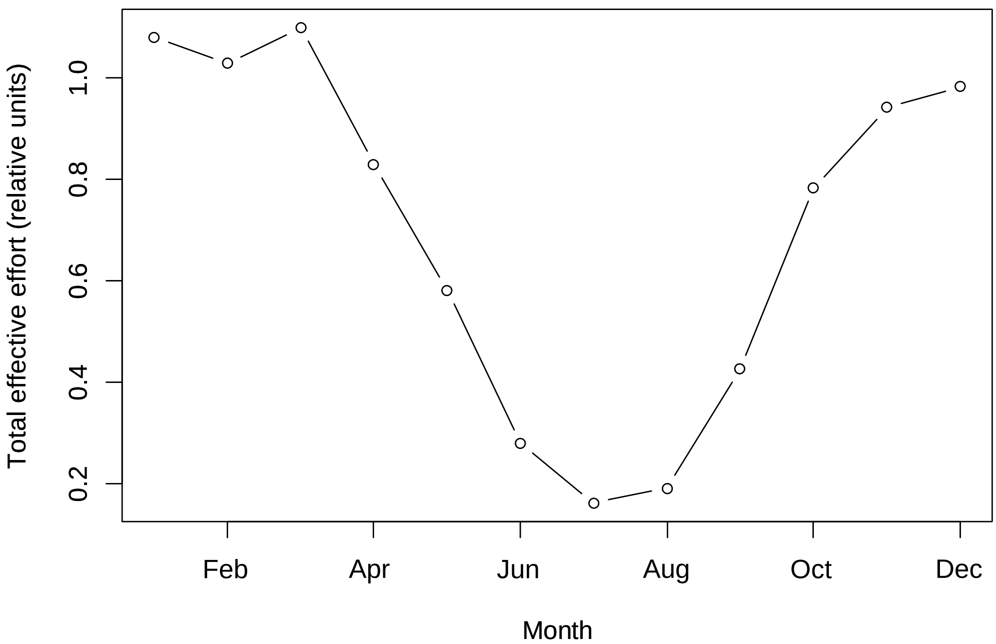

Figure 12-4. Seasonal pattern of fishing effort in select six-minute grid sites in Moreton Bay.

Figure 12-5 plots the catch rate (catch per unit effort) by sequential month from select six-minute grid sites, showing both the increase in abundance of Brown Tiger Prawns over the years and the seasonal pattern of decline due to mortality each autumn and inactivity in the winter. The increase in abundance is shown more clearly in Figure 12-6, which plots the annual average catch rate.

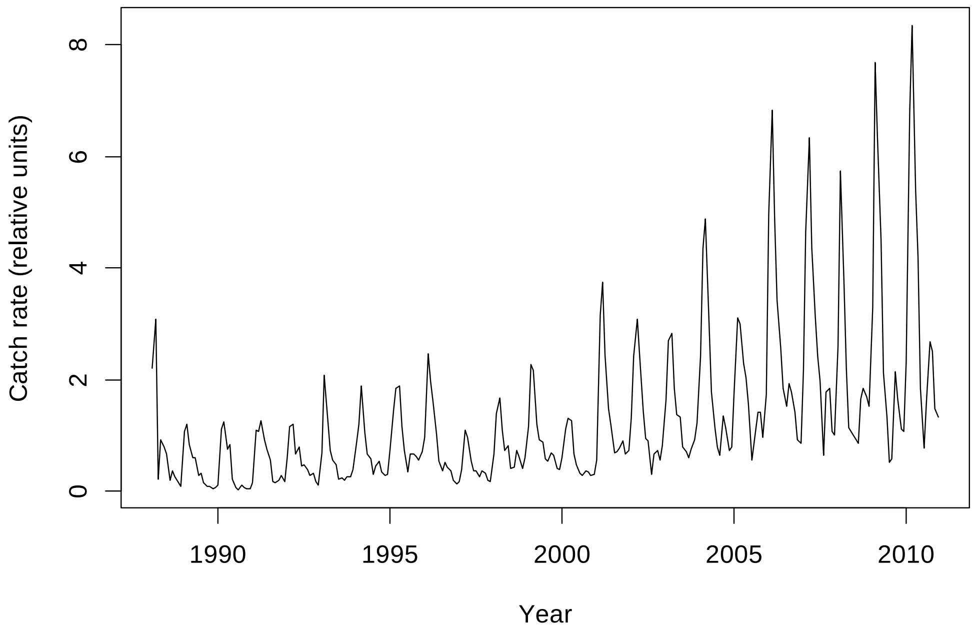

Figure 12-5. Monthly series of catch rate of Brown Tiger Prawns from select six-minute grid sites in Moreton Bay.

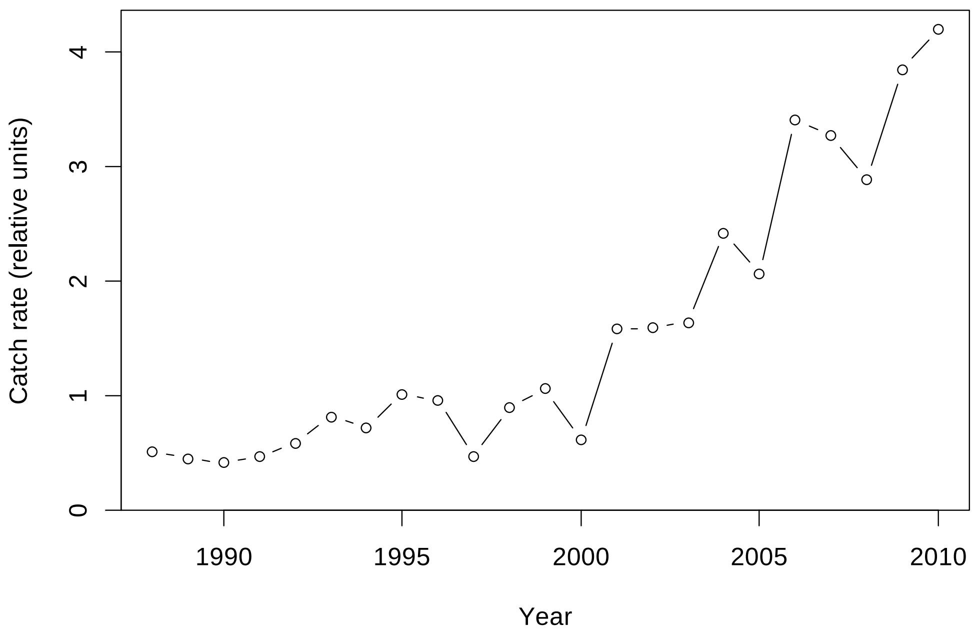

Figure 12-6. Annual series of catch rate of Brown Tiger Prawns from select six-minute grid sites in Moreton Bay.

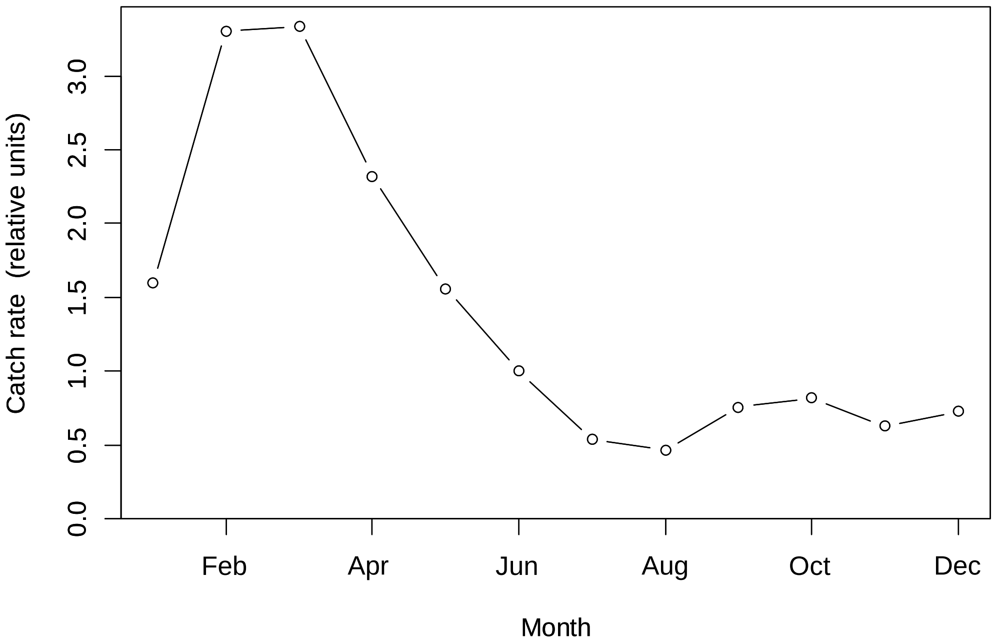

Figure 12-7. Seasonal catch rate of Brown Tiger Prawns from select six-minute grid sites in Moreton Bay.

12.4.5 Validity of catch curves

Figure 12-7 suggests that a catch curve could be meaningfully fitted only to data from March to June. Before March, substantial recruitment takes place. After June, the fishing effort is very low in July and August (resulting in inaccurate catch rates), and the catchability of tiger prawns probably increases in September and October, due to increasing temperature. The onset of spawning in October–November may also contribute to an increase in catchability at this time, especially for adult females which may need to spend more time feeding (and hence, are more catchable) as their ovary weight increases (Courtney and Masel 1997).

The data to fit a catch curve for each year are plotted in Figure 12-8. The lines in the figure are roughly straight except for the early years (1988–91) when the logbook system was new and there may have been implementation problems with it.

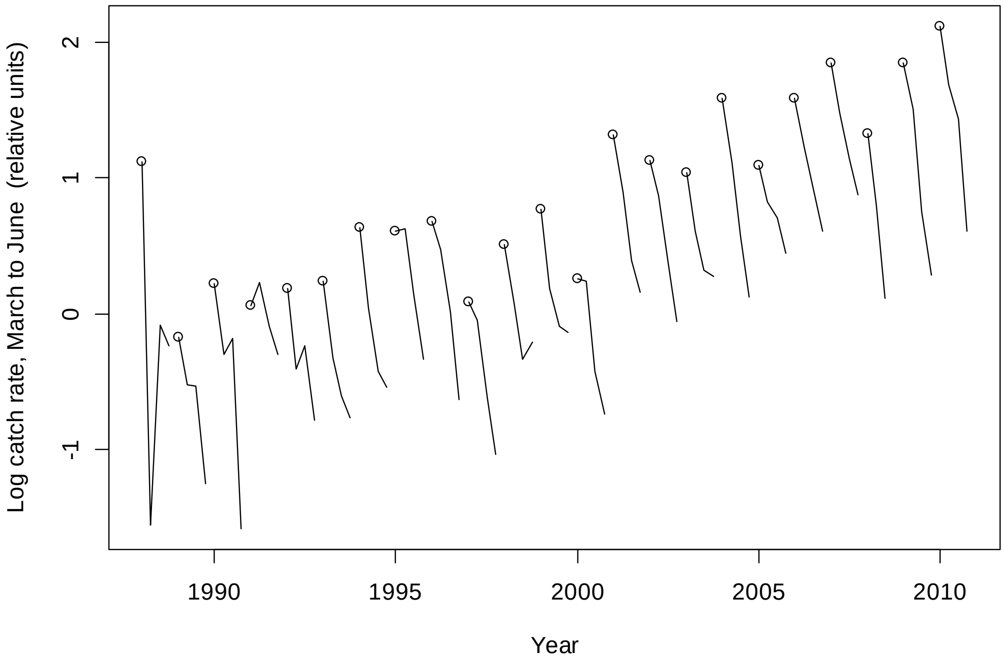

Figure 12-8. Logarithms of catch rates from March to June each year, to which straight lines can be fitted to provide an estimate of the Brown Tiger Prawn's monthly total mortality rate for each year.

12.4.6 Seasonal effort and catch rate by location

Seasonal patterns of fishing effort and catch rate for each site are plotted in Figures 12-9 and 12-10. Figure 12-9 shows that, in the southern part of the bay (sites 23, 24 and 4), the effort is very low from April to November. We presume that fishers refrain from fishing these sites at these times because there are very few prawns there. Hence these sites appear to function as tiger prawn nurseries: prawns migrate out of them from April onwards. Fishers have commented that they catch large tiger prawns in site 4. Possibly the extreme southern part of Moreton Bay, with its multitude of small islands, is more productive for tiger prawns, and allows them to grow faster.

Figure 12-10 shows abnormally high catch rates (i.e., substantially higher than indicated by catch-curve theory) in site 18 in April and in site 19 in May. This observation is consistent with the above migration hypothesis; it appears that prawns from the southern part of the bay migrate *into* sites 18 and 19. Therefore sites 18, 19, 23, 24 and 4 were excluded from the detailed catch-curve analysis presented below. To include sites 18 and 19 would have artificially decreased the total mortality rates, while to include sites 23, 24 and 4 would have artificially increased them.

There are also suggestions of abnormally high catch rates in May in sites 8 and 13. These sites are not adjacent to the presumed nursery area, so it was more difficult to make a case for their exclusion. The discrepancies could be due simply to random error.

Sites 8, 13, 14, 19 and, to a lesser extent, 12, show sharp increases in catch rates in September, indicating the probable presence of prawns from the previous season in these sites. These sites may constitute a spawning ground and destination for large adult prawns. The catch rates fall again in November, indicating that the effort is not directed at new-season recruits.

The above points provide the rough picture of migration of Brown Tiger Prawns within Moreton Bay shown in Figure 12-11. The overall trend is for prawns to migrate to the north-eastern part of the bay. This is consistent with the movements derived from the tag-recapture study of Brown Tiger Prawns in the bay in the early 1970s (Figure 6-8). Seasonal length-frequency data on a fine spatial scale would have provided better information than this inference based on catch rates, but such data were not available.

The fishing effort from September onwards (Figure 12-9) rises comparatively much faster than the Brown Tiger Prawn catch rate. This time of year in Moreton Bay is associated with high catches of Eastern King Prawns and Greasyback Prawns, so most of the effort is not directed at tiger prawns.

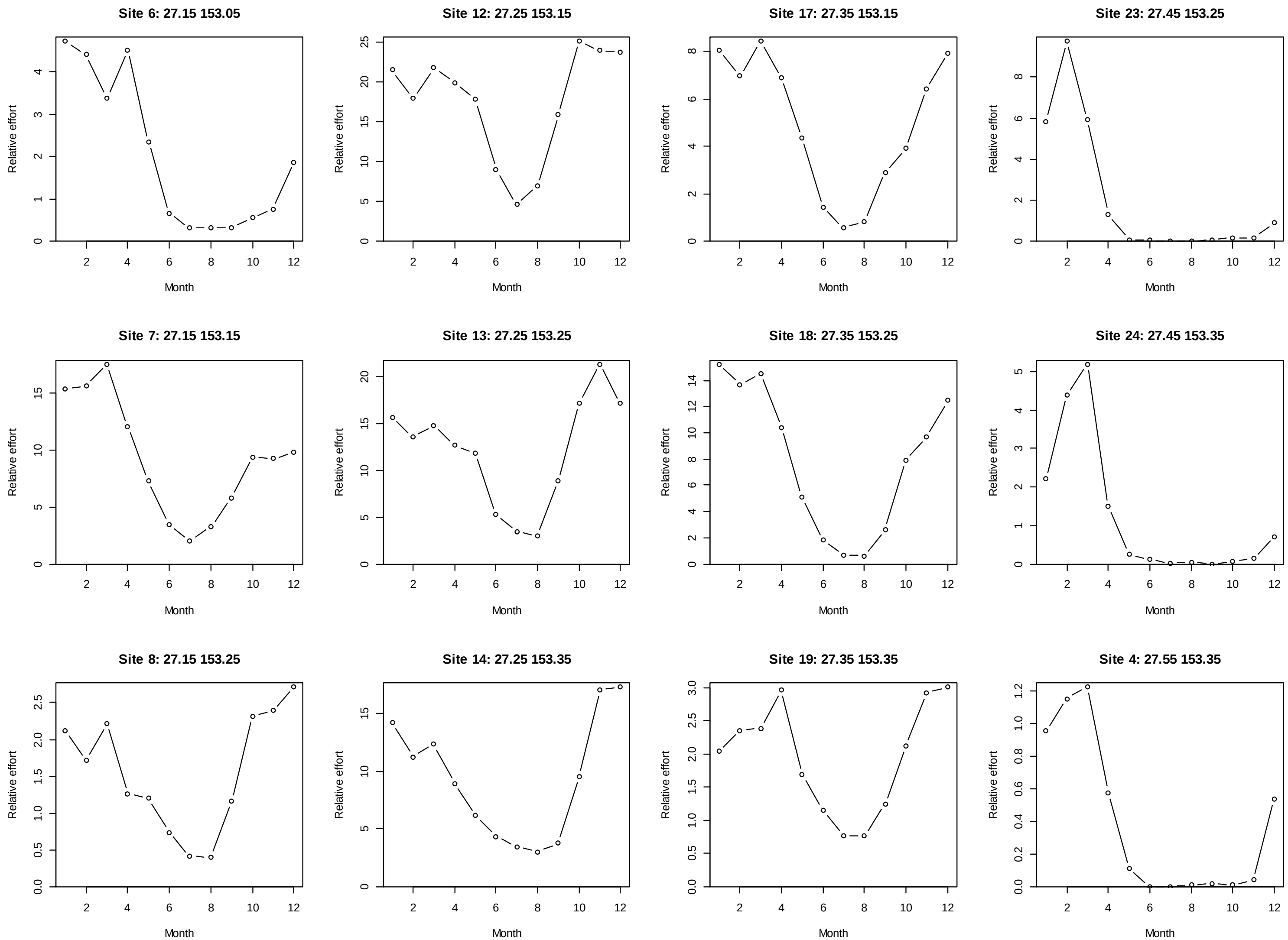

Figure 12-9. Relative fishing effort expended, by season and six-minute grid site, showing very low effort in the southern part of the bay (Sites 23, 24 and 4) from April to November.

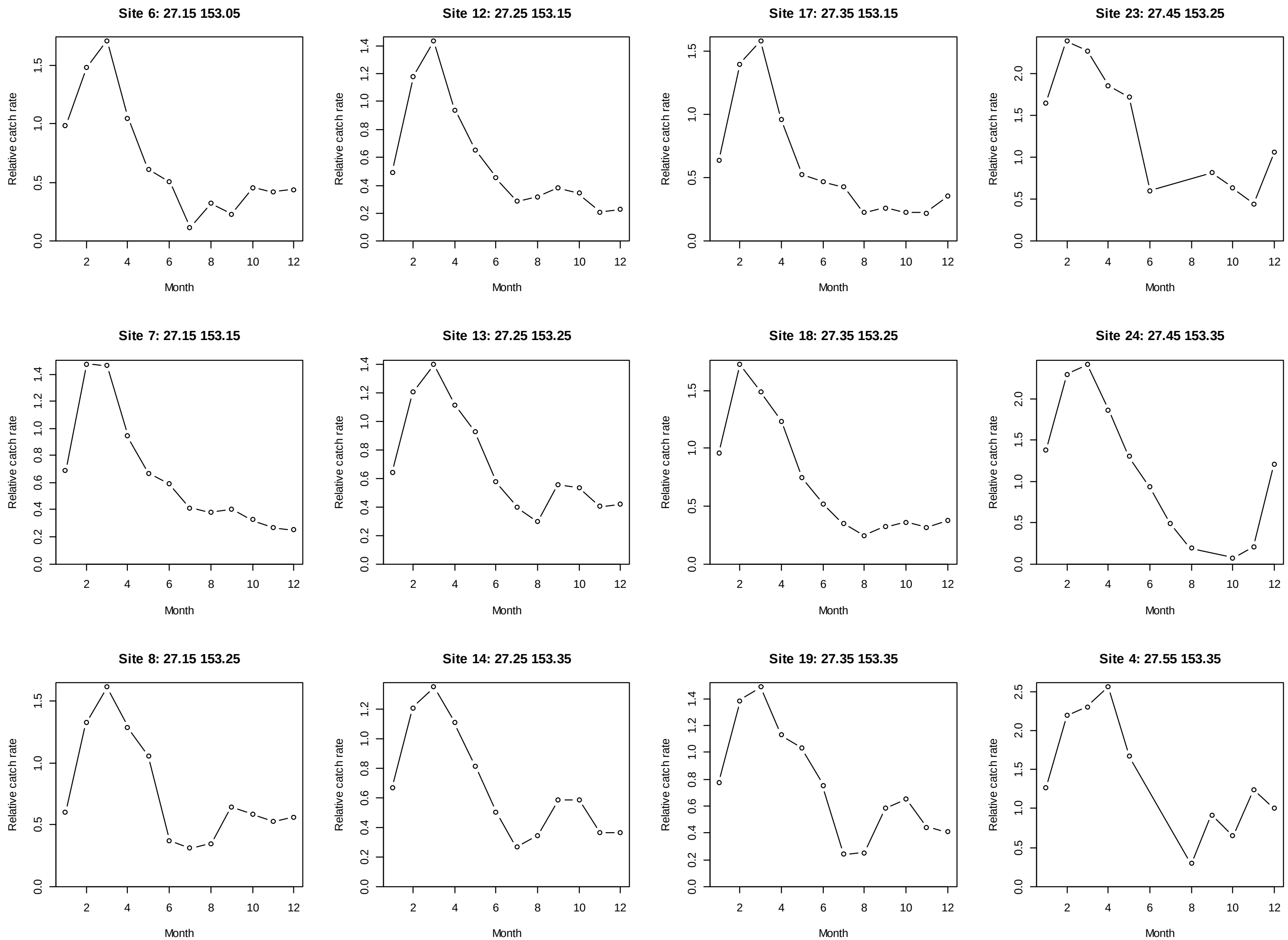

Figure 12-10. Relative catch rates of Brown Tiger Prawns, by season and location, showing abnormally high catch rates in Site 18 in April and Site 19 in May, which appear to be due to immigration from Sites 23, 24 and 4.

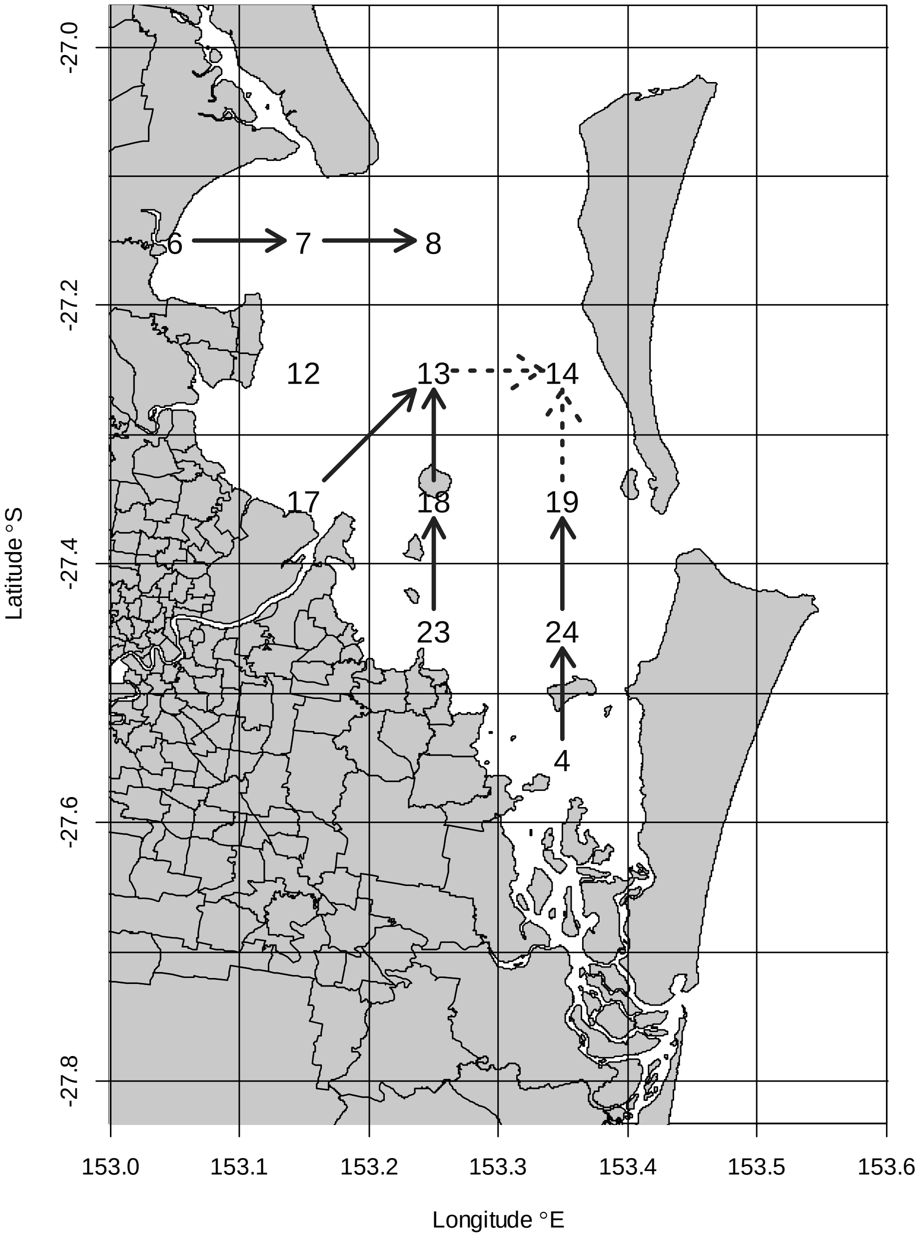

Figure 12-11. Migration patterns of Brown Tiger Prawns within Moreton Bay, imputed from seasonal catch rates. Fine-scale information on seasonal lengths of prawns would have been a more authoritative data source, but was not available. The arrows indicate directions of migration. Dotted arrows indicate that many large prawns remained in sites 13 and 19.

12.4.7 Estimation of total mortality rate from March to June

The total mortality rate (Z) was estimated by the method of catch curves, as described in section 12.3.3. The instantaneous total mortality rate, measured from March to June each year, is plotted in Figure 12-12. It is evident that the total mortality rate has, if anything, increased over the years. It has not decreased, as would be expected from the significant decline in fishing effort, if the natural mortality rate (M) were constant. This result is consistent with the hypothesis that natural mortality is density-dependent, and the natural mortality rate has increased as the population size has increased.

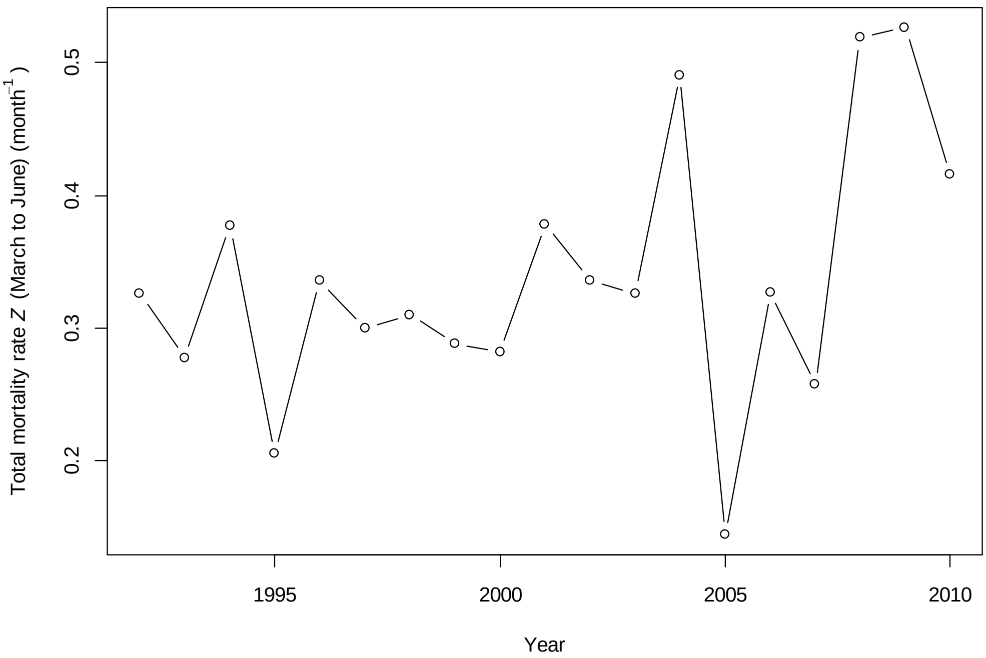

Figure 12-12. Estimates of total mortality rate by year for the March–June period, for select six-minute grid sites in Moreton Bay.

12.4.8 Survival from June to October

The relative abundance of tiger prawns in June each year, as estimated from the catch curve analysis, is plotted in Figure 12-13. This figure shows an increase over the years, but by a somewhat lesser rate than the increase in year-round tiger prawn abundance.

For analysis of the abundance of large prawns late in the calendar year, sites 6 and 17 were omitted from the analysis. Catch rates at these sites showed no decrease in November and December, indicating that they may have considerable large numbers of new recruits. Analysis late in the year therefore included only sites 7, 8, 12, 13 and 14.

The estimated mortality rate from June to October is plotted in Figure 12-14 and shows a gradual decrease, by about 0.09 month^{-1} from 1992 to 2010 (apparent values roughly from 0.15 to 0.06 month^{-1}). The year 2008 was regarded as anomalous, because the estimated abundance in June was very low (Figure 12-13) but in October was normal. This year was omitted from the fitted straight line in Figure 12-14. The linear decrease in survival rate is statistically significant ($t_{1, 16} = 3.316$; $P < 0.005$). The decrease in mortality rate can be compared with the decrease in effort shown in Figure 6-13.

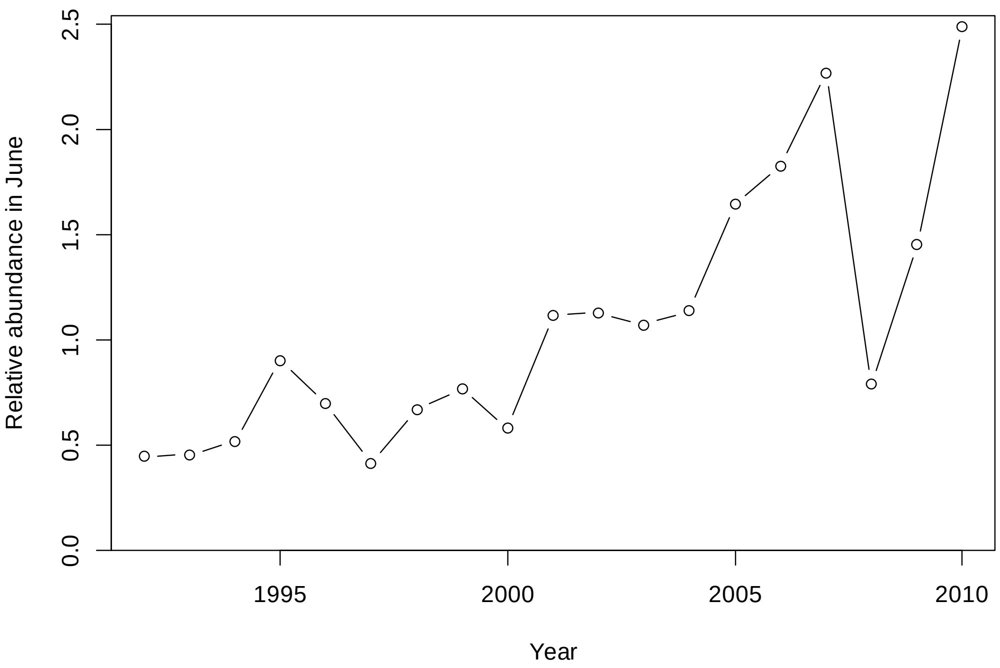

Figure 12-13: Estimated relative abundance of tiger prawns in June each year, from select six-minute grid sites in Moreton Bay.

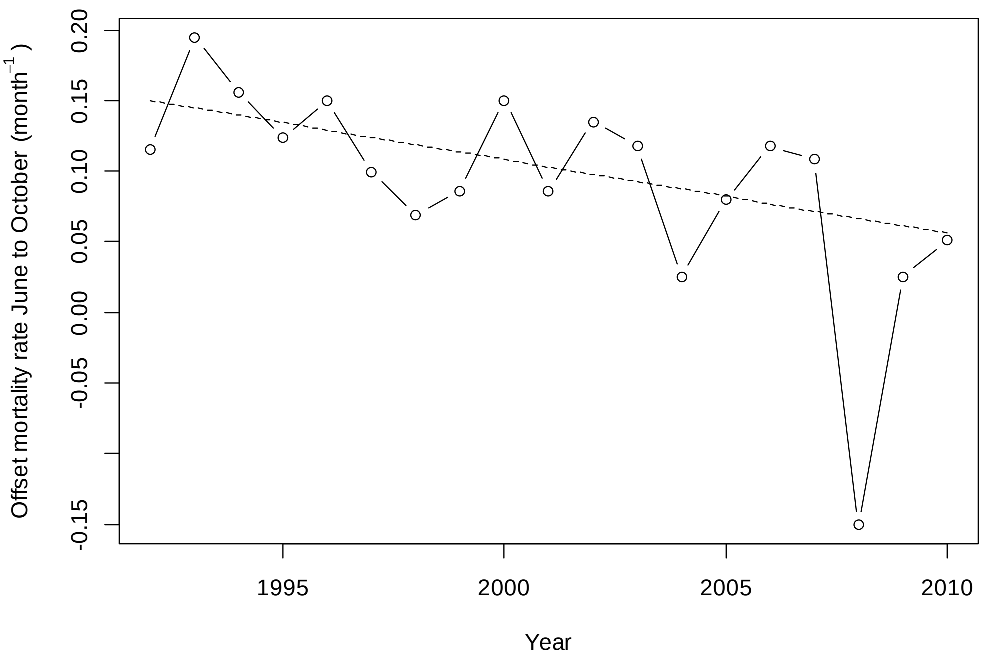

Figure 12-14: Estimated mortality rate of tiger prawns from June to October, with a fitted straight line (which excludes 2008). The value plotted is 'offset' from the true mortality rate because it does not take into account the increased catchability of tiger prawns in October: only changes from year to year are important, not the literal levels.

Figure 12-14 does not take into account the difference in catchability of tiger prawns between June and October. As ovary development increases rapidly in the October–November spawning period, the adult female prawns may need to consume more food to support the development. This change in behaviour may further increase their catchability at this time. Therefore only changes from year to year are important in Figure 12-14, not the literal levels. Indeed, it is possible for the apparent mortality rate to be negative, which would be nonsense but for the catchability effect combined with some growth of individual prawns over the period.

12.5 DISCUSSION

The results indicate that:

1) The population size of Brown Tiger Prawns in Moreton Bay has increased dramatically over the period that the logbook data are available (i.e., 1988–2010), especially from 2001 onwards.
2) The total mortality rate from March (the peak month for fishing effort) to June appears not to have changed significantly, despite a big fall in annual fishing effort. This may be due to compensatory natural mortality, whereby as the population size has increased, so has the natural mortality rate.
3) The total mortality rate of tiger prawns from June to October has significantly decreased. This decrease is more gradual over many years than the rise of tiger prawn abundance and the decrease in fishing effort, which both began fairly suddenly in 2001.

It is difficult to judge the relative contributions of the reduction in fishing effort versus environmental effects in the recovery in the tiger prawn population. Environmental effects may include a decrease in chemical pollution of Moreton Bay as public awareness and government regulation have taken effect, and possible recovery of seagrass beds that serve as nursery areas. Moreton Bay trawl fishers have stated that these effects are important, and that Moreton Bay is much less polluted today than it was 20 years ago, but firm scientific data are not available. The drought that prevailed in southeast Queensland from about 1999 to 2007 may have reduced the amount of agricultural nutrient runoff entering Moreton Bay from the Brisbane River. A reduction in excess nutrients is probably good for Brown Tiger Prawns because the nutrients feed algae that block sunlight from reaching seagrass. The drought may well have facilitated recovery of seagrass beds in the bay, possibly contributing to the increase in tiger prawn population size.

If the increase in survival rate from June to October were due purely to the reduction in fishing effort, it would allow some very rough calculations of mortality rates, as follows. The log-survival rate (Figure 12-14) has risen by about 0.4 since 1990. Dividing by the time period (four months), this equates to a decrease of about 0.1 month^{-1} in the average instantaneous total mortality rate (Z), and hence also in the average instantaneous fishing mortality rate (F). If F has fallen by the same factor as effort (i.e., a factor or three), then F for June–October may have fallen from about 0.15 month^{-1} to about 0.05 month^{-1}.

Inference of mortality rates for the March–June period is even more speculative, but the following comments can be made. The value of F for the March–June period is probably higher than for June–October, due to the very low levels of effort in July and August. Also, the fishers have probably become better at targeting tiger prawns in the first half of the year, because the relative price has improved compared to smaller prawns, especially Greasyback Prawns; hence F for March–June has probably fallen by a factor of less than three. A factor of two may be reasonable, and a very rough estimate may be that the value of F for March–June has fallen from about 0.2 month^{-1}

to about 0.1 month^{-1}. Given the estimate of Z of about 0.3 month^{-1} from Figure 12-12, the value of the instantaneous natural mortality rate (M) for March–June may have increased from about 0.1 month^{-1} to about 0.2 month^{-1}.

The analysis indicates that fishing mortality in the June–October period may be an important factor in the population dynamics of tiger prawns. Fishing in this period may disproportionately deplete the spawning stock, possibly due to high catchability of prawns in September, October and November, as females prepare for spawning.

To improve profitability of the fishery, it is suggested that fishers consider closing the fishery in the period from June to October, which is already a period of low profitability. This would protect the Brown Tiger Prawn spawning stock, increase the catch rates in the lucrative pre-Christmas period (November–December), and provide fishers with time to do vessel maintenance, arrange markets for the next season's harvest, and, if they wish, work at other jobs. Currently, effort in the fishery is low and spawning stock closures are not required, but a closure for some or all of the June–October period would help to protect spawning stock in the future, if the level of effort increases beyond that corresponding to maximum sustainable yield.

Because of the importance of the June–October period, a closure for some or all of this period may be highly effective at both maintaining spawning stock and improving fishers' profitability. The following points offer support for this strategy:

- The June–October period is already a time of low fishing effort and low profitability.
- Even this low level of fishing may have a detrimental effect on the Brown Tiger Prawn spawning stock.
- Prawn stocks that have not been fished for several months would provide higher catch rates during the pre-Christmas (November–December) period, during which product prices are high.
- A winter closure may improve fishers' lifestyles by providing more time for vessel maintenance, product marketing, recreation, holidays, and possibly working in other jobs.
- Such a closure would safeguard against a future rise in effort levels, which may occur if otter trawling in Moreton Bay becomes more profitable.

It is emphasised that at current effort levels there is probably no need for a closure to maintain spawning stock and recruitment. Still, fishers may wish to consider the costs and benefits, and compare a winter closure to other possible closure periods.

13 Abiotic influences on the abundance and catch rate of commercially important prawns in Moreton Bay (Objective 5B)

By A. Courtney and M. O'Neill

This section of the report addresses:
Objective 5B. For the four important prawn species in the bay, identify empirical evidence for the environmental factors driving the variable strength of prawn recruitment and the timing of seasonal prawn behaviour, which are both strongly evident in the bay. The predictive outcome of the work will allow dynamic-tuning of harvest/market strategies to better capture the opportunities presented by variable environmental conditions and also mitigate associated risks.

13.1 Abstract

This section of the report investigated the effects of air temperature, rainfall, freshwater flow, the southern oscillation index (SOI) and lunar phase on the catch rates of four commercially important prawn species in Moreton Bay. The response variable was prawn catch rate, based on over 200,000 daily logbook records from the fishery over 23 years (1988–2010). Freshwater flow was deemed to have a much more significant effect on the prawn catch rates than rainfall and SOI. The effects of Brisbane River flow were examined as this was the largest river in the region with the greatest volume of freshwater flowing into the bay. Flow in the preceding month prior to catch (i.e., 30 days prior; Logflow1_30) and two months prior (31–60 days prior; Logflow31_60) had strong positive effects on Banana Prawn catch rates. Average air temperature in the preceding 4–6 months (Temp121_180) also had a large positive effect on Banana Prawn catch rates. Flow in the month preceding catch (Logflow1_30) had a strong positive influence on Greasyback Prawn catch rates. Air temperature in the preceding two months prior to catch (Temp1_60) had a large positive effect on Brown Tiger Prawn catch rates. No obvious abiotic influences were detected for Eastern King Prawns, although catch rates declined with increasing air temperature 4–6 months prior to catch. As most Eastern King Prawn catches occur in October to December in the bay, this indicates that catch rates for this species decline with increasing winter temperatures. In most cases, the prawn catch rates declined with the waxing lunar phase (i.e., high luminance/full moon), and increased with the waning moon (i.e., low luminance/new moon). SOI appears to explain little additional variation (~ < 2%) in prawn catch rates, although its influence was slightly higher for Banana Prawns.

13.2 Introduction

Abiotic factors, such as rainfall, freshwater flow and temperature can affect commercial landings of prawns (Glaister 1978; Tanimoto *et al.* 2006; Vance *et al.* 1985), although the mechanisms underlying the causes and effects are not clear. For example, annual landings of Banana Prawns (*Fenneropenaeus merguiensis*) are positively correlated with annual rainfall (Staples *et al.* 1995), but it is unknown whether this is due to: increased prawn survival; increased population size due to increased available habitat associated with flooding; increased growth rates and hence, increased biomass; increased catchability due to increased emigration from estuaries or 'flushing' of the prawns seaward; or combinations of the above. This section of the report presents exploratory analyses on the relationships between several abiotic factors and the commercially important prawn species of Moreton Bay.

13.3 MATERIALS AND METHODS

13.3.1 Logbook catch data

The effects of abiotic factors on the catch rate of commercially important prawns of Moreton Bay were investigated using the daily logbook records reported by otter trawl fishers for the period 1/1/1988 to 31/12/2010 (i.e., 23 years). Logbook data were obtained from Fisheries Queensland who oversees the program and database. Moreton Bay is a multispecies trawl fishery and while three species (Greasyback Prawns, *Metapenaeus bennettae*, Brown Tiger Prawns, *Penaeus esculentus* and Eastern King Prawns *Melicertus plebejus*) account for most of the catch by weight and value, 20 prawn categories have been recorded in the fishery's logbook database. Banana Prawns (*F. merguiensis*) usually constitute a relatively minor component, although catches can be significant, especially in high-rainfall years. Other prawn species that contribute minor catches include Endeavour Prawns (*Metapenaeus endeavouri* and *Metapenaeus ensis*), coral prawns (*Metapenaeus novaeguineae*), red spot prawns (*Melicertus longistylus*), school prawns (*Metapenaeus macleayi*) and hardback prawns (*Trachypenaeus fulvus*). Several species of squid, crabs, bugs, mantis shrimp and cuttlefish are also retained as byproduct in the fishery.

The multispecies nature of the fishery complicates analysis of the logbook data. For most logbook data records, fishers do not process or record the catch to species level. Nor is there a market incentive for them to do so. Common market-based prawn catch categories used in the logbook, such as 'bay prawns', represent a commercial size class of prawns, rather than any one species. This category is therefore comprised of several species, predominantly Greasyback Prawns (*M. bennettae*) and to a lesser extent, Eastern King Prawns (*M. plebejus*). The 'tiger prawn' logbook category more-accurately reflects catches of the Brown Tiger Prawn (*P. esculentus*) because this species is by comparison, more readily identified by fishers, and also because the higher market prices for this species act as an incentive to fishers to market it separately, and hence, record its landings more accurately. Given these characteristics of the fishery logbook data, the following decision rules were used to estimate catches for the four main prawn species groups:

1) Greasyback Prawns (comprised of five species groups) = 'greasy and school prawn' + 'bay prawn' + 'greasy prawn' + 'mixed bait' + 'unspecified prawn'
2) Eastern King Prawns (comprised of three species groups) = 'blue leg king' + 'eastern king' + 'king'
3) Tiger prawns (comprised of one species) = 'tiger' and
4) Banana Prawns (comprised of one species) = 'banana'.

Daily catches of these prawn species groups were derived for each vessel. The number of hours fished per day for each vessel is also provided in the logbook database and was used in the analyses as a measure of effort to standardise catch rates.

13.3.2 Abiotic data

Data on daily rainfall, maximum daily air temperature, freshwater flow in southeast Queensland rivers, and the monthly Southern Oscillation Index (SOI) were obtained from the Department of Environment and Resource Management (DERM) and the Bureau of Meteorology (BOM) (Table 13-1). Rainfall and flow data were log-transformed to normalise the distributions. As prawn catch rates can also vary with lunar phase (Courtney *et al.* 1996), this was also considered in the analyses.

Table 13-1. Details of the candidate abiotic variables.

Environmental variable	Description	Monitoring stations
Freshwater flow	Daily river flow (megalitres, ML) data monitored by Queensland Department of Environment and Resource Management	1) 142001A Upper Caboolture 2) 142202A Sth Pine at Drapers 3) 143001C Brisbane R Savages 4) 143107A Bremer R Walloon 5) 143108A Warrill Ck Amberley 6) 143113A Purga Ck Loamside 7) 145014A Logan R Yarrahappini 8) 145102B Albert R Bromfleet
Rainfall	Bureau of Meteorology. Daily data obtained.	1) 40043 Cape Moreton Lighthouse 2) 40245 Toowong Bowls Club 3) 40468 Cannon Hill Bowls Club
Temperature	Bureau of Meteorology. Maximum daily air temperature used.	1) 40043 Cape Moreton Lighthouse 2) 40265 Redlands HRS 3) 40004 Amberley AMO
Southern Oscillation Index (SOI)	Bureau of Meteorology. Monthly measures used.	SOI is calculated from the monthly or seasonal fluctuations in the air pressure difference between Tahiti and Darwin.
Lunar phase	Daily measure of lunar phase, that includes waxing and waning phases and based on algorithms that measure luminance where full moon = 1 and new moon = 0.	

The effects of abiotic variables on catch rates may be immediate or delayed. An example of an immediate effect is the increase in prawn catchability that can occur during flooding as the increase in volume and flow of freshwater flushes adult prawns seaward towards the fishing fleet. An example of a delayed effect is when a January flood increases the area of habitat for post-larval Banana Prawns, hence increasing the survival of the prawns, but the resulting increase in catch rates of adults is not detected until four months later in April. For these reasons, a range of lag periods were considered. For rainfall data, three lags were examined as follows:

1 Lograin1_30. The log-transformed average daily rainfall from the previous 30 days prior to the catch date reported in the logbook.
2 Lograin31_60. The log-transformed average daily rainfall from 31 to 60 days prior to the catch date reported in the logbook.
3 Lograin61_90. The log-transformed average daily rainfall from 61 to 90 days prior to the catch date reported in the logbook.

The same lag periods were considered for the flow data (i.e., Logflow1_30, Logflow31_60 and Logflow61_90). These time lags are presented diagrammatically in Figure 13-1.

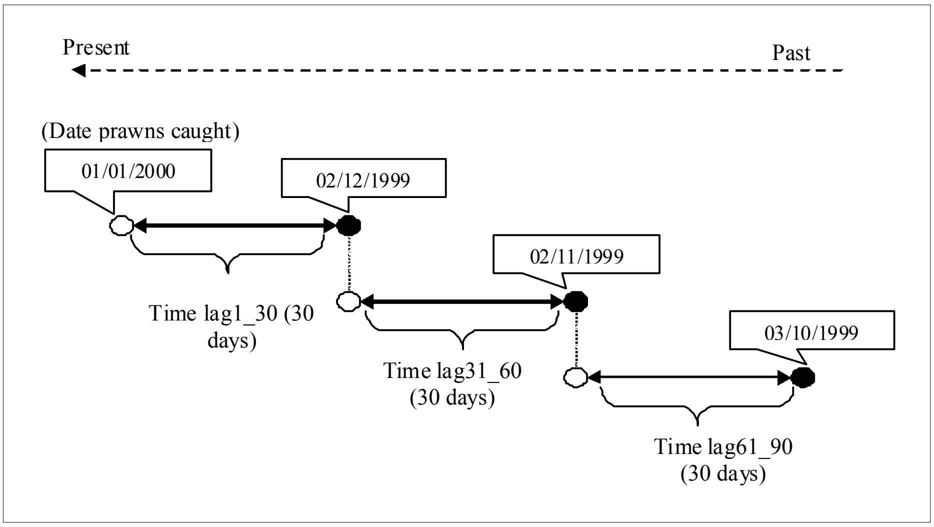

Figure 13-1. Illustrated process of how time lags were applied to the rainfall and flow data. Slightly different lags were applied to the temperature and SOI data. Diagram borrowed from Tanimoto *et al.* (2006).

Two lag periods were considered to examine seasonal effects of temperature on prawn catch rates, each based on a period of 60 days, as follows:

1) Temp1_60. The mean maximum daily air temperature for the previous 60 days prior to the catch date reported in the logbook.
2) Temp121_180. The mean maximum daily air temperature in the period from 121 to 180 days prior to the catch date reported in the logbook.

SOI data from the Bureau of Meteorology are provided for calendar months (i.e., not daily) and therefore a different approach was used to derive lags for this variable. For example, if the logbook reported prawn catch date was 15 June, then the non-lagged SOI value was for June (i.e., SOI_0). For a lag time of one month (SOI_1) the SOI from the previous month (i.e. May) was used. For a lag time of two months, (SOI_2), the SOI value from two months earlier (i.e., April) was used and so on, up to a maximum lag of 6 months (SOI_6). A summary of the abiotic variables and their respective lags is provided in Table 13-2.

13.3.3 Statistical analyses

The software package GenStat Version 12 (GenStat 2007) was used for all statistical analyses. Correlation analyses were undertaken on the abiotic terms to determine whether they were independent and to avoid the problem of co-linearity in the modelling. For example, if freshwater flow and rainfall were highly correlated, then only the more influential of the two terms should be included in the model. Similarly, while 'month' is a commonly fitted term when modelling prawn catch data, it was not included here because it was considered to be highly correlated with the two temperature terms (Temp1_60 and Temp61_120).

Table 13-2. Explanatory variables examined for their influence on prawn catch rates. The influence of each variable was examined on the daily prawn catch for each vessel, obtained from the CFISH logbook database for the period from 1988 to 2010.

Variable Name	Description	Type of Variables
Lunar phase	Two lunar phase covariates were used. 1) Lunar: raw lunar phase index based on luminance, 2) Lunaradv: raw index advanced 7 days. (Courtney *et al.* 1996; O'Neill and Leigh 2006)	Variate (continuous)
Vessel_id	This variable represents individual vessel effects on the response variable (i.e., prawn catch)	Factor (Categorical)
Year	Calendar year	Factor (categorical)
Month	Calendar month	Factor (categorical)
SOI_0	Current monthly Southern Oscillation Index	Variate (continuous)
SOI_1	Monthly Southern Oscillation Index for previous month	Variate (continuous)
SOI_2	Monthly Southern Oscillation Index two months prior to current month	Variate (continuous)
SOI_3	Monthly Southern Oscillation Index three months prior to current month	Variate (continuous)
SOI_4	Monthly Southern Oscillation Index four months prior to current month	Variate (continuous)
SOI_5	Monthly Southern Oscillation Index five months prior to current month	Variate (continuous)
SOI_6	Monthly Southern Oscillation Index six months prior to current month	Variate (continuous)
Lograin1_30	Log transformed mean rainfall for preceding 30 days (mm)	Variate (continuous)
Lograin31_60	Log transformed mean rainfall from preceding 31 to 60 days (mm)	Variate (continuous)
Lograin61_90	Log transformed mean rainfall from preceding 61 to 90 days (mm)	Variate (continuous)
Logflow1_30	Log transformed mean river flow for preceding 30 days (ML)	Variate (continuous)
Logflow31_60	Log transformed mean river flow from preceding 31 to 60 days (ML)	Variate (continuous)
Logflow61_90	Log transformed mean river flow from preceding 61 to 90 days (ML)	Variate (continuous)
Temp1_60	Mean daily maximum air temperature for preceding 60 days (°C)	Variate (continuous)
Temp121_180	Mean daily maximum air temperature for preceding 121 to 180 days (°C)	Variate (continuous)

The prawn catch data were normalised by log-transformation. For some species, logbook data were dominated by zero catches, e.g., of the 205,178 daily logbook records analysed, 87.8% recorded zero catch of Banana Prawns. As zero-inflated catch data can be problematic (Mayer *et al.* 2005; Taylor *et al.* 2011), a two-part conditional model was used to examine the effects of the candidate abiotics and derive adjusted catch rates. The first part was a generalised linear mixed model (GLMM) that analysed the presence/absence of catch data using a binomial distribution and logit link. The second part was a linear mixed model (LMM) that used a normal distribution on the log-scale to analyse the non-zero catch data. In both models, year was treated as a random variable and the abiotic terms were fixed. For the LMM, individual vessel identification was also treated as a random variable.

13.4 RESULTS

Daily flow data from eight DERM monitoring stations in southeast Queensland (Table 13-1) were examined. Average daily flow in the Brisbane River was 2571 ML, measured at Savages Crossing, which was by far the highest of the stations examined (Figure 13-2). The next highest average daily flow was in the Logan River, at 874 ML. Flows in Purga Creek and the Upper Caboolture and Pine Rivers were comparatively very low. The Brisbane River was therefore considered likely to be the most influential source of freshwater flow on the bay's prawn populations and was therefore included for further analyses.

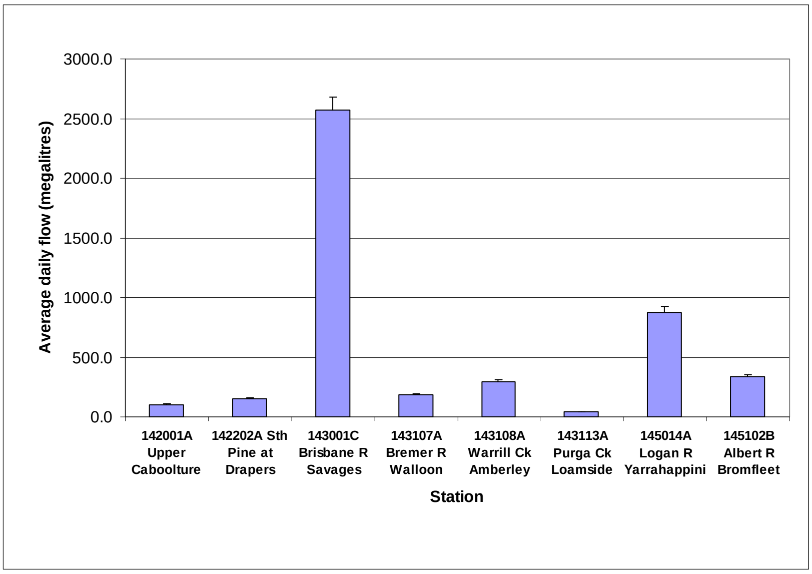

Figure 13-2. Average daily freshwater flow from eight DERM monitoring stations in southeast Queensland.

To obtain a clearer visual understanding of long-term trends in flow in the Brisbane River, the data were log-transformed (Figure 13-3). Under this log-scale, flow values between 5 and 6 represent severe drought periods, while values between 11 and 12 represent severe flooding. It is noteworthy that the severe flood of the summer of 2010/2011 resulted in the highest monthly flow in the 60+ year data series, and that it was also greater than the infamous 1974 flood. The low monthly flows that declined from about 6.5 in 2003 to 5.5 in 2008 reflect the extended drought in southeast Queensland at that time.

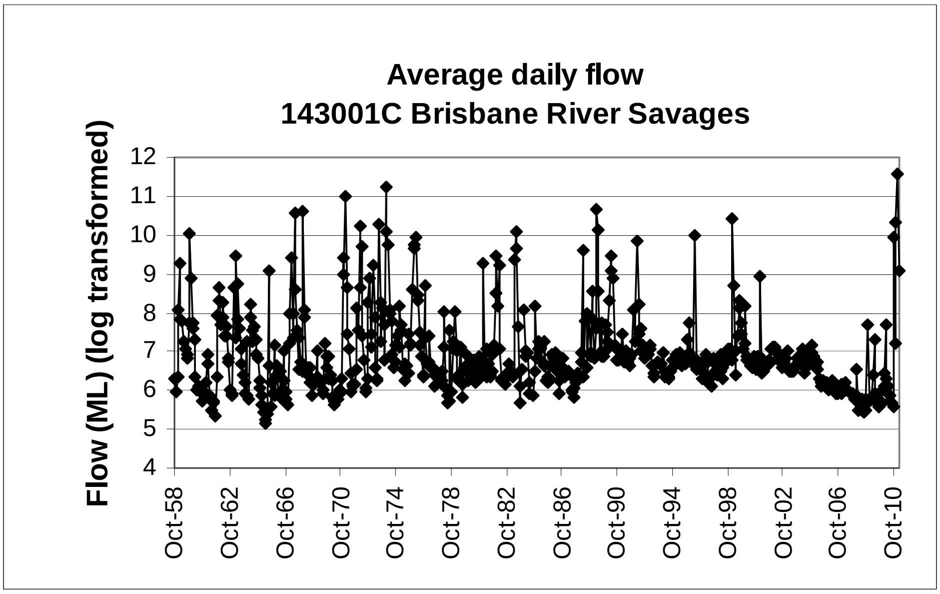

Figure 13-3. Monthly average daily freshwater flow in the Brisbane River. Note the high flow associated with 2010/2011 flood event.

Daily rainfall data were obtained from three Bureau of Meteorology weather stations (Table 13-1): the Cape Moreton Lighthouse and the Toowong and Cannon Hill bowls clubs. Rainfall was highly variable, both within and between stations, and there are few obvious patterns in the data (Figure 13-4). Data from the bowls clubs had more missing values, and was therefore less robust.

Maximum daily air temperature data from 1965 to 2011 were obtained from three Bureau of Meteorology weather stations: Cape Moreton Lighthouse, Redlands HRS and Amberley AMO. Amberley is approximately 60 kilometres inland from the coast and data from this station are only provided for contrast with the coastal stations of Redlands and Cape Moreton. Average monthly temperatures at Amberley are 1–2^{o}C higher than at Redlands and Cape Moreton (Figure 13-5). Variation in average monthly temperature at Amberley is also greater than the coastal stations. Cape Moreton was the coolest of the three locations, with average monthly temperatures varying between about 18^{o}C and 29^{o}C.

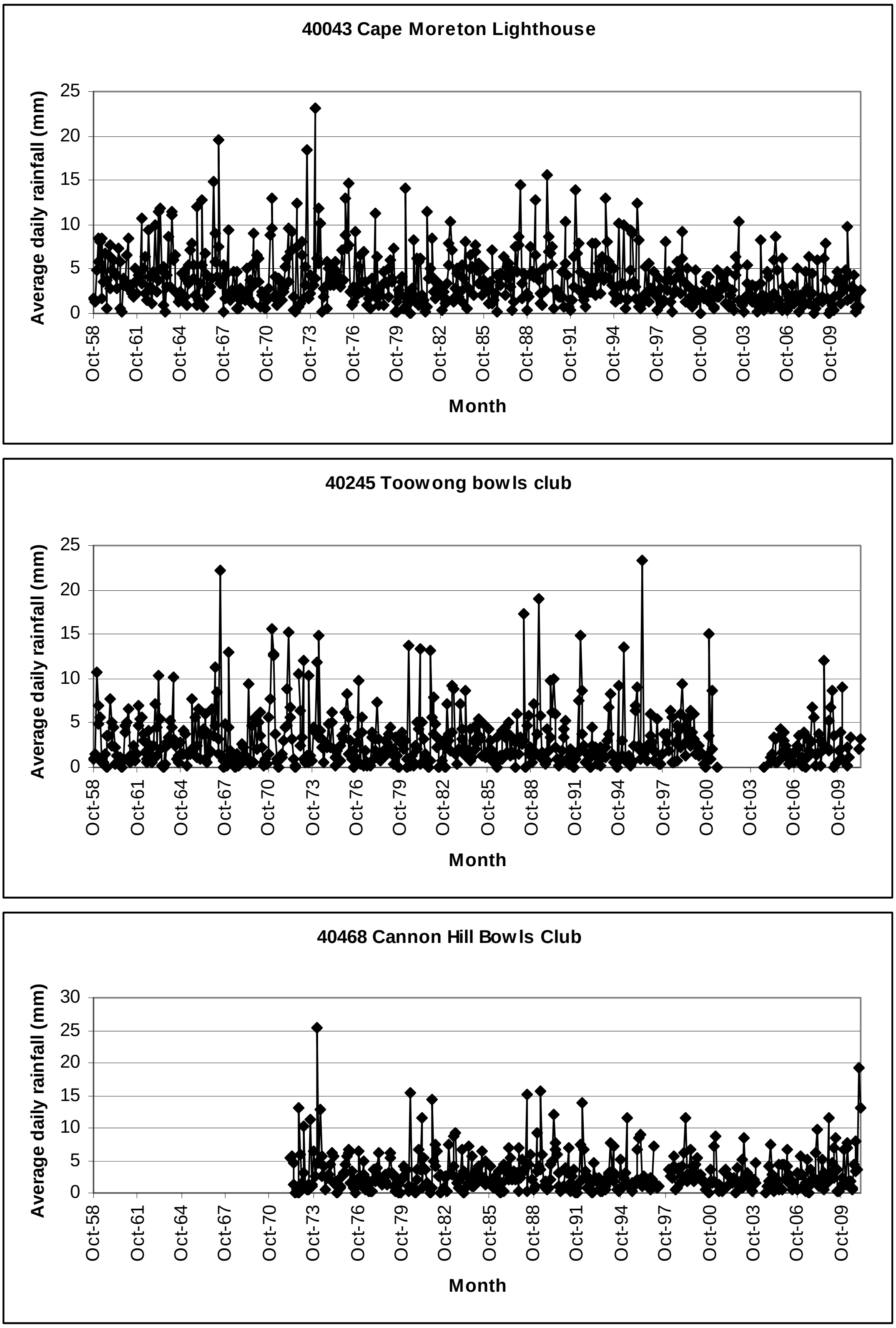

Figure 13-4. Monthly average daily rainfall (mm) from three Bureau of Meteorology weather stations in southeast Queensland.

Interestingly, over the ~46 years examined, average monthly temperatures at Cape Moreton showed a slight increase. In the 1960s, minimum monthly temperatures commonly fell below 19°C, while maximum average monthly temperatures above 27°C were uncommon. In recent years, minimum average temperatures have not fallen below 19°C and maximum monthly temperatures have been consistently above 27°C. This slight increasing trend in air temperature was not as obvious at Amberley and Redlands, and the underlying cause is unclear.

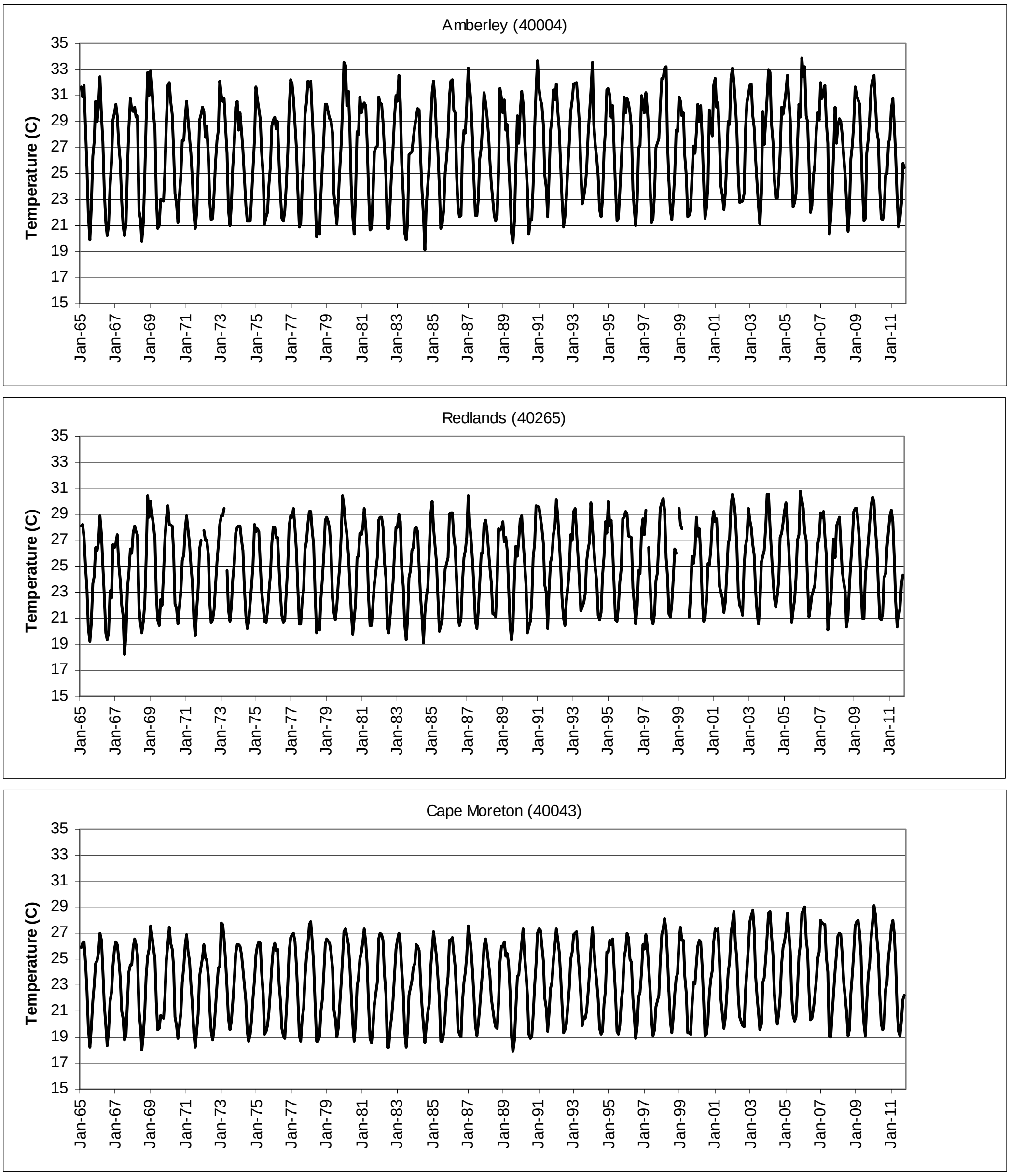

Figure 13-5. Average monthly air temperatures from three weather stations in southeast Queensland. The averages were based on maximum daily air temperature measures.

Monthly SOI values from January 1970 to May 2011 were obtained from the Bureau of Meteorology (Figure 13-6). The peak index of 31.6 occurred in November 1973, shortly before the 1974 Brisbane flood. Low values from 2003 to 2007 are generally associated with the drought conditions in southeast Queensland at this time. Conversely, the elevated values in the later half of 2010 were associated with heavy rains and flooding in the region.

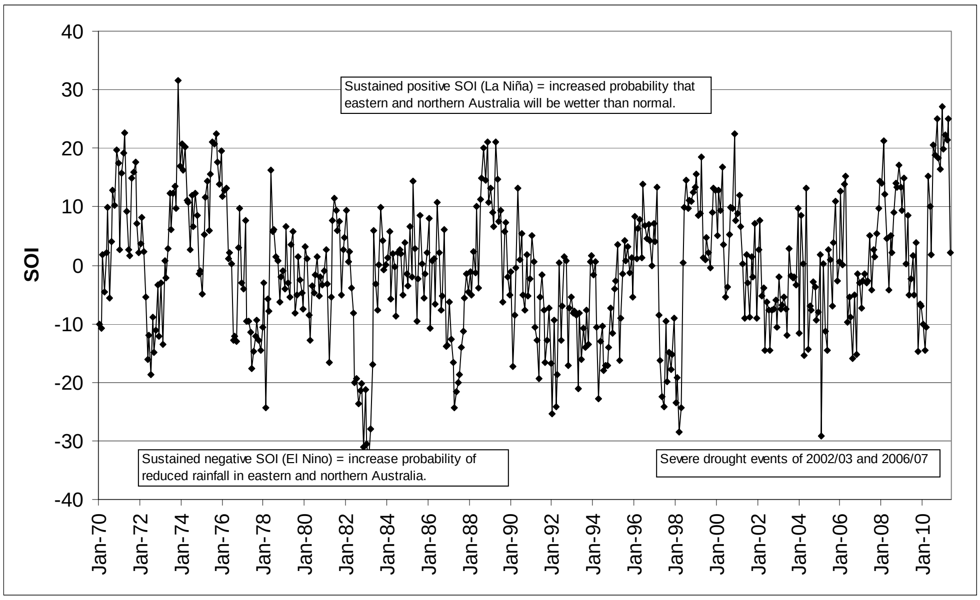

Figure 13-6. Monthly Southern Oscillation Index (SOI) from January 1970 to May 2011.

13.4.1 Correlations between abiotic terms

Correlation coefficients between the three stations (Cape Moreton Lighthouse, Toowong and Cannon Hill) for rainfall were generally low and commonly < 0.4 (Table 13-3). The highest coefficient was 0.4157 between Lograin1_30 Cape Moreton and Lograin31_60 Cannon Hill. The lowest was between Toowong and Cape Moreton. This may be due to poorer quality of the Toowong data, which had the most missing values of the three datasets.

Table 13-3. Correlation coefficients for lagged monthly average rainfall data from three weather stations.

		1	2
1	Lograin1_30 Cape Moreton	-	
2	Lograin1_30 Cannon Hill	0.3961	-
3	Lograin1_30 Toowong	0.2976	0.348
1	Lograin31_60 Cape Moreton	-	
2	Lograin31_60 Cannon Hill	0.4157	-
3	Lograin31_60 Toowong	0.1916	0.1972
1	Lograin61_90 Cape Moreton	-	
2	Lograin61_90 Cannon Hill	0.4036	-
3	Lograin61_90 Toowong	0.3573	0.3581

Of the three stations examined, Cape Moreton Lighthouse rainfall data had the highest correlation with freshwater flow data in the Brisbane River (Table 13-4). The highest correlation was 0.3533 between Lograin1_30 Cape Moreton and Logflow1_30. The Toowong rainfall showed the lowest correlation with flow.

Table 13-4. Correlation coefficients between rainfall measured at three weather stations and freshwater flow in the Brisbane River (Savages Crossing monitoring station), with lags applied. Cape Moreton rainfall data consistently show the highest correlation with the flow.

		1	2	3
1	Lograin1_30 Cape Moreton	-		
2	Lograin1_30 Cannon Hill	0.3961	-	
3	Lograin1_30 Toowong	0.2976	0.348	-
4	Logflow1_30	0.3533	0.2468	0.204
1	Lograin31_60 Cape Moreton	-		
2	Lograin31_60 Cannon Hill	0.4157	-	
3	Lograin31_60 Toowong	0.1916	0.1972	-
4	Logflow31_60	0.323	0.2414	0.1523
1	Lograin61_90 Cape Moreton	-		
2	Lograin61_90 Cannon Hill	0.4036	-	
3	Lograin61_90 Toowong	0.3573	0.3581	-
4	Logflow61_90	0.2945	0.2333	0.1717

No correlation analyses were undertaken using the Amberley data as the coastal monitoring stations were considered more likely to explain any temperature effects on the prawn catches. Redlands and Cape Moreton air temperatures were highly correlated (i.e. > 0.95) when the same lags were applied (Table 13-5), and therefore only one of these temperature data sources should be included in any modelling of the prawn catch data, to avoid the problem of multicollinearity.

Table 13-5. Correlation coefficients for temperature measured at Cape Moreton and Redlands. Measures from the two stations are highly correlated.

		1	2	3
1	Temp1_60 Cape Moreton	-		
2	Temp121_180 Cape Moreton	-0.2014	-	
3	Temp1_60 Redlands	0.9722	-0.3254	-
4	Temp121_180 Redlands	-0.1137	0.9817	-0.2321

Correlations between the SOI and Brisbane River flow data ranged between a low of 0.1271 and a maximum of 0.2089 (Table 13-6). The highest correlation was between SOI_4 and Logflow61_90. Predictably, correlations among the lagged SOIs (i.e., SOI_0, SOI_1, SOI_2, SOI_3, SOI_4, SOI_5 and SOI_6) were all high, and declined with increasing lag period. The results suggest a weak but positive relationship between SOI and flow in the Brisbane River.

Table 13-6. Correlation coefficients for the SOI and flow in the Brisbane River, with lags applied.

		1	2	3	4	5	6	7
1	SOI_0	-						
2	SOI_1	0.6631	-					
3	SOI_2	0.6387	0.6862	-				
4	SOI_3	0.6142	0.6698	0.6948	-			
5	SOI_4	0.516	0.6386	0.674	0.691	-		
6	SOI_5	0.4879	0.5343	0.6143	0.6478	0.6762	-	
7	SOI_6	0.4317	0.4704	0.5056	0.5717	0.6099	0.6594	-
8	Logflow1_30	0.1435	0.1503	0.1565	0.1515	0.183	0.1855	0.2014
8	Logflow31_60	0.181	0.1326	0.1525	0.1681	0.188	0.195	0.1924
8	Logflow61_90	0.1271	0.1573	0.1362	0.1635	0.2089	0.2076	0.1999

There was no correlation between the SOI and rainfall at Cape Moreton for any combination of lag periods (Table 13-7). These results suggest that while the SOI probably affects rainfall over large areas, such as the Brisbane River catchment, it has no relationship with Cape Moreton rainfall. It appears that while both SOI and Cape Moreton rainfall are correlated with flow in the Brisbane River, they are not correlated with one another.

Table 13-7. Correlation coefficients for the SOI and rainfall at Cape Moreton, with lags applied.

		1	2	3	4	5	6	7
1	SOI_0	-						
2	SOI_1	0.6631	-					
3	SOI_2	0.6387	0.6862	-				
4	SOI_3	0.6142	0.6698	0.6948	-			
5	SOI_4	0.516	0.6386	0.674	0.691	-		
6	SOI_5	0.4879	0.5343	0.6143	0.6478	0.6762	-	
7	SOI_6	0.4317	0.4704	0.5056	0.5717	0.6099	0.6594	-
8	Lograin1_30 Cape Moreton	-0.0154	-0.0579	-0.0565	-0.0279	0.046	0.042	0.0102
8	Lograin31_60 Cape Moreton	-0.0106	-0.0134	-0.0462	-0.0411	-0.0017	0.0537	0.0258
8	Lograin61_90 Cape Moreton	0.0135	-0.0307	-0.0078	-0.0498	-0.0337	0.0023	0.0594

13.4.2 Modelling the effects of freshwater flow and temperature on prawn catch rates

In terms of freshwater influences on Moreton Bay prawn catch rates, the flow data were considered to be the most influential, compared to the rainfall and SOI data. As rainfall was more highly correlated with flow (Table 13-4) than SOI (Table 13-6), rainfall may be a suitable proxy in the absence of flow data. For these reasons, the models focused mainly on quantifying flow effects.

For Greasyback Prawns *M. bennettae* freshwater flow in the preceding 1-30 days (i.e., Logflow1_30) was the most influential flow considered (Table 13-8). The parameter value for Logflow1_30 was 0.1137 (Table 13-12), indicating a large positive effect of flow on Greasyback Prawn catches. Flows in the other lagged periods (i.e., Logflow31_60 and Logflow61_90) had little effect.

Table 13-8. The GLMM and LMM for the effects of abiotic factors on Greasyback Prawns *M. bennettae* catches. The Wald statistics were calculated by dropping each fixed term from the full explanatory model.

Binomial model					
Random term	**Estimated variance components**	**s.e.**	**Residual term**		
Year	0.063	0.019	Deviance: -2*Log-Likelihood		588191
			Residual degrees of freedom		205082
Fixed term	**Wald statistic**	**d.f.**	**Wald/d.f.**		**chi pr**
Temp121_180 Cape Moreton	7132.29	1	7132.29		<0.001
Temp1_60 Cape Moreton	473.99	1	473.99		<0.001
Lunaradv	0.36	1	0.36		0.551
Lunar	5.09	1	5.09		0.024
Logflow61_90	0.47	1	0.47		0.492
Logflow31_60	0	1	0		0.964
Logflow1_30	198.94	1	198.94		<0.001

Logcatch (non-zero) LMM					
Random terms	**Estimated variance components**	**s.e.**	**Residual term**		
VesselID	0.2771	0.027	Deviance: -2*Log-Likelihood		140250
Year	0.0725	0.022	Residual degrees of freedom		159841
Fixed terms	**Wald statistics**	**n.d.f.**	**F statistic**	**d.d.f.**	**F pr**
Log hours trawled per day	4015.67	1	4015.67	159824	<0.001
Logflow1_30	865.67	1	865.67	157984	<0.001
Logflow31_60	159.8	1	159.8	159618	<0.001
Logflow61_90	21	1	21	157713	<0.001
Lunar	21.41	1	21.41	159615	<0.001
Lunaradv	5.87	1	5.87	159608	0.015
Temp1_60 Cape Moreton	1321.77	1	1321.77	159124	<0.001
Temp121_180 Cape Moreton	22873.33	1	22873.33	159201	<0.001

Catch rates of greasybacks were also significantly affected by air temperatures in the preceding months (i.e., Temp1_60 and Temp121_180), as measured at Cape Moreton (Table 13-8). The parameter value for Temp121_180 was -0.1734 (Table 13-12), which indicates a large negative effect of the temperature 4–6 months before capture. The two lunar phase terms, Lunar and Lunaradv, were both significant. Parameter estimates were -0.03094 and -0.01619, respectively, which indicate slight negative effects, which equate to declines in catch rates around the full moon. Adjusted catch rates based on the LMM, fitted the observed data reasonably well, with the exception of very high and very low catch rates (Figure 13-7) in recent years.

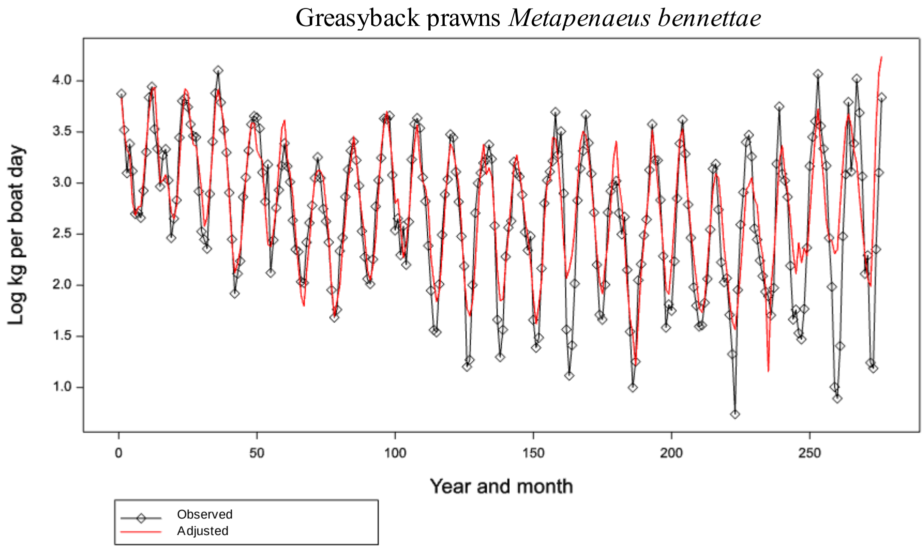

Figure 13-7. Observed and adjusted catch rates of Greasyback Prawns from Moreton Bay, based on the LMM of Table 13-8.

For all four species considered, the number of hours trawled each day (Log hours trawled per day) used in the LMMs was found to have a significant positive influence on daily catch rate. Note the high value of Wald statistic (i.e., > 2000) for each species, except for Banana Prawns. This was expected as the more hours a fisher trawled, the higher the expected daily catch. Banana Prawns appear to be an exception possibly because, as schooling species, their catch rates tend to be less correlated with hours fished, but rather whether the fisher has the skills to locate schools.

All three lagged flow terms significantly affected the catch rate of Eastern King Prawns (Table 13-9). However, in contrast to the Greasyback Prawns, flow effects were very slight, and either slightly positive (increasing catches) or negative (decreasing catches), depending on the specific lag period (Table 13-12). Parameter values for Logflow1_30, Logflow31_60 and Logflow61_90 were 0.05800, 0.009736 and -0.02204, respectively. Temp121_180 had the most significant affect on the king prawn catches. The Temp121_180 parameter estimate was -0.1064, which indicates a strong negative effect 4–6 months prior to catch (Table 13-12). The adjusted catch rates for Eastern King Prawns from the LMM fitted closely to the observed data, although deviances were more pronounced in recent years (Figure 13-8).

Table 13-9. The GLMM and LMM for the effects of abiotic factors on Eastern King Prawns *M. plebejus* catches. The Wald statistics were calculated by dropping each fixed term from the full explanatory model.

Binomial model

Random term	Estimated variance components	s.e.	Residual term	
Year	0.146	0.044	Deviance: -2*Log-Likelihood	550331.8
			Residual degrees of freedom	205082

Fixed term	Wald statistic	d.f.	Wald/d.f.	chi pr
Temp121_180 Cape Moreton	17354.7	1	17354.7	<0.001
Temp1_60 Cape Moreton	6154.51	1	6154.51	<0.001
Lunaradv	45.5	1	45.5	<0.001
Lunar	2.15	1	2.15	0.142
Logflow61_90	10.36	1	10.36	0.001
Logflow31_60	3.35	1	3.35	0.067
Logflow1_30	0.01	1	0.01	0.93

Logcatch (non-zero) LMM

Random term	Estimated variance components	s.e.	Residual term	
VesselID	1.0362	0.0827	Deviance: -2*Log-Likelihood	91154.25
Year	0.0361	0.011	Residual degrees of freedom	133605

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f	F pr
Log hours trawled per day	2278.74	1	2278.74	133437	<0.001
Logflow1_30	183.39	1	183.39	129264.2	<0.001
Logflow31_60	4.14	1	4.14	132757.8	0.042
Logflow61_90	18.97	1	18.97	128428.2	<0.001
Lunar	18.92	1	18.92	133285.7	<0.001
Lunaradv	38.9	1	38.9	133278.4	<0.001
Temp1_60 Cape Moreton	823.34	1	823.34	130922.2	<0.001
Temp121_180 Cape Moreton	8144.45	1	8144.45	132282.5	<0.001

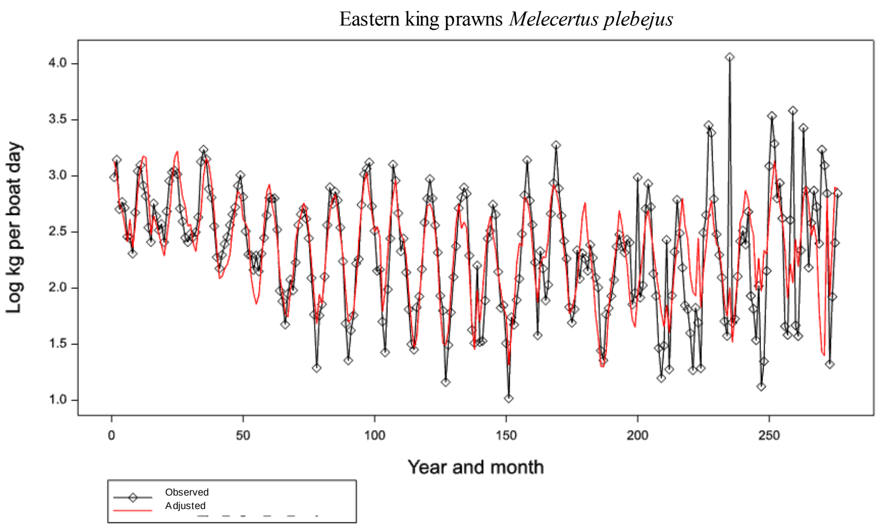

Figure 13-8. Observed and adjusted catch rates of Eastern King Prawns from Moreton Bay, based on the LMM of Table 13-9.

Air temperature in the preceding 60 days prior to capture (i.e., Temp1_60) had the most significant effect on catch rate of Brown Tiger Prawns *P. esculentus* (note the high Wald statistic value, Table 13-10). The parameter estimate for Temp1_60 was 0.2031 (Table 13-12), which indicates a large positive temperature effect. Temp121_180 also had a significant positive effect, with a parameter value of 0.1102. Logflow1_30 and Logflow61_90 also had a significant effect on tiger prawn catch rates, but parameter values for these terms were very low, indicating slight effects. Lunar phase effects on tiger prawn catches were also significant, but again the parameter values were very low and negative. This indicates that catch rates of tiger prawns decline with lunar luminance, which equates to lower rates around the full moon, and higher rates around the new moon. The adjusted catch for the tiger prawns from the LMM fitted the observed catch rates very well, and was the best fit of the four prawn species examined.

Table 13-10. The GLMM and LMM for the effects of abiotic factors on Brown Tiger Prawns *P. esculentus* catches. The Wald statistics were calculated by dropping each fixed term from the full explanatory model.

Binomial model				
Random term	**Estimated variance components**	**SE**	**Residual term**	
Year	0.577	0.174	Deviance: -2*Log-Likelihood	570006.1
			Residual degrees of freedom	205082
Fixed term	**Wald statistic**	**d.f.**	**Wald/d.f.**	**chi pr**
Temp121_180 Cape Moreton	4701.23	1	4701.23	<0.001
Temp1_60 Cape Moreton	3398.24	1	3398.24	<0.001
Lunaradv	4.88	1	4.88	0.027
Lunar	2.19	1	2.19	0.139
Logflow61_90	103.5	1	103.5	<0.001
Logflow31_60	37.27	1	37.27	<0.001
Logflow1_30	21.25	1	21.25	<0.001

Logcatch (non-zero) LMM					
Random term	**Estimated variance components**	**SE**	**Residual term**		
VesselID	0.3578	0.0356	Deviance: -2*Log-Likelihood		91264.85
Year	0.1663	0.0502	Residual degrees of freedom		138805
Fixed term	**Wald statistic**	**n.d.f.**	**F statistic**	**d.d.f.**	**F pr**
Log hours trawled per day	3467.73	1	3467.73	138764.9	<0.001
Logflow1_30	170.27	1	170.27	138404.6	<0.001
Logflow31_60	3.4	1	3.4	138631.5	0.065
Logflow61_90	48.81	1	48.81	138411.9	<0.001
Lunar	146.54	1	146.54	138553.1	<0.001
Lunaradv	6.69	1	6.69	138553.5	0.01
Temp1_60 Cape Moreton	37487.03	1	37487.03	138675.4	<0.001
Temp121_180 Cape Moreton	10815.03	1	10815.03	138687.7	<0.001

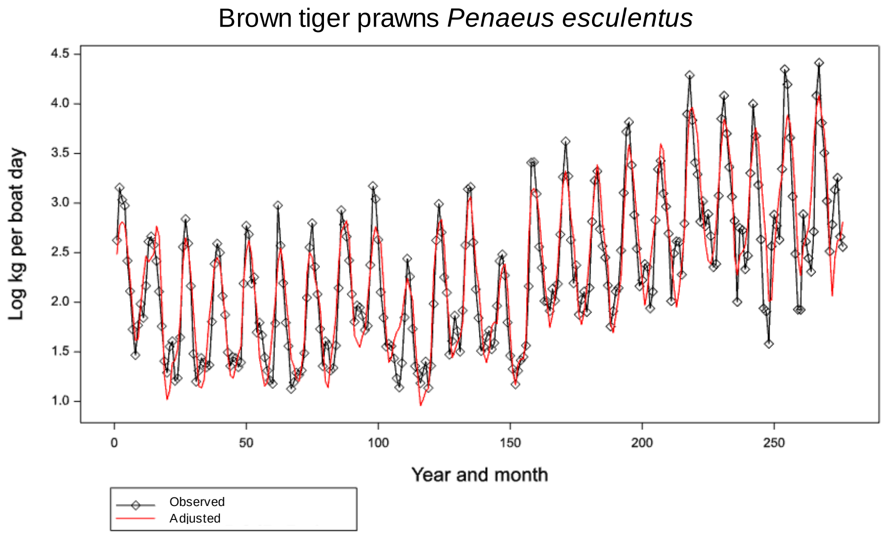

Figure 13-9. Observed and adjusted catch rates of Brown Tiger Prawns from Moreton Bay, based on the LMM of Table 13-10.

Banana Prawns were present in about 22% of the 205,178 logbook records and the least abundant of the four species considered. Hence the number of degrees of freedom and non-zero observations is relatively low in the LMM (Table 13-11). Temp121_180, as measured at Cape Moreton, was the most highly significant term for Banana Prawn catches (Table 13-11), with a parameter value of 0.2107 (Table 13-12), indicating that average temperature 4–6 months (i.e., 121 to 180 days) prior to catch had a large, positive effect. Logflow1_30 and Logflow31_60 also had a significant effect on Banana Prawn catches. Parameter values for these terms were 0.1205 and 0.1042 respectively, indicating that flow during these periods had a large positive effect. Logflow61_90 was also significant, but the parameter value for this term was comparatively small (0.0423). Lunar phase influences were not significant for Banana Prawns in the LMM, although the Lunar term was significant in the binomial model. Adjusted catch rates derived from the LMM fitted the observed data reasonably well (Figure 13-10).

Table 13-11. The GLMM and LMM for the effects of abiotic factors on Banana Prawns *F. merguiensis* catches. The Wald statistics were calculated by dropping each fixed term from the full explanatory model.

Binomial model					
Random term	**Estimated variance components**	**s.e.**	**Residual term**		
Year	0.847	0.256	Deviance: -2*Log-Likelihood		793323.3
			Residual degrees of freedom		205082
Fixed term	**Wald statistic**	**d.f.**	**Wald/d.f.**		**chi pr**
Temp121_180 Cape Moreton	7575.36	1	7575.36		<0.001
Temp1_60 Cape Moreton	1823.39	1	1823.39		<0.001
Lunaradv	1.57	1	1.57		0.21
Lunar	7.77	1	7.77		0.005
Logflow61_90	689.74	1	689.74		<0.001
Logflow31_60	305.19	1	305.19		<0.001
Logflow1_30	1046.94	1	1046.94		<0.001

Logcatch (non-zero) LMM					
Random term	**Estimated variance components**	**s.e.**	**Residual term**		
Vessel ID	0.393	0.046	Deviance: -2*Log-Likelihood		29352.45
Year	0.19	0.058	Residual degrees of freedom		24966
Fixed term	**Wald statistic**	**n.d.f.**	**F statistic**	**d.d.f.**	**F pr**
Log hours trawled per day	510.57	1	510.57	24944	<0.001
Logflow1_30	159.45	1	159.45	21197.1	<0.001
Logflow31_60	156.96	1	156.96	24896.2	<0.001
Logflow61_90	16.99	1	16.99	23608.4	<0.001
Lunar	1.72	1	1.72	24810.5	0.19
Lunaradv	2.78	1	2.78	24823.6	0.096
Temp1_60 Cape Moreton	296.53	1	296.53	24865	<0.001
Temp121_180 Cape Moreton	4159.19	1	4159.19	24952.7	<0.001

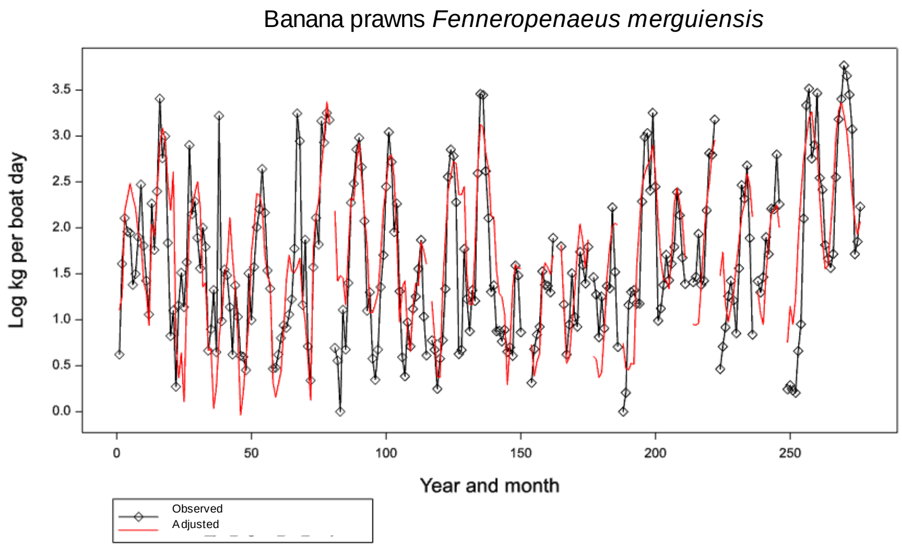

Figure 13-10. Observed and adjusted catch rates of Banana Prawns from Moreton Bay, based on the LMM of Table 13-11.

Table 13-12. Abiotic parameter estimates for four commercially important prawn species in Moreton Bay from the LMM for each species. Standard errors in parentheses. Large effects (i.e., greater than an absolute value of 0.1) are bolded for clarity.

Abiotic term	Greasyback Prawns *Metapenaeus bennettae*	Eastern King Prawns *Melicertus plebejus*	Brown Tiger Prawns *Penaeus esculentus*	Banana Prawns *Fenneropenaeus merguiensis*
Logflow1_30	**0.1137 *** (0.00386)**	0.05800 *** (0.004283)	0.04867 *** (0.003730)	**0.1205 *** (0.00954)**
Logflow31_60	0.05476 *** (0.004332)	0.009736 ** (0.0047878)	-0.007530 NS (0.0040835)	**0.1042 *** (0.00832)**
Logflow61_90	0.02200 *** (0.004802)	-0.02204 *** (0.005060)	-0.03230 *** (0.004624)	0.04231 *** (0.010264)
Temp1_60	0.04067 *** (0.001119)	0.03244 *** (0.001130)	**0.2031 *** (0.00105)**	0.06623 *** (0.003846)
Temp121_180	**-0.1734 *** (0.00115)**	**-0.1064 *** (0.00118)**	0.1102 *** (0.00106)	**0.2107 *** (0.00327)**
Lunar	-0.03094 *** (0.006688)	-0.02885 *** (0.006632)	-0.07784 *** (0.006430)	-0.02552 NS (0.019469)
Lunaradv	-0.01619 ** (0.006685)	0.04122 *** (0.006609)	-0.01659 ** (0.006414)	-0.03263 NS (0.019575)

NS not significant, ** $P<0.05$, ***$P<0.001$

13.4.3 Influence of the SOI on prawn catch rates

The SOI was correlated with freshwater flow (Table 13-6) and therefore may be a suitable proxy in circumstances where flow data are not available. Exploratory analyses were therefore undertaken to examine the range of lagged SOIs on prawn catches. GLMs were developed using the log-transformed non-zero catch data for each species as a response variable with an identity link function. For each of the four prawn species, explanatory terms log hours fished per day, Temp1_60 and Temp121_180 were firstly included in the model. The range of lagged SOIs (SOI_0, SOI_1, SOI_2…SOI_6) were then added sequentially to each model using the GenStat RSEARCH procedure to determine which explained the most variation for each species. The final models for each species are presented in Table 13-13.

For all four species, the results show that including SOI in the model explained very little additional variation. For Greasyback, Eastern King and Brown Tiger Prawns, addition of the SOI term explained 1% or less variation. The highest amount of variation explained was 2.3% for Banana Prawns. Different SOI lag periods were significant between species. For example, SOI_0 explained the most variation for Brown Tiger Prawns and Banana Prawns, while SOI_6 and SOI_5 were more influential for Greasyback and Eastern King Prawns (Table 13-13).

13.5 DISCUSSION

Courtney *et al.* (1995a) examined correlations between prawn catch rate in Moreton Bay and water temperature, depth and salinity, using monthly research sampling data over a two-year period. Abundance of each species was negatively correlated with depth. Catch rates of Greasyback Prawns was also negatively correlated with salinity, which is consistent with the positive freshwater flow influence found in the present study. Apart from the depth effect, no other abiotic factors had a significant effect on the catch rates of Eastern King Prawns or Brown Tiger Prawns. Loneragan and Bunn (1999) found a significant correlation between annual reported commercial prawn catches from the logbook database and summer flow in the Logan River, in the southern end of Moreton Bay. They did not include fishing effort in their analyses, although they did recommend that future analyses should. The number of hours trawled each day per fisher was considered in our analyses.

Table 13-13. Accumulated analyses of variance for the effect of SOI lags on prawn catches. Only the non-zero, log-transformed catch component was included for each prawn species.

Greasybacks *M. bennettae*

Change	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Log hours trawled per day	1	2090.613	2090.613	2079.61	<.001
Temp1_60 Cape Moreton	1	3225.426	3225.426	3208.45	<.001
Temp121_180 Cape Moreton	1	15140.02	15140.02	15060.35	<.001
SOI_6	1	499.424	499.424	496.8	<.001
Residual	141852	142602.4	1.005		
Total	141856	163557.9	1.153		

Percentage variance accounted for was 12.8% compared to 12.5% without SOI_6.

Eastern King Prawn *M. plebejus*

Change	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Log hours trawled per day	1	718.4225	718.4225	826.88	<.001
Temp1_60 Cape Moreton	1	1658.646	1658.646	1909.04	<.001
Temp121_180 Cape Moreton	1	5946.385	5946.385	6844.08	<.001
SOI_5	1	132.5462	132.5462	152.56	<.001
Residual	116457	101182.1	0.8688		
Total	116461	109638.1	0.9414		

Percentage variance accounted for was 7.7% compared to 7.6% without SOI_5.

Brown Tiger Prawns *P. esculentus*

Change	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Log hours trawled per day	1	3958.166	3958.166	4915.5	<.001
Temp1_60 Cape Moreton	1	31876.96	31876.96	39586.8	<.001
Temp121_180 Cape Moreton	1	6830.228	6830.228	8482.2	<.001
SOI_0	1	1320.473	1320.473	1639.85	<.001
Residual	120099	96708.77	0.8052		
Total	120103	140694.6	1.1714		

Percentage variance accounted for was 31.3% compared to 30.3% without SOI_0.

Banana Prawns *F. merguiensis*

Change	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Log hours trawled per day	1	145.058	145.058	109.97	<.001
Temp1_60 Cape Moreton	1	0.018	0.018	0.01	0.907
Temp121_180 Cape Moreton	1	4507.832	4507.832	3417.41	<.001
SOI_0	1	736.755	736.755	558.54	<.001
Residual	19950	26315.61	1.319		
Total	19954	31705.27	1.589		

Percentage variance accounted for was 17.0% compared to 14.7% without SOI_0.

This section examined the effects of a range of lagged abiotic terms on the catch rates of four commercially important prawn species in Moreton Bay. The influence of rainfall was not directly determined. While measures of rainfall from various BOM monitoring stations in southeast Queensland provide information on the amount of precipitation, the most direct and influential source of freshwater on Moreton Bay prawns is river flow. In our analyses we examined measures of flow from the Brisbane River taken at Savages Crossing on the prawn catch rates. Future analyses may explain more variation in the prawn catch rates by including flows from other rivers in southeast Queensland (i.e., Caboolture, Logan and Albert Rivers). We limited our analyses to the Brisbane River as it accounted for the great majority of freshwater flowing into Moreton Bay (Figure 13-2).

Rainfall may be a useful proxy in the absence of flow data, but the results indicate that flow is a much more influential explanatory term. In the present study, highest correlation between rainfall and flow was 0.3533, for Logflow1_30 and Lograin1_30 at Cape Moreton (Table 13-4). This suggests a low to moderate correlation between Cape Moreton rainfall and Brisbane River flow. Tanimoto *et al.* (2006) examined a range of models to explain variation in Queensland Banana Prawn catch rates and concluded river flow explained more variation than rainfall. They suggested this was likely because measures of rainfall do not necessarily reflect the volume of water flowing in rivers, mainly because they do not consider the size or area of the catchments. In the present study, rainfall varied significantly between the three measuring stations (Table 13-3) and the more reliable Cape Moreton data probably do not adequately correlate highly with the amount of rainfall received by the large Brisbane River catchment area. Vance *et al.* (2003) discussed the effects of rainfall and catchment size on Banana Prawn catches in the Gulf of Carpentaria. The effect of rainfall on Banana Prawn landings from relatively small catchments (i.e., the northeast Gulf) occurred over a relatively short period immediately after the rain, while the effects from large catchments (i.e., the southeastern Gulf) lasted much longer and had greater effects on offshore catches.

Of the abiotic terms examined, the most influential was air temperature over the preceding 4–6 months (Temp121_180 parameter value 0.2107, Table 13-12) for Banana Prawns. Banana Prawns are mainly caught from March to May in Moreton Bay, and so the air temperatures from September to January are responsible for this strong positive effect. Flows in the preceding 1–2 months before capture (i.e., January to April) also had strong positive effects on Banana Prawn catches. Flow in the immediate 30 days prior to capture also had a strong positive effect on the catch rate of Greasyback Prawns (Logflow1_30 parameter value 0.1137, Table 13-12). This relatively short-term or immediate effect may be due to the physical effects of flow making the Greasyback Prawns more catchable to the commercial fleet, rather than increasing their population size or biomass. Interestingly, flows had very slight positive or very slight negative influence on Eastern King and Brown Tiger Prawn catches. Temperature in the preceding 60 days prior to capture had a strong positive effect on tiger prawn catch rates (Temp1_60 parameter value 0.2031, Table 13-12). This was the most influential abiotic factor on the tiger prawns. The only relatively influential factor for Eastern King Prawns was air temperature in the preceding 4–6 months. The Temp121_180 parameter value for Eastern King Prawns was -0.1064, which indicates that the higher the average temperatures in the preceding 4–6 months, the lower the expected catch. As Eastern King Prawns are mainly caught from

October to December in Moreton Bay, this indicates that temperatures between April and August (i.e., winter) are responsible for this effect. In brief, if winter is warmer than usual, the expected catch rate of Eastern King Prawns would be lower than normal.

The results may provide some understanding of climate change effects on these four prawn species over the coming decades. In terms of the broad-scale geographical distribution of the species around the Australian continent, Moreton Bay and southeast Queensland approximate the northern-most distribution for the Greasyback and Eastern King Prawns, which are temperate/sub-tropical species. Conversely, the region approximates the southern-most distribution of the Brown Tiger and Banana Prawns, which are tropical species. It may be noteworthy therefore, that temperature influences were strongly negative for the two temperate/sub-tropical species, but strongly positive for the two tropical species. This might suggest that the abundance and/or distribution of Greasyback and Eastern King Prawns may decline in this region with increasing temperature expected from climate change, while banana and tiger prawn abundances and distributions in the region might be expected to increase. The effects of climate change on the abiotics and faunal communities of southeast Queensland are complex and uncertain, and therefore any discussion about their likely effects on the prawn population dynamics should be considered cautiously.

Adding SOI terms to the models explained only very little (i.e., 1–2%) additional variation in catch rate. This suggests that the SOI is not an important factor explaining variation in the Moreton Bay prawn catch rates. SOI is clearly an important climatic parameter for explaining variation in rainfall in northern and eastern Australia, but it appears to have relatively little influence on the localised conditions of Moreton Bay.

14 Corporate management of fisheries: a potential alternative governance structure for the Moreton Bay prawn fishery (Objective 5C)

By S. Pascoe

This section of the report addresses:
Objective 5C. Further development of the corporate governance model, including detail on how each licence holder type (i.e., T1/M1 and M2) could participate, likely locations for the business, initial operating cost estimates, and how each participating fisher could be paid.

14.1 ABSTRACT

An examination of alternative governance systems was requested by the industry at one of the early steering committee meetings, particularly systems that may give them greater autonomy in decision making as well as help improve the marketing of their product. Consequently, a review of alternative co-management systems was undertaken. Given the characteristics of the fishery and the key issues confronting the industry, particular attention was given to the potential for corporate management, a form of co-management that allows greater autonomy in both decision making and marketing. This section of the report outlines the general review, and highlights particular opportunities for the Moreton Bay prawn fishery. The review looks at systems that have been implemented or proposed for other small fisheries internationally, with a particular focus on self-management as well as the potential benefits and challenges for corporate management.

14.2 INTRODUCTION

The use of economic incentives for the management of fisheries has gained increased interest over recent years (Beddington *et al.* 2007; Grafton *et al.* 2006; Hilborn *et al.* 2005a). Foremost of these instruments is the use of individual transferable quotas (ITQs), which introduces a limited form of user rights and is generally believed to result in improved economic performance of the fishery (Costello *et al.* 2008; Grafton 1996; Townsend *et al.* 2006). ITQs, however, are often considered inappropriate for some fisheries. For example, ITQs require an estimation of a total allowable catch (TAC). For some short-lived species, such as many species of prawns, annual stock abundance is highly influenced by environmental fluctuations (Staples and Vance 1987), and estimating an accurate TAC is difficult,[11] and even where possible could be costly. Underestimation of the TAC can potentially result in substantial economic losses to the industry through foregone fishing opportunities, while overestimation

[11] Exceptions to the rule always exist, with considerable success in estimating TACs for several prawn species in the Northern Prawn Fishery.
Dichmont C. M., Pascoe S., Kompas T., Punt A. E., Deng R. (2010). On implementing maximum economic yield in commercial fisheries. *Proceedings of the National Academy of Sciences* **107**, 16-21.
Punt A. E., Deng R. A., Dichmont C. M., Kompas T., Venables W. N., Zhou S., Pascoe S., Hutton T., Kenyon R., van der Velde T., Kienzle M. (2010). Integrating size-structured assessment and bioeconomic management advice in Australia's northern prawn fishery. *ICES Journal of Marine Science* **67**, 1785-1801.

could lead to dissipation of any rent generated and, potentially, biological overexploitation of the resource.

There are particular problems for the management of small fisheries that make adoption of some of these market-based instruments difficult. 'Small' in this context is in terms of the number of participants, which differentiates it from the concept of 'small-scale' fisheries that are characterised by potentially large numbers of operators using relatively low levels of capital. In contrast, many small fisheries are characterised by varying levels of capital (e.g. small or large vessels), and the fishery is constrained either geographically (i.e. small area) or biologically (i.e. small stocks).

The challenge facing these fisheries is that their ability to support the research necessary to derive appropriate TACs is limited as the cost of economic and biological assessments is relatively fixed for a fishery irrespective of its number of participants, but does vary based on number of species to be assessed. Small multispecies fisheries are hence particularly disadvantaged. As the estimation itself is often costly, the pay-offs from this research in terms of improved profits may be low, if not negative for relatively small fisheries. These fisheries are also often data poor as a consequence, as generally little or no data are collected nor thorough assessments undertaken. Assuming an estimate of an appropriate TAC could be undertaken cost effectively, the cost of ITQ management is also considerably higher than other forms of management (Beddington *et al.* 2007), and this may be an additional impediment to their implementation in small fisheries.

Appropriate incentives can be generated through mechanisms other than market-based instruments. Interest by both industry and management in greater industry involvement in management decision making is also increasing internationally. Considerable benefits of co-management have been identified, including increased compliance and smoother transitions to new management systems (Grafton 2005; Jentoft 1989; Jentoft *et al.* 1998; Pomeroy and Rivera-Guieb 2006). Most Australian fisheries have moved from a centralised management model to a consultative model involving a system of management advisory committees that include industry and other stakeholders (Neville 2008). At the Commonwealth level, a number of formal co-management agreements are being trialled for which some management responsibilities are being devolved to the industry directly. In the USA, regional fisheries management councils take on a similar role, although the dominance of industry members on these groups has been criticised, with claims that inherent conflicts of interest and the institutional exclusion of broader public interests may lead to management failures (Okey 2003). Hence, while there is potentially a continuum of co-management models with varying degrees of delegation to stakeholders, in practice, most co-management models tend to be largely advisory with limited management responsibility.

Another management system that has been recently proposed is community-based management and the use of community quotas (Holland and Ginter 2001; Leal 1998). This involves allocating some form of property or use right to a community, and the community as a whole determining how the resource is to be exploited for its broader benefit. For example, under the Alaskan community development quota scheme, quotas are allocated to several indigenous communities who determine how the quota is to be caught, and receive a return from the harvesters for use of this quota (Holland

and Ginter 2001). Profits generated from the use of the quota are being re-invested in the harvesting and processing sector, building equity in these activities (Holland and Ginter 2001). Several examples of other community-run fisheries exist, where the community plays an active role in determining access, harvest and enforcement (Leal 1998; Uchida and Wilen 2007).

A third variant of industry-driven management is corporate management (Townsend 1995; Townsend 2010; Townsend and Pooley 1995). Corporate management involves total devolution of management responsibilities to a corporation that effectively operates the fishery as a sole owner. Hence, many of the benefits perceived by Scott (1955) might be realised—benefits that ITQs and other imperfect rights-based systems aim to achieve but often fall short due to imperfect property rights and other impediments to the market-based instruments that prevent their full functioning.

Since its proposal in 1995 (Townsend 1995; Townsend and Pooley 1995), corporate management has only evolved in a small number of fisheries, although a wider range of fisheries appear to be ideal candidates for such a governance structure, and small fisheries in particular. The aim of this commentary is to present an outline as to how corporate management may be an effective governance structure for small fisheries in which other rights-based measures may be impractical. It is argued that such a system is likely to provide many of the economic benefits of an ITQ system, and may even avoid some of the perceived social costs.

14.3 INDUSTRY INVOLVEMENT IN MANAGEMENT AND THE ECONOMIC THEORY OF CLUBS

Industry involvement in fisheries management is often considered in terms of co-management. Co-management encompasses a wide range of institutional structures, ranging from industry having an advisory role in essentially a government management system, to the reverse structure where government has an advisory or facilitating role[12] in essentially an industry self-management structure (Jentoft and McCay 1995; Pomeroy and Berkes 1997; Sen and Raakjaer Nielsen 1996). A key perceived advantage of co-management is that it has been seen as a way of developing more-effective management strategies utilising industry knowledge and, as a result of greater buy-in by industry, with greater compliance. Consequently, the focus of co-management has largely been on the harvest strategy side. Within the fishery, individuals still compete for the resource within the boundaries established by the management plan. The introduction of more rights-based measures can reduce this competition, but harvesting is still largely uncoordinated.

Fisheries resources are considered impure public goods as, unregulated, they are non-excludable. However, they are not pure public goods as they are rivalrous in production—what one fisher takes reduces the available catch for other fishers. Fisheries managers aim to alter the public good status of the resource by limiting access (removing the non-excludability problem). At one extreme, this may be

[12] This may include providing facilitating legislation and setting the 'ground rules' under which the fishery may operate (e.g. sustainability requirements, performance criteria etc.) in much the same way that government is involved in many other (non-fishing) industries.

through limiting licences or, at the other extreme, limiting the amount of catch individual fishers may take (e.g. individual transferable quotas).

Impure public goods and common-pool goods such as fisheries can also be converted to club goods (Uchida *et al.* 2010). Club goods are a type of good in economics that has properties of excludability through requiring membership of the 'club'. A club is a voluntary group that gains mutual benefits from cooperatively sharing a resource, reducing rivalry and potentially reducing costs of production and management (Buchanan 1965; Sandler and Tschirhart 1997). Economic models of clubs have been developed that illustrate their ability to maximise the welfare of the group through coordinated action in cases where individuals would have no incentive to undertake such actions (Buchanan 1965; Stollery 1988). With voluntary membership, individuals join clubs when their expected benefits exceed any costs associated with joining the club. With a large number of individuals, multiple clubs may develop, each aligned to the objectives of its members. However, when some individuals do not belong to any club, instability results and the benefits of club membership may be eroded (Pauly 1967).

Numerous examples of producer clubs exist in fisheries, mostly in the form of fisheries cooperatives. Cooperatives are generally developed to help market the catch of their members, but in some cases have evolved to undertake a management role directly. Within Europe, producer organisations have been established in most countries with the aim of coordinating marketing, although in some countries additional management responsibilities have been devolved.

The development of clubs (in the economic sense) in fisheries provides a mechanism by which greater management responsibility can be devolved to the clubs. In the UK, producer organisations have been given responsibility for managing and monitoring the quota allocated to their members.[13] Different models have evolved, with some producer organisations operating individual quota systems while others operate at a more aggregated (and competitive) level (Hatcher 1997). Individual fishers are free to join whichever producer organisation best meets their own interests. Membership is not compulsory, although there are disadvantages in not being in a producer organisation (other than marketing benefits) in terms of greater restrictions on catch (e.g. monthly limits). This illustrates another key feature of successful clubs, namely, that for them to be successful, members must have some form of privilege over non-members (Sandler and Tschirhart 1997; Uchida *et al.* 2010).

In other countries, even greater management responsibility is devolved to fisher organisations. In Japan, fisheries cooperative associations (FCAs) are allocated territorial user rights over coastal areas for exclusive use by their members. Within these associations, fisheries management organisations (FMOs) have also evolved that are responsible for management of particular zones or species within the FCA areas as well as marketing the product. Membership of the FMOs range from 10 to 300

[13] To a large extent this system is similar to the concept of community quotas in which the quota is allocated to a group or community rather than individuals. Wingard J. D. (2000). Community transferable quotas: Internalizing externalities and minimizing social impacts of fisheries management. *Human Organization* **59**, 48-57. These have also been successful elsewhere. Langdon S. J. (2008). The Community Quota Program in the Gulf of Alaska: A Vehicle for Alaska Native Village Sustainability? *American Fisheries Society Symposium* **68**, 155-194.

members, and is controlled by the FCA (to prevent fishers trying to move into the most successful FMOs) (Uchida and Wilen 2004). Analysis of economic performance in the fisheries suggests that members of FMOs with coordinated harvesting and marketing earn substantially higher incomes than non-members (Uchida and Wilen 2007). Similar benefits in terms of higher fisher incomes of self-management groups relative to non-members has been observed in Korea (Uchida *et al.* 2010), Alaska (Deacon *et al.* 2008; Deacon *et al.* 2010; Holland and Ginter 2001), South America (Leal 1998), and Norway (Leal 1998).

Several studies have demonstrated that self-management by fishers, particularly in conjunction with an individual transferable quota system, is more efficient than government-based management (Arnason 2007; Baskaran and Anderson 2005; Leal 1998; Stollery 1988). However, others suggest that, for small fisheries with few participants, self-management may be successful without ITQs (Brown 2000).[14]

Self-management can be seen as an end point in the continuum of the co-management spectrum,[15] where fishers (through the development of an appropriate club) are collectively fully responsible for decisions on when, how much and how to harvest. Self-management in this regard is not individuals making separate decisions in isolation, but a single decision-making body comprised of industry members making decisions for all of its members. In this regard, the fishery operates as any other business sector such as agriculture, mining or small business, where the business determines where, what and how much to produce, but the government provides a regulatory framework that determines how the businesses are able to operate (e.g. sets maximum operating hours, pay rates, and environmental standards). Hence, self-management does not remove the role of the State entirely (Grafton 2000; Neville 2008). For example, only the State can grant the initial access privileges to the fishers, and enforce these privileges to ensure new entrants do not undermine the governance system (Pomeroy and Berkes 1997). Further, fisheries create other externalities (e.g. environmental impacts, conflicts with recreational fisheries etc.) that would require a broad regulatory framework to be established by the State within which the club would operate. Where multiple clubs form, individual group decisions may also impinge on other groups, to the detriment of all groups (e.g. if two groups try to maximise their own members' benefits it may result in an overall reduction in benefits) (Hilborn *et al.* 2005b).[16] Game theoretic studies of clubs have also suggested that overall benefits derived from multiple clubs may be lower than those from a single club (or coordinated activities between clubs) (Sterbenz and Sandler 1992), and that it is likely that more clubs would develop than is optimal if

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[14] Further examples of successful self-management models currently in operation with and without individual quotas are provided in a recent FAO technical paper. Townsend R., Shotton R., Uchida H. (2008) 'Case studies in fisheries self-governance.' FAO, Rome.

[15] Some co-management studies term this end point as 'fully delegated' in terms of responsibilities (Neville 2008) and suggest a greater role of government involvement is required than we suggest here. Other studies in the broader literature go further, and the term self-management is the generally accepted term used to describe this (Townsend *et al.* 2008). Others have suggested that the term self-management is confusing to stakeholders who see it involving no checks or balances (Hollamby *et al.* 2010), although clearly this is not the case.

[16] Critics of industry self-management also suggest that individuals on the management boards may be more motivated by their own self-interests than those of their larger constituency or of the broader society. Okey T. A. (2003). Membership of the eight Regional Fishery Management Councils in the United States: are special interests over-represented? *Marine Policy* **27**, 193-206.

unconstrained (Scotchmer 1985). Hence, the State has a role in potentially limiting the number of clubs that would be recognised for self-management purposes. In the case of small fisheries, it is likely that only one club could realistically operate. Similarly, as noted above, non-members of the club can potentially cause instability, and the benefits of such a system may be eroded. The State may, therefore, insist that membership of the club is compulsory if self-management is to be granted. The practicality of this is unclear, as individuals within the club could potentially still not comply with the group decision, although it would be up to the remainder of the group to enforce compliance. Finally, the State may have a role in information and research provision, particularly in small fisheries where the ability of the groups to undertake appropriate research is limited.

14.4 FROM SELF-MANAGEMENT TO CORPORATE MANAGEMENT

The corporate management model (Townsend 1995; Townsend 2010; Townsend and Pooley 1995) differs from the traditional self-management model in several ways. Institutionally, the group forms an actual company (rather than a collective or cooperative) with fishers as shareholders of the company. The catch (and in effect the rights to the catch in the fishery) is owned by the company rather than the individual fishers, who are effectively sub-contracted to take the catch. The corporation acts as a sole owner of the fishery, and determines how much is to be caught in any week given the costs and market conditions that week. Fishers are shareholders in the corporation, and hence directly benefit through the higher profits that might be achieved.

The potential implication of this, compared to other forms of co- or self-management, is that fishers (shareholders) have a direct vote in the direction of management in the fishery (rather than just representation). While self-management and community-based management relies on a consensus to be reached, corporate management may function on a non-unanimous basis, based on majority rule given the one-share, one-vote principle (Townsend 2010). Fishers also gain a greater stake in future management outcomes than just current outcomes as their share values will reflect these (Townsend 1995).

While the original model of corporate management was focused on fisheries management, corporate management can encompass harvesting, management and marketing responsibilities (Figure 14-1). In most fisheries, marketing is either uncoordinated, or at best managed through some form of cooperative or producers' organisation. Where cooperatives or producers' organisations exist, these are primarily responsible for disposing of the product once landed for the best price possible. However, if too much is landed at a particular time, then the prices received will still be low even with a coordinated marketing strategy. The corporation has the ability to control the supply to meet the needs of the market, resulting in more stable supply to buyers as well as more stable (and higher) prices to the fishers (shareholders). While a potential criticism of this may be that the corporation could operate as a monopolist (Townsend 2010), for most fisheries products there is a substantial international trade that would limit monopoly-type actions. For small fisheries in particular, the potential for the corporation to substantially increase price through withholding supply is limited, although the potential to reduce price decreases through oversupply at certain times of the year is substantial.

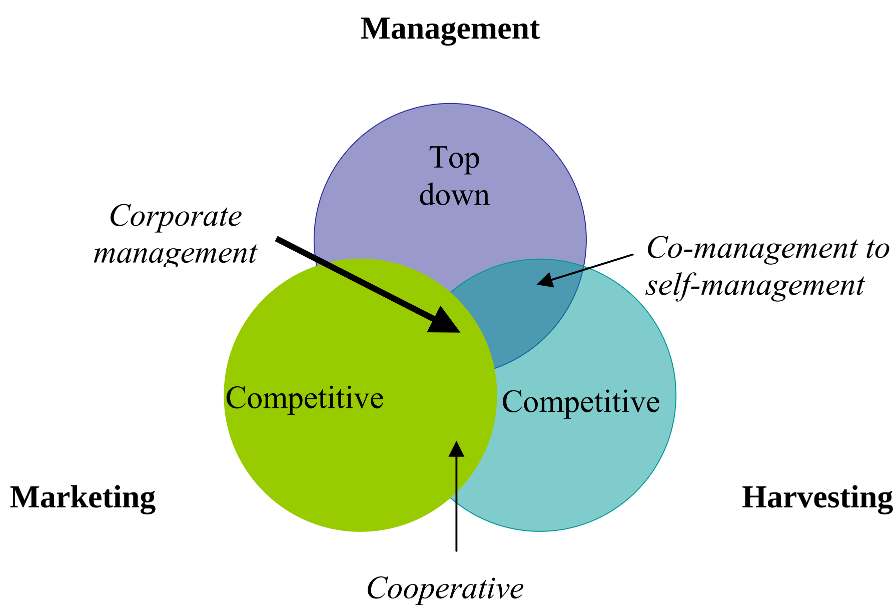

Figure 14-1. Interactions between management, harvesting and marketing.

Several examples of fisheries which have evolved into a corporate-type management structure exist (Townsend *et al.* 2008). The New Zealand Challenger Scallop Enhancement Company was established by quota owners to enhance scallop production through seeding scallop grounds, but has developed to take on a full range of management responsibilities (supervised by the Ministry of Fisheries), including quota setting, weekly catch limits and rotations/closures (Mincher 2008). In Chile, access rights to loco and other shellfish species are allocated exclusively to regional fisher associations who are responsible for managing their areas (Castilla and Gelcich 2008). In Western Australia, sole ownership of the fishery has been effectively realised in Exmouth Gulf, with one company owning all licences, while management in Shark Bay is negotiated with government by an industry association representing all licence holders (Kangas *et al.* 2008). In the Australian Northern Prawn fishery, licence holders have formed an industry association that is taking an active role in day-to-day management, although management responsibility has not been fully devolved.

14.5 A POTENTIAL CORPORATE MANAGEMENT MODEL FOR THE MORETON BAY PRAWN FISHERY

A model for how such a system may work can be derived from the earlier proposals of Townsend (1995) and more recent experiences in self-management around the world. As a first step, fishers would need to form a company that had both management and marketing responsibilities. Fishers would all be shareholders in this company, and would receive a dividend based on its profits. How the shares are established requires a similar allocation mechanism as might be applied for an individual quota or effort unit system, so would be no more complex. Indeed, where some form of allocation process has already taken place, this can be directly translated into shareholding. Other considerations in establishing shares are outlined below.

The company would employ real-time management. Based on the market and stock conditions (and potentially how much of a sale had been secured already), the company would determine how much to catch each week. That is, set a quota week by week, and potentially for each individual.

There are a number of different models for how the catch is taken and returns that may be generated for the industry as a whole. One model is that all the catch would belong to the company, and fishers would be paid as if they were employed skippers (using the same share system as currently employed in most fisheries). The company would 'share' the fishing activity between the different members who were willing to undertake the harvesting (i.e. some get it this week, some get it next week). Fishers who choose to pull out entirely of the harvesting activities will still receive a dividend based on their share in the company. This is analogous, in concept, to leasing quota to the remaining fleet under an individual quota system.

Another model is that fishers 'bid' to take the catch that week, and effectively pay the company a royalty to do so. The economic theory of clubs suggests that some form of fee 'per visit' (commonly referred to as a toll) is an efficient exclusion mechanism and is likely to achieve an optimal (from the club's objective) outcome (Sandler and Tschirhart 1997). In such a situation, the top bidders, who are also likely to be the most efficient fishers, get to take the catch. The royalty forms part of the income to the company and is returned to all members through their dividends. The company would buy the product from the fishers at a given price and resell it as would any wholesale business, with the difference adding to company profits. This may result in some fishers being regularly excluded, but they will still receive a return on the profits of the company.

A potential problem with both of these approaches is that the corporation cannot directly control the activities of the vessels at sea that are operating independently (the so called 'principal-agent' problem), and hence the optimal catch may not be achieved (Townsend 2010). This may be less of an issue for fisheries that are small geographically and numerically. For larger fisheries, the corporation may develop its own form of individual quota system (transferable or non-transferable) for controlling the activity of the vessels undertaking the harvest.

Other variations are also possible. An advantage of the corporate management system is that fishers (shareholders) may choose which mechanism best achieves their overall set of objectives, which may include equity and social considerations as well as profit maximisation.

14.5.1 Establishing shareholdings

Allocating shareholdings in a fishery is analogous to allocating other fishing rights or privileges, and lessons can be learned from experiences to date, particularly in relation to individual quota allocations. Allocating statutory rights and/or shares in a fishery is a highly contentious issue. Most effort-control systems effectively allow equal access to all licence holders, but definition of individual effort or catch quotas results in some individuals being granted a greater share than others.[17] The most common approach has been to allocate shares based on a combination of previous fishing activity as well as the level of capital invested in the fishery. The shares are usually allocated to the owner of the capital (i.e. the boat owners) since they have made an investment in the industry, although in some cases allocations have been made to processors (Fina 2011; Matulich and Sever 1999) and non-owner skippers who have had substantial involvement in the fishery (Abbott *et al.* 2010; Fina 2011).

A general principle that has been established by successful quota allocation processes is that shareholdings need to reflect the level of capital invested in the fishery. For catch-quota-based systems, this is implicit in the allocation if historic catches are used as the basis of the allocation, because vessel capital contributes to these catches. For effort quotas, capital is often explicitly considered (for example, effort units based on days fished and vessel size).

There are generally three types of capital: human, vessel and stock. Fishing generates three forms of returns to these types of capital: income to human capital, a return on investment to vessel capital, and a return to the resource generally referred to as resource rent. The latter is often captured in the value of quota or licences that allow access to the resource, although there is considerable debate as to whether or not this rent should be extracted for the benefit of the general community, who, in many fisheries, are the legislated owners of the resource.

The importance of human capital (e.g. skill of the skipper and crew) on production can be substantial (Pascoe and Coglan 2002), and in some cases this has developed over successive generations of fisher families (Coglan and Pascoe 2007). Embedded also in the human capital is knowledge about how the fishery operates, and it is capturing this knowledge directly into management that is often seen as a key advantage of co-management (Grafton 2005). The labour component of human capital, however, is directly rewarded for its role in production through income, so it could be argued that it does not necessarily need to be recognised in the allocation of shares.[18] Further, in most fisheries, crew (other than skippers) are fairly transient, moving in and out of the fishery depending on available options. A case could be argued for employed skippers to receive some share in the fishery as they have had to invest in training in order to obtain appropriate qualifications, and have built up considerable human capital in the process (e.g. experience leading to greater efficiency).

In other sectors, the value of a company (i.e. the sum of the value of its shares) generally reflects the level of capital invested and the expectations about discounted future economic profits (if any) that are generated. In most companies, economic profits, that is, profits over and above those that represent a normal return on capital

[17] The potential also exists for an equal allocation to all incumbents, and relying on secondary markets to re-allocate fishing rights to those who value them most. Libecap G. D. (2007). Assigning property rights in the common pool: Implications of the prevalence of first-possession rules for ITQs in fisheries. *Marine Resource Economics* **22**, 407-423. However, this approach is rarely adopted as it benefits those who are less efficient and have had less involvement in the fishery over those who have made a greater investment and/or are more efficient.

[18] This is a potentially spurious argument as capital also receives a return, but is generally accepted that this forms part of the allocation process.

invested, are minimal (if any) as competition should dissipate them. However, in fisheries, economic profits are often interpreted as a return to the unpriced stock input, and generating resource rents is increasingly being seen as a key objective of Australian fisheries management (DAFF 2007; Department of Employment Economic Development and Innovation (DEEDI) 2009; Pascoe *et al.* 2009).

While too much vessel capital is generally employed in fisheries, this does represent the level of investment by industry and should form a key component to share allocation. In fisheries where rationalisation takes place, those fishers who leave are compensated generally on the basis of their access rights (e.g. licence, effort units or quota holdings), but the decision to leave factors-in the alternative use of the vessel capital (if any) or what they may receive for its sale (for either reuse or scrap) (Kitts *et al.* 2001; Muallil *et al.* 2011; Pradhan and Leung 2004). Including the existing vessel capital in the share allocation process will enable rationalisation of capital within the corporation with no real loss to the individuals. Effectively, individuals exchange their vessel capital for shares in the corporation, and the corporation rationalises this capital to either keep the most efficient vessels or sell the existing vessels in order to introduce a smaller, newer and more-efficient fleet.

The other key capital in the fishery is the fish stock itself. As this is a community-owned resource, there is justification for the State to be a shareholder, effectively collecting resource rent on behalf of the community through the corporation dividends. The level of State ownership could, in theory, represent the level of potential resource rent in the fishery, although extracting all rent from the fishery would reduce the incentive for industry to undertake rationalisation and other management actions to maximise this rent, so a level of State ownership that is less than that reflecting the full contribution of the resource may be more appropriate.[19]

Given that management is devolved to the corporation, some significant State ownership is essential to also ensure that other objectives of fisheries management, particularly in relation to environmental externalities generated, are minimised.[20] While restrictions could be legislated to ensure environmental or social externalities are minimised (which reflects the way most fisheries are currently managed), active State participation in the management decision making is still important.

For the Moreton Bay prawn fishery, an allocation model based on both hull units and days fished may be necessary to establish shareholdings for the fishers' share of the corporation. The former represents capital investment in the industry while the latter represents activity levels. From the production-function work in the earlier part of the report, days fished has a greater impact on the marginal product of the vessels than hull units, and the coefficients of the production function could be used to provide an implicit weighting on each component.[21] The use of days fished could also be used to allocate shares to long-term employed skippers in the fishery. From the economic survey, employed skippers receive an average of around 25 per cent of the revenue.

[19] Part of the resource rent that accrues to the other shareholders will be returned to the general community through the normal taxation system as income tax.

[20] The potential role of the State in self-managed fisheries was discussed above.

[21] For example, the marginal product of a hull unit is around 0.4 for an average boat, while the marginal product of an additional unit of effort is around 1. Given this, a one-third allocation of shares based on hull units and two-thirds based on effort may be a reasonable system.

On this basis, it may be reasonable to allocate 25 per cent of the shares of boats that employ skippers to these skippers. The final allocation process would need to be developed by both the State and industry to ensure equitable treatment of all concerned. The State is ultimately responsible for implementing any allocation mechanism as, until that point, there is nothing to allocate.

14.5.2 Coordinating marketing and harvest

The main benefit of the corporate management system is that it enables real-time management to ensure that the market is not flooded when stocks are abundant, driving the price down for all. By managing the catches each week they can also ensure a more consistent supply to the retailers/wholesalers which will also help secure a better price. Coordinated marketing also ensures that the fishers do not compete with themselves on the sale of the product, further forcing prices down. The corporation is effectively the sole seller of the produce, and can develop links with retailers and wholesalers to ensure a better price. This does not necessarily give the corporation monopoly power as similar products can be supplied from other fisheries or imported. However, it creates a more even balance of power between the buyers and fishers, enabling better prices to be received.

The management of the corporation, including the marketing aspects, will require employment of a full-time manager (or CEO) and potentially, another marketing manager. These positions could come from the existing pool of fishers, but there are likely to be greater benefits from employing people with these professional skills. The new positions increase the cost to the corporation (and hence to the shareholders), but is likely to also result in greater benefits compared to competition between fishers for product and markets. Additional costs associated with marketing activities could potentially be reduced by also marketing other Moreton Bay produce (e.g. from the crab and fish fisheries), operating as a more general cooperative for the bay.

14.5.3 Key challenges

Generally, fishers are largely independent and may believe they can operate better outside the group, so under a voluntary system many may choose to do so. Fishers who operate outside the corporation could still be effectively uncontrolled, and could undermine the corporation by landing higher quantities of product than optimal and selling at a discounted price to clear it. From the theory of clubs, this is likely to destabilise the corporation to the detriment of all producers in the fishery. For this reason, there may be merits in including some transferable quota system in the management mix, with members of the corporation effectively pooling their quota, and those who choose to remain outside the corporation operate under individual quotas. An extreme—but draconian—measure could be to allocate all rights to operate in the fishery solely to the corporation. Non-membership would therefore not be an option. This is likely to be efficient but inequitable, so may be administratively difficult.

The system would also require a substantial change in the culture of the fishery. Fishers would need to change the way they operate, with substantially less independence. When they fish and how much they catch would be subject to substantially more control than under the current system, but they would directly receive the benefits and would also have an active voice in determining how the activity was to be shared between the members.

Not all vessels would be required in the fishery. Because there is considerable underutilised capacity in the fishery, the same catch could be taken with fewer vessels. An advantage of the corporate model is that it would allow consolidation of vessels to improve the efficiency of the fleet. Owners of old vessels could retire their vessels and either live off their dividends or sell their shares in the corporation, or for those who wished to remain in the fishery, team up with other fishers to share use of the better vessels. Similarly, fishers could team up to bring in newer, more-efficient vessels.

14.6 CONCLUSIONS

The Moreton Bay prawn fishery satisfies all of the key conditions for a successful self-management and potentially corporate management system. The fishery is small in terms of number of participants and in geography. Unlike other fisheries that have progressed down the self-management route, the key market for the product is right on the doorstep. A corporate management model offers an advantage over a self-management model in that it can coordinate both marketing and management to take advantage of this unique geographical advantage.

The above review is not a definitive guide to all the benefits and/or pitfalls of such a governance structure, but does identify some key benefits and issues that need to be addressed in more detail. The key benefits of such a system include:

- integration of harvest strategies with marketing strategies;
- coordination of catch and sales to ensure best prices and lowest fishing costs;
- greater industry involvement in determining the future of their fishery and how it is to be managed; and
- ability to share in the profits of the company even if not fully active in harvesting (potentially a built-in pension scheme).

Corporate management will require changes in the way fishers operate. In particular, the decision on when to fish and what to catch will be taken away from the individual and decided by the collective. Problems will develop if individuals do not join the corporation but continue to fish and market their own product separately. While this may seem an attractive option to fishers who believe they can do better independently, it is likely to be just a short-term advantage with an overall long-term cost to themselves as well as the rest of the industry. However, if fishers are willing to accept these changes, then they may benefit substantially more than under the current system which has greater individual freedom but substantially lower rewards.

There are still substantial areas that need further consideration, particularly in relation to the allocation of shares, including who should be allocated shares (e.g. just licence holders or also some employed skippers). Similarly, how harvesting activity is to be allocated by the corporation to the fishers. These are largely issues that cannot be answered without substantial consultation with those likely to be affected, and these groups cannot give these issues serious consideration until the point at which they are likely to become a reality.

15 Benefits and adoption

The beneficiaries of the research are the Moreton Bay otter trawl fishers, the MBSIA and the Queensland Department of Agriculture, Fisheries and Forestry (DAFF) fishery managers, who now have a detailed understanding of the current status of the fishery, its economic performance and how profitability of the fishery might be improved. The fishers now have knowledge of corporate governance models that could be applied to their fishery to improve management and profitability, and the challenges to implementing such models.

The abiotic analyses not only provide an improved understanding of the effects of flow, rainfall, temperature, SOI and lunar phase on their catches, but they are also relevant to the Eastern King Prawn fishery, which is Queensland's most valuable commercial fishery (i.e., $30 million annually), of which approximately 90% of the catch and effort occurs outside the bay. The analysis showed that recruitment in the Eastern King Prawn fishery declined with increasing winter air temperatures (Table 13-12), and this may be used to help explain annual variation in the catch and stock status. To this end, the abiotic analyses benefit the stock assessment, long-term monitoring and management of the Eastern King Prawn fishery in Queensland, New South Wales, and their respective fishery managers.

The closure harvest strategy evaluations indicate that, depending on the assumptions made about the selectivity of the trawl gear, there is potential to increase the value of the annual tiger prawn catch by 5–20%. As the tiger prawn catch in Moreton Bay is valued at approximately $2 million annually, this expected increase in catch value equates to $100,000 to $400,000. It is important to note however, that there would also be some loss of revenue by closing the fishery at this time, due to preventing the harvest of other prawn species, predominately greasybacks. Also, the closure would result in reduced operational costs, which have not been factored into our analyses, hence profitability would be further increased.

16 Further development

During the project, fishers expressed interest in improving spatial management of the fishery. Although there are some available data showing trends in the spatial distribution, size and abundance of Greasyback, Eastern King and Brown Tiger Prawns in Moreton Bay through time, more sampling is required to pursue these management objectives. Additional tagging studies may also be required to estimate movement, migration and emigration rates into and out of areas of interest. The CSIRO were responsible for un-published 1973 tag-recapture data from Moreton Bay, and we have presented a general description of the movements (and growth) of Brown Tiger Prawns based on these data (Figure 6-8), but new tagging studies could provide further useful information.

The model used in the harvest strategy evaluations could be further improved to more accurately reflect the prawns' population dynamics and the effects of fishing mortality. Eventually, the technology could be transferred to the MBSIA, and other fishers' associations, in the form of a tool that would allow them to take ownership of evaluating other management strategies. Due to the relatively short duration of the project, development of the model was limited to the tiger prawns, which are the most valuable component of the bay trawl catch. Further development of the model should include the Greasyback and Eastern King Prawns. Inclusion of Banana Prawns in such models of the Moreton Bay fishery is probably not warranted due to their irregular catch rate which is heavily affected by environmental conditions, particularly freshwater flow. It is important to note that the Eastern King Prawns which are caught in the bay also contribute to a large and valuable offshore fishery. As such, any modelling designed to evaluate the effects of fishing EKP in Moreton Bay should consider all sources of fishing mortality on the stock, including the offshore population dynamics.

The economic analyses were based on a single survey of fishers. Future analyses would be improved if such economic data were obtained more frequently, or possibly, continuously.

Further consideration should also be given to: (a) an improved and coordinated marketing program for Moreton Bay's trawl caught product; (b) adopting a corporate management model of the fishery by both industry and government; and (c) an alternative boat-replacement policy for the ageing M2 fleet.

17 Planned outcomes

This report provides the Moreton Bay otter trawl fishers and the fishery managers with detailed information on the fishery, including: (a) long-term trends in catch, effort and catch rates, based on analysis of the logbook data; (b) past and new (i.e., from this report) economic analysis of the fishery; (c) abiotic influences on the prawn catch rates; (d) evaluation of temporal closures for tiger prawns; and (e) other governance models for the fishery. With this information, stakeholders are now in a stronger position to make informed strategic decisions about the fishery.

All of our analyses and modelling strongly indicate that the abundance of Brown Tiger Prawns in Moreton Bay has increased in recent years, concurrently with a large (i.e., 70%) reduction in effort. To this end, the tiger prawn stock appears to have recovered from previous decades of high effort and is currently considered to be at or around maximum sustainable yield (MSY). Landings and catch rates of tiger prawns have been at record high levels in recent years. While the harvest strategy evaluation is preliminary, it does indicate potential to increase the value of the tiger prawn catch. This is because reducing effort at certain times of the year reduces fishing mortality on sub-optimal-sized tiger prawns, allowing them time to grow to larger, more-valuable sizes. Due to annual variability in the size and timing of recruitment, it may be more effective for fishers to consider flexible closure periods, based on a within-season, industry-driven data collection program, rather than a fixed closure.

A range of other corporate governance models that could be applied to the Moreton Bay otter trawl fishery were presented. In one particular model, 'ownership' of the fishery is devolved to a company in which fishers and government are shareholders. The company manages the fishery and coordinates marketing to ensure that the best prices are received and that the catch taken meets the demands of the market. Coordinated harvesting would result in increased profits, which would be returned to fishers in the form of dividends. Corporate management offers many of the potential benefits of an individual quota system without formally implementing such a system.

A corporate management model offers an advantage over a self-management model in that it can coordinate both marketing and management to take advantage of the fishery's location to the large consumer base of Brisbane. The main challenges to implementing such a model are likely to be individuals choosing to remain outside of the corporation as competitors, and determining how the shares are allocated.

18 Conclusion

All of the project's objectives have been met, including Objectives 5A to 5E, which were given to the research group in April 2011.

Objective 1. Review the literature and data (i.e., economic, biological and logbook) relevant to the Moreton Bay trawl fishery.

This review (section 6) includes descriptions of the biology of the main prawn species, trends in logbook catch and effort data, Fisheries Queensland LTMP data on Eastern King Prawns sampled in Moreton Bay, previous economic analyses of the fishery, gear selectivity and a history of management of the fishery. As the review provides details on temporal variation in prawn abundance and trawl mesh selectivity, it also addresses Objectives 5D and 5E.

Objective 2. Identify and prioritise management objectives for the Moreton Bay trawl fishery, as identified by the trawl fishers.

Results from the survey of fishers, which sought input on management priorities and harvest strategies, are provided in section 7. Fishers identified 11 key issues that they felt were a priority for management (Table 7-2). These included highly contentious and political subject matter (i.e., bycatch, prawn imports, marketing and fuel costs), most of which were beyond the scope of the project and expertise of the research consortium. Nevertheless, the summary of issues is useful for management and captures the interest and priorities of the fishers. After the project began, additional specific objectives (i.e., Objectives 5A to 5E) for the researchers were developed with the project steering committee over several months. These are listed under section 5 Objectives and have also been addressed.

Objective 3. Undertake an economic analysis of the Moreton Bay trawl fishery.

The economic analysis was based on information provided by fishers during the survey interviews (Appendix 3 section 22) and their logbook data. It indicates that although the fishery is reasonably technically efficient (i.e., mean technical efficiency of 0.71), profitability is marginal, and in the long term, the T1/M1 and M2 fleets are economically unviable. Viability of the T1/M1 licence holders is slightly worse due to their higher capital investment costs. Economic performance is a key driver of effort in the fishery. Marginal profit per hour fished peaks in March and falls to a minimum in July and August, when average profitability falls below zero.

Objective 4. Quantify long-term changes to fishing power for the Moreton Bay trawl fishery.

This objective was addressed because of the need to standardise catch rates so that long-term trends could be assessed, stock assessments could be undertaken and harvest strategies evaluated. Long-term (i.e., 1988–2010) change in fishing power of the Moreton Bay fleet was quantified by collecting information on the different technologies adopted by fishers and examining their effects on catch rates. Data on technological changes, when they were adopted, and other factors influencing fishing power, were obtained from the fishers by interview (see survey Appendix 3 section 22). The rate at which technologies (i.e., GPS, DGPS, radar, sonar, plotter, computer-based navigation, autopilot, communication systems, fishing gear, engine power, etc.) were adopted was quantified. This information was then 'married' to the fishers' daily catch history. Generalised linear modelling was then used to determine the effects of each technology on the catch rates for each prawn species. Analyses that used Brown Tiger Prawns and Eastern King Prawns as the response variable indicated that vessel fishing power has increased by 10–30% over the 23 years, while fishing power associated with Greasyback Prawn catches has declined by approximately 10%. The adjusted catch rates which take account of these changes in fishing power show that abundance for all prawn species is stable or has increased, indicating that the concurrent reduction in effort has benefited the stocks. This is particularly noticeable for Brown Tiger Prawns.

Objective 5. Assess priority harvest strategies identified in 2 (above). Present results to, and discuss results with, MBSIA, fishers and Fisheries Queensland.

Initially it was intended to evaluate harvest strategies for the three main commercially important species (i.e., Greasyback, Eastern King and Brown Tiger Prawns), however, this proved to be too ambitious given the limited project duration and resources. As a result, the project focused on evaluating monthly closures on the catch and landed value of Brown Tiger Prawns, which are the most valuable component of the catch, valued at about $2 million annually.

Before evaluating closures for the Brown Tiger Prawns (i.e., section 11) it was necessary to quantify key population parameters, in particular, mortality rates and catchability. These are required for modelling the population and estimates of these parameters were derived in section 10. Prior to this work, there was no published information on the catchability or natural mortality of Moreton Bay tiger prawns. As such, this section of the report should be considered as part of the work required to evaluate harvest strategies (i.e., it directly addresses Objective 5A).

The tiger prawn harvest strategy evaluations also included information on selectivity, hence addressing Objective 5E. Findings from the evaluations were strongly affected by assumptions made about selectivity. The harvest strategy evaluations indicate potential to increase the value of the tiger prawn catch by 5–20% annually (i.e., $100,000–$400,000) by closing the fishery in January, when sub-optimal-sized tiger prawns recruit to the fishery. The multispecies nature of fishery complicates identifying strategies that increase the value of the harvest. We did not consider the effects of fishers not being able to harvest Greasyback Prawns, or other species, during the closure.

When results from the closure evaluations were presented, some fishers expressed concern over the migration of tiger prawns in the bay. Movements of Brown Tiger

Prawns were reviewed in section 6, however, section 12 presents an additional analysis of the spatial movement of tiger prawns, based on catch rates from high-resolution six-minute by six-minute logbook sites from the bay. This analysis indicates that the tiger prawns move in a northerly direction from the southern end of the bay from February to May (Figure 12-11). There is also a general movement from west to east and shallow to deep water at this time. This analysis also showed that the fishing mortality rate in the June–October period had declined markedly in recent years, which may at least partially explain the recovery observed in the tiger prawn population. Closing the fishery at this time (i.e., June–October) may be a strategy for preventing recruitment overfishing in the future, should effort levels rise again and be deemed as excessive. Section 12 addresses Objectives 5A and 5D.

While we did not evaluate harvest strategies for the Greasyback Prawns, it is unlikely this species would benefit from temporal closures as much as the tiger prawns. This is because greasybacks display extended recruitment to the fishery over several months (Courtney *et al.* 1995a) and therefore the likelihood of identifying a closure period that significantly increases the size of the prawns, and hence increases their landed value, is low, as there are multiple 'waves' of small recruits entering the fishery almost year-round. Furthermore, greasybacks are a very small species with limited growth potential, especially males which do not grow larger than about 7 g (Figure 6-2), and so there is little benefit to be gained from temporal closures for this species. Temporal closures designed to reduce growth overfishing on Eastern King Prawns in Moreton Bay also would have no virtually benefit to Moreton Bay fishers, as this species is highly migratory. Closures for this species would largely benefit the fishery for this species outside of Moreton Bay. Of the commercially important prawn species in Moreton Bay, Brown Tiger Prawns appear to show the greatest potential benefits from temporal closures.

The abiotic analyses presented in section 13 address Objective 5B. Fishers requested this objective to better understand factors affecting recruitment variability, and how this might be used to predict catches and improve marketing.

Section 14 addressed Objective 5C which pertains to the development of a corporate governance model of the Moreton Bay trawl fishery. This includes a review of alternative co-management systems. This section of the report outlines the general review, and highlights particular opportunities for the Moreton Bay prawn fishery. The review looks at systems that have been implemented or proposed for other small fisheries internationally, with a particular focus on self-management as well as the potential benefits and challenges for corporate management.
(O'Brien 1994)
Results from the study were presented to the fishers, the MBSIA and the fishery managers during six project steering committee meetings between August 2010 and October 2011. Results were also presented to the Australian Council of Prawn Fisheries Research and Development Forum at the Gold Coast Convention Centre 26 October 2011. Data, results and the literature review from the study were also disseminated by the MBSIA on their website:
Moreton Bay Seafood Industry Association (MBSIA)(http://www.mbsia.org.au/)

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20 Appendix 1. Intellectual property

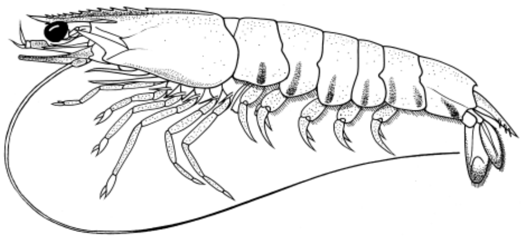
No intellectual property has arisen from the research.

21 Appendix 2. Staff

(in alphabetical order)

- Dr Peter Baxter, Centre for Applications in Natural Resource Mathematics (CARM, UQ)
- Dr Tony Courtney, Principal Fisheries Biologist (DAFF)
- Dr James Innes, Fisheries Economist (CSIRO)
- Mr Marco Kienzle, Fishery Resource Assessment Scientist (DAFF)
- Ms Michelle Landers, Fisheries technician (DAFF)
- Ms Jennifer Larkin, Fisheries technician (DAFF)
- Dr George Leigh, Fishery Resource Assessment Scientist (DAFF)
- Mr Michael O'Neill, Fishery Resource Assessment Scientist (DAFF)
- Dr Sean Pascoe, Fisheries Economist (CSIRO)
- Mr Andrew Prosser, Fisheries Biologist (DAFF)
- Dr David Sterling, MBSIA
- Professor You-Gan Wang, Centre for Applications in Natural Resource Mathematics (CARM, UQ)

22 Appendix 3. Survey of fishing power changes, economics and harvest strategies



Fishing Power, Economics and Harvest Strategy Survey Moreton Bay Otter Trawl Vessels 2010

This questionnaire relates to the following vessel ONLY

Vessel Name - ……………………………………………………

Vessel Symbol - ……………………………………………………

Interviewee and Date - ……………………………………………………

Record number (6000+)- ……………………………………………………

Answering the Survey –
The survey will provide information to establish the catching ability of your vessel. The questions are designed to record the historical change in your vessel and fishing gear characteristics.

Please provide dates on all vessel/gear changes where possible. This information is very important for us to understand the changes that occurred in your fishery over time. If a question does not accommodate your vessel/gear set up, please specify in your own words. If exact figures are not available please provide careful estimates. If you don't know some details please write "DON'T KNOW" for the question.

Individual vessel owners'/operators' information will be treated as strictly confidential. No individual or business will be able to be identified from the results in any reports. Your individual information will be entered onto an electronic database that has restricted access.

Vessel And Licence Specifications

Please provide information on changes to the vessel listed on the cover for the period from **purchase date to present**. If certain vessel specifications have changed more than twice, please record this information on **the back of page**. If exact figures or dates are not available please provide careful estimates. If you just don't know some details please write down **"DON'T KNOW".**

Purchase Details	
When did you purchase this vessel?	…………… /…………(M/Y)
Purchase price of vessel?	$………………………
Year vessel was built?	………………………
How many hull units for this vessel (M1 should be able to say, but M2 may not have hull units)?	....
Estimated value of licence and symbol (either T1/M1 or M2 Excludes other symbols)?	Licence value $........................ Symbol value $........................
Insured value of boat	$................................
Estimated value of replacement value of vessel?	$................................

Owner/Skipper Relationship				
How have you been related to the skipper(s)? Please tick the relevant box. If there was more than one type of skipper, please record the years operated by each skipper.				
	Owner-Skipper	**Related Family Member**	**Non-Family Skipper**	**Other**
Moreton Bay	☐ ……………… (year to year)	☐ ……………… (year to year)	☐ ……………… (year to year)	☐ ……………… (year to year)
Repeat details if required	☐ ……………… (year to year)	☐ ……………… (year to year)	☐ ……………… (year to year)	☐ ……………… (year to year)

For T1/M1 only, approximately how much of your trawl fishing effort (i.e. each year) is expended in Moreton Bay?

10% or less	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**

For T1/Mi only, if you do trawl elsewhere, what percentage of your effort is spent in the other sectors of the Queensland trawl fishery?

Eastern king prawn (outside the Bay)	**Scallop fishery**	**North Queensland tiger/endeavour prawns**	**Red spot king prawns**	**Banana prawns**	**Beam trawl**	**Other**
%	%	%	%	%	%	%

Vessel Specifications	**When you first fished with this vessel.**	**Provide details of any changes that have been made during your ownership/operation, with the first change in gear recorded first.**
1. Engine manufacturer	……………………………(type) Age of engine ………… .(Years)	………………………….(type) ………../……… (M/Y) Age of engine ……… .(Years)
2. Engine Rated Power–(hp or kW)	……………(hp)…………(kW)	…………(hp)……………(kW) ………/……..(M/Y)
3. Engine Rated RPM	…………………………(RPM)	…………(RPM)……/….(M/Y)
4. Maximum trawling RPM	…………………………(RPM)	…………(RPM)……/….(M/Y)
5. Normal trawling RPM Targeting Bay prawns	…………………………(RPM)	…………(RPM)……/….(M/Y)
Targeting Greasy prawns	…………………………(RPM)	…………(RPM)……/….(M/Y)
Targeting king prawns	…………………………(RPM)	…………(RPM)……/….(M/Y)
Targeting tiger prawns	…………………………(RPM)	…………(RPM)……/….(M/Y)
Targeting other species (please specify e.g., squid)	…………………………(RPM) …………………………..(species)	…………(RPM)……/….(M/Y) …………………………..(species)
6. Normal trawling speed for Targeting Bay prawns	…………………………(knots)	………(knots) …../….. (M/Y)
Targeting Greasy prawns	…………………………(knots)	………(knots) …../….. (M/Y)
Targeting king prawns	…………………………(knots)	………(knots) …../….. (M/Y)
Targeting tiger prawns	…………………………(knots)	………(knots) …../….. (M/Y)
Targeting other species (please specify e.g., squid)	…………………………(knots) …………………………..(species)	……… (knots)……/….(M/Y) …………………………..(species)
7. Steaming speed (knots)	…………………………(knots)	………(knots) …../….. (M/Y)
8. Reduction	…………… :1	…………. :1 ……/….. (M/Y)
9. Max. Fuel Capacity (litres)	……………………………….(l)	…………(l) ……/…….. (M/Y)
10. Fuel Consumption (litres per night)	………………..(litres per night)	…………………(litres per night) ………/……… (M/Y)
11. Propeller Diameter (inches or cm)	……………(")……………(cm)	……………(")……………(cm) ………/……… (M/Y)
12. Propeller Pitch (inches)	………………(")	……… (") ……/…….. (M/Y)
13. Kortz Nozzle (tick box)	Yes ☐ No ☐	Yes ☐ ………../……… M/Y installed

Vessel Specifications: continued. (complete only if you have changed vessel specifications more than once)

Vessel Specifications	**Additional Changes**	**Additional Changes**
1. Engine manufacturer	…………..…………..….(type) …........./…..…… (M/Y) Age of engine ………… .(Years)	…………..………..….(type) …........./…..…… (M/Y) Age of engine ……… .(Years)
2. Engine Rated Power–(hp or kW)	……………(hp)...……………(kW) ……..…/…...…(M/Y)	…………(hp)...……….(kW) …..…/……(M/Y)
3. Engine Rated *RPM*	……………(RPM)……/….. (M/Y)	…………(RPM)…/….. (M/Y)
4. Maximum trawling *RPM*	……………(RPM)……/….. (M/Y)	…………(RPM)…/….. (M/Y)
5. Normal trawling *RPM* Targeting Bay prawns	……………(RPM)……/….. (M/Y)	…………(RPM)…/….. (M/Y)
Targeting Greasy prawns	……………(RPM)……/….. (M/Y)	…………(RPM)…/….. (M/Y)
Targeting king prawns	……………(RPM)……/….. (M/Y)	…………(RPM)…/….. (M/Y)
Targeting tiger prawns	……………(RPM)……/….. (M/Y)	…………(RPM)…/….. (M/Y)
Targeting other species (please specify e.g., squid)	…………(RPM)……/…..(M/Y) …………………………….(species)	…………(RPM)……/…..(M/Y) …………………………….(species)
6. Normal trawling speed for Targeting Bay prawns	….……(knots) …..../….... (M/Y)	….…..…(knots) ……/...... (M/Y)
Targeting Greasy prawns	….……(knots) …..../….... (M/Y)	….…..…(knots) ……/...... (M/Y)
Targeting king prawns	….……(knots) …..../….... (M/Y)	….…..…(knots) ……/...... (M/Y)
Targeting tiger prawns	….……(knots) …..../….... (M/Y)	….…..…(knots) ……/...... (M/Y)
Targeting other species (please specify e.g., squid)	…………(knots)……/…..(M/Y) …………………………….(species)	…………(knots)……/…..(M/Y) ………………………….(species)
7. Steaming speed (knots)	…..…………(knots) ……/……. (M/Y)	…...…(knots) ……/...... (M/Y)
8. Reduction	.... :1 …..…/…..… (M/Y)	.... :1 ……/..…. (M/Y)
9. Max. Fuel Capacity (litres)	……………..…(l) ……/....... (M/Y)	……..…(l) ……/……..... (M/Y)
10. Fuel Consumption (litres per night)	…………………(litres per night) ……….../……...... (M/Y)	…………………(litres per night) ……….../……...... (M/Y)
11. Propeller Diameter (inches or *cm*)	……………(”)..................(cm) ……….…/.......... (M/Y)	……………(”)..................(cm) ……….…/.......... (M/Y)
12. Propeller Pitch (inches)	…...............… (”) ……/……... (M/Y)	…..........… (”) ……/……... (M/Y)
13. Kortz Nozzle (tick box)	Yes ☐ ..../.......... M/Y installed	Yes ☐ ..../.......... M/Y installed

Navigation Capabilities

One of the most important aspects to fishing is the ability to find and trawl the most productive areas. Specialised navigation equipment plays an important role in identifying and returning to productive fishing grounds. Please provide the following details for the vessel listed on the cover. If exact dates are not available please provide careful estimates. If you don't know some details write **"DON'T KNOW"** for the question.

Navigational Equipment	**Has the equipment ever been used on the vessel?** (Tick one box for each question. Please provide month/year if equipment was installed after the vessel was purchased)	**Has the equipment been updated or retired since first use?** (please provide month/year of change)
1. Colour Echo sounder	☐ No ☐ Yes, already installed when vessel purchased ☐ Yes, installed after vessel purchased (......../…....)	☐ 1st update ..../........ ☐ 2nd update …..../........ ☐ retired …..../…....
2. Sonar	☐ No ☐ Yes, already installed when vessel purchased ☐ Yes, installed after vessel purchased (......../…....)	☐ 1st update ..../........ ☐ 2nd update …..../........ ☐ retired …..../…....
3. Radar	☐ No ☐ Yes, already installed when vessel purchased ☐ Yes, installed after vessel purchased (......../…....)	☐ 1st update ..../........ ☐ 2nd update …..../........ ☐ retired …..../…....
4. Satellite Navigation (SatNav)	☐ No ☐ Yes, already installed when vessel purchased ☐ Yes, installed after vessel purchased (......../…....)	☐ 1st update ..../........ ☐ 2nd update …..../........ ☐ retired …..../…....
5. Global Positioning System (GPS)	☐ No ☐ Yes, already installed when vessel purchased ☐ Yes, installed after vessel purchased (......../…....)	☐ 1st update ..../........ ☐ 2nd update …..../........ ☐ retired …..../…....
6. Differential GPS (DGPS)	☐ No ☐ Yes, already installed when vessel purchased ☐ Yes, installed after vessel purchased (......../…....)	☐ 1st update ..../........ ☐ 2nd update …..../........ ☐ retired …..../…....
7. Plotter (interfaced with GPS)	☐ No ☐ Yes, already installed when vessel purchased ☐ Yes, installed after vessel purchased (......../…....)	☐ 1st update ..../........ ☐ 2nd update …..../........ ☐ retired …..../…....
8. Autopilot	☐ No ☐ Yes, already installed when vessel purchased ☐ Yes, installed after vessel purchased (......../…....)	☐ 1st update ..../........ ☐ 2nd update …..../........ ☐ retired …..../…....
9. GPS interfaced with the autopilot	☐ No ☐ Yes, already installed when vessel purchased ☐ Yes, installed after vessel purchased (......../…....)	☐ 1st update ..../........ ☐ 2nd update …..../........ ☐ retired …..../…....
10. Radar interfaced with the GPS/Plotter	☐ No ☐ Yes, already installed when vessel purchased ☐ Yes, installed after vessel purchased (......../…....)	☐ 1st update ..../........ ☐ 2nd update …..../........ ☐ retired …..../…....
11. GPS interfaced with computer mapping software eg. CPLOT.	☐ No ☐ Yes, already installed when vessel purchased ☐ Yes, installed after vessel purchased (......../…....)	☐ 1st update ..../........ ☐ 2nd update …..../........ ☐ retired …..../…....

Searching Capabilities

Please provide the following details for the vessel listed on the cover. If exact figures are not available provide careful estimates. If you don't know some details write **"DON'T KNOW"** for the question.

Try-Gear Net			
1. Does your fishing vessel use try-gear? If yes, on a normal night what percentage do you use try gear? If "No", then go to next section (Communication Devices)	☐ Yes ☐ No ☐ Less than 25 % of the night worked ☐ 25 % to 50% of the night worked ☐ 50 % to 75% of the night worked ☐ More than 75 % of the night worked		
2. When did this fishing vessel first start using try-gear?	………..../……….. Month/Year		
3. What type of try-gear do you use in the Moreton Bay Prawn fishery?	☐ Beam	☐ Otter	
4. What is the total head rope length of the try-gear (fathoms or metres)?	……………(fm) or ………………(m)		
5. In which position do you tow the try-gear?	☐ Stern	☐ Port	☐ Starboard
If you changed details of your try gear usage, repeat the details below.			
6. When did you change your try gear?	………..../……….. Month/Year		
7. What type of try-gear do you use in the Moreton Bay Prawn fishery?	☐ Beam	☐ Otter	
8. What is the total head rope length of the try-gear (fathoms or metres)?	……………(fm) or ………………(m)		
On a normal night what percentage do you use try gear? If "No", then go to next section (Communication Devices)	☐ Less than 25 % of the night worked ☐ 25 % to 50% of the night worked ☐ 50 % to 75% of the night worked ☐ More than 75 % of the night worked		
9. In which position do you tow the try-gear?	☐ Stern	☐ Port	☐ Starboard

Note: 1 fathom = 6 feet or 1.8 metres

Communication Devices

The ability to communicate with other vessels could influence where you fish. This is just another aspect how technology could influence your catch rates and play an important role to identify productive fishing grounds. Please provide the details of communication equipment installed or carried on the vessel listed on the cover. If exact dates/figures are not available please provide careful estimates. If you just don't know some details please write **"DON'T KNOW"** for the question.

Communication Devices	**Has the equipment ever been used on the vessel?** (Tick one box for each question. **Please provide month/year if equipment was used after the vessel was purchased**)	**What is the relative amount you use each device to communicate at present?**	
		From **vessel** to **vessel**? (per 100 communications)	From **vessel** to **shore**? (per 100 communications)
1. HF Radio	☐ No ☐ Yes, already used when vessel purchased ☐ Yes, but first used after the vessel was purchased. ………/……. M/Y End Use Date ……/……M/Y	☐ No ☐ less than 25 % ☐ 25 to 50 % ☐ 50 to 75 % ☐ more than 75%	☐ No ☐ less than 25 % ☐ 25 to 50 % ☐ 50 to 75 % ☐ more than 75%
2. VHF Radio	☐ No ☐ Yes, already used when vessel purchased ☐ Yes, but first used after the vessel was purchased. ………/……. M/Y End Use Date ……/……M/Y	☐ No ☐ less than 25 % ☐ 25 to 50 % ☐ 50 to 75 % ☐ more than 75%	☐ No ☐ less than 25 % ☐ 25 to 50 % ☐ 50 to 75 % ☐ more than 75%
3. UHF Radio	☐ No ☐ Yes, already used when vessel purchased ☐ Yes, but first used after the vessel was purchased. ………/……. M/Y End Use Date ……/……M/Y	☐ No ☐ less than 25 % ☐ 25 to 50 % ☐ 50 to 75 % ☐ more than 75%	☐ No ☐ less than 25 % ☐ 25 to 50 % ☐ 50 to 75 % ☐ more than 75%
4. 27 meg Marine Radio	☐ No ☐ Yes, already used when vessel purchased ☐ Yes, but first used after the vessel was purchased. ………/……. M/Y End Use Date ……/……M/Y	☐ No ☐ less than 25 % ☐ 25 to 50 % ☐ 50 to 75 % ☐ more than 75%	☐ No ☐ less than 25 % ☐ 25 to 50 % ☐ 50 to 75 % ☐ more than 75%
5. Mobile phone	☐ No ☐ Yes, already used when vessel purchased ☐ Yes, but first used after the vessel was purchased. ………/……. M/Y End Use Date ……/……M/Y	☐ No ☐ less than 25 % ☐ 25 to 50 % ☐ 50 to 75 % ☐ more than 75%	☐ No ☐ less than 25 % ☐ 25 to 50 % ☐ 50 to 75 % ☐ more than 75%
6. Satellite phone	☐ No ☐ Yes, already used when vessel purchased ☐ Yes, but first used after the vessel was purchased. ………/……. M/Y End Use Date ……/……M/Y	☐ No ☐ less than 25 % ☐ 25 to 50 % ☐ 50 to 75 % ☐ more than 75%	☐ No ☐ less than 25 % ☐ 25 to 50 % ☐ 50 to 75 % ☐ more than 75%
7. Email	☐ No ☐ Yes, already used when vessel purchased ☐ Yes, but first used after the vessel was purchased. ………/……. M/Y End Use Date ……/……M/Y	☐ No ☐ less than 25 % ☐ 25 to 50 % ☐ 50 to 75 % ☐ more than 75%	☐ No ☐ less than 25 % ☐ 25 to 50 % ☐ 50 to 75 % ☐ more than 75%
8. Others (please specify, eg. Cb radio, fax, etc.) …………………………………	☐ No ☐ Yes, already used when vessel purchased ☐ Yes, but first used after the vessel was purchased. ………/……. M/Y End Use Date ……/……M/Y	☐ No ☐ less than 25 % ☐ 25 to 50 % ☐ 50 to 75 % ☐ more than 75%	☐ No ☐ less than 25 % ☐ 25 to 50 % ☐ 50 to 75 % ☐ more than 75%

Turtle Exclusion Devices (TED) and Bycatch Reduction Devices (BRD)

The use of TEDs and BRDs can change your catching ability. Please provide the following information. If exa dates/figures are not available please provide careful estimates. If you just don't know some details please wr **"DON'T KNOW"** for the question.

Turtle Exclusion Devices (TEDs)	
When did you start using a TED?	………..…../............... M/Y (compulsory introduction of TEDs 05/99)
Please tick each of the following devices this fishing vessel has used during your ownership/operation? **TEDs:**	
Super Shooter…………………………………..…..	….☐ Start date …../….. End date ..…/…..
AusTED……………………………………………...	….☐ Start date …../….. End date ..…/…..
Nordmore…………………………………………..	….☐ Start date …../….. End date ..…/…..
Seymour……………………………...…………	….☐ Start date …../….. End date ..…/…..
Kevin Wicks………………………………………	….☐ Start date …../….. End date ..…/…..
Standard…………………………………………...	….☐ Start date …../….. End date ..…/…..
Weedless………….………………………………	….☐ Start date …../….. End date ..…/…..
Flounder…………..……………………….…….	….☐ Start date …../….. End date ..…/…..
Own Design………………………………………	….☐ Start date …../….. End date ..…/…..
Don't Know………………………………………	….☐ Start date …../….. End date ..…/…..
Others (please specify)……………………………	….☐ Start date …../….. End date ..…/…..

Bycatch Reduction Devices (BRD)	
When did you start using a BRD?	………..…../............... M/Y (compulsory introduction of BRDs 12/02)
Please tick each of the following devices this fishing vessel has used during your ownership/operation? **BRDs:**	
Square mesh panel ………………………………..	….☐ Start date …../….. End date ..…/…..
Square mesh codend………………………………	….☐ Start date …../….. End date ..…/…..
Half round square mesh codend……………………...	….☐ Start date …../….. End date ..…/…..
Fisheye…………………………………………….	….☐ Start date …../….. End date ..…/…..
Bigeye……………………………….…………	….☐ Start date …../….. End date ..…/…..
Radial escape section…………………………...	….☐ Start date …../….. End date ..…/…..
V-Cut and Bell Cod End…………………………...	….☐ Start date …../….. End date ..…/…..
Popeye Fish excluder……………………………	….☐ Start date …../….. End date ..…/…..
Don't know……………………………………..	….☐ Start date …../….. End date ..…/…..
Others (please specify)……………………………	….☐ Start date …../….. End date ..…/…..

Trawl Gear Types

The trawl gear essentially determines how effectively a vessel fishes, especially by changing swept area. The setup of trawl gear varies with vessels and many different net types are used. The following table is designed for you to record information on trawl-gear starting from when you first fished with the vessel until 30 June 2010.

All questions relate to the main trawl nets, not the cod-end.

- The first column is for you to record the **original** trawl gear when you first started fishing with the vessel listed on the cover.
- The next 3 columns are for you to record any changes from the original gear. P**lease record the new details and the month/year when the change occurred**. If there were more than 3 changes, please record details on the back of the page.

Moreton Bay Otter Trawl Fishery

Trawl-Gear Please answer questions row by row.	**When you first fished with this vessel**	**Provide details of any gear changes that have been made during your ownership/operation.**		
1. Net Type (Please tick one box) Single…….. Double......... Triple........... Quad............ Five………. Please specify Month/Year of changes	………☐……… ………☐……… ………☐……… ………☐……… ………☐………	………☐……… ………☐……… ………☐……… ………☐……… ………☐……… ……./…… M/Y	………☐……… ………☐……… ………☐……… ………☐……… ………☐……… ……./…… M/Y	………☐……… ………☐……… ………☐……… ………☐……… ………☐……… ……./…… M/Y
2. Total Net Head Rope Length Please specify Month/Year of changes	…………(fm)	……………(fm) ……./…… M/Y	……………(fm) ……./…… M/Y	……………(fm) ……./…… M/Y
3. Net mesh size (inches ") Please specify Month/Year of changes	……………… (")	……………… (") ……./…… M/Y	……………… (") ……./…… M/Y	……………… (") ……./…… M/Y
4. Did/Do you use knotless mesh?	☐ No ☐ Yes	☐ No ☐ Yes ……./…… M/Y	☐ No ☐ Yes ……./…… M/Y	☐ No ☐ Yes ……./…… M/Y
5. Ground Gear Type (tick box) Drop chain................................ Drop mud rope.......................... Drop chain with sliding rings..... Danglers or Christmas-treedrops Looped ground chain................. Drop rope with chain................. Other (please specify)................ Please Specify Month/Year of changes	………☐……… ………☐……… ………☐……… ………☐……… ………☐……… ………☐……… ☐……………….	………☐……… ………☐……… ………☐……… ………☐……… ………☐……… ………☐……… ☐………………. ……./…… M/Y	………☐……… ………☐……… ………☐……… ………☐……… ………☐……… ………☐……… ☐………………. ……./…… M/Y	………☐……… ………☐……… ………☐……… ………☐……… ………☐……… ………☐……… ☐………………. ……./…… M/Y
6. Ground line specification Maximum gauge of chain (mm) Style of chain link (please circle one style)	…………(mm) short/regular/long	…………(mm) short/regular/long	…………(mm) short/regular/long	…………(mm) short/regular/long
Do you use Stainless steel chain? Please Specify Month/Year of changes	☐ Yes ☐ No	☐ Yes ☐ No ……./…… M/Y	☐ Yes ☐ No ……./…… M/Y	☐ Yes ☐ No ……./…… M/Y

7. Otter-boards types (tick box) Bison....................... Louvre..................... Flat Timber............... Flat Timber-steel ..... Kilfoil...................... Collins…….............. Other (please specify)... Please specify Month/Year of changes	..........☐........ ....☐........ ....☐........ ....☐........ ....☐........ ....☐........ ☐....................	..........☐......... ....☐......... ....☐......... ....☐......... ....☐......... ....☐......... ☐.................... ..../...... M/Y	..........☐......... ....☐......... ....☐......... ....☐......... ....☐......... ....☐......... ☐.................... ..../...... M/Y	..........☐......... ....☐......... ....☐......... ....☐......... ....☐......... ....☐......... ☐..................... ..../...... M/Y
8. Otter-board dimensions Length (feet)............ Height (feet)............ Please Specify Month/Year of changes	...............(ft) ....(ft)	...............(ft) ....(ft) ..../...... M/Y	...............(ft) ....(ft) ..../...... M/Y	...............(ft) ....(ft) ..../...... M/Y
9. Do you have a hopper on board your vessel?	☐ Yes ☐ No			
10. Do you have any comments on factors that you believe effects your vessel fishing performance? (i.e., fishing gear/designs, vessel performance, vessel design)	…………………………………………………………………… …………………………………………………………………… …………………………………………………………………… …………………………………………………………………… ……………………………………………………………………...			

Economic Survey Questions

Total Value of Sales

	2008-09 tax year	**2009-10 tax year**
Total revenue from sale of all catch	$...............................	$...............................
% Breakdown for Moreton Bay trawl fishery -		
'Bay' prawns	……………………%	……………………%
Greasy prawns	……………………%	……………………%
King prawns	……………………%	……………………%
Tiger Prawn	……………………%	……………………%
Other Species	……………………%	……………………%
% Of income by fishery sector -		
Trawl Inside Bay	……………………%	……………………%
Trawl Outside Bay	……………………%	……………………%
Non Trawl Fishing (e.g., pot, line, gill net)	……………………%	……………………%
Is this gross or net of agent commission?	Gross / Nett	Gross / Nett

Who do you mainly sell your product to?

……………………………………………………………………………………………

……………………………………………………………………………

Personal/Family Details

Age of Skipper	……………. Years	Family Fishing History (number of generations of fishermen)	……………..…
Total years fishing	……………. Years	Years as a skipper	………… Years
Highest level of formal education	…………………………………………………………………… ……………………………………………………………………		

Training courses and other qualifications achieved	………………………………………………………………………… …………………………………………………………………………

Fishing (Trip) Costs

Item	Cost/day at sea (estimate)		Total cost over year (from accounts)	
	2008-09	**2009-10**	**2008-09**	**2009-10**
Fuel and oil costs	$....................	$....................	$....................	$.....................
Fuel use (litres)	………..l/day	………..l/day	…………..l	…………..l
Ice costs	$....................	$....................	$....................	$.....................
Gear maintenance costs (fix, repair, clean, etc.)	$....................	$....................	$....................	$.....................
Trip related costs List some of these 1)……………………… 2)……………………… 3)………………………	$....................	$....................	$....................	$.....................
Other running costs (e.g. packaging, freight)	................$/kg	................$/kg	$....................	$.....................

Annual Crew Costs

Are you the skipper	☐ Yes ☐ No		
Average number of crew (excluding owner/skipper)	……………………..	% of time employ a skipper	……………………..%
Total crew payments from accounts	2008-09	$...............................	Include/exclude skipper?
	2009-10	$...............................	Include/ exclude skipper?
Skipper Share (if not owner)	…………………..% Gross / Nett revenue		
Crew Share	…………………..% Gross / Nett revenue	Fixed Payments	…………………$/week

(Net revenue in this case is net of trip costs)

Other costs

Item	**2008-09**	**2009-10**
Boat repairs and maintenance (annual costs not already covered above)	$......................	$......................
Engine repairs and maintenance	$......................	$......................
Gear replacement (capital item costs borne solely by owner)	$......................	$......................
Other repairs and maintenance	$......................	$......................
Safety compliance costs (equipment)	$......................	$......................
Lease/wharf fees (beach plot rent where applicable)	$......................	$......................
Insurance costs	$......................	$......................
Other rental or hire costs (e.g. workshop)	$......................	$......................
Administration costs (e.g. accountancy, telephone, bank charges, etc.)	$......................	$......................
Interest payments		
Fishing business loan repayment – Amount paid off <u>Capital</u>	$......................	$......................
Fishing business loan repayment – Amount paid off <u>Interest</u>	$......................	$......................
Other costs (e.g. vehicle costs,.)	$......................	$......................

Harvest Strategy Evaluation Questions

Please rate how you feel about the following statements in regard to the Moreton Bay trawl fishery. For each statement tick one box.

1) Current management of the Moreton Bay prawn trawl fishery is very good.

Strongly disagree	**Disagree**	**Neither disagree or agree**	**Agree**	**Strongly agree**

2) There are too many trawlers in Moreton Bay prawn trawl fishery.

Strongly disagree	**Disagree**	**Neither disagree or agree**	**Agree**	**Strongly agree**

3) There is too much trawl fishing effort in Moreton Bay.

Strongly disagree	**Disagree**	**Neither disagree or agree**	**Agree**	**Strongly agree**

4) The M2 vessels should have effort units.

Strongly disagree	**Disagree**	**Neither disagree or agree**	**Agree**	**Strongly agree**

5) The size of the prawns that are being harvested is too small and well below the size needed to maximise value from the fishery.

Strongly disagree	**Disagree**	**Neither disagree or agree**	**Agree**	**Strongly agree**

6) The value of the prawn catch could be improved by using larger mesh.

Strongly disagree	**Disagree**	**Neither disagree or agree**	**Agree**	**Strongly agree**

7) Additional seasonal or spatial closures could increase the value of the prawn catch.

Strongly disagree | **Disagree** | **Neither disagree or agree** | **Agree** | **Strongly agree**

8) The Moreton Bay prawn trawl fishery cannot compete against imported vannamei prawns.

Strongly disagree	**Disagree**	**Neither disagree or agree**	**Agree**	**Strongly agree**

9) The main market for the Moreton Bay prawn trawl fishery should be the supply of bait-prawns.

Strongly disagree	**Disagree**	**Neither disagree or agree**	**Agree**	**Strongly agree**

10) Are their other technical changes that could be implemented to improve management of the fishery?

……………………………………………………………………………………………………
……………………………………………………………………………………………………
……………………………………………………………………………

23 Appendix 4: R code for analysis in section 12

Code to plot fishing effort by year

```
x = read.csv("Moreton Bay Otter trawl data 1988-2010.csv",
header=TRUE)
y1 = c(table(x$FishingStartDateYear)) / 1000
x1 = as.numeric(names(y1))
plot(x1, y1, type = "b", xlab = "Year", ylab =
"Unstandardised effort  (thousands of nights)", yaxs = "i",
ylim = c(0, 1.04 * max(y1)))
```

Code for Figure 12-1

```
lf0 = glm(Tiger ~ -1 + Auth + fYear + Cell * fMonth, family =
quasipoisson(link = "log"))
BoatCoef = coef(lf0)[paste("Auth", levels(Auth), sep="")]
hist(exp(BoatCoef) / 10, 20, main = "",
xlab = "Boat efficiency", ylab = "Frequency")
```

Code for Figures 12-2 and 12-3

```
plot((tapply(MonthSeq1, MonthSeq1, mean) - 1) / 12 + 1988,
tapply(Effort1, MonthSeq1, sum) / (10 * tapply(Days1,
MonthSeq1, sum)), type = "l", xlab = "Year", ylab =  "Fishing
efficiency (relative units)")
plot(tapply(Month1, Month1, mean), tapply(Effort1, Month1,
sum) / 1e5, type = "b", xlab = "Month", ylab =         "Total
effective effort (relative units)")
```

Code for aggregation of data

```
MC = paste(MonthSeq, Cell) # Month-cell combination
Month1 = tapply(Month, MC, mean)
Year1 = tapply(Year, MC, mean)
Tiger1 = tapply(Tiger, MC, sum)
MonthSeq1 = tapply(MonthSeq, MC, mean)
Site1 = tapply(Site, MC, mean)
Cell1 = factor(levels(Cell)[tapply(as.numeric(Cell), MC,
mean)])
Effort1 = tapply(exp(BoatCoef)[Auth], MC, sum)
Days1 = tapply(Auth, MC, length)
```

Code for Figures 12-4 and 12-7

```
plot(tapply(Year1, Year1, mean), tapply(Effort1, Year1, sum))
plot((tapply(MonthSeq1, MonthSeq1, mean) - 1) / 12 + 1988,
tapply(Tiger1, MonthSeq1, sum) / tapply(Effort1, MonthSeq1,
sum), type = "l", xlab = "Year", ylab =                "Catch
rate (relative units)")
y = tapply(Tiger1, Year1, sum) / tapply(Effort1, Year1, sum)
plot(tapply(Year1, Year1, mean), y, type = "b", xlab = "Year",
ylab = "Catch rate (relative units)", yaxs = "i", ylim = c(0,
1.04 * max(y)))
y = tapply(Tiger1, Month1, sum) / tapply(Effort1, Month1, sum)
plot(tapply(Month1, Month1, mean), y, type = "b", xlab =
"Month", ylab = "Catch rate  (relative units)", yaxs = "i",
ylim = c(0, 1.04 * max(y)))
```

Code for Figure 12-8

```
x = tapply(Year1 + (Month1 - 3) / 4, MonthSeq1, mean)
y = log(tapply(Tiger1, MonthSeq1, sum)) - log(tapply(Effort1,
MonthSeq1, sum))
z = tapply(Month1, MonthSeq1, mean)
l = z >= 3 & z <= 6
x[!l] = NA
y[!l] = NA
plot(x, y, type="l", xlab = "Year",
ylab = "Log catch rate, March to June  (relative units)")
l1 = x == floor(x) # March
points(x[l1], y[l1])
```

Code for Figures 12-9 and 12-10

```
# Monthly pattern of effort
par(mfcol = c(3, 4))
fMonth1 = factor(Month1)
for (i in 1:nlevels(Cell1)) {
 l = as.numeric(Cell1) == i
 SiteCurrent = mean(Site1[l])
 y = tapply(Effort1[l], fMonth1[l], sum) / 1000
 y[is.na(y)] = 0
 plot(as.numeric(levels(fMonth1)), y, xlab = "Month", ylab =
"Relative effort", main = paste("Site ", SiteCurrent, ": ",
levels(Cell1)[i], sep = ""), type = "b", ylim = c(0, 1.02 *
max(y)), yaxs = "i")
}

# Monthly pattern of CPUE
fYear1 = factor(Year1)
fMonth1 = factor(Month1)
fSite1 = factor(Site1)
lf = glm(Tiger1 ~ -1 + fYear1 + fMonth1 : Cell1 +
offset(log(Effort1)), family = quasipoisson(link = "log"))
Recruit1 = exp(coef(lf)[paste("fYear1", levels(fYear1),
sep="")][as.numeric(fYear1)])
Fit1 = fitted(lf)

par(mfcol = c(3, 4))
for (i in 1:nlevels(Cell1)) {
 l = as.numeric(Cell1) == i
 SiteCurrent = mean(Site1[l])
 y = tapply(Fit1[l], Month1[l], sum) /
  tapply(Effort1[l] * Recruit1[l], Month1[l], sum)
 plot(tapply(Month1[l], Month1[l], mean),
  y, xlab = "Month", ylab = "Relative catch rate",
  main = paste("Site ", SiteCurrent, ": ", levels(Cell1)[i],
sep = ""),
  type = "b", ylim = c(0, 1.02 * max(y)), yaxs = "i")
}
```

Code for Figure 12-12

```
# Use a GLM to do the catch curve analysis.
l = !is.na(match(Site1, c(6, 7, 8, 12, 13, 14, 17))) & Month1
>= 3 & Month1 <= 6
```

```
x = Month1 - 6 # Define intercept to apply to month 6, to
measure how many prawns are alive in June in each year.
lf2 = glm(Tiger1 ~ -1 + fYear1 / x + fSite1 +
offset(log(Effort1)), family = quasipoisson(link = "log"),
subset = l)

# Plot Z.
YearsCurrent = as.numeric(levels(fYear1))
l = YearsCurrent >= 1992 # Remove inconsistent years.
plot(YearsCurrent[l], -coef(lf2)[paste("fYear1",
levels(fYear1), ":x", sep="")][l], xlab = "Year", ylab =
expression("Total mortality rate " ~~ italic(Z) ~~ "(March to
June) (month"^Abstract~")"), type = "b", mar = c(5, 5, 4, 2))
```

Code for Figure 12-13

```
LogCpueJun = coef(lf2)[paste("fYear1", levels(fYear1), sep =
"")]
YearsCurrent = as.numeric(levels(fYear1))
l = YearsCurrent >= 1992
plot(YearsCurrent[l], exp(LogCpueJun)[l], xlab = "Year", ylab
= "Relative abundance in June", type = "b", yaxs = "i", ylim =
c(0, 1.02 * max(exp(LogCpueJun[!is.na(LogCpueJun)]))))
```

Code for Figure 12-14

```
SitesCurrent = c(7, 8, 12, 13, 14)
MonthsCurrent = 7:12
fMonth2 = factor(paste(Year1, Month1))
l = !is.na(match(Site1, SitesCurrent)) & !is.na(match(Month1,
MonthsCurrent))
lf3 = glm(Tiger1 ~ -1 + fMonth2 + fSite1 +
offset(log(Effort1)), family = quasipoisson(link = "log"),
subset = l)

for (i in MonthsCurrent) {
 x1 = coef(lf3)[paste("fMonth2", levels(fYear1), " ", i, sep =
"")]
 names(x1) = levels(fYear1)
 assign(paste("LogCpue", i, sep = ""), x1)
}

YearsCurrent = as.numeric(levels(fYear1))
l = YearsCurrent >= 1992
for (i in MonthsCurrent) {
 y = get(paste("LogCpue", i, sep = "")) - LogCpueJun
 l1 = l & !is.na(y) & YearsCurrent != 2008 # Anomalous year
 plot(YearsCurrent[l], -y[l] / (i – 6),
  xlab = "Year", ylab = expression("Offset mortality rate June
to October" ~ " (month"^ {- 1} ~ ")"),
 main = month.name[i], type = "b")
 lf4 = lm(y[l1] ~ YearsCurrent[l1])
 lines(YearsCurrent[l1], -fitted(lf4) / (i – 6), lty = 2)
 readline("Press enter to continue")
}
```