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Stock assessment of the Queensland (Australia) east coast banana prawn (*Penaeus merguiensis*) fishery

Queensland Government
Department of **Primary Industries and Fisheries**

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Executive summary

The banana prawn fishery is characterised by highly variable catches, which are believed to be largely affected by environmental factors including rainfall, salinity, river flow and temperature. While extensive studies of banana prawn biology and population dynamics have been conducted in the Gulf of Carpentaria, relatively little research has been undertaken off the east coast of Queensland, and the influence of environmental factors on banana prawn catches is largely unknown.

This study was the first investigation of the status of the banana prawn stock off the Queensland east coast and used a regional (eight sub-stock areas), monthly based and age-structured model to represent the prawn stock dynamics. Due to the lack of biological studies on banana prawn from the Queensland east coast, biological parameter values of natural mortality and growth rates that were estimated in the Gulf of Carpentaria were assumed to apply. Standardised monthly catch rates (CPUE) of banana prawns were used as a relative index of population abundance.

CPUE was standardised by using a linear mixed model fitting using restricted maximum likelihood (REML). The final model considered the year, month, sub-stock area, fishing method, air temperature and river flow. Catches of king and tiger prawns were also included to improve the measurement of targeted effort. River flow generally resulted in an immediate increase in otter trawl catch rates, possibly because the flow promotes the downstream movement of prawns to areas fished by the otter trawlers, thus increasing their catchability. Temperature effects were less important for the Cairns and Tully areas, possibly because the temperature range was less variable in these areas.

The results of the age-structured model showed that the current exploitable biomass levels (biomass in 2004) were about 50 to 70% of B_0 (virgin biomass). The biomass trends were relatively stable in the Tully, Mackay and the Fitzroy areas, but significant declines were observed during the late 1990s in the Townsville and Moreton areas, falling below 40% of B_0. While extremely high total catches which caused declines in the biomass seemed to be influenced by severe flooding events, it is unclear whether river flow affects recruitment of banana prawns or simply affects catchability. Further modification of the stock assessment model is necessary to investigate the effect of river flow on banana prawn population dynamics.

Major recommendations include:

- establish whether the parameter estimates applied from Gulf of Carpentaria banana prawn stocks (natural mortality, spawning patterns, and growth rates) accurately reflect the population dynamics of the east coast stocks
- amend the commercial fishing logbook system to enable improvements to the standardisation of CPUE and hence obtain more accurate indices of abundance
- undertake a formal stock assessment of the Queensland banana prawn fishery once every three to four years to examine the status of banana prawn stock. Standardised catch rates should also be monitored annually
- adopt the biologically-based limit reference point of B_{MSY}.

1 Introduction

1.1 Biology

In the Indo-West Pacific, banana prawns (*Penaeus merguiensis*) are distributed from the Persian Gulf to Thailand, Hong Kong, the Philippines, Indonesia to New Guinea, New Caledonia and northern Australia (Grey *et al.* 1983). In Australia they are distributed from Shark Bay and Exmouth Gulf in Western Australia through the Northern Territory, the Gulf of Carpentaria and the Queensland coast to northern New South Wales.

The biology and population dynamics of banana prawns have received considerable research attention (Dredge 1985; Munro 1975; Staples 1985; Staples and Vance 1985; Staples *et al.* 1985; Vance *et al.* 1985). Adults are trawled in schools in depths between 16 and 25 m (Grey *et al.* 1983). Adult females broadcast eggs into the water column (i.e. there is no brood). The eggs have a diameter of approximately 0.27 mm and are thought to be demersal. Fertilisation takes place externally and hatching to a pelagic non-feeding nauplius stage occurs within 1–2 days after spawning. Over the next 2–3 weeks, the young prawns develop through a protozoea stage, followed by a mysis stage and a postlarval stage that settles out of the water column into a benthic phase. Postlarval banana prawns settle in mangrove-lined, muddy estuaries and over the following 2–3 months grow into juveniles. Juveniles are tolerant of a broad range of salinities and may ascend several kilometres upstream to almost freshwater. When they are about half the length of adult size they leave the estuary and continue to grow, mature, mate and spawn in open offshore waters. Dall *et al.* (1990) put forward four general prawn life cycle types, based on the affinity that species have for an estuarine phase and suggested that *P. merguiensis* falls into the Type 2 life cycle, preferring estuaries or estuarine-like environments during part of their development.

1.2 Environment

Biological studies of banana prawns in the Gulf of Carpentaria revealed that a number of environmental factors may affect the various life cycle stages (Figure 1.1). Although it is not well known whether this life cycle and the environmental drivers in tropical regions are applicable in subtropical waters, Meager *et al.* (2003) found similar seasonal patterns of postlarval and juvenile catches and environmental effects in Logan River, a subtropical estuary in South East Queensland. Meager *et al.* (2003) also found that the period of postlarval and juvenile recruitment was more restricted in the Logan River than in tropical regions. The present study considered the following environmental variables for which data were available: a) rainfall, b) river flow and c) air temperature.

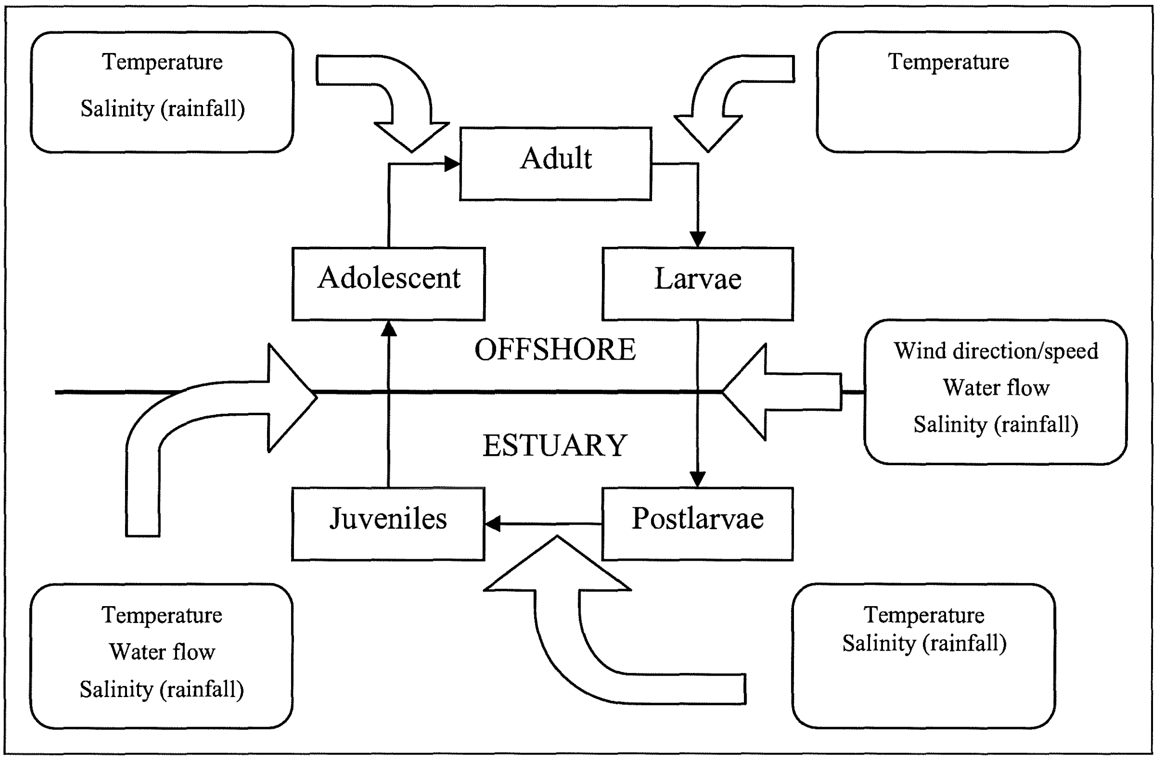

Figure 1.1 Basic life cycle of the banana prawn and the environmental factors in the Gulf of Carpentaria which may possibly affect each stage. (Sources: (Staples 1985; Staples and Vance 1987; Vance *et al.* 2003; Vance *et al.* 1985).

Rainfall

Rainfall is highly correlated with offshore commercial catches of banana prawns in the south-eastern Gulf of Carpentaria (Staples *et al.* 1994; Vance *et al.* 1985). It has been suggested that rainfall has different effects on different stages of the banana prawn life cycle:

- high rainfall increases emigration of juvenile banana prawns from the estuaries (Staples 1985; Staples and Vance 1987; Vance *et al.* 2003; Vance *et al.* 1998; Vance *et al.* 1985)
- increased rainfall prevents immigration, settlement and survival of postlarvae (Barrett and Gillespie 1973; Barrett and Gillespie 1975; Meager *et al.* 2003; Staples and Vance 1987)
- rainfall runoff may increase the overall productivity due to increased nutrient input, which may contribute to increased growth and survival rates of prawns (Robins *et al.* 2005; Staples and Vance 1985; Vance *et al.* 2003).

However, the influence of rainfall on juvenile emigration from the estuaries to offshore waters tends to vary depending on geographical areas with local climate patterns (Meager *et al.* 2003). Off the western peninsula of Malaysia, where rainfall is consistently high throughout the year, rainfall has little influence on emigration of juvenile banana prawns (Ahmad-Adnan *et al.* 2002). In contrast, off the east coast of Queensland, Meager *et al.* (2003) found low juvenile catches in the Logan River following high rainfall (low salinity), which indicates that rainfall stimulates the

emigration of juveniles to offshore waters in this subtropical estuary. Loneragan and Bunn (1999), on the other hand, failed to detect any significant effect of river flow (low salinity) on offshore commercial catches in the Logan River.
In the Fitzroy River, the largest catchment on the Queensland east coast, a significant positive correlation was found between summer rainfall (and river flow) and offshore annual catches (Robins *et al.* 2005).

River flows

Although river flow and rainfall effects could be assumed to have equal influence on prawn catches, there is evidence to suggest that flows are the more influential. Glaister (1978) found a significant correlation between river flow and school prawn catches in northern New South Wales, but not with rainfall. He suggested that flows were more influential because they not only include rainfall effects, but also other factors such as catchment size. Vance *et al.* (2003) also highlighted the influence of catchment size, which is captured in flow events, on offshore banana prawn catches in the Gulf of Carpentaria.

Temperature

Temperature may influence the survival of larvae and settlement of postlarvae (Haywood and Staples 1993; Staples and Heales 1991; Vance *et al.* 1985). Temperature may also affect the behaviour of adults, particularly during the period of emergence from the sediment (Vance *et al.* 2003). Vance *et al.* (1985) found a significant positive correlation between winter temperature and annual banana prawn catch in the Mornington Island and Groote Eylandt areas in the Gulf of Carpentaria. This may be a result of higher egg production and survival of larvae in these areas from winter spawnings. Vance *et al.* (1985) also found a significant negative correlation between summer temperature and annual prawn catch in the Karumba region, where the water temperature regularly exceeds 30 °C. The laboratory study conducted by Staples and Heales (1991) revealed that such high temperatures might increase the mortality of juvenile banana prawns, which could explain the negative effect. However, Vance *et al.* (2003) failed to detect any significant effect of summer temperature on prawn catch in any regions in the Gulf of Carpentaria, possibly because summer temperature was confounded by summer rainfall, which was a dominant environmental variable in the Gulf. In subtropical Queensland, where the seasonal variation in water temperature is much higher than in tropical waters, higher temperatures were associated with the higher juvenile catches in Logan River (Meager *et al.* 2003).

1.3 Spatially defining sub-stock areas

The affinity banana prawns have for shallow estuarine and coastal habitats, combined with logbook information on their distribution and their apparent inability to undertake significant migrations suggests that the fishery is likely comprised of sub-stocks or populations along the coast. While sub-stocks are unlikely to be completely independent of each other, those separated by large distances are likely to be more independent than adjacent sub-stocks. In the present study, logbook data on reported landings were used with information on catchments and river systems to define sub-stock areas. Logbook grids (30' × 30' grid) where banana prawn catches were reported were identified and allocated to a sub-stock. Each sub-stock was comprised of 2–7 grids.

About 96% of all landings for the period 1988–2004 have been reported from nine sub-stock areas shown in Figure 1.2.

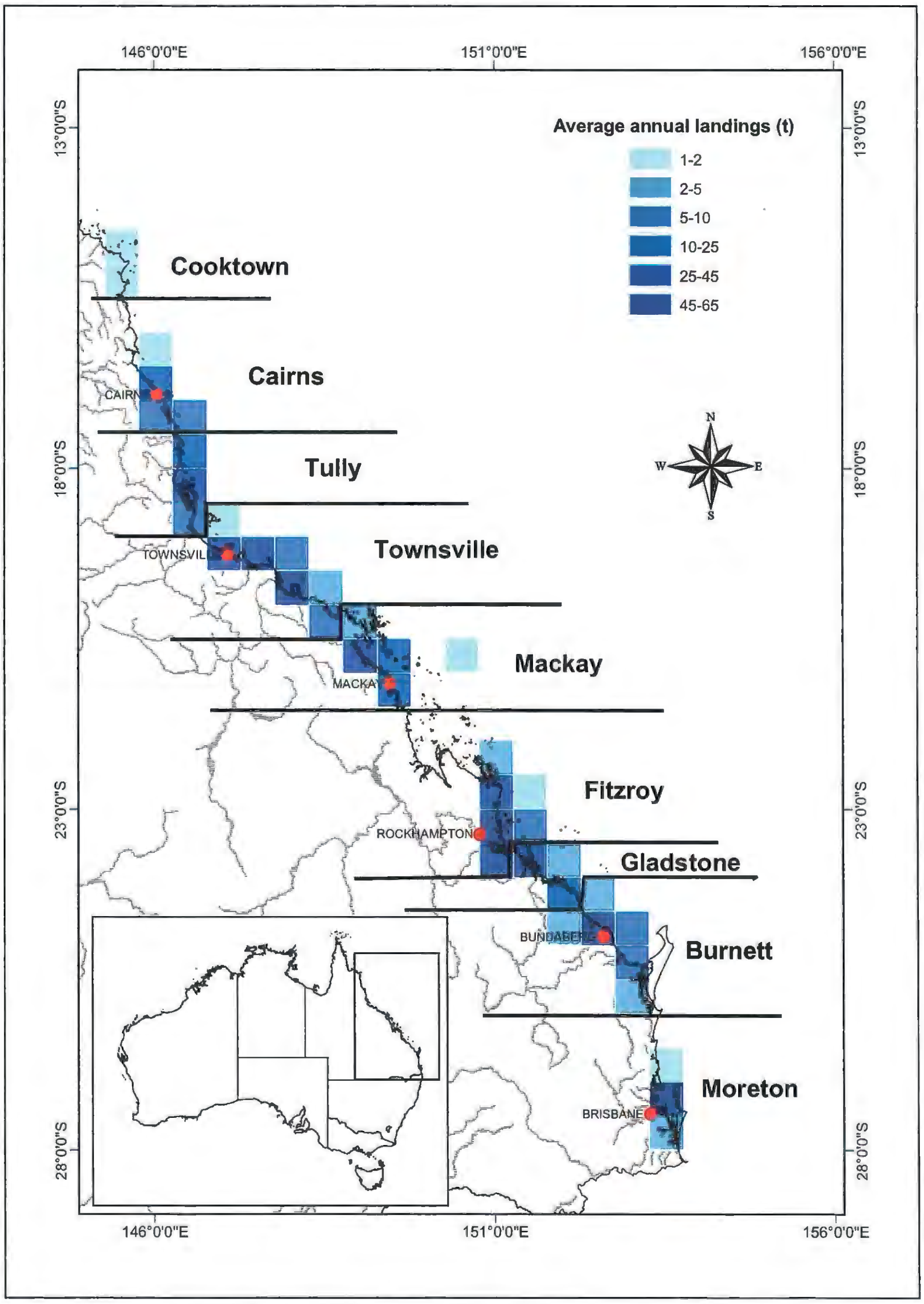

Figure 1.2. Nine sub-stock areas that comprise the Queensland banana prawn fishery. The average reported annual catch of banana prawns (1988–2004) is provided for each 30' × 30' grid.

1.4 Research history of the Queensland banana prawn fishery

The Queensland banana prawn fishery has received relatively little research attention and has not previously been quantitatively assessed. Five studies have been undertaken: two biological studies (Dredge 1985; Meager *et al.* 2003), two on bycatch (Hyland 1985; Stobutzki *et al.* 2000) and one bioeconomic evaluation of the beam trawl fishery (Campbell and Reid 2000; Reid and Campbell 1999).

Although no formal assessment was undertaken, Dredge (1985) suggested the fishery was heavily exploited, based on a comparison of the number of vessels operating on the Queensland east coast and the Gulf of Carpentaria. Dredge described size modal progressions, movements and reproductive biology of *P. merguiensis* in the Burnett River estuary and suggested the population displays two generations each year, one based on spawning from February to May, the other based on spawning from August to December. Dredge also suggested that some adult banana prawns over-winter in the river, returning from offshore to inshore, and then contribute to the spring spawning.

Hyland (1985) quantified beam trawl catch rates of banana prawns and other estuarine prawn species from the Caboolture, Pine, Brisbane and Logan Rivers using a voluntary logbook program before the mandatory CFISH program commenced in 1988. Hyland also described the bycatch from the Logan River, recording 93 species, with 12 species comprising 90% of the weight. Stobutzki *et al.* (2000) described the bycatch from the Queensland banana prawn otter trawl fishery and recorded 316 taxa with 25 species accounting for 80% of all individuals. The bycatch community structure varied with location and formed distinct groupings along a latitudinal axis. It was estimated that about 4500 t of bycatch was produced annually for a reported otter trawl catch of about 580 t of banana prawns.

Reid and Campbell (1999) and Campbell and Reid (2000) undertook a bio-economic analysis of the Queensland beam trawl fishery, which includes significant catches of banana prawns. The value of the recreational fishery and the value of marginal increases in catches of target species were estimated under the scenario of closing the beam trawl fishery. They concluded that any marginal benefits from closing the fishery would not justify the costs.

1.5 Objectives

The objectives of this assessment were to:

1. collate historical, commercial and recreational catch and effort data available for the banana prawn fishery on the Queensland east coast
2. investigate the influence of environmental factors (i.e. rainfall, river flow and air temperature) on banana prawn catch rates
3. describe the trend and current status of the banana prawn stock on the Queensland east coast
4. advise on management, monitoring, reporting and/or further research required to improve or enable future assessment of the Queensland banana prawn fishery.

2 Fishery

2.1 History and background

The history of commercial prawn trawl fisheries in Australia has been reviewed by Ruello (1974), Walker (1974), and Haysom (1985). According to Ruello (1974) and Haysom (1985), commercial prawn fishing in Queensland probably started along the Brisbane River in the 1840s using hand scoop net or scissor nets. The fishery for juvenile banana prawn in the Fitzroy River started in the 1880s. Beam trawling was introduced in southern Queensland rivers in the 1900s (Ruello 1974), but the development of the otter trawl industry in Queensland did not occur until the mid-1900s.

Although a variety of set nets and beam trawls are used in estuaries on the east coast of Australia, Ruello (1974) noted that prawn stocks including banana prawns in Moreton Bay remained unfished until 1950, when commercial otter trawling officially commenced in the area. The otter trawl fishery grew rapidly in Moreton Bay (Ruello 1974) and eventually spread to the Gold Coast and Hervey Bay in 1954 (Haysom 1985). The Commonwealth Government's *Challenge* survey of the prawn resources off the east coast of Queensland in 1957 and 1959 contributed to the extension of prawn trawling northwards along the entire Queensland east coast (Haysom 1985).

A major commercial otter trawl fishery for banana prawns producing an average catch of about 4400 t occurs in the Gulf of Carpentaria (Lucas *et al.* 1979; Perdrau and Garvey 2003; Somers 1985; Staples 1980; Staples 1985; Staples *et al.* 1985; Vance *et al.* 2003; Vance *et al.* 1985). The inter-annual variation in the catch is high, between 2000 and 8000 t, and this variability is often associated with the amount of rainfall in the adjacent estuarine prawn nursery areas (Vance *et al.* 2003; Vance *et al.* 1985). The Queensland east coast commercial fishery for banana prawns extends over a large latitudinal range, but reported total landings are minor compared to the Gulf. Williams (2002) identified an additional recreational harvest in the order of 10–100 t annually, based on cast netting in Moreton Bay, but the source of these data is unclear.

2.2 Commercial sector

Since the 1950s there have been several initiatives to record the catch of prawns from the Queensland east coast. The first of these was the Queensland Fish Board Data (1957–1980). There were also a number of voluntary logbook programs from 1968 to 1987 that were usually part of research projects. These voluntary logbook data are generally referred to as the 'historical trawl data' and include some records for banana prawn catch and CPUE. However, because they were voluntary programs they did not comprehensively cover the entire fleet and therefore cannot be used to estimate total landings of banana prawns or other prawn species. It was widely agreed that a more comprehensive program was required and in 1988 the compulsory logbook database program (CFISH) was implemented. The CFISH program remains operational and was designed to record all landings and fishing effort throughout the

Queensland trawl fishery, including all catches and trawl fishing effort for banana prawns.

Early (1957–1980) estimates of annual commercial landings of banana prawns from Queensland were estimated by using data from the Queensland Fish Board database (these are likely to be biased low). Estimates of landings from more recent years (1988–2004) were obtained from the compulsory logbook database program (CFISH).

Queensland Fish Board Data

The commercial prawn catches from the Queensland east coast were recorded from 1957 to 1980 by the Queensland Fish Board data. This recording method did not include prawn species identification, fishing location (latitude, longitude, fish grid) or fishing effort. The annual banana prawn catches during this period were estimated by assuming that the proportion of banana prawn in the total prawn landings was equal to the average ratio derived from the recent species specific CFISH logbook data. The average ratio of banana prawn catch weight to all prawn species in each sub-stock area between 1988 and 2004 is shown in Table 2.1. Note that the ratio for Cooktown was not included because there were no prawn catches reported from the Queensland Fish Board data from 1957 to 1980. These data were not used in the standardisation of banana prawn catch rate, but in the calculation of total catches which were considered in the stock assessment model.

Table 2.1 The average weight ratio of banana prawn to all prawn species in each sub-stock area obtained from CFISH data from 1988 to 2004. The values in parenthesis are standard deviations (s.d.) of the average. Note that the ratio for the Cooktown area was not included in the table since no prawn catches were recorded in the Queensland Fish Board data.

Sub-stock area	Average Ratio (s.d.)
Cairns	0.014 (0.007)
Tully	0.141 (0.077)
Townsville	0.175 (0.113)
Mackay	0.208 (0.083)
Fitzroy	0.188 (0.103)
Gladstone	0.376 (0.159)
Burnett	0.179 (0.063)
Moreton	0.029 (0.025)

When these ratios were applied to the Fish Board data, the estimated average annual banana prawn catches from 1957 to 1980 was 124.2 t (Figure 2.1). The estimated catches increased rapidly following the financial year of 1969, reaching a peak of 221 t in 1980. However, the Queensland Fish Board data is likely to underestimate the banana prawn catches particularly in early years in the northern regions (Cairns, Tully, Townsville and Mackay), and further modification was applied to obtain more robust estimates of catch (see Section 4).

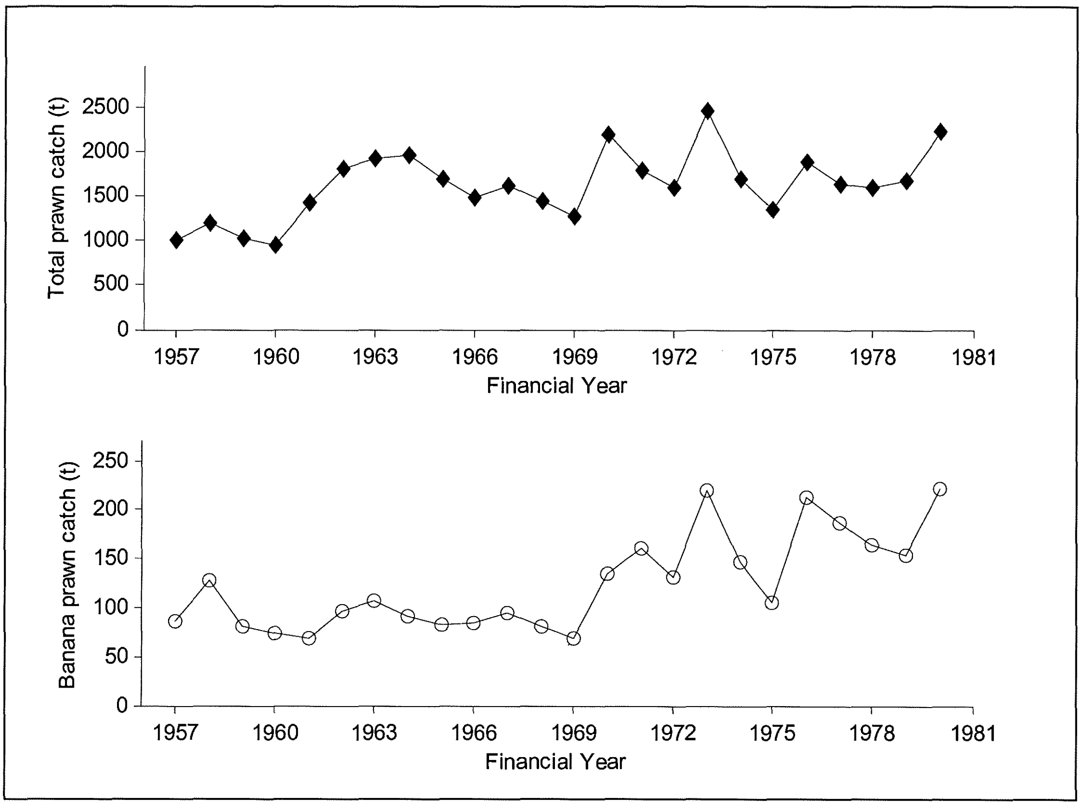

Figure 2.1 Annual commercial catches of all prawn species (top) and estimated banana prawn catches (bottom) in Queensland east coast waters from financial year 1957 to 1980.

Queensland Compulsory Logbook (CFISH) data

Although both beam trawl and otter trawl operators were encouraged to use a single 'trawl' logbook system (i.e. the otter trawl 'OT' series logbooks), from 1988 through to the mid-1990s the beam trawl operators recorded a significant proportion of their catch and effort statistics in a separate 'Mixed fishery logbook MI100'. It was not until 1998 that both sectors consistently used the same OT trawl logbooks and reported landings in the Mixed logbook database declined to negligible levels. The beam trawl catch and effort are therefore based on logbook data extractions from both the Mixed logbook and Trawl fishery logbook databases. All trawl caught prawns are now recorded by fishers in a single logbook database, based on the OT series.

Commercial catches from the otter trawl, beam trawl and stripe net fishery from 1988 to 2004 are plotted in Figure 2.2. About 76% of the annual commercial catch was taken in the otter trawl fishery. The beam trawling accounted for approximately 22% of the catch, and the stripe net fishery was a very minor component of commercial banana prawn catches (i.e. ~1.2% of total annual catch).

As indicated by Ruello (1974), the banana prawn fishery is characterised by erratic annual landings. The annual catch from otter trawl fishery has been highly variable, ranging from 230 t to 978 t (average = 509 t), while catch from the beam trawl fishery was relatively steady and slightly increasing over time, ranging from 71 t to 235 t (average= 133 t).

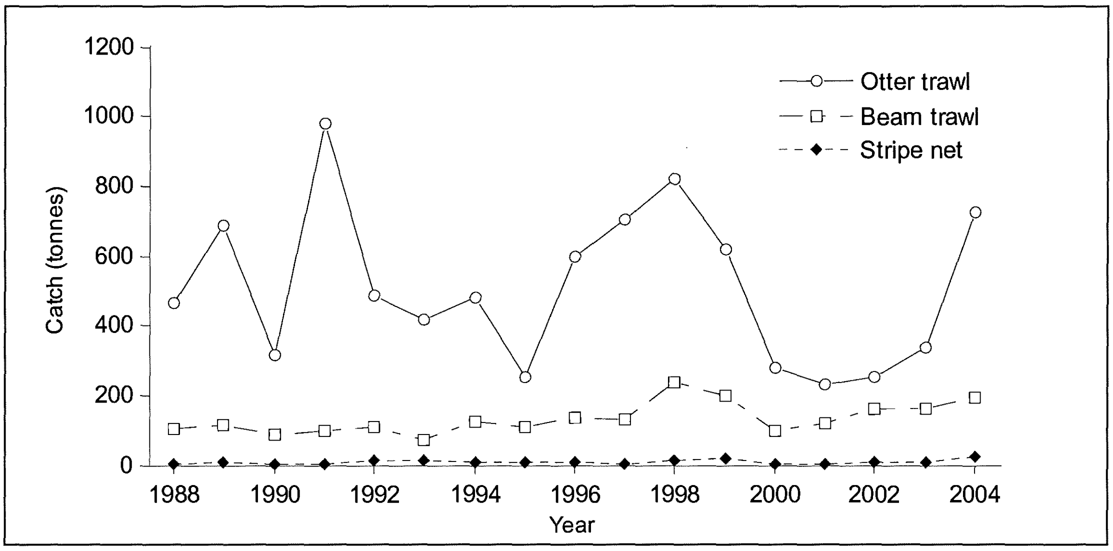

Figure 2.2. Reported total annual landings of banana prawns in Queensland east coast from the CFISH logbook database.

Figure 2.3 shows the mean annual catch of banana prawns reported from the different sectors and sub-stock areas from 1988 to 2004. The mean annual catch was greatest in the Townsville area (153.0 t), followed by the Fitzroy (112.4 t) and the Burnett areas (92.5 t). These three areas accounted for more than half of the total banana prawn catch from the Queensland east coast (54%) from 1988 to 2004. The beam trawl fisheries are largely located in the southern regions particularly in the Fitzroy, Burnett and Moreton areas, possibly due to the large river catchments in these areas. Catches of banana prawns from the stripe net fishery are largely restricted to the Mary River in the Burnett area.

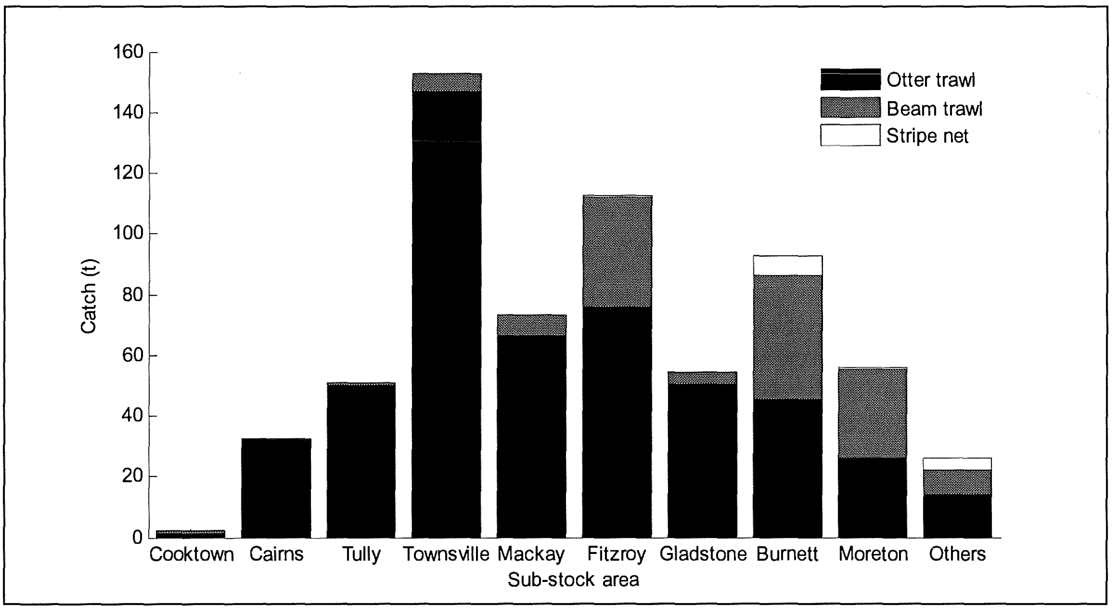

Figure 2.3 Average annual catch of banana prawns for each fishing method and sub-stock area, from 1988 to 2004. 'Others' is the average annual catches from outside of the sub-stock areas.

Figure 2.4 shows the average daily catch for each fishing method and sub-stock area. Note that the stripe net fishery is not displayed due to its small catches. Among the nine sub-stock areas, the highest average daily catch from the otter trawling occurred in the Gladstone area (129.3 kg/day/boat), while the lowest was in the Moreton area (22.4 kg/day/boat). The average daily catch from the beam trawling was much lower than that of the otter trawl. The highest beam trawl catch rate occurred in the Cooktown area (101 kg/day/boat) and the lowest in the Moreton area (20.9 kg/day/boat).

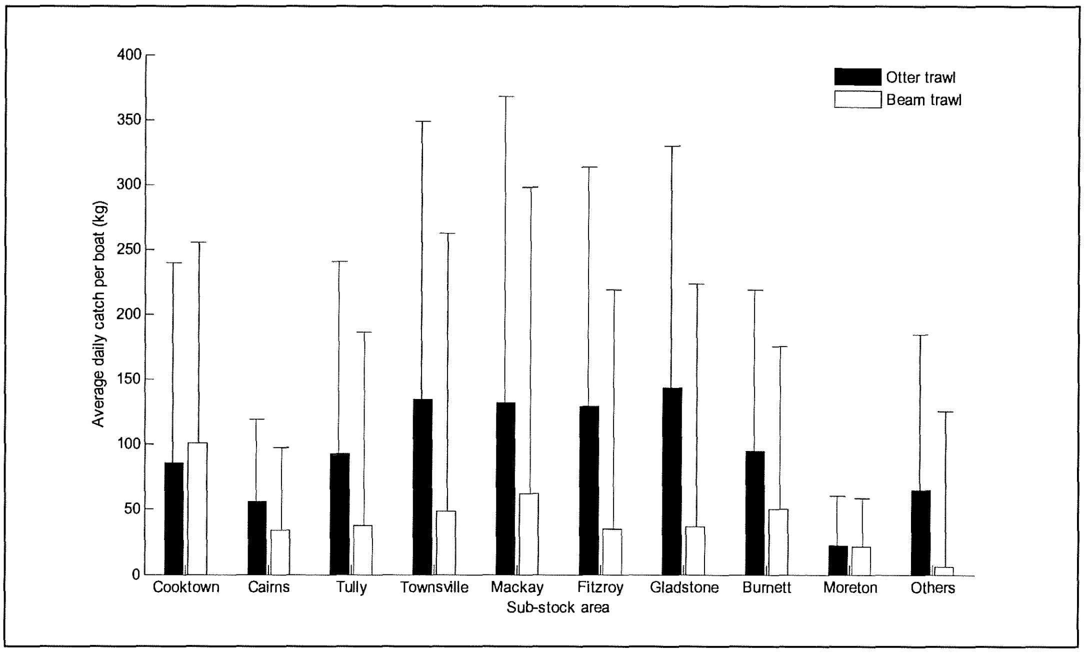

Figure 2.4 Average daily reported banana prawn catches (+ standard deviation) for otter and beam trawling in each sub-stock area (1988–2004).

The annual banana prawn catches (1988–2004) in each sub-stock area are shown in Figure 2.5. Variations in the annual catches were observed for all sub-stock areas. It is notable that the high total annual catches in 1991, 1997 and 1998 were largely attributed to the Townsville area, which accounted for approximately 42–51% of total landings in these years. The annual catches dropped dramatically for most of the sub-stock areas in 2000 and remained low until 2003. A significant increase in the annual catches was observed in 2004, largely due to catches from the Burnett and the Townsville areas.

The average monthly catch of banana prawns in each sub-stock area from 1988 to 2004 is shown in Figure 2.6. The banana prawn fishery is fairly seasonal, 78–88% of annual catches were reported from February to June for all sub-stock areas. Catches increase dramatically from early summer, reaching a peak in autumn (March and April), and then drop sharply from late autumn with very low catch in winter and spring.

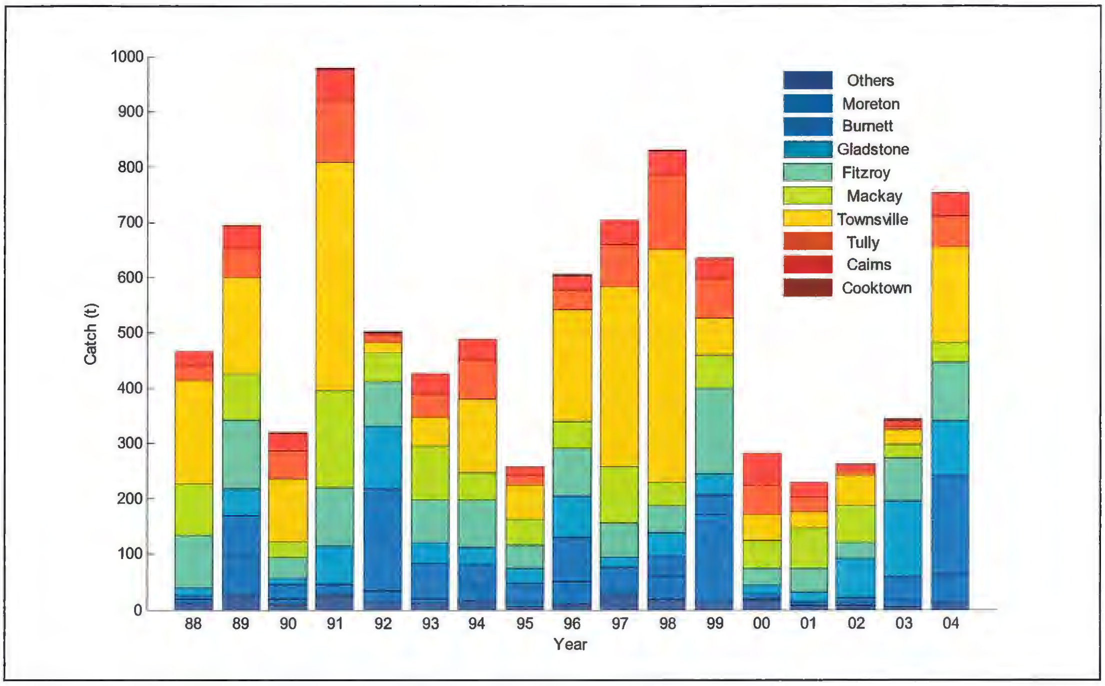

Figure 2.5 Reported regional annual commercial catch (t) of banana prawn from Queensland east coast waters, 1988–2004.

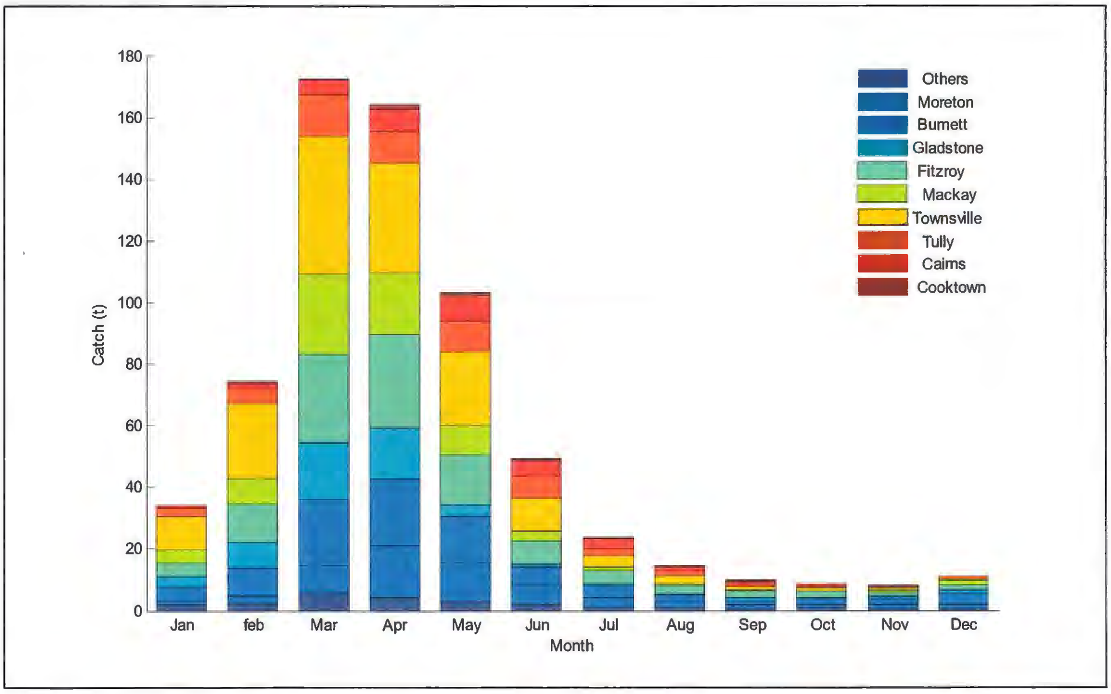

Figure 2.6 Average monthly commercial catch (t) of banana prawn from Queensland east coast waters, 1988–2004.

A review of the catch by vessel and year showed that 1251 different vessels caught banana prawns from 1988 to 2004 off the east coast of Queensland. Of these, 65 vessels had both beam and otter trawl licences, and 429 vessels accounted for about 90% of the total cumulative catch. The annual number of commercial vessels reporting banana prawns has tended to decrease since the late 1980s with a major drops in 1990, 1995 and 2001, but has increased gradually since 2001 (Figure 2.7).

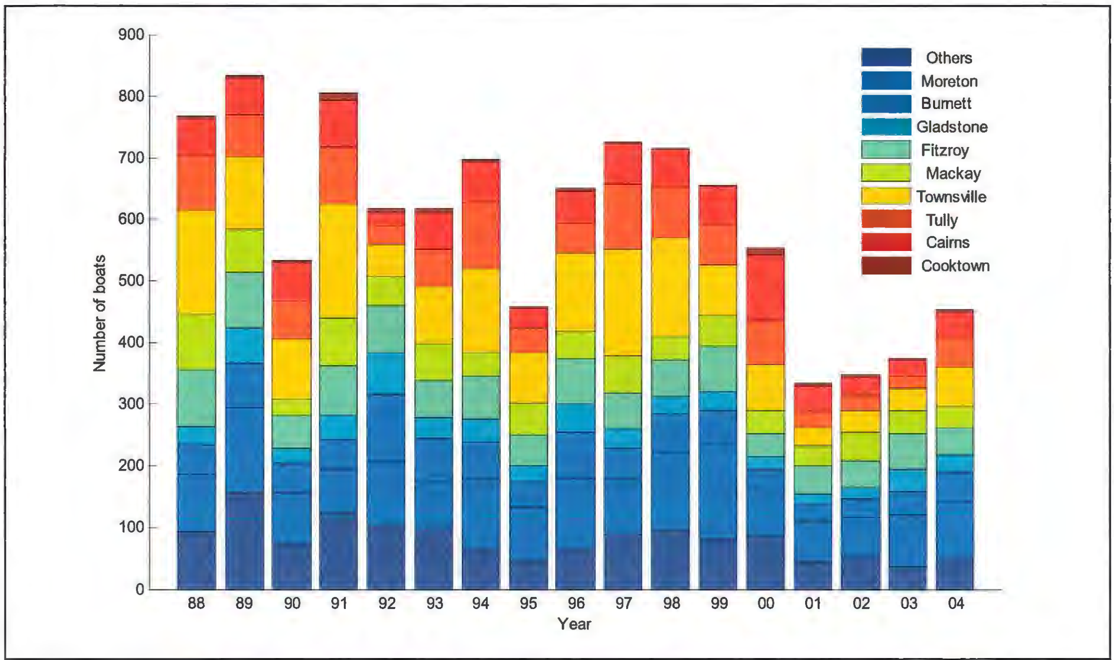

Figure 2.7 Annual number of commercial vessels catching banana prawn from the Queensland east coast, 1988–2004.

Annual commercial fishing effort (number of days fished) fluctuated between years, but a major increase was observed from the mid-1990s with peak of 14 819 days in 1999 (Figure 2.8). The effort dropped substantially in 2000 and again in 2001. Effort increased from 2001 to 2004, mainly due to the increased effort in the Moreton area, to a level close to the average of the time series. From 1988 to 2004, the Moreton area had the highest mean annual fishing effort among sub-stock areas (2531 days/year), followed by Fitzroy (1593 days/year) and Burnett (1470 days/year). Major reductions in annual effort were observed in the northern region (Cairns to Mackay).

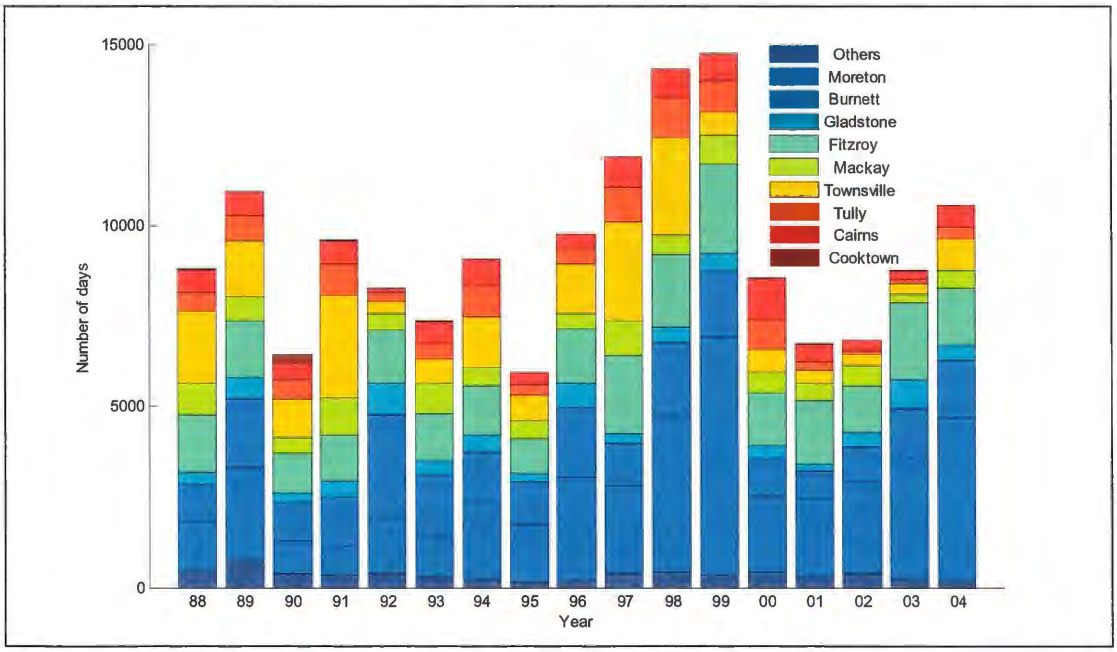

Figure 2.8 Annual number of days fished for banana prawn from the Queensland east coast, 1988–2004.

2.3 Recreational sector

As there is no recreational logbook database for prawns in Queensland, the only information on recreational catches is from the following:

1. Queensland recreational fishing surveys (RFISH), 1999 and 2002
2. National Recreational and Indigenous Fishing Survey (NRIFS), 2003
3. *Aspects of the use of baitnets and castnets in Queensland recreational fisheries* by McPherson *et al.* (unpublished, 1999), which identified the species composition of the recreational prawn fishery in Moreton Bay.

Queensland Recreational Fishing Survey (RFISH) data

Queensland recreational fishing surveys conducted in 1999 and 2002 estimated total recreational prawn catches (all species) from 15 geographical districts in Queensland. The fishing surveys estimated that about 76 t and 133 t of all prawn species were caught in Queensland in 1999 and 2002 respectively. No information on species composition was provided in these surveys; however, it is believed that banana prawns are the main recreational prawn species due to their inshore distribution. According to survey data from McPherson *et al.* (unpublished, 1999), about 96% of recreational prawn catches by cast netting in Moreton Bay were banana prawns. By applying this proportion, the total banana prawn catches in each sub-stock area were estimated by allocating the 15 geographical regions into the eight sub-stock areas (without the Cooktown area) (see Table 2.2). The Far North and Fitzroy Statistical Division (SD) were further divided into two areas (Cairns/Tully and Fitzroy/ Gladstone respectively) by taking proportions of total beam trawl catches from these sub-stock areas that were obtained from CFISH data (Table 2.3). Note that a) the Cooktown area was incorporated into the Cairns area due to its small total catches recorded in the CFISH database (Figure 2.3) and b) beam trawl catches were chosen to calculate the proportions of recreational catches because both sectors occur in rivers and estuaries.

Table 2.2 Allocation of the 15 geographical districts into the eight banana prawn sub-stock areas in Queensland East Coast waters.

District	Sub-stock area
Far North Statistical Division (SD)	Cairns/Tully
Northern SD	Townsville
Mackay SD	Mackay
Fitzroy SD	Fitzroy/Gladstone
Wide Bay-Burnett SD	Burnett
Brisbane City	Moreton
Brisbane Statistical Division Balance (SDB)	Moreton
Caboolture Region	Moreton
Gold Coast City	Moreton
Logan City	Moreton
Moreton SDB	Moreton
Redland Shire	Moreton
Sunshine Coast Statistical Sub-Division (SDD)	Moreton
Darling Downs SD*	–
SW/CW/NW SD*	–

* Note that Darling Downs SD and South West SD, Central West SD, North West SD (SW/CW/NW) were not included because they are not located on the east coast.

Table 2.3 Proportions used to divide RFISH districts into sub-stock areas.

District	Sub-stock area	Ratio
Far North SD	Cairns	0.631
	Tully	0.368
Fitzroy SD	Fitzroy	0.891
	Gladstone	0.108

National Recreational and Indigenous Fishing Survey (NRIFS)

The National Recreational and Indigenous Fishing Survey by Henry and Lyle (2003) provided estimates of recreational fish species catches from each of the Australian states and territories for the period May 2000 to April 2001. The survey estimated that about 54 t of prawns were caught by recreational fishers in Queensland during this period. Since there is no information on species composition or regional catches, the following process was applied to derive the estimates of banana prawn catches in each sub-stock area:

1. Total estimated prawn catch of 54.618 t was divided into 15 districts by using the proportion of estimated recreational prawn catches in each district defined in the RFISH data (1999 and 2002).
2. Banana prawn catches in each district were calculated by assuming 96% of prawn catch was banana prawn.
3. The total banana prawn catches in each sub-stock area were estimated by allocating 15 geographical regions into 8 sub-stock areas (Table 2.2).

Note again that the estimated banana prawn catches from Far North SD and Fitzroy SD were divided into two sub-stock areas respectively, by using the ratio shown in Table 2.3.

The estimated recreational banana prawn catch in each sub-stock area is summarised in Table 2.4. Total recreational catches of banana prawns from the Queensland east coast were estimated at about 73 t and 129 t from the 1999 and 2002 RFISH surveys. Apart from the Moreton area, the recreational catches increased for all sub-stock areas, especially for the Burnett (from 3 t to 30 t), Mackay (2 t to 23 t) and Townsville (6 t to 13 t) areas. The total recreational catch estimated from the 2000 NRIFS was about 52 t, which was almost 30% lower than the 1999 RFISH data. The banana prawn catches were highest in the Moreton area in all three years of records.

Table 2.4 Recreational banana prawn catches (kg) in each sub-stock area estimated from RFISH (1999, 2002) and NRIFS (2000) data.

Area for total catch	RFISH 1999	NRIFS 2000	RFISH 2002
Burnett	3229	8385	29108
Cairns	5859	4239	10487
Fitzroy	10016	6272	14173
Gladstone	1213	760	1717
Mackay	2129	6396	22539
Moreton	40992	18785	31454
Townsville	6124	4951	12971
Tully	3423	2476	6126
Total	72984	52265	128576

2.4 Management

Fisheries (East Coast Trawl) Management Plan 1999

The Queensland prawn trawl fishery is managed by the Queensland Department of Primary Industry and Fisheries (DPI&F) in accordance with the:

- *Fisheries Regulation 1995* (Fisheries Act 1994)
- *Fisheries (East Coast Trawl) Management Plan 1999.*

The fishery is managed by input control through limited entry, regulation on mesh size control, effort allocation, vessel and gear restrictions, and spatial and temporal closures. However, there are no specific input controls for banana prawns.

The Plan specifies Review Events for the principal targeted species, including eastern king prawns, bay prawns, Moreton Bay bugs, redspot king prawns, saucer scallops and tiger prawns, but no specific target or limit reference points are specified for banana prawns. The Review Events are based on reported logbook catch rates (CPUE) that are specific to recruitment and spawning period for each species. The underlying intention of the Review Events was that, should catch rates of recruits or spawning stock fall below 70% of those from 1988 to 1997, a review would be instigated. The response by management when a Review Event is triggered, or subsequent action to be taken, is not specified in the Plan.

In November 1999, the DPI&F introduced large seasonal closures in the Queensland east coast trawl fishery, summarised as:

- The annual northern closure of the otter trawl fishery between 15 December to 1 March from latitude 22°00.00'S to latitude 10°41.25'S (northern tip of Cape York).
- The annual southern closure of the trawl fishery between 20 September to 1 November from latitude 28°09.88'S to latitude 22°09.88'S (QECTMP 2004) This closure is restricted to depths of less than 50 fathoms and excludes Moreton Bay.

The northern and southern closures affect the otter trawl fisheries in five northern areas (Cooktown, Cairns, Tully, Townsville and Mackay) and three southern areas (Fitzroy, Gladstone, Burnett) respectively (see Figure 2.9). However, the effect of the southern closure on banana prawn stocks is considered to be negligible since the banana prawn populations are very small during the closed period (September and October). The northern closure affects the effort and catch directed at the banana prawn fishery. Kerrigan *et al.* (2004) identified the broad scale reduction of fishing effort in the banana prawn and bay prawn otter trawl sectors after the implementation of the 1999 Management Plan.

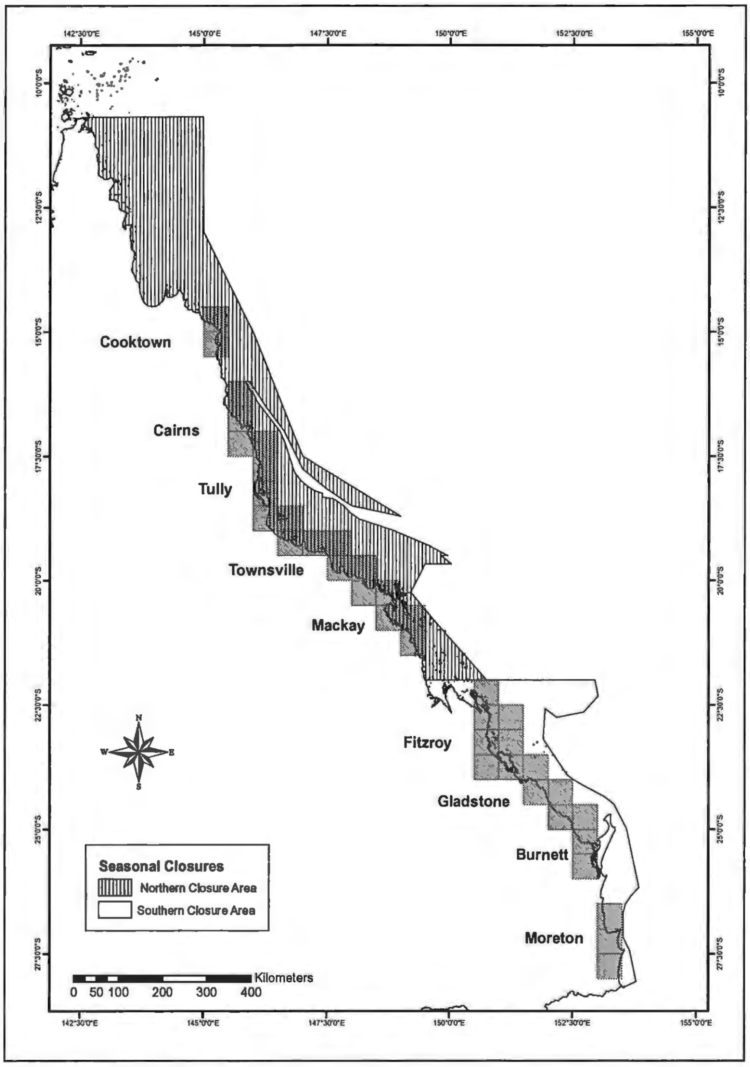

Figure 2.9 Areas subjected to the annual northern and southern closures, introduced in November 1999. Grey shading indicates grids in the nine sub-stock areas

The Great Barrier Reef Representative Area Program (RAP)

Approximately 70% of the catch and effort in the Queensland east coast otter trawl fishery (ECTF) occurs in the Great Barrier Reef World Heritage Area (GBRWHA) (Bibby and Kerrigan 2003). Approximately 49% of the GBRWHA was permanently closed to trawling under the *Great Barrier Reef Marine Parks Act 1975*, the *Marine Parks Act 1982* and associated legislation. In July 2004, the Commonwealth Government increased the permanently closed area with the GBRWHA to 66%, under the *Representative Areas Program* (RAP) (Kerrigan *et al.* 2004). Figure 2.10 shows the banana prawn trawling areas for the period from January 2001 to March 2004, as determined from Vessel Monitoring System (VMS) records, and the new RAP areas that were implemented in July 2004. Approximately 18% of the otter trawl fishing effort that was directed at banana prawns within the GBRWHA was affected by the RAP (Good and Peel unpublished).

Although the effect of the RAP on the banana prawn stock is unknown, its effect on the catch and effort data used in this study (from January 1988 to December 2004) was considered to be negligible because it only affected the last six months of the data used here (July 2004 to December 2004), and this time of year is generally when catch and effort in the banana prawn fishery are very low (see Figure 2.6).

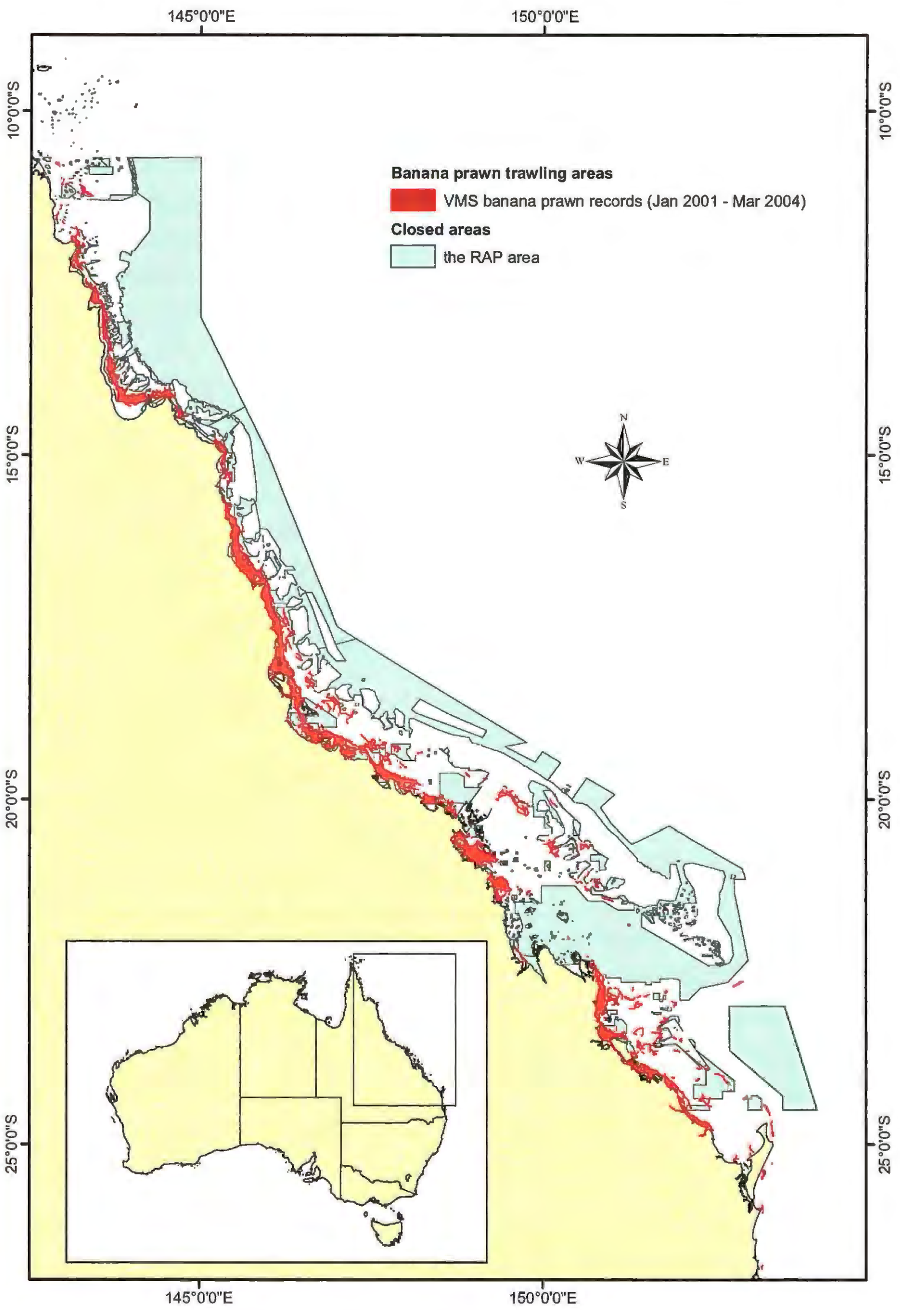

Figure 2.10 Banana prawn trawling areas, derived by marrying the VMS positional information with the logbook catches of banana prawns, for the period from January 2001 to March 2004. Also shown are the recently implemented closed RAP areas.

3 Standardisation of catch rates

In order to obtain the most reliable time series of catch rates, the data were standardised to remove as much variation as possible that was due to sources other than changes in abundance. To assess the stock it is necessary to have some understanding of the abiotic factors affecting the biomass and/or recruitment to the fishery. For example, if reported landings are high in a particular year then it is necessary to determine whether it is due to high fishing effort, or an environmental factor that has increased recruitment, and therefore catches, or a combination of the two. Conversely, should landings in a particular year be low it is necessary to determine whether it is due to low fishing effort levels or environmental effects, or both. The standardisation analysis in the present study considered a range of time-lagged environmental influences on the catch rate of banana prawns.

Two sources of banana prawn catch and effort data were considered: 1) the compulsory CFISH logbook data from 1988 to 2004 and 2) the historical trawl data (voluntary logbook records) prior to 1988. Separate analyses were conducted for each source due to inconsistencies between the two datasets. The CFISH data were analysed to investigate a range of time-lagged environmental factors on catch rates. Once the most significant explanatory variables were identified, the data were standardised and used in the stock assessment model. Due to the limited quantity and quality on the historical trawl data, they were only analysed to provide historical information on banana prawn catch rates.

3.1 Materials and methods

CFISH logbook data (1988–2004)

Commercial catch and effort records over the period of 1988 to 2004 from the Queensland east coast banana prawn fishery were obtained from the CFISH logbook database. The records include the otter trawl fishery data (fishing method codes 7 and 17), the beam trawl fishery data (fishing method code 47) and the stripe net fishery data (fishing method code 84). The trawl data were accessed on 6/9/2004 using the SQL code 'dump9a', which is held by the Assessment and Monitoring Group, Fisheries Policy and Sustainability, Fisheries, Queensland Department of Primary Industries and Fisheries Building, Brisbane. The old and new species codes used for the banana prawn extractions were 701901 and 28711050, respectively. Details of the data extraction are provided in Table 3.1.

Since Cooktown had very small banana prawn catches compared with other areas (see Figure 2.3 in Section 2), it was considered that the importance of the banana prawn sector in this area was minor and therefore was omitted from the analysis. Furthermore, the stripe net fishery was a very minor component of the commercial banana prawn sector on the east coast of Queensland (1.2% of total commercial catches from 1988 to 2004), therefore this standardisation process concentrated only on otter and beam trawling.

Table 3.1 The decision rules and retrieval conditions used to extract the banana prawn catch and effort data from the commercial CFISH logbook database.

Data	Details	Notes
CFISH data extraction	6/9/2004; SQL script held by Assessment and Monitoring, Fisheries Policy and Sustainability, Fisheries; Primary Industries Building, Brisbane.	SQL code: 'dump9a';
Time period	1/1/1988 to 31/12/2004	
Daily records	Only daily records were analysed and were identified by the same operation date and end date of fishing. Non-daily (bulk) records were included only in the total catch and effort summaries.	Data were grouped by vessel_id and operation date to make daily (banana prawn catches > 0). Effort = (end date – operation date) +1; (bulk data is effort > 1)
Year	Calendar year	
General stock or fishing area	All east coast latitudes north of 29°S and west of 152.5°E.	
Logbook grids analysed in the standardisation procedure	Cooktown: G12, G13 Cairns: H15, H16, H17, I17 Tully: I18, I19, I20 Townsville: J20, J21, K21, L21, L22, M22, M23 Mackay: N23, N24,O24, O25 Fitzroy: R27, R28, R29, R30, S28, S29 Gladstone: S30, T30, T31 Burnett: U31, U32, V32, V33, V34 Moreton: W36, W37, W38	Selected grids = (average annual reported landings between 1988 and 2004 > 1 tonne) Grid allocated from formula—not CFISH grid table (through dump 9a). Data with no location excluded (through dump 9a).
CFISH grids used to calculate the total catch of banana prawns in each sub-stock area		The distribution of the total catch in each sub-stock area is provided in APPENDIX 2
Related catches	Daily banana prawn catches were matched against daily total catches of king and tiger prawns (i.e. red spot king, eastern king, blue leg king, tiger, western king prawns).	Used in the analysis to correct for target fishing. 'Related' defines each vessel and day of fishing.
Fishing method codes	Otter trawling: 7, 17, Beam trawling: 47 Stripe netting: 84	Identifies otter, beam trawling and stripe netting. Note that the stripe netting is not included in the standardisation analysis.
Species codes	Banana prawns: 701901 Red spot king prawns: 701303 , Eastern king prawns: 701305, Red spot & blue leg king prawns: 701399, Tiger prawns: 701902, King prawns: 701904, Western king prawns: 701910, King + Tiger prawns: 701910	New CFISH species codes were implemented in 2005 (Table 3.2).
File name and location	M:\sustainable fisheries\stock assessment\Banana prawns\Data	

Table 3.2 Species code list from CFISH.

Species code	Common name	Scientific name	New species code
701901	Prawn – banana	*Penaeus merguiensis*	28711050
701303	Prawn – red spot king	*Melicertus longistylus*	28711048
701304	Prawn – eastern king	*Melicertus plebejus*	28711052
701305	Prawn – blue leg king	*Melicertus latisulcatus*	28711047
701399	Prawn – red spot and blue leg king		28711908
701902	Prawn – tiger	*Penaeus esculentus*	28711044
701904	Prawn – king unspecified		28711910
701910	Prawn – western king	*Melicertus latisulcatus*	28711047
701917	Prawn – king+tiger		99280004

The CFISH logbook database does not contain any information about targeted effort or targeted species. The logbook data retrieval was therefore specified for each vessel and each day where catches of banana prawns were recorded (i.e. where banana prawn catches were greater than zero kilograms). Of those records, it is likely that some vessels were targeting other species and the banana prawns were caught incidentally. Catches of other prawn species (i.e. king and tiger prawns) were also considered to standardise catch rates.

A relatively small number of logbook records (978 records or 0.6% of the total data) had their fishing effort incorrectly recorded as more than one boat-day. These records are commonly referred to as 'bulked' effort records and were excluded from the standardisation analysis. (Note that while these data were excluded from the standardisation process, their catches were included in the total catch summaries and the stock assessment models.) There were another 9343 banana prawn catch records (6% of total data) with no fishing effort information provided. These records were assumed to have one boat-day of effort and included in the standardisation process.

Table 3.3 shows the number of catch records in each sub-stock area for each fishing method (otter or beam trawl). Although the Townsville area had the highest total landings, the Fitzroy area had the highest number of catch records, followed by the Burnett area. Records for Cooktown and areas outside of sub-stock areas were not included in the standardisation analysis.

Table 3.3 Number of daily catch records in each sub-stock area and fishing method from 1988 to 2004. Note that catch records for Cooktown and Other areas outside of the sub-stock areas are provided in parenthesis since they were not included in the standardisation analyses.

Sub-stock area	Otter Trawl	Beam Trawl	Total
(Cooktown)	(209)	(198)	(407)
Cairns	9656	30	9686
Tully	9169	329	9498
Townsville	18136	2139	20275
Mackay	8347	1895	10242
Fitzroy	9721	16985	26706
Gladstone	5939	1761	7700
Burnett	8013	13513	21526
Moreton	18797	23344	42141
(Others)	(3674)	(2198)	(5872)
Total	87778	59996	154053
Total (without Cooktown and Others)	(87778)	(59996)	(147774)

Historical trawl data (1968–1987)

The data represent voluntary logbook records of banana prawn catches prior to the implementation of the compulsory QFISH logbook system in 1988. The historical trawl data in this study were obtained from 12 logbook programs. Table 3.4 summarises the number of daily banana prawn catches and vessels analysed and years available in each logbook program. No logbook programs overlapped in time, although there were periods when a collection program ceased and a similar program started. Reported latitudes and longitudes for catches were matched to QFISH grids. By using the same grids used in the CFISH logbook data, historical trawl data were allocated into nine sub-stock areas. Table 3.5 shows the number of catch records in the historical trawl data for each sub-stock area. Due to a limited number of records available in Cooktown and Mackay, data from these areas were not analysed. Records with no spatial information regarding grids were not analysed. The raw data resided in the HTRAWL database within the QFISH system. Readers should consult O'Neill *et al* (2005) for further description of the logbook types and data.

Table 3.4 Summary of historical trawl data obtained from 12 logbook programs.

Source	Description	# of records	# of vessels	Years
AFS	Australian Fisheries Service (now AFMA) logs	694	126	1980–1987
BH	*Burnett Heads Research Station Voluntary Logbook Program*	1191	142	1977–1983, 1986–1987
BH85	As above	39	13	1985
CF88	CFISH pre 1988	15	5	1987
CS1B	CSIRO (B)ay	8917	131	1969–1974
CS1N	CSIRO (N)orth, King &tiger prawn	6634	72	1974–1979
DI01	Diary data entry (DE)	195	6	1977–1981, 1983–1987
DI02	Diary data entry (DE) (Log_desc)	322	18	1968–1969, 1974–1980, 1983–1987
DI03	Historic DE- CSIRO grids	12	2	1980,81,84
DPI	DPI research log	85	12	1986–1987
ECP	CSIRO research log	1805	226	1970–1979
UL02	Historic DE- SUNFISH grids	26	7	1979, 1983–1986

Table 3.5 Number of daily catch records in each sub-stock area from historical trawl data 1986–1987. Note that catch records for Cooktown, Mackay and Other areas outside of the sub-stock areas are provided in parenthesis since they were not included in the standardisation analyses.

Sub-stock area	# record
(Cooktown)	(32)
Cairns	1238
Tully	479
Townsville	460
(Mackay)	(11)
Fitzroy	753
Gladstone	422
Burnett	507
Moreton	15616
(Others)	(1990)
Total	19935
Total (without Cooktown, Mackay and Others)	(18465)

Environmental data

As described in Section 1.2, this study considered three environmental factors: rainfall, river flow and air temperature. Because rainfall and river flow effects may be correlated, separate analyses were conducted and the variable that produced the smaller deviance was included in the final standardisation model.

Rainfall and air temperature data were obtained from the Australian Bureau of Meteorology. Weather stations located within the corresponding CFISH grids in each sub-stock area were identified (Figure 3.1).

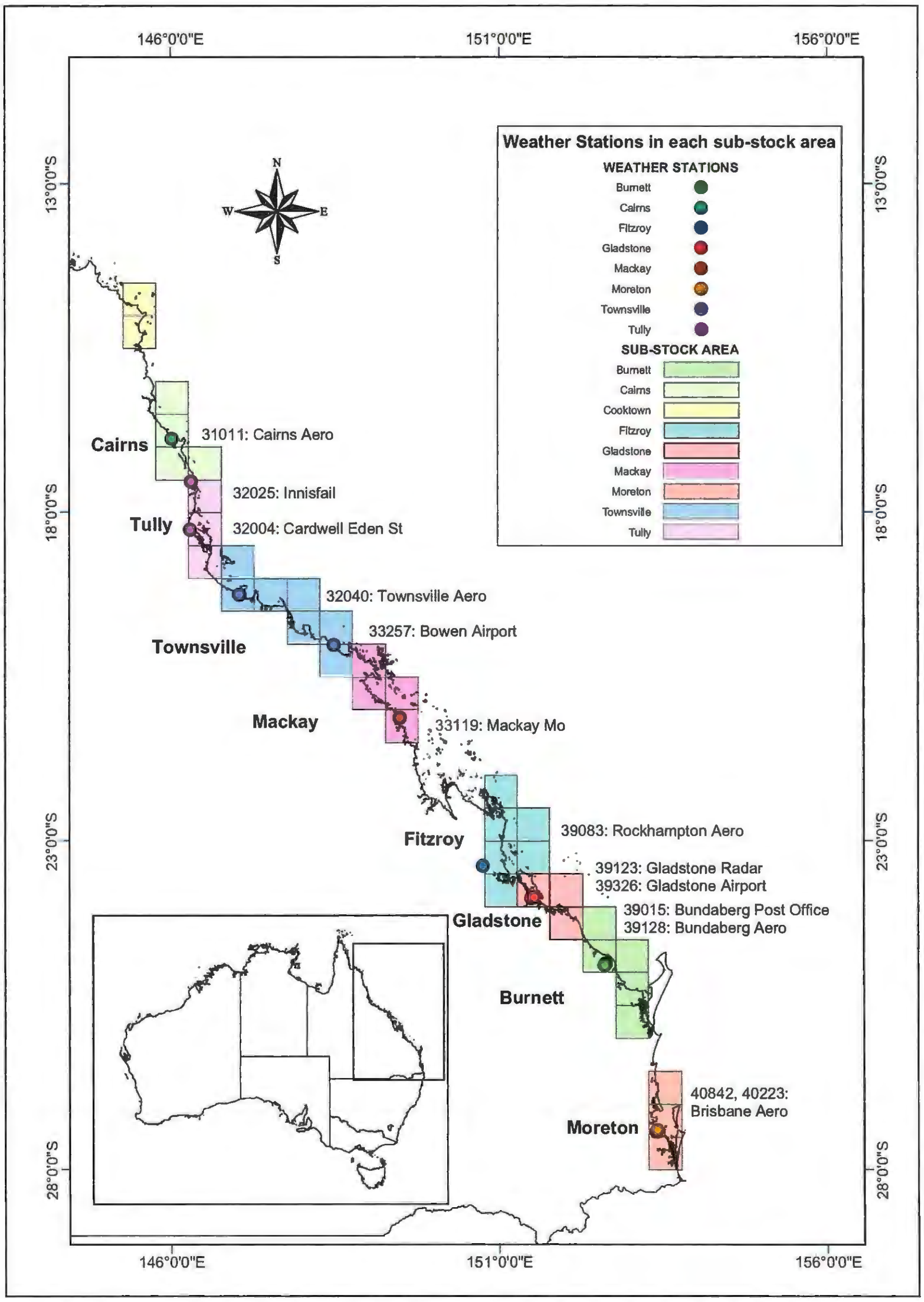

Figure 3.1 Weather stations used to obtain rainfall and air temperature data in each stock area. No stations were selected for Cooktown since it was not included in the standardisation analysis. The number represents the Bureau of Metrology weather stations.

Where there were more than two weather stations per sub-stock area, a mean, adjusted for the data missing from each site, was taken as the daily value. When there was no daily record available in the sub-stock area, missing values were estimated by using a linear regression model for rainfall or temperature as:

$$\text{LogRain}_{ijkl} \text{ or } \text{Temp}_{ijkl} = \mu + \text{Year}_i + \text{Month}_j + \text{Area}_k + (\text{Month}\times\text{Area})_{jk} + \varepsilon_{ijkl}$$

where: LogRain_{ijkl} = ln(rain+0.05): (0.05 = minimum rainfall record)

Temp_{ijkl} = daily temperature

μ = grand mean of log(rain+0.05) or daily temperature

Year_i = effect of ith year (i = 1988-2004)

$Month_j$ = effect of jth month (j=1-12)
$Area_k$ = effect of kth sub-stock area (k = 1-8; Burnett, Cairns, … ,Moreton)
$(Month \times Area)_{jk}$ = interaction between month and sub-stock area
ε_{ijkl} = natural variation attribute to the $ijkl$th individual observation.

Note that rainfall data were transformed [ln(rain+0.05)] due to the high skewness caused by the large number of zero rainfall observations. This model estimated monthly average rainfall in each sub-stock area. The model considered seasonal patterns specific to each sub-stock area (Month×Area) and took account of the differences between years (i.e. dry year vs wet year). Missing rainfall and temperature records accounted for 1.1% and 5.9% of the total number of days during the study period, respectively. Note that this study only used rainfall and air temperature records with data quality coded '1' (quality controlled and acceptable) and '2' (not quality controlled), as defined by the Bureau of Meteorology.

River flow data were obtained from the Queensland Department of Natural Resources, Mines and Water. In each catchment, downstream gauging stations where flow data were largely available between the period of 1988 and 2004 were identified, and total daily river flow in each sub-stock area were calculated by summing each gauged data in the corresponding estuary (mgl/day). A total of 39 gauging stations were selected corresponding to 28 catchments on the east coast of Queensland (Table 3.6). The location of these stations in each sub-stock area is shown in Figure 3.2. For some catchments, flow data were obtained from more than one gauging station (e.g. catchment nos 137 and 143). This was because data were not available from the gauging station that was located near the mouth of the river. Flow data were therefore obtained from two or more gauging stations located in tributaries that were distant from the river mouth.

In order to mitigate flooding and to maintain water supply for agriculture, industry, and urban uses, most of Queensland's major rivers (e.g. Brisbane, Fitzroy and Burdekin) are regulated and managed with weirs and/or barrages (see Comments in Table 3.6). Significant water extraction is expected from these infrastructures, and it is not possible to estimate the accurate total flow of each catchment using the gauged data. However, Vance *et al.*(1985) used gauged flow data from small creeks off the main rivers in the Gulf of Carpentaria which accurately reflected variation in flow from the catchment. Robins *et al.* (2005) adjusted the raw gauged data for the Fitzroy River to take account of the amount of extracted water, but found that there were was very little difference in the flow-catch correlations when using either the raw flow data or the adjusted data (Dr Julie Robins, 2005, pers. comm., 6 June). It was therefore concluded that the raw flow data measured at the gauging stations can provide an adequate indication of the flow pattern for each catchment, and this was therefore used in the present analysis.

This study used flow records with the data quality code of '9' or '10' (normal data), '59' (derived height), '69' (derived discharge) and '130' (not quality controlled but reliable), which were defined by the Department of Natural Resources, Mines and Water. Where there was no daily flow record available (4% of total records), missing values were estimated from other stations located within the same sub-stock area. A separate linear mixed model (LMM) was run in each sub-stock area shown as:

$$LogFlow_{ij} = \mu + Station\ (fixed)_i + Date\ (random)_j + \varepsilon_{ij}$$

where: LogFlow = ln(flow+ min_flow)

- μ = grand mean of logflow
- $Station_i$ = effect of ith station (i = number of stations in each sub-stock area: 4 stations in Cairns, 5 in Tully, etc.)
- $Date_j$ = effect of jth date (j = 1~52600: number of date from 01/01/1987 to 31/12/2004)
- ε_{ij} = natural variation attribute to the ijth individual observation.

A linear mixed model (LMM) was chosen rather than a regression model because it treated the Date term as a random effect and was computationally less intensive. Note that river flow data were transformed by taking the natural log, ln(flow+minimum flow), due to the skewness and zero values.

Table 3.6 The gauging stations used in the standardisation analysis. Comments are provided on the adequacy of the gauged data in each area.

Sub-stock area	Catchment No.	Catchment	Station No.	Station Name	Catchment area (km^2)	Comment
Cairns	108	Daintree	108002A	Daintree River at Bairds	911	No major problem.
Cairns	110	Barron	110001D	Barron River at Myola	1945	No major problem.
Cairns	111	Mulgrave Russell	111007A	Mulgrave River at Peets Bridge	520	Tributaries are situated downstream.
Cairns	111	Mulgrave Russell	111101D	Russell River at Bucklands	315	No major problem.
Tully	112	Johnstone	112004A	North Johnstone River at Tung Oil	925	No major problem.
Tully	112	Johnstone	112101B	South Johnstone River at Upstream Centra	400	Tributaries are situated downstream.
Tully	113	Tully	113006A	Tully River at Euramo	1450	No major problem.
Tully	114	Murray	114001A	Murray River at Upper Murray	156	No information available.
Tully	116	Herbert	116001E	Herbert River at Ingham	8581	No information available.
Townsville	117	Black	117002A	Black River at Bruce Highway	256	No major problem.
Townsville	118	Ross	118104A	Ross River at Ross River Dam Headwater	761	At least two weirs downstream (Black School Weir and Gleeson Weir).
Townsville	119	Haughton	119003A	Haughton River at Powerline	1773	Val Bird Weir and Giru Weirs are situated downstream. Significant extractions occur from the river.
Townsville	120	Burdekin	120006B	Burdekin River at Clare	129876	Major extraction occurs downstream.
Townsville	121	Don	121003A	Don River at Reeves	1016	No information available.
Mackay	122	Proserpine	122005A	Proserpine River at Proserpine	360	No major problem.
Mackay	124	O'Connell	124001A	O'Connell River at Caping Siding	363	No major problem.
Mackay	125	Pioneer	125007A	Pioneer River at Mirani Weir Tailwater	1211	No major problem.
Mackay	126	Plane	126001A	Sandy Creek at Homebush	326	No major problem.
Fitzroy	129	Waterpark	129001A	Waterpark Creek at Byfield	212	No major problem.
Fitzroy	130	Fitzroy	130005A	Fitzroy River at the Gap	135757	Fitzroy River Barrage and Eden Bann Weir are situated downstream. Significant inflow from the high tides can occur in the lower section of estuary.
Gladstone	132	Calliope	132001A	Calliope River at Castlehope	1288	No significant weirs downstream.
Gladstone	133	Boyne	133005A	Boyne River at Awoonga Dam Headwater	2261	No significant weirs downstream.
Burnett	134	Baffle	134001B	Baffle Creek at Mimdale	1402	No major problem.
Burnett	135	Kolan	135008A	Kolan River at Bucca Weir Headwater	2385	No significant weirs downstream.
Burnett	136	Burnett	136001B	Burnett River at Walla	32100	Bingera Weir and Ben Anderson Barrage are situated downstream.
Burnett	137	Burrum	137303A	Burrum River at Lenthalls Dam HW	515	No significant weirs downstream.
Burnett	137	Burrum	137201A	Isis River at Bruce Highway	446	No significant weirs downstream.
Burnett	137	Burrum	137101A	Gregory River at Isis Highway	454	No major problem.
Burnett	137	Burrum	137003A	Elliott River at Dr Mays Crossing	251	No major problem.
Burnett	138	Mary	138014A	Mary River at Home Park	6845	Mary River Barrage is situated downstream.
Moreton	142	Caboolture	142001A	Caboolture River at Upper Caboolture	94	No major problem.
Moreton	142	Caboolture	142202A	South Pine River at Drapers Crossing	156	No major problem.
Moreton	143	Brisbane	143001C	Brisbane River at Savages Crossing	10180	Mt. Corsby Weir is situated downstream. Significant extraction occurs at Weir.
Moreton	143	Brisbane	143108A	Warrill Creek at Amberley	914	No major problem.
Moreton	143	Brisbane	143107A	Bremer River at Walloon	620	No major problem.
Moreton	143	Brisbane	143113A	Purga Creek at Loamside	215	No major problem.
Moreton	145	Logan Albert	145102B	Albert River at Broomfleet	544	No major problem.
Moreton	145	Logan Albert	145014A	Logan River at Yarrahappini	2416	No major problem.

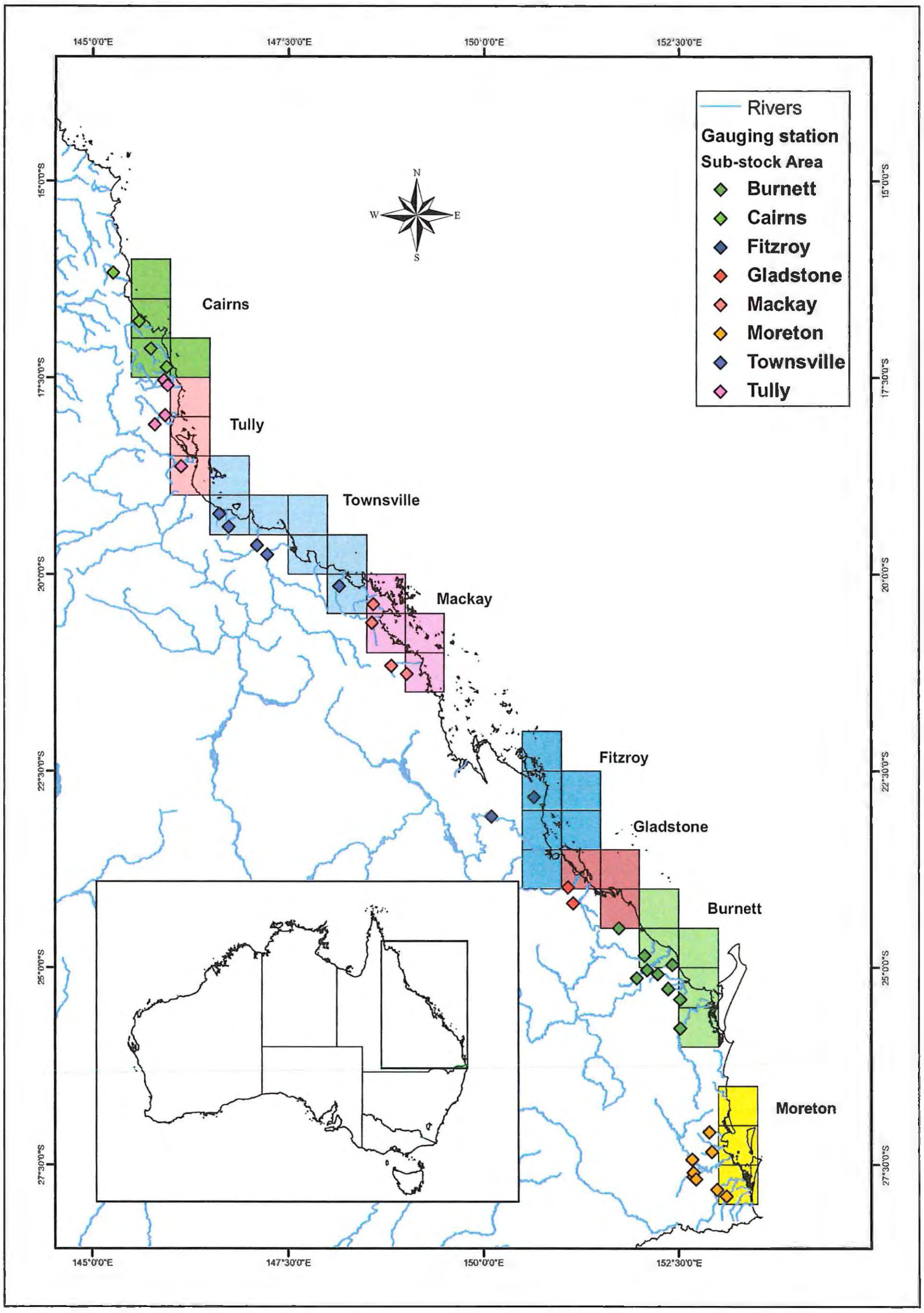

Figure 3.2 The location of gauging stations used to represent each sub-stock area.

River flow and rainfall

In order to include the effect of rainfall and river flow into the model, three time lags were produced and the total rainfall/flow for each time lag was calculated:

- Time lag1_30: previous 30 days of the fishing date
- Time lag31_60: from 30 to 60 days prior to the fishing date
- Time lag 61_90: from 61 to 90 days prior to the fishing date.

Note that each time lag contains 30 days of records. For example, if a banana prawn catch was recorded on 01/01/1990, then the total rainfall/flow for each time lag was obtained as follows:

- Total rainfall/flow from 31/12/1989 to 02/12/1989 (time lag1_30)
- Total rainfall/flow from 01/12/1989 to 02/11/1989 (time lag31_60)
- Total rainfall/flow from 01/11/1989 to 03/10/1989 (time lag61_90) (see Figure 3.3).

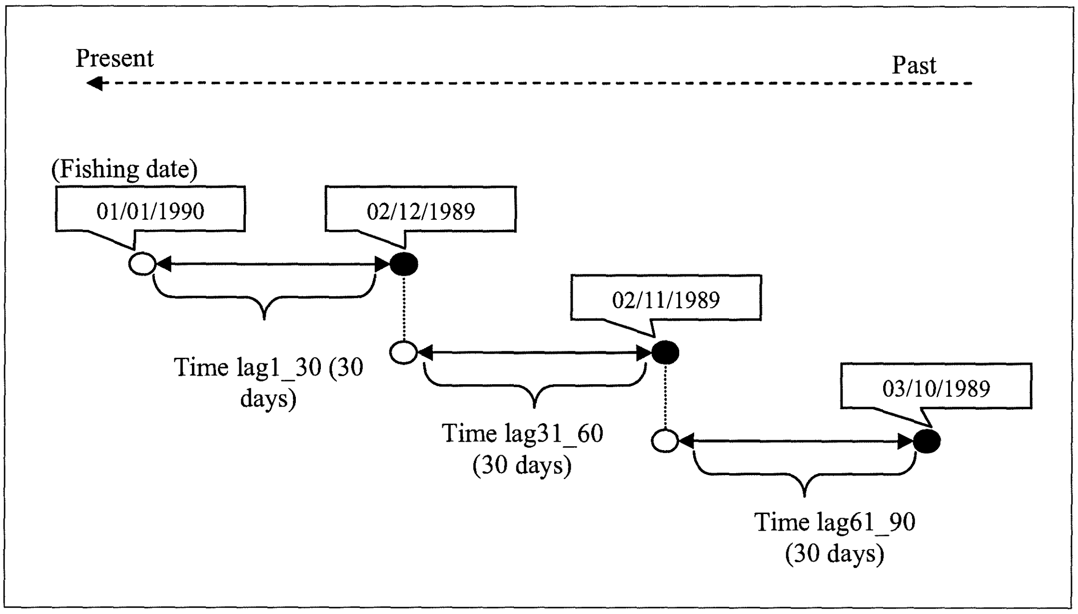

Figure 3.3 Illustration showing how the time-lagged rainfall and river flow measurements were calculated for a banana prawn catch reported on 01/01/1990. Closed circles include a date noted in the diagram, and open circles do not include dates in the diagram.

Temperature

In order to represent seasonal effects on banana prawn catch, daily mean 9 am air temperature for the preceding 60 days (time lag1_60) and 121 to 180 days (time lag121_180) of fishing date were calculated and used as covariates in each sub-stock area. Each time lag contains 60 daily observations.

Figure 3.4 shows how the temperature time lags were calculated for a banana prawn catch reported on 01/01/1990. For this example, two types of mean air temperature were calculated as follows:

- mean 9 am air temperature from 31/12/1989 to 02/11/1989 (time lag1_60)
- mean 9 am air temperature from 02/09/1989 to 05/07/1989 (time lag121_180).

In this case, mean temperature in time lag1_60 represents the seasonal effect of late spring to early summer, and time lag121_180 represents seasonal effect of late winter on the banana catch on 01/01/1990.

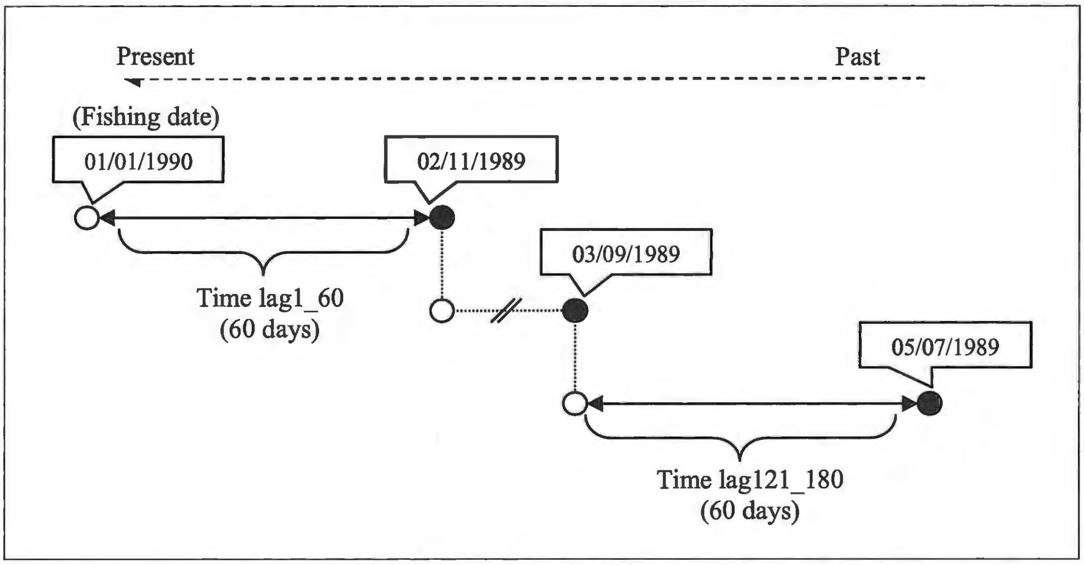

Figure 3.4 Illustration showing how the time-lagged air temperature measurements were calculated for a banana prawn catch reported on 01/01/1990. Open circle includes a date noted in the diagram, and closed circle does not include a date in a diagram.

Statistical analysis

The CFISH model

A linear mixed model (LMM) was used to standardise the banana prawn catch rates from the CFISH logbook data from 1988 to 2004. The response variable was the log-transformed daily banana prawn catch (logwt) for each vessel. Explanatory variables used in the analysis are shown in Table 3.7. Note that the other prawn species in the catch, which were comprised of king prawns and tiger prawns (referred to as 'logkingtiger'), were transformed by $\ln(X+1)$ due to zero values. The statistical software package GenStat Version8 (GENSTAT 2005) was used to undertake the analysis.

Table 3.7 Explanatory variables used in the linear mixed model for the CFISH logbook data (1988–2004).

Variable Name	Description	Type of Variables
Area	Eight Sub-stock areas (Burnett, Cairns, Fitzroy, Gladstone, Mackay, Moreton, Townsville, Tully)	Factor (categorical)
Logkingtiger	Log transformed corresponding catch of king and tiger prawns (in daily basis) (kg/day)	Variate (continuous)
Method	Fishing method (Otter trawl or Beam trawl)	Factor (Categorical)
Lograin1_30	Log transformed total rainfall for preceding 30 days (mm)	Variate (continuous)
Lograin31_60	Log transformed total rainfall from preceding 31 to 60 days (mm)	Variate (continuous)
Lograin61_90	Log transformed total rainfall from preceding 61 to 90 days (mm)	Variate (continuous)
Logflow1_30	Log transformed total river flow for preceding 30 days (mgl)	Variate (continuous)
Logflow31_60	Log transformed total river flow from preceding 31 to 60 days (mgl)	Variate (continuous)
Logflow61_90	Log transformed total river flow from preceding 61 to 90 days (mgl)	Variate (continuous)
Temp1_60	Daily air temperature averaged for preceding 60 days (°C)	Variate (continuous)
Temp121_180	Daily air temperature averaged for preceding 121 to 180 days (°C)	Variate (continuous)
Vessel_id	Vessel ID	Factor (Categorical)
Year	Calendar year	Factor (categorical)
Month	Calendar month	Factor (categorical)

The terms included in the analysis are shown in Table 3.8. As noted in the previous section, results from the two separate models, the Rainfall Model and the Flow Model, were compared. The environmental variables, sub-stock areas and fishing method were considered as fixed effects since they were of interest. Vessel ID and three-way interaction of year, month and sub-stock areas were treated as random effects, assuming a random selection from the overall population.

The effect of the king and tiger prawn catches (logkingtiger), river flow or rainfall and temperature variables were considered to be dependent of fishing method and sub-stock area. The model therefore included a three-way interaction between area, method and the covariates (i.e. logkingtiger, river flow and rainfall).

Variance components were estimated using the restricted/residual maximum likelihood (REML). The Wald test was used for testing the significance of fixed explanatory variables (GENSTAT 2005). REML was considered to be an appropriate technique for this analysis due to the large number of catch data observations and the unbalanced design. The level of significance used in the analysis was 0.05.

After developing the statistical model, standardised catch rates were calculated by the statistical model using modified data with constant values for vessel_id and mean fixed king and tiger prawn catches (logkingtiger) in each sub-stock area. This process included the effect of environmental variables but eliminated the effect of differences in vessel and king and tiger prawn catches.

Table 3.8 Terms of effects included in LMM. The Rain Model included rainfall, and the Flow Model included river flow. Other variable terms were the same in both models.

Terms	Rain model	Flow Model	Type of effects
Area.Method	+	+	Fixed
Area.Method.Logkingtiger	+	+	Fixed
Area.Method.Temp1_60	+	+	Fixed
Area.Method.Temp121_180	+	+	Fixed
Area.Method.Lograin1_30	+		Fixed
Area.Method.Lograin31_60	+		Fixed
Area.Method.Lograin61_90	+		Fixed
Area.Method.Logflow1_30		+	Fixed
Area.Method.Logflow31_60		+	Fixed
Area.Method.Logflow61_90		+	Fixed
Vessel_ID	+	+	Random
Year.Month.Area	+	+	Random

The historical trawl model

A linear mixed model (LMM) was used to standardise the banana prawn catch rates from the historical trawl data from 1968 to 1987. The response variable was the log-transformed daily banana prawn catch (logwt) for each vessel. Explanatory variables used in the analysis are shown in Table 3.7. Three-way interaction of year, month and sub-stock areas were included as a fixed effect to predict monthly average of historical catch rates for each year. VSN (unique vessel identifier code for the historical trawl data) was treated as random effects, assuming a random selection from the overall population of vessels. Variance components were estimated by restricted/residual maximum likelihood (REML), and Wald test was used for testing the significance of fixed explanatory variables.

Significant differences between the CFISH logbook data and the historical trawl data resulted in applying two independent standardisation models. The model for the historical trawl data was relatively simple compared to that for the CFISH data. The main differences between the CFISH logbook model and historical trawl model are summarised as follows:

- Seven sub-stock areas were analysed in the historical trawl model while eight areas were analysed in the CFISH model.
- No environmental variables were considered in the historical trawl model because of the limited quantity and quality of the catch and effort records.
- The historical trawl model did not include fishing method as a factor because all of the records were assumed to be from the otter trawl sector.

The statistical software package GenStat Version8 (GENSTAT 2005) was used to undertake the analysis.

Table 3.9 Explanatory variables used in the linear mixed model for the historical trawl data.

Variable Name	Description	Type of Variables
Area	Seven sub-stock areas (Burnett, Cairns, Fitzroy, Gladstone, Moreton, Townsville, Tully)	Factor (categorical)
Year	Calendar year	Factor (categorical)
Month	Calendar month	Factor (categorical)
VSN	Vessel ID recorded in the historical trawl data	Factor (Categorical)

3.2 Results

Environmental data

Although both annual rainfall and river flow varied between years, within each sub-stock area rainfall and flow followed similar trends (Figure 3.5). It is noteworthy that although some sub-stock areas had similar levels of annual rainfall, the level of river flow between these similar areas varied significantly. For example, in the period 1988 to 2004, the mean annual rainfall in Fitzroy was similar to that of Burnett and Gladstone (see Table 3.10). However, the annual river flow in Fitzroy was about 20 times that of Gladstone and about two times that of Burnett. These differences probably reflect differences in the total catchment areas in each sub-stock area. The total catchment area for Fitzroy and Burnett are 135 969 km^2 and 44 398 km^2 respectively, both of which are much larger than that of Gladstone (3549 km^2).

As seen in Table 3.10, the mean annual rainfall was highest for the Tully area, followed by the Cairns and Mackay areas, with the lowest in the Fitzroy area. The mean annual river flow was the highest in the Tully area followed by the Townsville and the Fitzroy area. Mean annual river flow was lowest in the Gladstone area.

The annual flow in 1991 was extremely high in the Townsville and Fitzroy areas. This was due to the extensive floods in the Burdekin and Haughton Rivers in February, and in the Fitzroy River in January, which were among the largest recorded for these rivers (Bureau of Meteorology 2005).

Table 3.10 The mean annual rainfall and river flow in each sub-stock area. The numbers within brackets are standard deviations.

Sub-stock area	Rainfall (mm)	River flow (10^6 mgl)
Cairns	1939.3 (579.0)	3.2 (1.7)
Tully	2790.2 (777.5)	8.9 (4.8)
Townsville	950.4 (461.1)	8.1 (10.2)
Mackay	1557.2 (570.1)	1.0 (1.0)
Fitzroy	716.8 (271.4)	4.2 (5.2)
Gladstone	813.9 (262.0)	0.2 (0.2)
Burnett	929.5 (281.4)	2.3 (2.0)
Moreton	1067.8 (323.5)	1.4 (1.2)

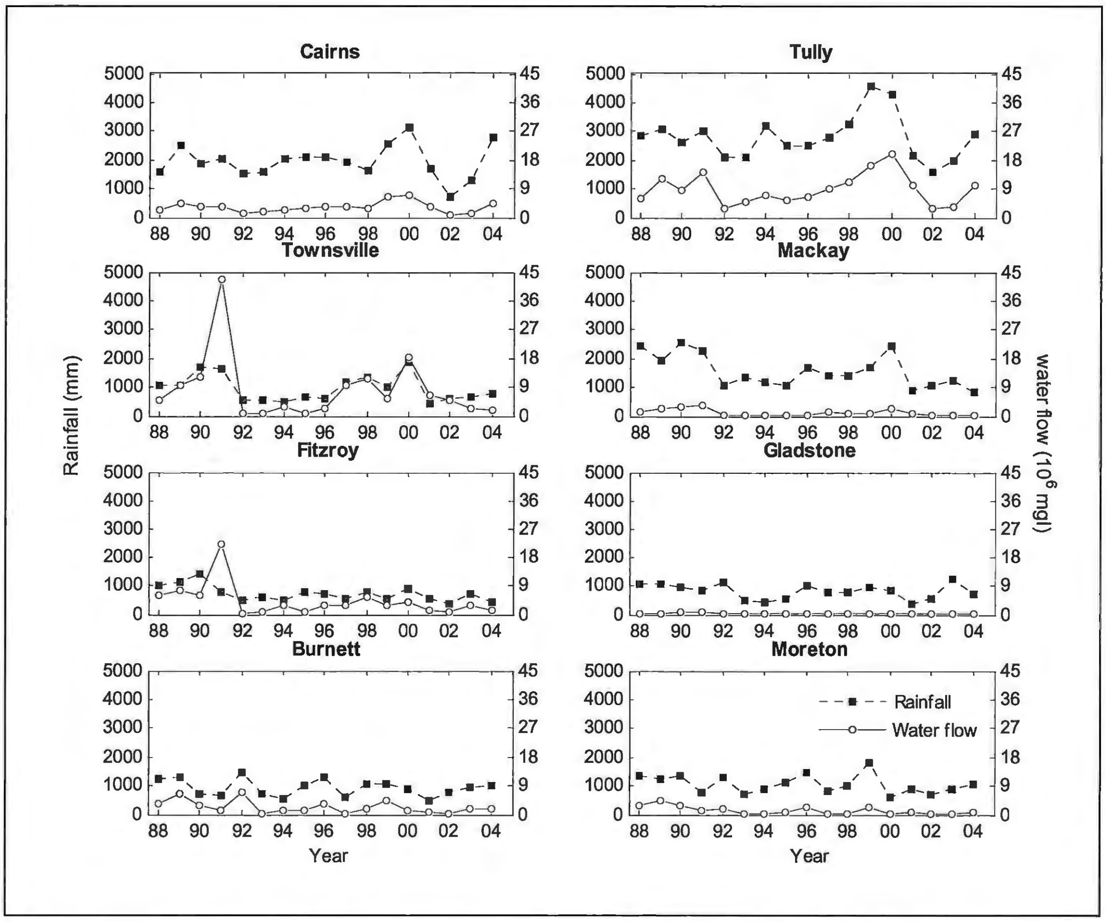

Figure 3.5 Average annual rainfall (dash line) and river flow (solid line) for each sub-stock area from 1988 to 2004.

The seasonal patterns of rainfall and river flow were fairly consistent for all sub-stock areas (Figure 3.6). From December to April the southern areas (Moreton to Fitzroy) received about 60–63% of their annual rainfall, while the northern areas (Mackay to Cairns) received about 70–80%.

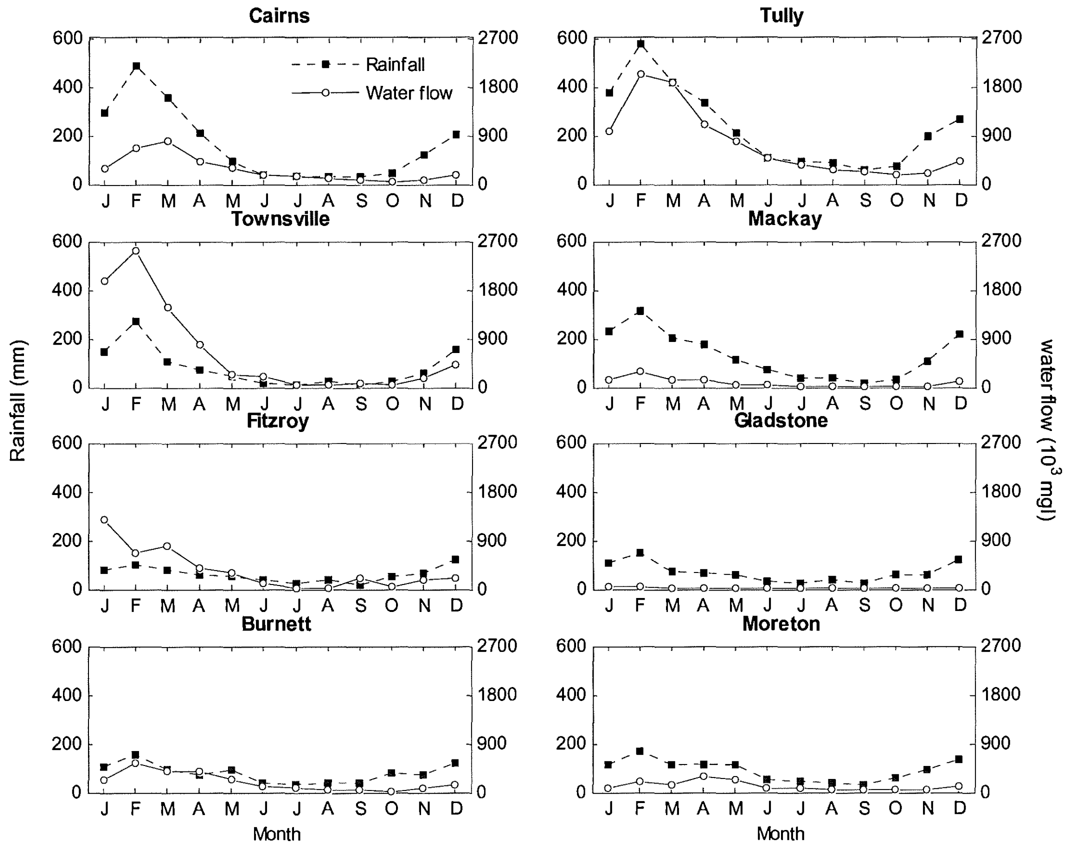

Figure 3.6 Average monthly rainfall (solid line) and river flow (dash line) for each sub-stock area from 1988 to 2004.

There was little variation in the monthly mean air temperature (from 1988 to 2004) between sub-stock areas (Figure 3.7). The range in mean monthly air temperatures was smallest in Cairns (7 °C) and increased with increasing latitude to a maximum in the Moreton area (11.2 °C).

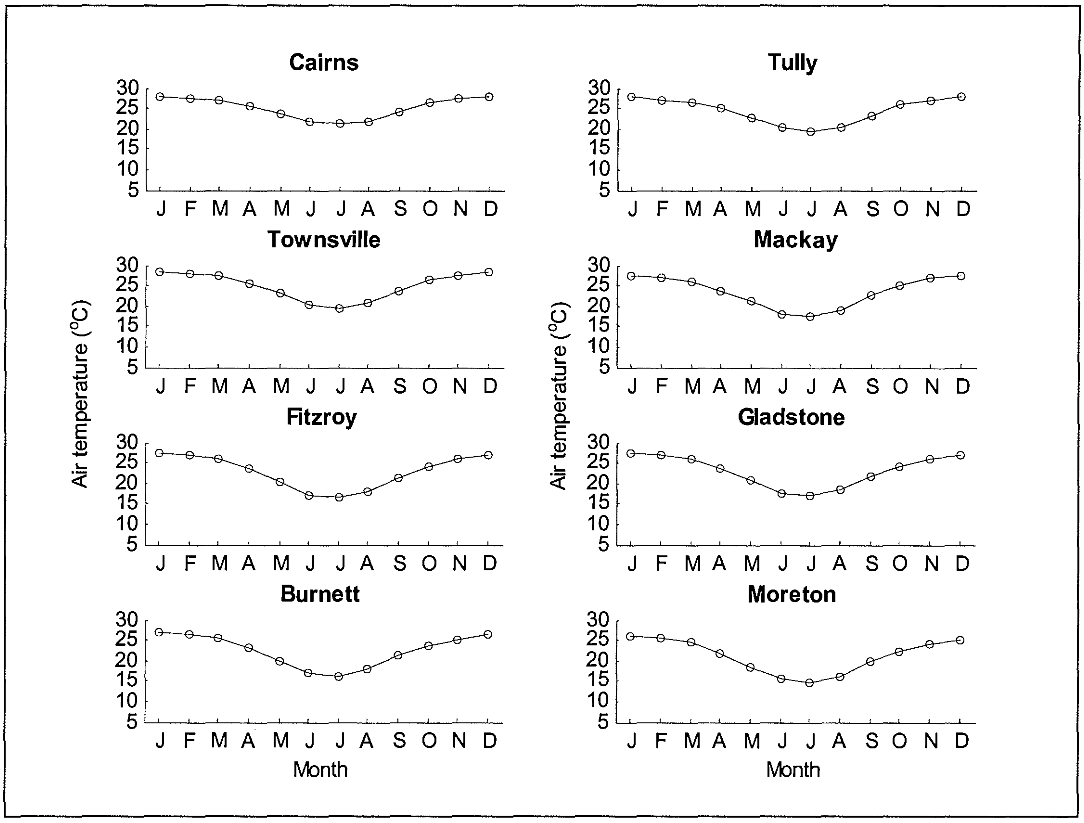

Figure 3.7 Average monthly air temperature for each sub-stock area, from 1988 to 2004.

Standardised catch rates 1988 to 2004

Exploratory Model

The results of the linear mixed model (REML) for the Rainfall Model and the Flow Model were summarised in Table 3.11 and Table 3.12, respectively. Since the Wald statistics are all significant, it was concluded that the parameters associated with these variables were significantly different from zero and therefore should be included in the model. All interaction effects were highly significant ($p < 0.001$) for both of the models, which indicates that the effects of king and tiger prawn catches and abiotic factors on banana prawn catches vary with fishing method and sub-stock area.

Table 3.11. Results of the linear mixed model (REML) for the Rainfall Model. The Wald statistics were calculated by dropping each fixed term from the full exploratory model.

Rainfall Model

Random term		Residual term	
Estimated Variance Components (s.e.)		Residual variance (s.e.)	1.013 (0.004)
Vessel ID	0.488 (0.023)	Deviance (-2Log-likelihood)	157616.19
year.month.area	0.192 (0.009)	Residual degrees of freedom (d.f)	147659

Fixed terms	Wald Statistics	d.f	χ^2 probability
area.method	14245.31	16	<0.001
area.method.logkingtiger	5546.41	16	<0.001
area.method.temp121_180	945.1	16	<0.001
area.method.temp1_60	644.17	16	<0.001
area.method.lograin31_60	359.75	16	<0.001
area.method.lograin1_30	292.18	16	<0.001
area.method.lograin61_90	100.33	16	<0.001

Table 3.12: Results of the linear mixed model (REML) for the Flow Model. The Wald statistics were calculated by dropping each fixed term from full exploratory model.

Flow Model

Random term		Residual term	
Estimated Variance Components (s.e.)		Residual variance (s.e.)	1.009 (0.004)
vessel	0.488 (0.023)	Deviance (-2Log-likelihood)	157043.34
year.month.area	0.188 (0.008)	Residual degrees of freedom (d.f)	147659

Fixed terms	Wald Statistics	d.f	χ^2 probability
area.method	13488.21	16	<0.001
area.method.logkingtiger	5545.19	16	<0.001
area.method.temp121_180	821.87	16	<0.001
area.method.temp1_60	733.47	16	<0.001
area.method.logflow1_30	700.94	16	<0.001
area.method.logflow31_60	241.4	16	<0.001
area.method.logflow61_90	114.35	16	<0.001

Table 3.13 Correlation coefficients for rainfall and river flow variables in each sub-stock area. All coefficients differed significantly from zero ($p < 0.001$).

	Cairns	Tully	Townsville	Mackay	Fitzroy	Gladstone	Burnett	Moreton
Corr(lograin1_30,logflow1_30)	0.595	0.793	0.746	0.640	0.458	0.636	0.782	0.569
Corr(lograin31_60,logflow31_60)	0.607	0.779	0.708	0.647	0.511	0.621	0.774	0.585
Corr(lograin61_90,logflow61_90)	0.610	0.777	0.716	0.663	0.526	0.516	0.722	0.580

As seen in Table 3.13, there was a high correlation between rainfall and river flow for the corresponding time lags, indicating that rainfall and river flow reflect each other. Importantly, the total deviance of the Flow Model was smaller than that of the Rainfall Model, which indicated that the Flow Model explained more variation in the catch rates (Table 3.11 and Table 3.12). Furthermore, in terms of practical perspective, the river flow data were more reliable than the rainfall data because the rainfall data were collected from only eight gauging stations that were located near the coast, while the river flow data were collected from 39 gauging stations that were distributed widely across the catchments and sub-stock areas. For these reasons, the Flow Model was selected as the final model for the standardisation of catch rate.

Final Model

River flow effects

Table 3.14 shows the parameter estimates for the river flow, temperature and the effects of king and tiger prawn catches for the final Flow Model. In general, the time lag1_30 and time lag31_60 river flows were found to have a significantly positive effect ($p < 0.01$) on otter trawl catch rates. This implies that increased river flow in the period up to 60 days prior to fishing increases the otter trawl catch. The time lag31-60 river flow had a small marginally negative effect ($p = 0.059$) in Mackay. In general, the time lag61-90 river flow had no significant effect on otter trawl catches, with the exception of the Townsville area which experienced a statistically significant negative effect ($p < 0.01$), and the Mackay area which experienced a statistically significant positive effect ($p < 0.05$). It is important to note that the Wald statistics for river flow declined with increasing lag time and were at a minimum for the largest time lag (i.e. time lag61_90; see Table 3.12), indicating that the shorter/more recent flow events affect catches more than the larger/more delayed flows.

The effects of river flow on beam trawl catch rates were less consistent. River flow was not significant for any time lags in the Cairns and Townsville areas. The time lag1_30 river flows had a significant negative effect ($p < 0.05$) in the Tully, Fitzroy and Moreton areas, which indicate that increased river flow decreased the beam trawl catch rate in these sub-stock areas. The time lag31_60 river flows were only statistically significant in the Burnett area (negative effect) and marginally significant in the Moreton area (positive effect, $p = 0.064$). The time lag61_90 river flows were significant in the Fitzroy, Gladstone, Burnett and Moreton areas. Among these, positive effects were found in all areas except Gladstone. Collectively the results suggested that increased river flow from the preceding 61 to 90 days before fishing increased the beam trawl catch rate in the Mackay, Fitzroy, Burnett and Moreton areas, but decreased catch rates in Gladstone. Note that magnitudes of flow coefficients were generally small, indicating the small effects of flow on daily banana prawn catch.

Temperature effects

In general, the air temperature in the 60 days (Temp1_60) prior to fishing had a highly significant effect on both otter trawl and beam trawl catch rates. The only exceptions were for the Cairns and Tully areas (Table 3.14). The air temperature during the 121–180 days prior to fishing had: a) a significant positive effect on the otter trawl catch rates in all areas except for the Tully area, and b) a significant positive effect on the beam trawl catch rates from the southern region (Fitzroy to Moreton).

The purpose of including temperature in the standardisation model was to model seasonality through two time lags; time lag1_60 and time lag121_180. Figure 3.8

illustrates the effects of these time lagged temperatures on banana prawn catch rates in each sub-stock area. It is generally found that peaks in catch rates occur in autumn (March, April or May). The unrealistic trend for beam trawl catch rates in Cairns was likely due to the very limited number of records observed in this area (30 observations).

Effect of king and tiger prawn catch

The effects of the king and tiger prawn catch on the catch rates of banana prawns in the otter trawl fishery were highly significant in all sub-stock areas (see Table 3.14). As expected, the parameter estimates were all negative, which suggests that banana prawn catch rates in the otter trawl fishery declined with increased catches of king and tiger prawns. The effects of the king and tiger prawn catches on the banana prawn catch rates in the beam trawl fishery were highly significant for all sub-stock areas except for the Cairns, Townsville and Gladstone areas. The only positive effect in the beam trawl fishery occurred in the Fitzroy area. This positive effect implies that the banana prawn catch rates increased with increased catch rates of king and tiger prawns. It should be noted, however, that the positive effect found in the Fitzroy area may be due to the small proportion of king and tiger prawn catches observed for beam trawling in this area (i.e. 2.2% of total beam trawl records).

Table 3.14 Parameter estimates of effects in the Flow Model on (natural log transformed) banana prawn catch in each fishing method and sub-stock area. The values in parenthesis are standard error of estimated values.

	Logflow1_30		Logflow31_60		Logflow61_90		Temp1_60		Temp121_180		Logkingtiger	
	Otter	Beam	Otter	Beam	Otter	Beam	Otter	Beam	Otter	Beam	Otter	Beam
Cairns	0.248 (0.034)**	-0.362 (0.926)	0.108 (0.03)**	0.255 (0.751)	0.037 (0.025)	-0.644 (0.559)	-0.007 (0.017)	-0.283 (0.27)	0.083 (0.02)**	0.108 (0.223)	-0.144 (0.007)**	0.137 (0.19)
Tully	0.146 (0.033)**	-0.488 (0.1)**	0.114 (0.027)**	0.136 (0.098)	0.035 (0.023)	-0.094 (0.074)	0.06 (0.014)**	0.054 (0.039)	0.024 (0.018)	0.117 (0.048)*	-0.173 (0.007)**	-0.447 (0.111)**
Townsville	0.153 (0.014)**	-0.025 (0.021)	0.041 (0.011)**	0.027 (0.023)	-0.046 (0.012)**	0.008 (0.029)	0.079 (0.012)**	0.074 (0.024)**	0.114 (0.013)**	0.002 (0.018)	-0.247 (0.005)**	-0.014 (0.051)
Mackay	0.075 (0.016)**	0.051 (0.023)*	-0.027 (0.014)’	0.015 (0.023)	0.034 (0.015)*	0.037 (0.023)’	0.13 (0.012)**	0.06 (0.016)**	0.089 (0.012)**	-0.018 (0.015)	-0.236 (0.008)**	-0.189 (0.043)**
Fitzroy	0.036 (0.009)**	-0.02 (0.008)*	0.063 (0.009)**	0.012 (0.008)	0.005 (0.007)	0.016 (0.007)*	0.122 (0.009)**	0.054 (0.008)**	0.081 (0.01)**	0.071 (0.009)**	-0.17 (0.009)**	0.085 (0.031)**
Gladstone	0.018 (0.01)’	-0.017 (0.014)	0.062 (0.009)**	-0.008 (0.014)	0.012 (0.008)	-0.039 (0.012)**	0.13 (0.014)**	0.033 (0.014)*	0.104 (0.011)**	0.03 (0.014)*	-0.204 (0.014)**	0.051 (0.07)
Burnett	0.083 (0.012)**	0.003 (0.01)	0.051 (0.011)**	-0.023 (0.009)*	-0.009 (0.01)	0.027 (0.009)**	0.109 (0.01)**	0.032 (0.009)**	0.11 (0.01)**	0.04 (0.009)**	-0.21 (0.009)**	-0.091 (0.031)**
Moreton	0.081 (0.014)**	-0.126 (0.015)**	0.07 (0.014)**	0.027 (0.015)’	-0.014 (0.014)	0.062 (0.014)**	0.048 (0.007)**	0.012 (0.007)’	0.093 (0.008)**	0.115 (0.007)**	-0.168 (0.007)**	-0.113 (0.011)**

**=$p \le 0.01$; * = $0.01 < p \le 0.05$; ’ = $0.05 < p \le 0.1$

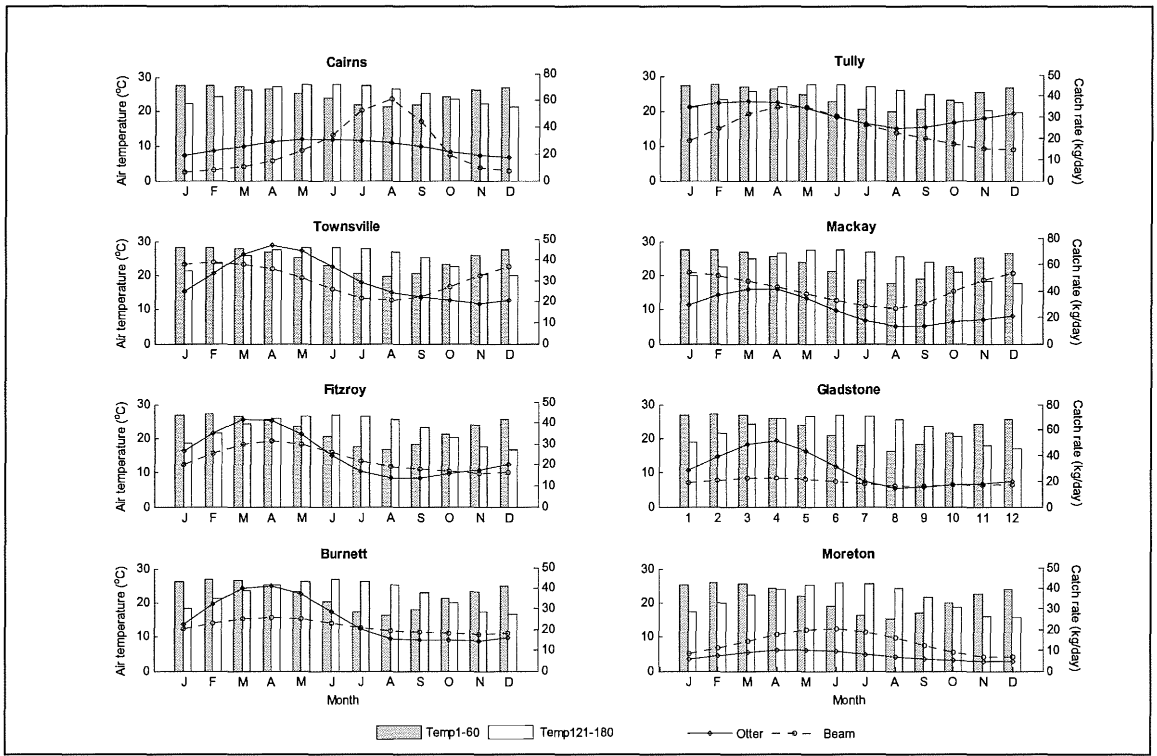

Figure 3.8 The predicted average monthly catch rate (kg/day) of banana prawns for each fishing method and sub-stock area calculated from the temperature coefficients. For each sub-stock area, the mean values for the other terms (i.e. logkingtiger and river flow time lag1-30, river flow time lag 31_60 and river flow time lag61_90) were used in the model.

Standardised monthly catch rates for each fishing method and sub-stock area from the final model are provided in a relative scale (i.e. a proportion scaled to standardised catch rate in April 1989 for otter trawls and May 1988 for beam trawls) in Figure 3.9 through to Figure 3.12. It is important to note that their catch rate trends were comparable within a sub-stock area but not across areas because each arca was scaled to its own catch rate. A plot of the model's residuals is provided in APPENDIX 3. In general, the standardised residuals from the mixed model were normally distributed, indicating that logging of the catch rate was an adequate transformation.

Strong seasonal patterns were observed in the standardised otter trawl catch rates for all sub-stock areas (Figure 3.9 and Figure 3.10), with consistent annual peaks in autumn (March–May). The long-term trends in catch rates from all areas were relatively stable. Low catch rates occurred in a) the Townsville area from 1992 to 1994, and from 1999 to 2001, but increased after 2001, b) the Gladstone area from 1999 to 2001 and c) the Burnett and Moreton areas from 2000 to 2002. Gaps in the monthly catch rates after 2000 may be due to a) the northern seasonal closure (15 December to 1 March) in the northern region (Cairns to Mackay) and b) the southern annual closure (20 September to 1 November) in the southern region. Note that Moreton Bay is exempt from the southern annual closure.

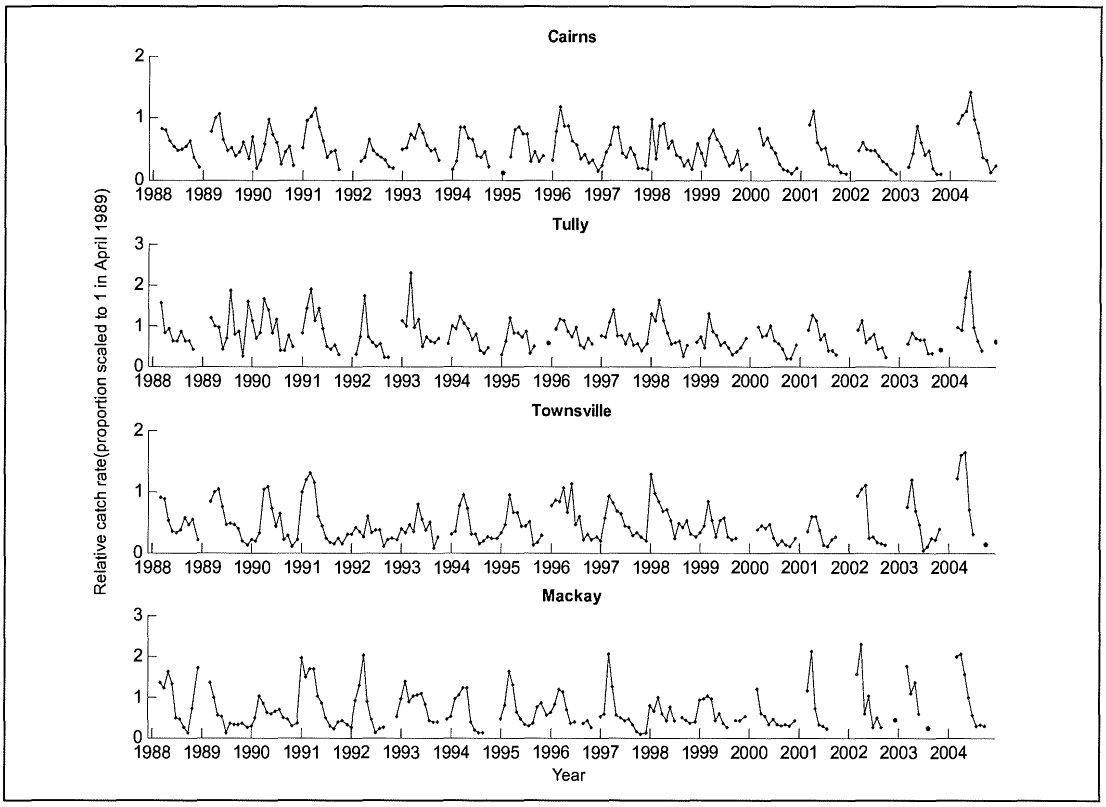

Figure 3.9 Standardised monthly otter trawl catch rates in the northern region (Cairns to Mackay) from January 1988 to December 2004.

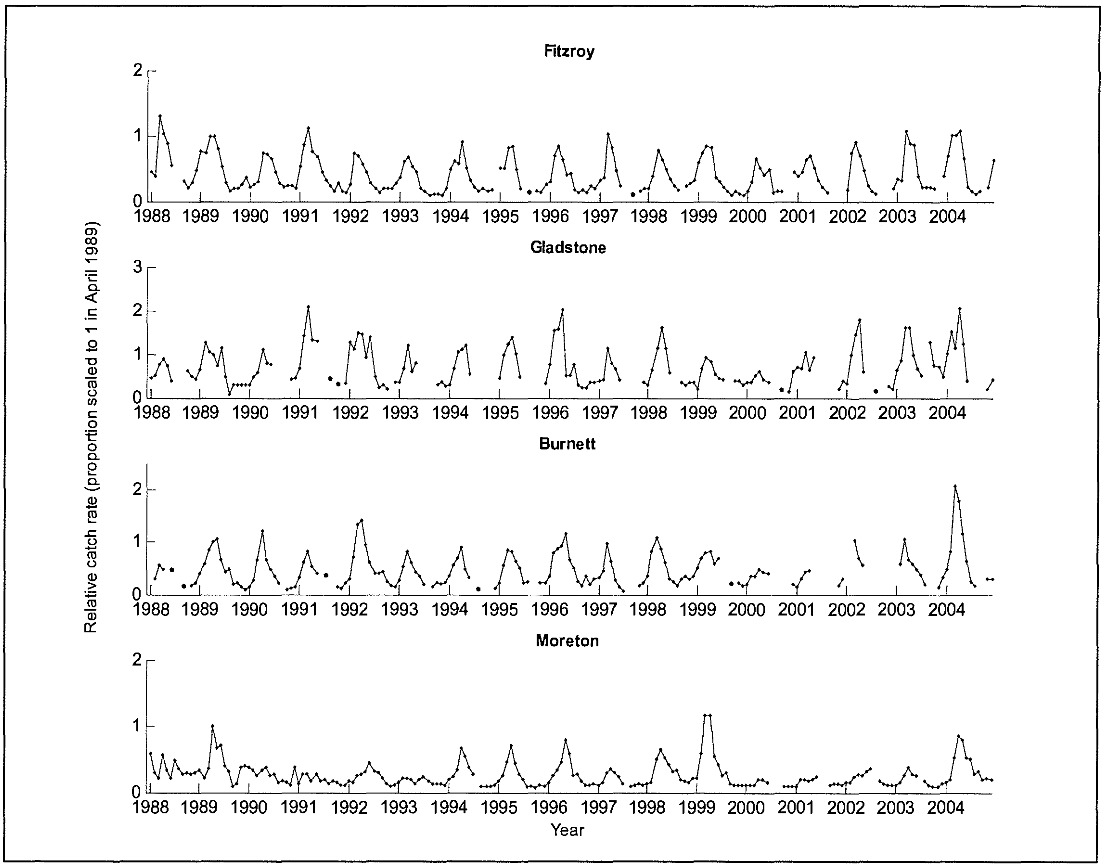

Figure 3.10 Standardised monthly otter trawl catch rates in the southern region (Fitzroy to Moreton) from January 1988 to December 2004.

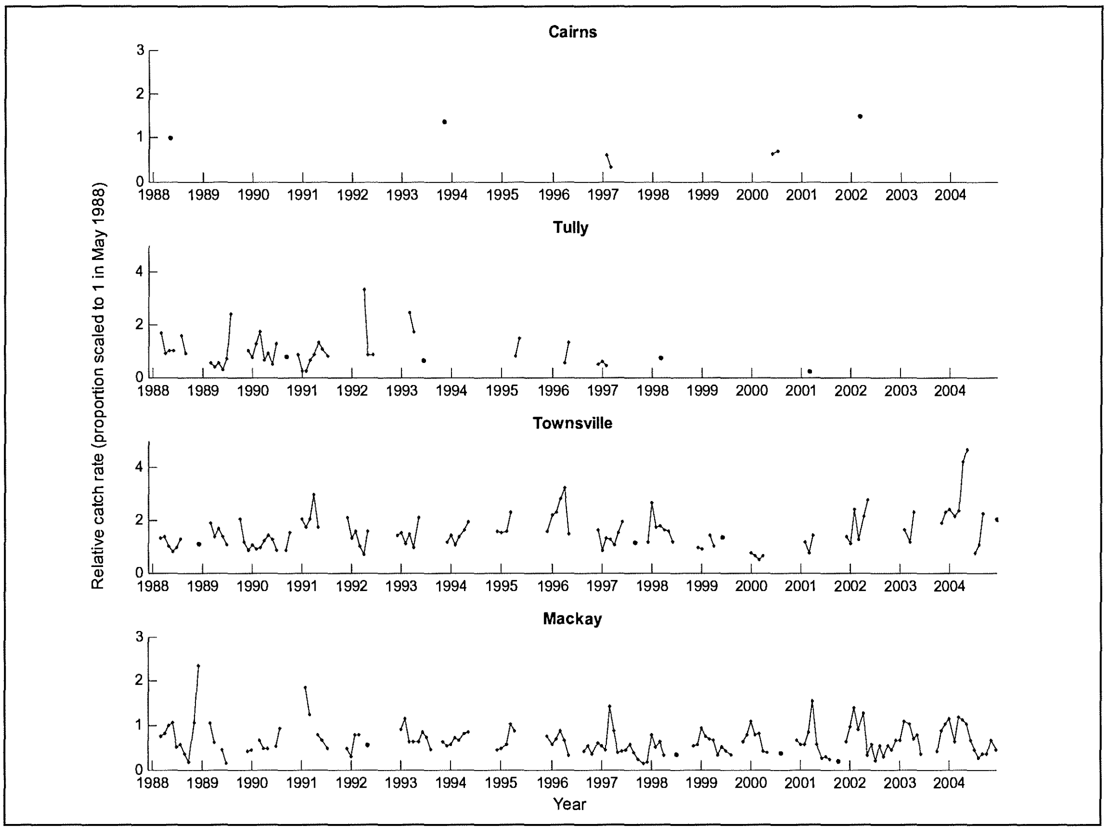

Figure 3.11 Standardised monthly beam trawl catch rates in the northern region (Cairns to Mackay) from January 1988 to December 2004.

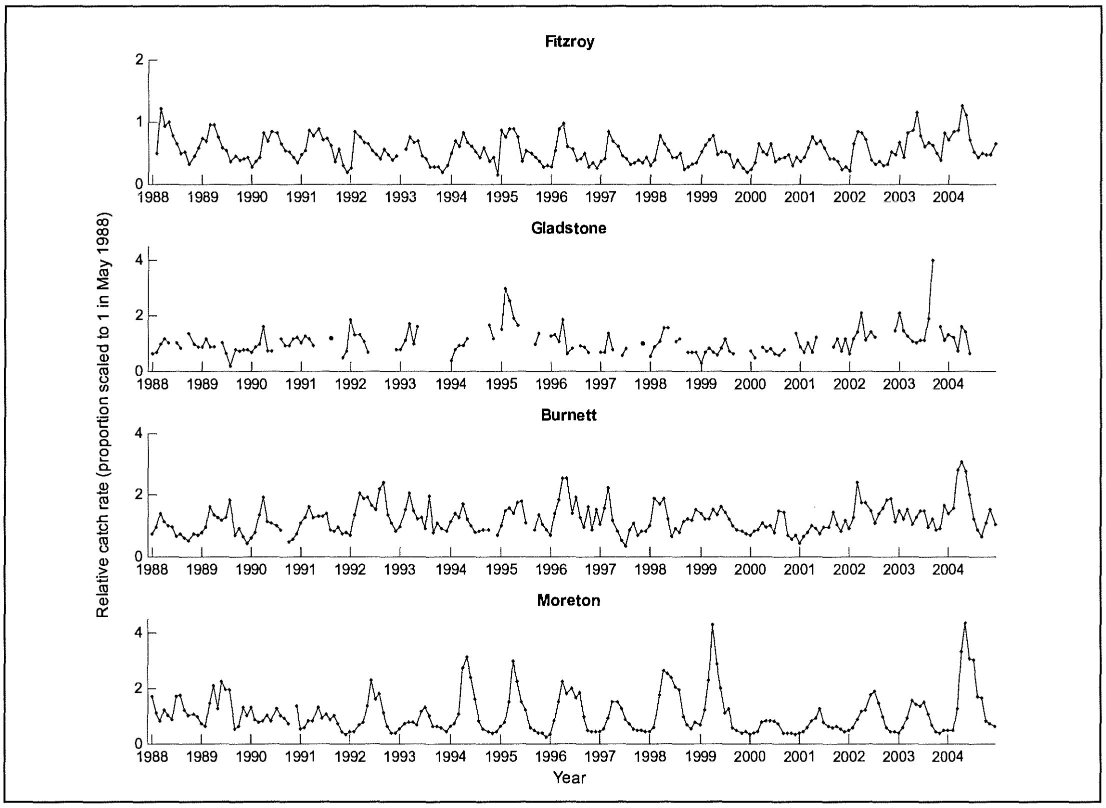

Figure 3.12 Standardised monthly beam trawl catch rates in the southern region (Fitzroy to Moreton) from January 1988 to December 2004.

In the northern region (Cairns to Mackay) the beam trawl fishery was highly seasonal and generally restricted to a short period each year between early summer and autumn (Figure 3.11). There were very few data from the Cairns and Tully areas with which to draw any conclusions. In the southern region (Fitzroy to Moreton) the beam trawl fishery tended to operate all year round, with peak catch rates in late summer to autumn (February to May).

Historical catch rates prior to 1988

The results of the linear mixed model for the historical trawl data (1968–1987) showed a significant fixed term effect of area, year and month (Table 3.15). The residual plots provided in APPENDIX 4 suggested that there was no evidence that the model was inadequate for describing the historical trawl data.

The standardised monthly catch rates of historical trawl data were shown in a relative scale (i.e. a proportion scaled to a standardised catch rate in May 1971) in Figure 3.13 and Figure 3.14. Highly variable catch rates were associated with limited data. In general, it is difficult to interpret the historical catch rate trends due to the paucity of historical trawl data. The Moreton area had more records from 1970 to 1979, which resulted in the continuous catch rate trend during this period. High catch rates were obtained in 1971 and 1974 in the Moreton area, possibly due to the flood events in these years. With the exception in 1971 and 1974, the overall trend was relatively stable from 1970 to 1977, but clearly declined in 1978 and 1988.

It is important to note that the historical trawl data and the CFISH logbook data were standardised to their own vessel identifiers (vessel_ID for the CFISH data and VSN for the historical trawl data), therefore these two time-series of standardised catch rates were not comparable.

Table 3.15. The results of the linear mixed model (REML) analysis for the historical trawl data. The Wald statistics were calculated by dropping each fixed term from the full exploratory model.

Historical model

Random term		Residual term	
Estimated Variance Components (s.e.)		Residual variance (s.e.)	0.914 (0.0098)
VSN	0.2482 (0.0263)	Deviance (-2Log-likelihood)	18088.53
		Residual degrees of freedom (d.f)	17973

Fixed terms	Wald Statistics	d.f	χ^2 probability
year.month.area	610.99	161	<0.001

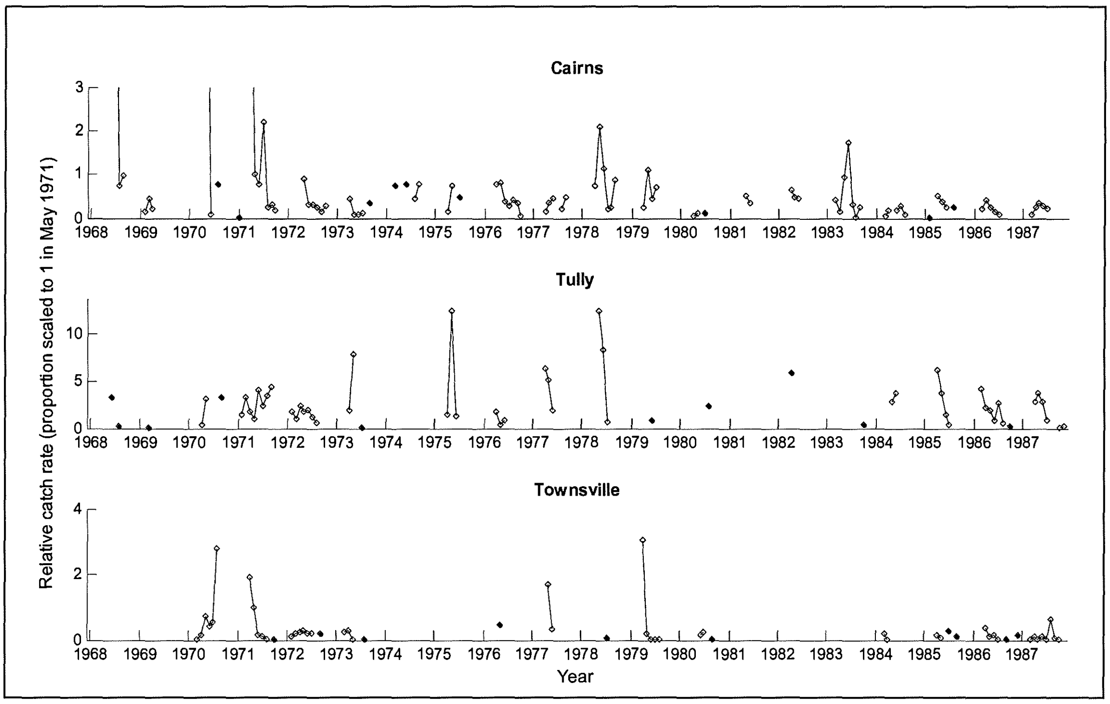

Figure 3.13 Standardised monthly catch rates of banana prawns for the northern region from January 1968 to December 1987. The Mackay area was not analysed due to a limited number of records available in the historical trawl data.

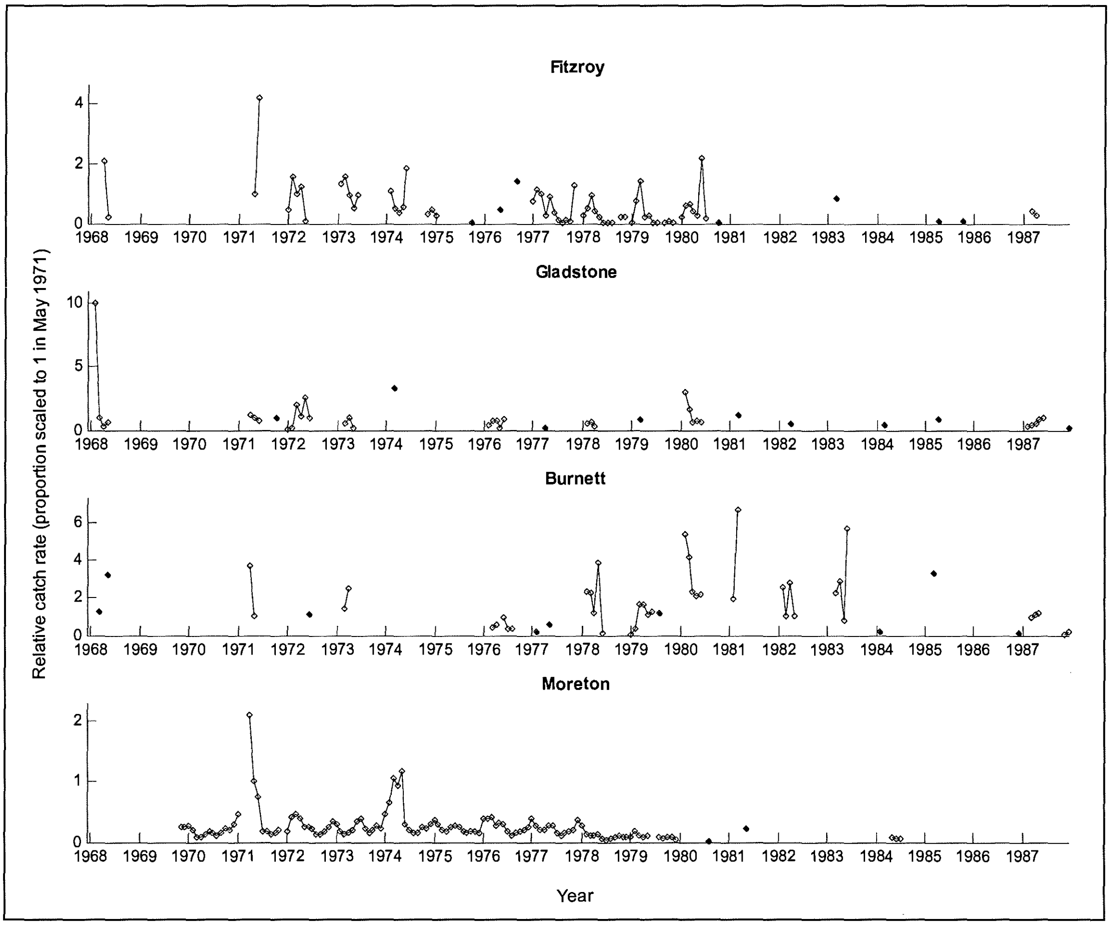

Figure 3.14 Standardised monthly catch rates of banana prawns for the southern region from January 1968 to December 1987.

3.3 Discussion

This section of the report examined the time lag effects of abiotic factors affecting Queensland banana prawn catch rates and developed models that can be used to standardise the catch rates. We examined a range of lag effects and concluded that the linear mixed model (LMM) that included river flow explained more variation than a similar model that included rainfall. This is 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.

Vance *et al.* (2003) discussed the effect of catchment size on flow and banana prawn catches in the north-eastern and south-eastern Gulf of Carpentaria. They concluded that the effect of rainfall on banana prawn landings from relatively small catchments (i.e. the north-east Gulf) occurred over a relatively short period immediately after the rain, while the effects from large catchments (i.e. the south-eastern Gulf) lasted much longer and had greater effects on offshore catches.

The catch of king and tiger prawns (i.e. the logkingtiger term) had a significant negative effect on the otter trawl catch rates of banana prawns, for all areas (Table 3.14). While the catches of these species improved the model's ability to explain variation in the banana prawn catch rates, they cannot be considered as an influential abiotic variable, but rather reflect the nature of the fishing activities which help us to understand the variation in banana prawn catch rates. The catch of kings and tigers should be considered in the model because the logbook provides no information on which species the fishers are targeting. Inclusion of the logkingtiger term helps overcome this problem. In brief, the higher the catch of the king and tiger prawns in the otter trawl fishery, the lower the catch of banana prawns. As long as the model contains no information about which species of prawns the fishers are targeting, there will remain a need to include the catch of other species as part of the standardisation model.

As seen in Figure 3.8, the seasonality in banana prawn catch rates was successfully captured by the two time-lagged temperature terms (temp1_60 and temp121_180). However, random effects from the interaction between sub-stock area, year and month were found to be significant (Table 3.12), which suggests that significant variation in the catch rate time series remained, even after extracting variation due to temperature and river flow. Air temperatures were less variable and less influential in the northern areas of Cairns and Tully.

The highly significant recent river flow (river flow time lag1_30 and time lag31_60) effects on otter trawl catch rates (Table 3.14) suggest that such flow events are likely to affect the catchability of banana prawns more than increasing the production or biomass of the stock. It is important to note that the Wald statistic (Table 3.12) declined with the increasing time lag of the flow. The results suggest that, for the otter trawl fishery, flows promote the immediate downstream movement of prawns to areas that are fished by otter trawlers.

In contrast to the otter trawl fishery, beam trawl catch rates in three of the eight sub-stock areas declined as a result of recent (time lag1_30) flows (Table 3.14). The only area that showed a positive influence in the beam trawl fishery from recent flows was

Mackay and it should be noted that the catch and effort from this region are only a very minor component of the beam trawl fishery. Thus, for the major beam trawl areas (i.e. Fitzroy, Burnett and Moreton) recent flow events (i.e. time lag1_30) had either negative effects, or no effect on catch rate.

In contrast to the recent river flow effect, the delayed river flows (i.e. river flow time lag61_90, Table 3.14) had a significant positive effect in the major beam trawl areas (i.e. Fitzroy, Burnett and Moreton). Robins *et al.* (2005) investigated the effect of river flow in the Fitzroy River estuary and found a significant positive correlation between the reported annual banana prawn catch (otter trawl and beam trawl combined) and summer river flow. Given that the beam trawl catch rates peak in the Fitzroy area in autumn (from March to April), the key river flow events with a time lag of 61–90 days are likely to occur in summer (December to January). Results from the present study (Table 3.14) suggest that delayed flows (time lag61_90) are more influential for beam trawl catch rates, as we found little evidence of delayed flow effects for the otter trawl fishery.

In order to account for these flow effects we offer the following speculative explanation. Flow events in December and January increase the survival, growth rates and productivity of post-larval and juvenile (3–13 mm CL) banana prawns in the very shallow (i.e. < 50 cm depth) mangrove nursery areas, primarily by increasing their available water-inundated habitat area. The improved survival and productivity of these age classes results in increased catch rates of sub-adults (15–25 mm CL) in the beam trawl fishery three months later in March and April. Vance *et al.* (2003) hypothesised that rainfall and flow events may increase the productivity of the banana prawn population in the Gulf of Carpentaria, by providing additional nutrients and mixing of adjacent waters from the rivers.

It is difficult to explain why the same flow events in December and January do not result in increased catches in the otter trawl fishery three months later in March and April. One possible explanation may be that those sub-adults (15–25 mm CL) that are flushed from the river in December and January to the open waters experience elevated natural mortality rates, possibly from predation, and as a result do not survive long enough to significantly increase the catch rates in the otter trawl fishery in March and April. Our results suggest that it is only the recent flow events (time lag1_30 and time lag31_60) that significantly increase the otter trawl catch rates, and that the delayed flows (time lag61_90) have no effect.

In brief, the major findings of the flow analyses can be summarised by the following:

- Immediate and recent flow events (i.e. river flow time lag1_30 and time lag31_60) have positive effects on otter trawl catch rates. This seems likely to be due to the promotion of movement of banana prawns into areas that experience otter trawl fishing effort and can therefore be considered to increase the catchability of the stock to the otter trawl fishery.
- Immediate and recent flow events (i.e. river flow time lag1_30 and time lag31_60) generally have negative effects on the beam trawl catch rates. The reason for this is unknown, but likely due to the flows removing juvenile and sub-adult banana prawns from the beam trawl estuaries.

- Flows with large time lags (river flow time lag61_90) generally have no effect on the otter trawl catch rates of banana prawns, but appear to have a positive effect on the beam trawl catch rates.

The present study suggests that recent flows increase the catchability of banana prawns in the otter trawl fishery. Increases in productivity, due to reduced mortality and increased growth rates may also occur, but our results suggest that any increased productivity seems more likely to occur for the younger post-larval and juvenile age classes (3–13 mm CL). Further research is required to test this hypothesis. Analyses that include longer time lags (i.e. 90 to 120 days) may also help us to understand how flows affect the different life history stages, age classes and catches.

4 Construction of total catch estimates

The estimation of total annual landings of banana prawns from the Queensland east coast included data from the commercial and recreational sectors. As described in Chapter 2, the following data were available for each sector:

- commercial catch of banana prawns estimated from Queensland Fish Board Data (1957–1980)
- commercial catch from the CFISH logbook data (1988–2004)
- recreational catch of banana prawn estimated from the RFISH and NRIFS surveys (1999, 2000 and 2002).

According to the history of trawl fisheries on the Queensland east coast (see Section 2.1), it is likely that the banana prawn fishery commenced at different times in each area. The fishery commenced in south-east Queensland in 1950 and expanded to north Queensland in later years. Based on this historical perspective and the Fish Board data (1957–1980), it is assumed that the banana prawn fishery commenced:

- in 1950 and 1954 in the Moreton and Burnett areas, respectively
- in 1957 in the Gladstone and Fitzroy areas, when the Fish Board data program commenced
- around 1967–1969 in the northern region (Cairns, Tully, Townsville and Mackay) (banana prawn catch data from 1957 to the mid-1960s is negligible).

4.1 Estimating total commercial catch

The intervals for which there are no catch data available for the commercial sector are:

- 1981 to 1987 for all sub-stock areas
- 1950 to 1957 for the Moreton area
- 1954 to 1957 for the Burnett area (all year ranges are inclusive).

In addition, as noted in Section 2.2, the Queensland Fish Board catch data for the northern region (Cairns to Mackay) were likely to underestimate total catch. Total catches for the northern region were therefore estimated from 1967 to 1980. The Fish Board data were more comprehensive in the southern part of the state and were therefore used to estimate the total banana prawn catch in the southern region (Fitzroy to Moreton).

For periods when no data were available, or when the Fish Board data were considered to underestimate catches, total banana prawn catches were estimated for each sub-stock area using the following procedure.

The northern region (Cairns, Tully, Townsville and Mackay)

The annual commercial banana prawn catch from 1967 to 1987 was estimated by:

a) averaging the annual catch from 1967 to 1969 from the Fish Board data
b) averaging the catch from the first three years of CFISH records (1988 to 1990)

c) interpolating catches for the period 1970 to 1987 when no data were available by applying an exponential trend line between catch estimates derived in a) and b)
d) where the actual Fish Board data were available (1970–1980), comparing the estimated catch to the reported catch in each year and when differences were observed, assuming the higher catch value for that year.

The southern region (Fitzroy, Gladstone, Burnett and Moreton)

The annual commercial banana prawn catch from 1981 to 1987 was estimated by:
e) averaging the catch from the last three years of Fish Board data (1978–1980)
f) averaging the catch from the first three years of CFISH records (1988 to 1990)
g) interpolating catches for the period 1981 to 1987 when no data were available by applying an exponential trend line between catch estimates derived in e) and f).

Estimates of total prawn catch for the Moreton and Burnett areas prior to 1957 were derived using the following procedure:

- For the Moreton area, the average catch for the first three years of Fish Board records (1957–1959) was estimated. In the absence of any further information on annual landings, and because landings were assumed to be negligible prior to 1950, this estimate was assumed to represent annual landings back to 1950.
- For the Burnett area, the average catch from the first three years of Fish Board records (1957–1959) was estimated and assumed to be representative of the mean catch back to the fishery's development in 1954.

4.2 Estimating total recreational catch

Although there are only three years of recreational catch data available, it is important to consider the recreational catch, as far as possible, when estimating total landings. The following procedure was applied to estimate total recreational catches for the period where there is no data available.

Recreational catches between 1988 and 2004

For the period between 1988 and 2004, when CFISH logbook data were available, it was assumed that annual standardised catch rates reflected trends in the banana prawn stock size (Begg *et al.* 2005).

It is likely that the beam trawl fishery CPUE more closely reflected the recreational CPUE because both sectors are located in rivers and estuaries. For this reason, the beam trawl standardised catch rates for 1999, 2000 and 2002 were used to calculate the recreational fishery effort in those years. However, because there are no consistent beam trawl data for the Cairns and Tully areas, standardised otter trawl CPUE from these areas were used as an index of abundance.

Table 4.1 Estimated recreational effort (days of effort) for those years when the recreational catch surveys were conducted. (Note the surveys did not record effort and so effort has to be derived.) Trends in the recreational fishery catch rates were assumed to reflect those of the beam trawl fishery. Standardised beam trawl catch rates were used. Because of the scant data from the Cairns and Tully areas, standardised catch rate estimates from the otter trawl fishery were used.

Cairns

Year	Catch (kg)	Catch rate	Recreational effort
1999	5859.243	15.705	373.080
2000	4238.686	12.918	328.131
2002	10487.321	13.382	783.682
Average	6861.750	14.002	494.965

Fitzroy

Year	Catch (kg)	Catch rate	Recreational effort
1999	10016.066	23.043	434.660
2000	6272.356	22.648	276.954
2002	14173.381	24.467	579.284
Average	10153.934	23.386	430.299

Tully

Year	Catch (kg)	Catch rate	Recreational effort
1999	3422.767	49.030	69.809
2000	2476.094	43.638	56.742
2002	6126.330	50.540	121.218
Average	4008.397	47.736	82.590

Gladstone

Year	Catch (kg)	Catch rate	Recreational effort
1999	1213.033	51.389	23.605
2000	759.637	53.843	14.108
2002	1716.520	99.977	17.169
Average	1229.730	68.403	18.294

Townsville

Year	Catch (kg)	Catch rate	Recreational effort
1999	6123.520	16.810	364.271
2000	4951.198	11.065	447.464
2002	12970.858	19.547	663.569
Average	8015.192	15.807	491.768

Burnett

Year	Catch (kg)	Catch rate	Recreational effort
1999	3228.965	83.191	38.814
2000	8385.091	62.581	133.987
2002	29108.278	106.097	274.354
Average	13574.111	83.956	149.052

Mackay

Year	Catch (kg)	Catch rate	Recreational effort
1999	2128.620	42.740	49.804
2000	6396.458	47.344	135.106
2002	22539.426	44.644	504.873
Average	10354.835	44.909	229.928

Moreton

Year	Catch (kg)	Catch rate	Recreational effort
1999	40991.746	15.259	2686.349
2000	18785.218	7.132	2634.085
2002	31453.761	12.323	2552.537
Average	30410.242	11.571	2624.324

Estimates of the recreational effort for 1999, 2000 and 2002 are provided in Table 4.1. For those years when there were no recreational survey catch data, it was assumed that the number of boat registrations in Queensland from 1986 to 2002 represented the trend in recreational fishing effort. An annual index of relative recreational fishing effort was estimated as the ratio of the number of boat registrations in each year from 1986 to 2002 to the average number of boat registrations in 1999, 2000 and 2002, when the survey data were available. A generalised linear model (GLM) with a log link (see Figure 4.1) was fitted to the indices from 1986 to 2002 and the predicted values from the model were used to construct a long-term trend line (see the solid line in Figure 4.1) of relative fishing effort from 1986 to 2004. The trend was assumed to be common across all sub-stock areas.

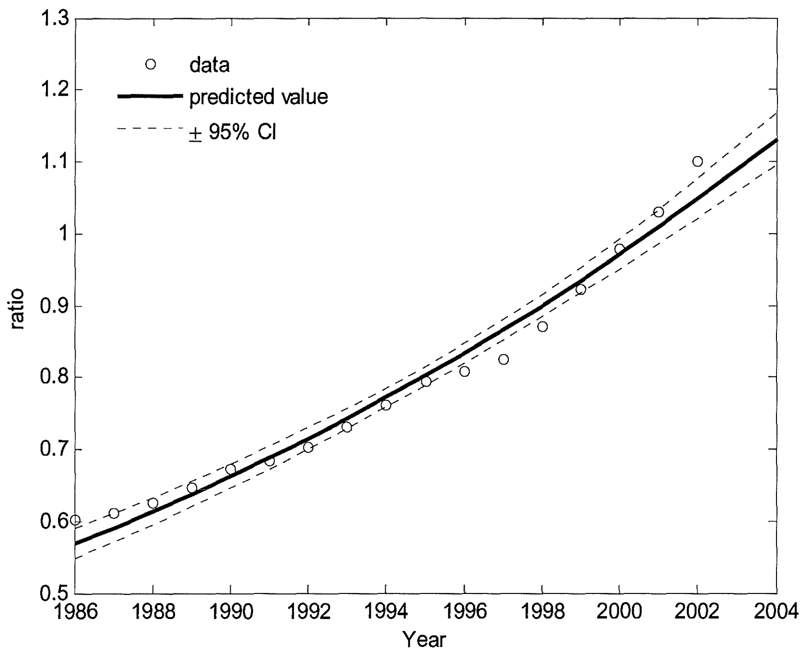

Figure 4.1 Predicted trend in relative effort for the recreational banana prawn fishery estimated from Queensland boat registration data (1986–2002). Ratio = (boat registration number) / (the average boat registration number in 1999, 2000, 2002).

An estimate of the recreational effort for each year when there was no catch data available was derived by multiplying the estimated average recreational effort for the years 1999, 2000 and 2002 in Table 4.1 by the relative effort index in Figure 4.1.

Total recreational catch was then calculated by multiplying the estimate of recreational effort by the catch rate estimate:

$$C_{rec\_catch,y} = E_{relative\_effort,y} \times cpue_{commercial,y}$$

where: $C_{rec\_catch,y}$ = estimated total recreational catch in year y (y = 1988–2004)

$E_{relative\_effort,y}$ = estimated effort in the recreational fisheries in year y

$cpue_{commercial,y}$ = standardised catch rate from the beam trawl fishery in year y.

Note that standardised otter trawl fishery catch rates were used for the Cairns and Tully areas.

Recreational Catches prior to 1988

For the period between 1950 and 1987, when standardised commercial catch rate were not available, a linear regression analysis was used to estimate the recreational catch. The linear model was fitted to the estimated recreational catches from 1988 to 2004 and projected back to 1950 defined as:

$$C_{historical\_rec\_catch,i,y} = area_i + year_y + area_i * year_y$$

where: $C_{historical\_rec\_catch,i,y}$ =predicted total recreational catch at year y (y=1950–1987)

$area_i$ = effect of ith sub-stock area (i=1–8: Burnett-Tully)

$year_y$ = effect of yth year (y=1950–1987)

$area_i * year_y$ = interaction effect of ith sub-stock area and yth year.

The results of regression analysis and the predicted recreational catches are shown in Table 4.2 and Figure 4.2, respectively.

Table 4.2 The results of regression analysis used to predict historical recreational catches (R^2=78.8)

Source	d.f.	SS	MS	Variance Ratio	F Probability
Regression	15	8.67E+09	5.78E+08	34.53	<.001
Residual	120	2.01E+09	16732631	-	-
Total	135	1.07E+10	79079057	-	-

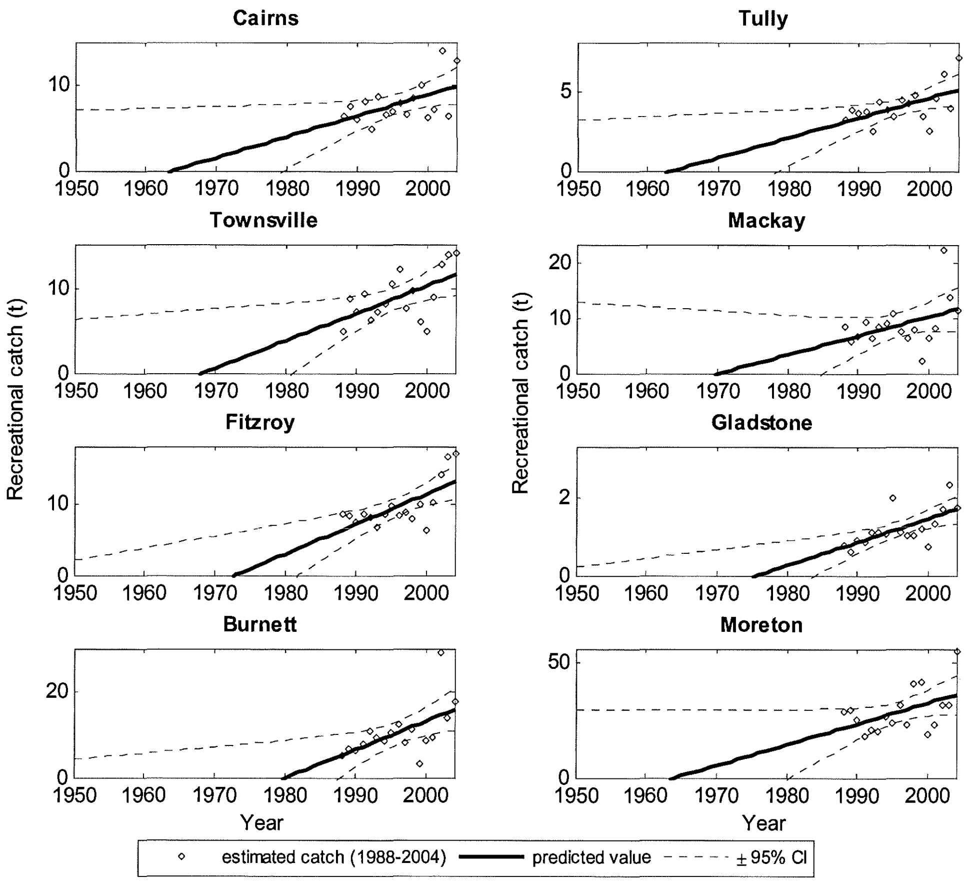

Figure 4.2 Predicted recreational catches for the period 1950 to 2004 based on the regression model.

Estimates of the combined total banana prawn catches (commercial + recreational) from 1950 to 2004 are shown in Figure 4.3. Although uncertainty in the total catches was considered in the stock assessment model as a part of the sensitivity analysis, it should be noted that significant uncertainty remains with respect to the older (i.e. pre-1988) commercial and recreational catch data.

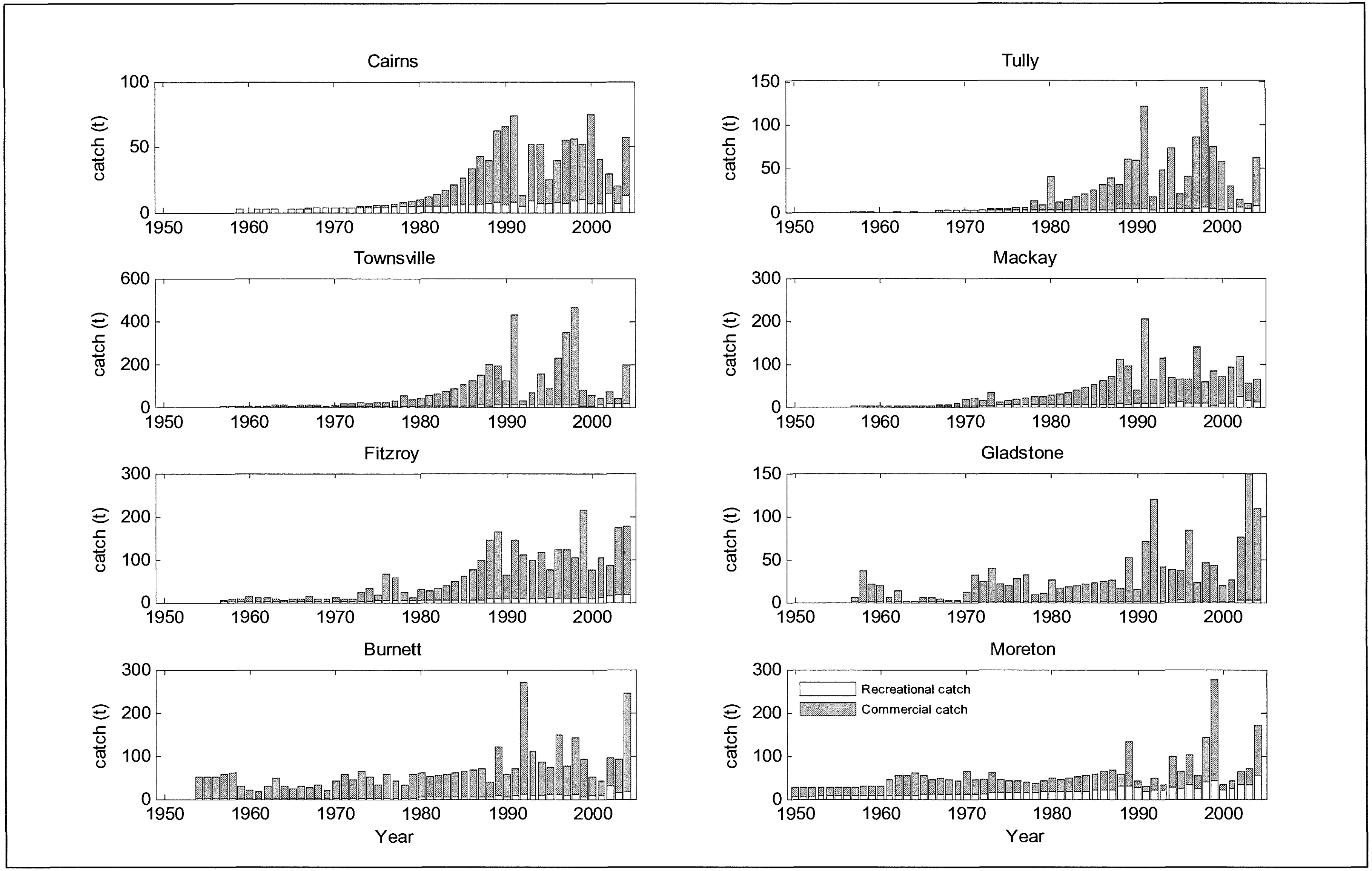

Figure 4.3 The estimated total banana prawn catches (t) from eight sub-stock areas for the period 1950 to 2004.

5 Stock assessment

5.1 Methods and materials

The population dynamics and status of the Queensland east coast banana prawn fishery were investigated by conducting a monthly age-structured model for each sub-stock area. A list of the biological parameters used in the model is provided in Table 5.1 followed by a description of the age-structured model. Since the model input parameters were deterministic, sensitivity analyses were investigated by running scenarios with different parameter values.

There are no specific Review Events or other reference points specified in the trawl fishery management plan (*Fisheries (East Coast Trawl) Management Plan 1999*) for banana prawn stocks. While we acknowledge the importance of monitoring catch rates in the fishery and that applying the 70% CPUE Review Event referred to in the Plan is attractive for its simplicity, the decision to use 70% CPUE was arbitrary and arguably no better than say 60% or 80% CPUE. For these reasons we chose to evaluate the stock status against a reference point that is more directly related to the biological productivity of the stock. We first assess the biomass of the banana prawn stock, and then identify the maximum sustainable yield (MSY) and the biomass required to produce MSY (B_{MSY}). We suggest that B_{MSY} may be an appropriate limit reference point for managing the banana prawn fishery. Estimates of B_{MSY} adopted as limit reference points in other stock analyses equate to approximately 40% of B_0 (virgin biomass) (Begg *et al.* 2005; O'Neill *et al.* 2005).

Biological parameters

Spawning index

In the Gulf of Carpentaria, banana prawns have a six-monthly spawning pattern (Rothlisberg *et al.* 1985) with two peaks per year: one in spring (August–October) and another in autumn (March). According to Dredge (1985), the spawning pattern for banana prawns from the central east coast of Queensland differs slightly from the Gulf, but also occurs in spring (September to December) and autumn (March to June). Garcia (1985) noted the spring spawning is usually the predominant spawning period for many penaeids and the importance of autumn spawning varies depending on the year, local environment and timing of occurrence. Rothlisberg *et al.* (1985) suggested that the autumn spawning contributes only a minor proportion to the subsequent population, and that the spring spawning was the only significant source of recruitment to the main commercial fishery in the Northern Prawn Fishery. The current assessment therefore assumed that spring spawning (September to December) was the major contributor of recruits to the fished population, and that a quarter of the annual egg production was produced during each of these months.

Growth

The growth rate of banana prawns was based on the von Bertalanffy growth curve described by Lucas *et al.* (1979). This curve is reasonable for adults and sub-adults, but tends to overestimate juvenile growth. Since juvenile banana prawns (≤ 20 mm CL) are generally caught by beam trawls, this study needed to derive an alternative growth function for juveniles. Haywood and Staples (1993) estimated growth rates of juvenile banana prawn from the north-eastern Gulf of Carpentaria as linear ranging from 0.63 to 1.65 mm CL week^{-1}. As the young prawns caught and modelled are most probably the fast growers, this study assumed the growth rate of juvenile banana prawns was 1.65 mm CL week^{-1}. The final growth function used for the current assessment was therefore a composite curve (Figure 5.1) based on the early work of Lucas *et al.*(1979) for adults and the linear growth rates obtained for juveniles by Haywood and Staples (1993).

Table 5.1 Banana prawn biological parameters used in the monthly age-structured model.

Biological parameters	Estimates	References
Natural Mortality (M)	0.05 week^{-1} (0.2 month^{-1})	Lucas *et al.* (1979)
Monthly Spawning Pattern	$\sum_{Jan}^{Dec} spawning = 1$	
January – August	0	Based on Dredge (1985)
September	0.25	
October	0.25	
November	0.25	
December	0.25	
Size at Maturity	> 25 mm	Rothlisberg et al. 1985
Von Bertalanffy Growth Equation	L_∞ K (week^{-1})	
Sex combined	38 0.08	Lucas *et al.* (1979)
Growth for juveniles	1.65 mm CL week^{-1}	Haywood and Staples (1993)
Carapace length to weight	$W=aCL^b$	
a, b (sex combined)	0.00175, 2.7878	Gribble and Dredge (1991)
Fecundity (linear size formula)	# eggs = 19944.7CL-441097	Crocos and Kerr (1983)

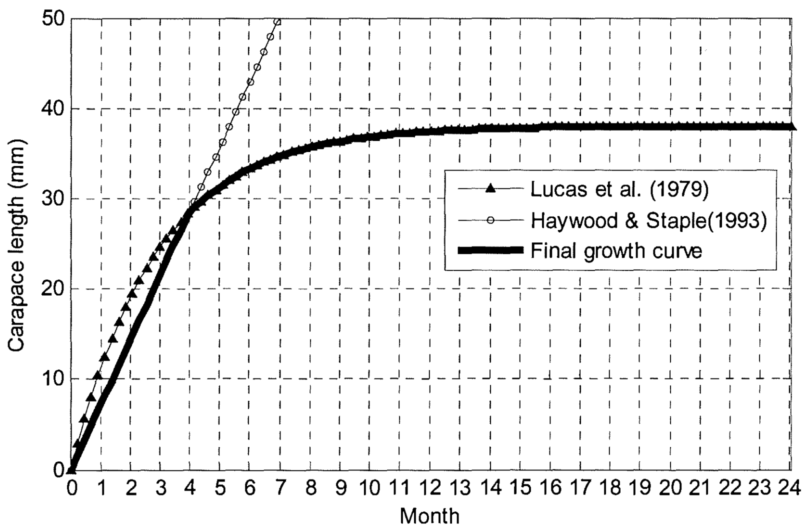

Figure 5.1 Composite growth curve used in the monthly age-structured model.

Natural mortality (M)

Penaeid prawns are subject to high mortality throughout their life cycle due to high level of predation and disease (Hyland and Gilmour 1988). Lucas *et al.* (1979) estimated the instantaneous rate of natural mortality (M) for banana prawns to be 0.05 week^{-1}. As discussed by Wang and Haywood (1999) however, the natural mortality rate is often much higher for the early life stages and decreases for adults. A few studies have examined the mortality rate of juvenile banana prawns (e.g. Haywood and Staples 1993; Wang and Haywood 1999) but their estimates vary with the models used. Haywood and Staples (1993) investigated the natural mortality of postlarval and juvenile banana prawn from the Embley River estuary in the Gulf of Carpentaria by using length-frequency analysis. They found that the mortality rate ranged from 0.23 to 0.94 week^{-1} depending on the season. Wang and Haywood (1999) assumed a size-dependent mortality model and estimated the mortality rate to be 0.89 week^{-1} at size 2 mm CL and 0.02 week^{-1} at 15 mm CL, which is lower than that of adults (0.05 week^{-1}) estimated by Lucas *et al.* (1979). Note that these estimates are dependent on the growth rate and if the growth rate is 1.65 mm week^{-1}, then the corresponding mortality rates are 1.46 week^{-1} for 2 mm CL prawns and 0.03 week^{-1} for 15 mm CL prawns. In view of the dissimilarities in these estimated values, a constant mortality rate of 0.05 week^{-1} was applied to all size classes. Application of a constant mortality rate is justified because most of the variation in M that was identified by Wang and Haywood (1999) occurred in size classes less than 10 mm CL and the model used herein only assesses the exploitable biomass, which we have assumed is limited to size classes larger than this. This estimate of M (0.05 week^{-1}) was also applied in the assessment of the Gulf of Carpentaria banana prawns by Vance *et al.* (2003).

Selectivity

It is important to note that beam trawl, stripe net and recreational fisheries operating in rivers and estuaries generally catch banana prawns that are subadults. Because banana prawns emigrate to offshore waters as they become adult, the selectivity of the large older prawns by these fishery sectors is expected to be low. The selectivity of juveniles by the otter trawl fishery is likely to be lower than that of the beam trawl fishery, but is high for adults. The age-specific selectivity of each method was therefore calculated by using the logistic equation (Haddon 2001):

$$S_{method,a} = \frac{1}{1+e^{-\log(19)\frac{(a-a_{50})}{(a_{95}-a_{50})}}}$$

where: $S_{method,a}$ = fishing selectivity at age a by the fishing method (*method* = otter or beam)

a_{50} = the age at which selectivity is 50%

a_{95} = the age at which selectivity is 95%.

Hereafter, whenever the 'beam' term is used in the context of *method*, it includes the stripe net and recreational fisheries.

According to unpublished data from Dredge (1985), 28 mm mesh had a 50% selectivity for 12 mm CL prawn. Courtney (1997) estimated selectivity of penaeid prawns by 41 mm mesh to be about 50% for 20 mm CL and more than 80% for size classes ≥ 23 mm CL. Given the above it was assumed that age at 50% and 95% selectivity for the:

- beam trawl sector was 2 months (14 mm CL) and 3 months (21 mm CL), respectively
- otter trawl sector was 3 months (21 mm CL) and 4 months (28 mm CL), respectively.

Note that the legal minimum mesh sizes for the otter trawl and beam trawl sectors in Queensland are 38 mm and 25 mm, respectively (exemptions apply for select areas and vessel lengths) (QECTMP 2004).

The selectivity curves for each fishing method are provided in Figure 5.2. The proportion of the adult banana prawn population (i.e. those older than 8 months) that is vulnerable to the beam trawl fishery is very low because most adults migrate from the rivers to open waters, where they experience the high selectivity of the otter trawl nets. Dredge (1985) found, using length frequency analysis, that a small proportion of adults remain in the central Queensland rivers. In addition, he also found that 3–4% of tagged adult banana prawns tagged outside of the rivers migrate back up the rivers and therefore become vulnerable to the beam trawl fishery. While the precise proportion of the adult population is unknown, it was assumed that approximately 8% (i.e. about 4% of adults remain in the river and an additional 4% return from the ocean) remain vulnerable to the beam trawl fishery.

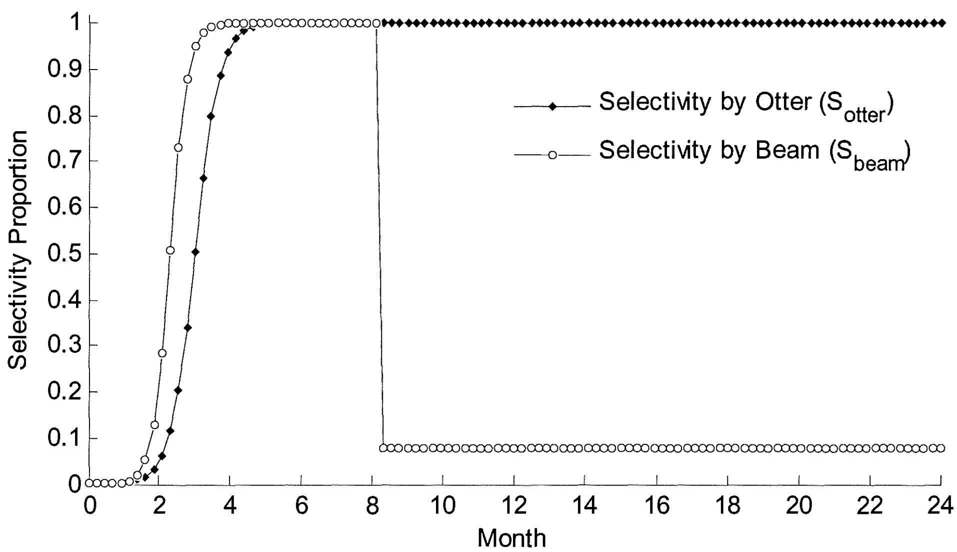

Figure 5.2 The selectivity curves for each fishing method applied in the monthly age-structured model.

Model description

An age-structured model was used to calculate the monthly population biomass and numbers of banana prawns. The model considered the survival of 2+,…, 24+ month old banana prawns for both sexes, and used the total catches (Figure 4.3) and standardised catch rates from the CFISH logbook data (1988–2004) (Figure 3.9 – Figure 3.12).

The population dynamics were assumed to follow the standard Baranov equations (Quinn and Deriso 1999). To ensure the population dynamics were stable at equilibrium at the assumed virgin state in 1950, the initial population numbers were calculated by running the model for a warm-up period of 12 years (1938–1949) with catch equal to zero. The initial number of banana prawns (N_0) for each age group was calculated as:

$$N_{0_a} = \hat{R}_0 \Phi_m e^{-M(a-2)} \qquad \text{for } a=2,...,24$$

where N_{0_a} = the initial banana prawn population of age a

$\hat{R}_0$ = the initial recruitment

Φ_m = the recruitment pattern for month m (= 1,12,11,…,1,12,11,…,3)

M = instantaneous rate of natural mortality.

The initial recruitment R_0 was estimated from the age-structured model.

The age-structured time dynamic calculation after the first month followed the equations:

$$N_{y,m,a} = \begin{cases} R_y \Phi_m & \text{for } a=2 \\ N_{y,m-1,a-1} e^{(-M+S_{otter,a-1}F_{otter,y,m-1}+S_{beam,a-1}F_{beam,y,m-1})} & \text{for } a=3,...,24 \end{cases}$$

where $N_{y,m,a}$ = the total prawn numbers of age a in year y and month m

R_y = the estimated annual recruitment for the year y

$S_{otter,a-1}$ = the proportion of prawns of age a-1 selected by otter trawling

$F_{otter,y,m-1}$ = the fishing mortality rate due to otter trawling in year y and month m-1

$S_{beam,a-1}$ = the proportion of prawns of age a-1 selected by beam trawling

$F_{beam,y,m-1}$ = the fishing mortality rate due to beam trawling in year y and month m-1.

The recruitment pattern, which represents the proportion of annual recruits in each month m, was calculated based on von Mises distribution (Mardia and Jupp 2000; O'Neill and Turnbull 2006):

$$\Phi_m = \frac{1}{2\pi I_0(\kappa)} e^{\kappa \cos\left(\frac{2\pi}{12}(m-\bar{r})\right)}$$

where I_0 = the modified Bessel function of the first kind of order 0
$\bar{r}$ = the estimated mode of the distribution
κ = the concentration parameter.
The recruitment pattern was standardised to sum to one ($\Phi_m / \sum \Phi_m$). The parameters $\bar{r}$ and κ were estimated by the age-structured model.

Annual recruitment was calculated by using the Beverton-Holt model of the spawning stock-recruitment relationship (Haddon 2001):

$$R_y = \frac{Eggs_{y-1}}{\alpha + \beta Eggs_{y-1}}$$

where R_y = the annual recruitment in year y
$Eggs_{y-1}$ = calculated index of spawning stock size (number of eggs produced) in year y-1
α and β = parameters of the Beverton-Holt relationship.

The stock-recruitment parameters α and β defined by Francis (1992) were used in the model shown as:

$$\alpha = \frac{Eggs_0(1-\hat{h})}{4\hat{h}\hat{R}_0}$$

$$\beta = \frac{5\hat{h}-1}{4\hat{h}\hat{R}_0}$$

where $Eggs_0$ = the initial spawning stock size
$\hat{R}_0$ = the initial recruitment
$\hat{h}$ = steepness of the stock-recruitment curve.
The value of $\hat{R}_0$ and $\hat{h}$ was estimated from the age-structured model.

The spawning stock index $Eggs_y$ was calculated as the sum of the products of the number of mature females and the fecundity index across the ages and months:

$$Eggs_y = \sum_m \sum_a 0.5 \rho_m N_{y,m,a} mat_a fecund_a$$

where ρ_m = monthly spawning pattern
$N_{y,m,a}$ = total number of banana prawns at age a in month m
mat_a = proportion of mature females at age a
$fecund_a$ = average number of eggs at age a derived from fecundity-length relationship.
The sex ratios of banana prawns were overall 1:1 (Kailola *et al.* 1993), thus half of the total number was assumed to be females.

The banana prawn biomass that was vulnerable to fishing was split into two due to the different fishing method selectivities.

$$B_{method,t} = \sum_a N_{t,a} S_{method,a} W_a$$

where $B_{method,t}$ = the exploitable biomass for each fishing method (otter and beam) at time t (year y and month m)

W_a = mean weight at age a derived from the von Betalanffy growth and length-weight relationship (Table 5.1).

The instantaneous rate of fishing mortality for each fishing method (F_{method}) was calculated as:

$$F_{method,t} = -\log\left(1 - \frac{C_{method,t}}{B_{method,t}}\right)$$

where $C_{method,t}$ = the monthly total prawn catch for each fishing method at time t.

Because it was unable to distinguish total banana prawn catches for each fishing method prior to 1988, the value of $C_{method,t}$ between 1950 and 1987 was estimated by using the proportion of otter trawled catch to total catch between 1988 and 1996 when CFISH data were available and also the fishing effort of otter trawling was relatively constant. The logistic regression was fitted to the proportion of otter trawling between 1988 and 1996 thus:

$$\log\left(\frac{\pi_{i,y,m}}{1-\pi_{i,y,m}}\right) = area_i + area_i * year_y + area_i * month_m$$

where $\pi_{i,y,m}$ = probability of otter trawling in ith sub-stock area, year y and month m (y=1988–1996)

$area_i$ = effect of ith sub-stock area (i=1–8: Burnett-Tully)

$area_i * month_m$ = interaction effect of ith sub-stock area and month m

$area_i * year_y$ = interaction effect of ith sub-stock area and yth year.

For the sub-stock areas where the effect of year was not significant (i.e. non-significant $area_i * year_y$) or negative, proportions of otter trawling were assumed to be constant across years (1950–1987).

The result showed that the effect of year on the Cains and Tully areas was positive and significant ($p < 0.001$). The proportion of the monthly catch due to otter trawling was projected back to 1950 (see Figure 1.1). Other areas were assumed to have constant proportion. Details of the results are provided in APPENDIX 5.

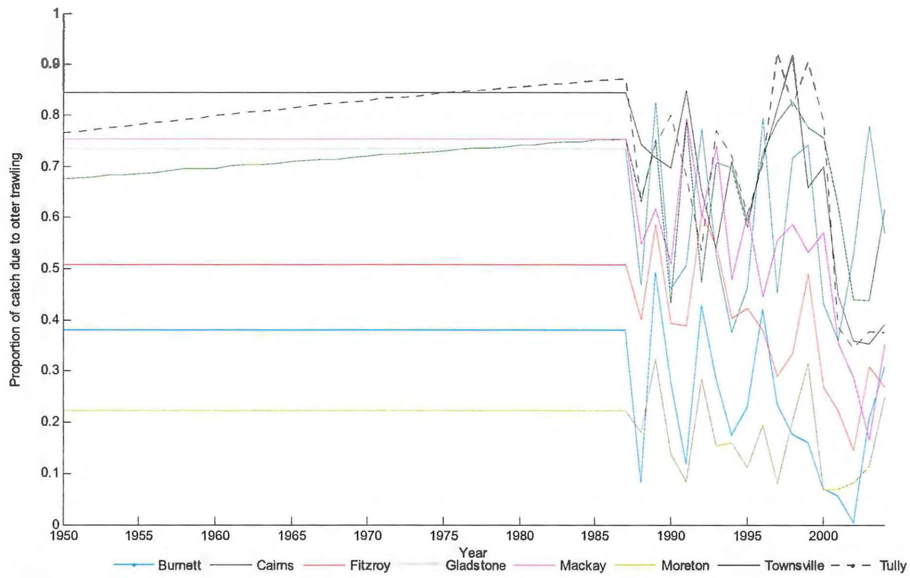

Figure 5.3 The estimated proportion of the total catch of banana prawns due to otter trawling in each sub-stock area. Prior to 1988 the proportion was assumed to be constant across years in the Burnett, Fitzroy, Gladstone, Mackay, Moreton and Townsville areas.

Catch rate (catch-per-unit-effort) was calculated as:

$$\hat{cpue}_{method,t} = q_{method,t} B_{method,t}$$

where $\hat{cpue}_{method,t}$ = the predicted catch rate for each fishing method (otter and beam) at time t

$q_{method,t}$ = the catchability of banana prawn by each fishing method at time t.

The catchability was calculated by the geometric mean of ratios given as:

$$q_{method} = \prod_{t}^{n} \left(\frac{cpue_{method,t}}{B_{method,t}} \right)^{\frac{1}{n}}$$

where $cpue_{method,t}$ = the monthly standardised catch rate for each fishing method

n = the total number of months from 1988 to 2004 (n=204).

The predicted catch for each fishing method was given by:

$$\hat{C}_{method,t} = \frac{F_{method,t}}{F_{method,t} + M} B_{method,t} \left(1 - e^{-F_{method,t} - M}\right).$$

Model fitting

The following parameters were estimated ($\hat{R}_0$, $\hat{h}$, κ, τ) in the analysis:

- $\hat{R}_0$, the virgin recruitment
- $\hat{h}$, the steepness of the Beverton-Holt stock recruitment curve
- τ, the estimated mode of the von Mises distribution
- κ, the concentration parameter in the von Mises distribution.

The model was fitted to the standardised CFISH monthly catch rates from January 1988 to December 2004 by minimizing differences between predicted and standardised CPUE in terms of sums of squares (*SS*) of the residuals:

$$SS = \sum_{method} \sum_{t} \left(\log(cpue_{method,t}) - \log(c\hat{pu}e_{method,t}) \right)$$

where $c\hat{pu}e_{method,t}$ = the predicted catch rate for each fishing method

$cpue_{method,t}$ = the standardised catch rate.

The residuals were assumed to exhibit a log-normal distribution. This analysis estimated the optimum parameter values by running the nonlinear Quasi-Newton optimization procedure in MATLAB called 'fminunc' function (MATLAB 2002).

To ensure exploitation rates ranged between zero and one, and to avoid the optimisation converging to unrealistically large population sizes with improbably low estimates of exploitation, two additional penalty terms were examined to test their influence on the minimisation. The first penalty function λ_1 ensured the combined otter and beam trawl catches in each month did not exceed the calculated exploitable biomass:

$$\lambda_1 = \begin{cases} 0 & if\left(\sum_{method} C_{t,method} \le B_t \right) \\ \sum \left(\sum_{method} C_{t,method} - B_t \right)^2 & otherwise \end{cases}$$

where B_t = the overall biomass at time t calculated by:

$$B_t = \sum_a N_{t,a} W_a \,.$$

The second penalty function λ_2 prevented extremely low exploitation rates (Hall and Watson 2000):

$$\lambda_2 = \begin{cases} 0 & if\, \frac{CN_y}{R_y} \ge \eta \\ 1000\left(\eta - \frac{CN_y}{R_y} \right)^2 & otherwise \end{cases}$$

where η was the minimum annual harvest fraction, and CN_y was the accumulated number of prawns caught across the fishing years calculated as:

$$CN_t = \sum_a N_{t,a} U_{t,a}$$

where, $U_{t,a}$ was the monthly harvest rate given as:

$$U_{t,a} = 1 - e^{(-S_{otter,a}F_{otter,t} - S_{beam,a}F_{beam,t})} \,.$$

The value 1000 was suggested by Hall and Watson (2000) to ensure adequate weighting in the optimisation. Values of 0.2, 0.1, and 0.01 for η were tested.

Once minimisation convergence was achieved, alternative initial parameter estimates were tested to ensure accurate SS. Due to the lack of contrast in the time series of catch rates from some regions, the λ_2 penalty function using η = 0.1 or 0.2 was required to obtain sensible model fits. Overall the range of penalty functions examined resulted in similar estimates of trends in biomass ratios and maximum sustainable yield.

The following assumptions were made to construct the age-structured model:

- standardised catch rate proportional to abundance
- constant natural mortality across all ages and years
- virgin state of banana prawn fishery in 1950
- constant catchability for each fishing method
- constant maturity
- constant fecundity
- constant selectivity by fishing method.

Model sensitivity

The influences of harvest fraction (η), natural mortality (M) and total catches on the model results were investigated using sensitivity analyses. As described in the previous section, three values of η (0.2, 0.1 and 0.01) were examined. The values of 0.2 and 0.1 were only applied in those the area where the model was unable to provide realistic results without constraint of λ_2 (η = 0.01). The natural monthly mortality rate of 0.15 and 0.25 were tested in addition to the base value of 0.2 (month^{-1}). Since there are uncertainties in the total catches due to the limited historical commercial and recreational catch records, the stock assessment model was also run based on the possible lower and higher total catches defined as:

$$\text{Higher/Lower catches} = \begin{pmatrix} \text{higher/lower historical} \\ \text{commercial catches} \\ \text{from 1950 to 1987} \end{pmatrix} + \begin{pmatrix} \text{higher/lower recreational} \\ \text{catches from 1950 to 2004} \end{pmatrix}.$$

Note that total commercial catches from 1988 to 2004 were assumed to be accurate. Higher/lower historical commercial catches were estimated from the higher/lower quartiles (25^{th} and 75^{th} percentiles respectively) of the average annual catches from 1950 to 1987 in each sub-stock area. Higher/lower recreational catches were based on the 25^{th} and 75^{th} percentiles of the three-year-average of annual catches in 1999, 2000 and 2002. The three levels of estimated total catch for each sub-stock area were shown in Figure 5.4.

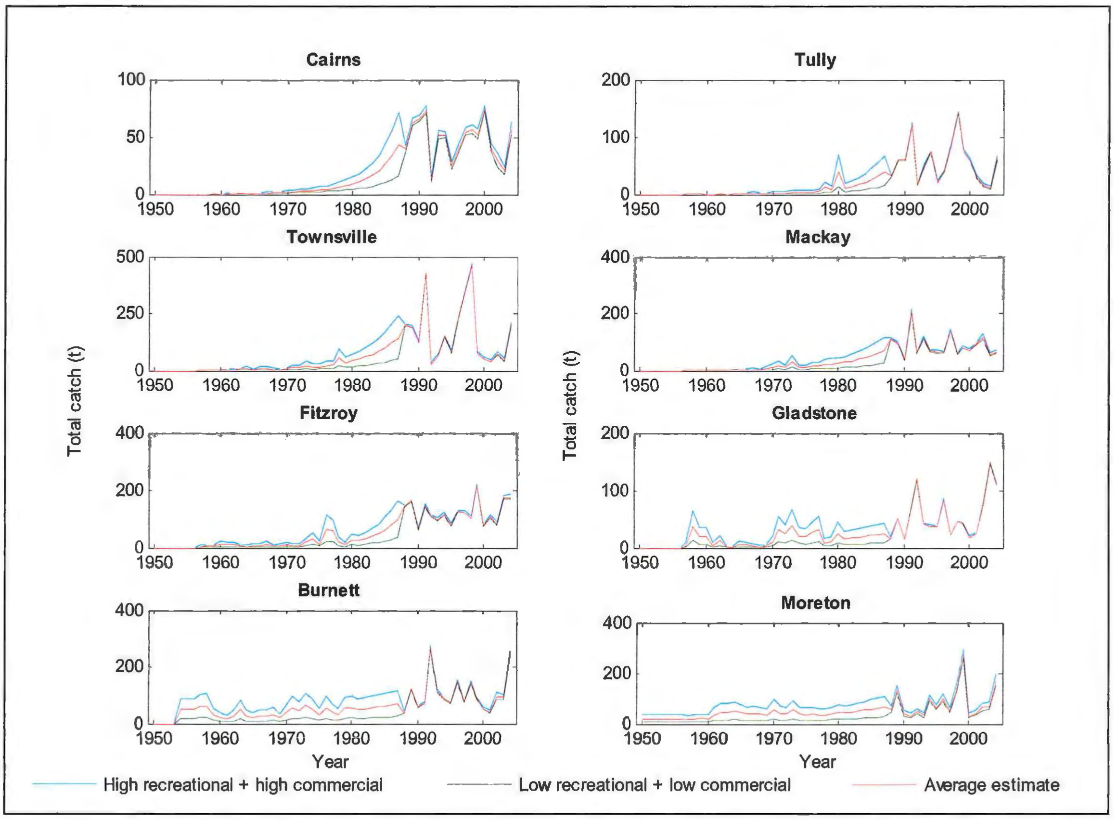

Figure 5.4 The estimated total catches (t) of banana prawn from 1950 to 2004 used in the sensitivity analyses.

A total of six sensitivity runs were conducted for each sub-stock area (Table 5.2). Sensitivity run D was set as the base model with M=0.2 and the average total catch estimate. For those sub-stock areas that resulted in realistic parameter estimates without the second penalty function (λ_2), the harvest fraction η was set to 0.01 for all sensitivity runs.

Table 5.2 The six combinations of fixed parameter values (instantaneous rate of natural mortality M and harvest fraction η) and total catch estimates that were used for the sensitivity analysis. All combinations were applied to each sub-stock area. The model run A was omitted if η = 0.01 provided realistic parameter estimates.

Model sensitivity run	η	M	*Total catch*
A	0.2	0.2	Average estimate
B	0.1 (0.01)	0.25	Average estimate
C	0.1 (0.01)	0.15	Average estimate
D	0.1 (0.01)	0.2	Average estimate
E	0.1 (0.01)	0.2	Higher catches
F	0.1 (0.01)	0.2	Lower catches

5.2 Results

The monthly age-structured model was unable to estimate realistic parameter values in the Gladstone area despite the application of penalty functions, and therefore fixed steepness values were assumed for this sub-stock area (Table 5.3). The fixed values of 0.4, 0.5 and 0.7 were calculated based on the steepness estimates from the near by Burnett and Fitzroy areas.

Table 5.3 Eight combinations of different fixed parameter values with fixed steepness used in the stock assessment model for the Gladstone area.

Model sensitivity run	*η*	*M*	*Steepness*	*Total catch*
A	0.2	0.2	0.5	Average estimate
B	0.1	0.25	0.5	Average estimate
C	0.1	0.15	0.5	Average estimate
D1	0.1	0.2	0.5	Average estimate
D2	0.1	0.2	0.7	Average estimate
D3	0.1	0.2	0.4	Average estimate
E	0.1	0.2	0.5	Higher catch
F	0.1	0.2	0.5	Lower catch

A summary of the stock assessment model results for each sub-stock area is provided in Table 5.4. The models for four areas, Cairns, Tully, Mackay and Fitzroy, provided informative parameter estimates without the need to apply a second penalty function (η = 0.01). These areas were referred to as *unconstrained* and did not require the model sensitivity run A to be applied. The Townsville, Gladstone, Burnett and Moreton areas did not have enough temporal contrast to obtain realistic parameter estimates, therefore the second penalty function was applied to these areas (referred to as *constrained* areas). The confidence intervals of the parameter estimates in model E for Cairns were not displayed because the model was unable to obtain the real standard errors derived from the Hessian matrix at the optimum point. The trend in the ratio of annual biomass to virgin exploitable biomass is provided in Figure 5.5.

The sensitivity analysis indicated that the model was quite robust for the range of natural mortality rates and total catch estimates that were considered. Similar estimates of the biomass ratio, MSY and steepness were obtained irrespective of the different parameter assumptions and combinations. All model runs showed a similar trend in biomass within a specific sub-stock area, although the results were more pessimistic for model A (higher harvest fraction η = 0.2) and slightly lower for model E (higher total catches).

With the exception of Gladstone, the estimates of steepness ranged from 0.3 to 0.68 and were statistically significant ($p < 0.05$) for all sub-stocks, except for models C, D and F in the Burnett area. This suggests that there are significant stock-recruitment relationships for all areas, except for the Gladstone and possibly the Burnett area. It is important to note that stock-recruitment relationships may exist in the Gladstone and Burnett areas, but the model was unable to detect them due to the lack of contrast in the standardised catch rate data in these areas. The steepness estimates were higher for Model A in the Townsville and Moreton areas due to the higher exploitation rate. The steepness in the northern region, with the exception of Cairns, appeared to be relatively low compared to the southern region (Table 5.4). The steepness was highest in Cairns (0.47–0.68).

The biomass was below the 40% B_0 limit reference point required to achieve MSY for at least one of the sensitivity runs in following areas and years:

- Cairns in 1991 and from 2000 to 2002
- Townsville in 1991 and from 1998 to 2002
- Burnett in 1992, 1993 and 2004
- Moreton in 1999 and 2000 (Figure 5.5).

The current exploitable biomass (i.e. biomass in year 2004) estimates, which ranged from 19 to 74% of B_0, were above the 40% B_0 limit reference point for all sub-stock areas except for model A in Gladstone (0.34) and Burnett (0.19). These low ratios resulted from the high exploitation rate which was imposed as the penalty function, λ_2 with $\eta = 0.2$.

The annual MSY estimated by the base model (model D) was largest for the Burnett area (165 t) followed by Townsville (144 t) and Fitzroy (132 t), and lowest for Cairns despite the high steepness estimates. Total annual MSY for the entire Queensland east coast was 802 t (based on model D). For the period from 1988 to 2004, the overall annual catch exceeded the MSY in 1989 (880 t), 1991 (1146 t), 1996 (829 t), 1997 (901 t), 1998 (1156 t) 1999 (910 t) and 2004 (1085 t), and was well below MSY in 1990 (470 t), 1995 (445 t), 2000 (437 t) and 2002 (420 t).

Table 5.4 Estimates of the a) steepness, b) ratio of the biomass in 2004 to the virgin biomass and c) maximum sustainable yield (MSY) for each sensitivity run and sub-stock area. A fixed steepness value was used for Gladstone. The numbers within brackets are 90% confidence intervals. [NS] indicates the estimates were NOT statistically significant at $\alpha = 0.05$.

Cairns

Run	Steepness	B_{2004}/B_0	MSY
A	-	-	-
B	0.47 (0.37; 0.59)	0.49 (0.22; 0.85)	39 (10; 66)
C	0.68 (0.48; 0.95)	0.45 (0.34; 0.91)	41 (34; 158)
D	0.57 (0.45; 0.72)	0.47 (0.24; 0.81)	40 (20; 66)
E	0.56	0.41	42
F	0.56 (0.46; 0.7)	0.53 (0.27; 0.84)	38 (17; 67)

Tully

Run	Steepness	B_{2004}/B_0	MSY
A	-	-	-
B	0.3 (0.24; 0.39)	0.61 (0.19; 0.76)	45 (8; 57)
C	0.34 (0.25; 0.47)	0.61 (0.17; 0.77)	47 (11; 62)
D	0.32 (0.24; 0.44)	0.61 (0.15; 0.76)	47 (10; 59)
E	0.33 (0.25; 0.43)	0.56 (0.14; 0.73)	46 (12; 57)
F	0.32 (0.24; 0.44)	0.66 (0.22; 0.80)	47 (8; 63)

Townsville

Run	Steepness	B_{2004}/B_0	MSY
A	0.41 (0.38; 0.44)	0.42 (0.34; 0.59)	141 (136; 151)
B	0.35 (0.32; 0.38)	0.58 (0.42; 0.67)	142 (122; 158)
C	0.36 (0.32; 0.42)	0.58 (0.42; 0.69)	146 (121; 170)
D	0.36 (0.32; 0.4)	0.58 (0.43; 0.69)	144 (123; 165)
E	0.35 (0.32; 0.39)	0.52 (0.37; 0.65)	144 (128; 162)
F	0.37 (0.32; 0.41)	0.63 (0.49; 0.72)	148 (124; 173)

Mackay

Run	Steepness	B_{2004}/B_0	MSY
A	-	-	-
B	0.33 (0.32; 0.34)	0.69 (0.3; 0.85)	164 (40; 159)
C	0.38 (0.28; 0.52)	0.65 (0.3; 0.77)	88 (53; 115)
D	0.35 (0.26; 0.46)	0.68 (0.34; 0.79)	88 (49; 119)
E	0.33 (0.26; 0.42)	0.6 (0.27; 0.71)	83 (52; 98)
F	0.38 (0.26; 0.54)	0.74 (0.38; 0.84)	96 (36; 146)

Fitzroy

Run	Steepness	B_{2004}/B_0	MSY
A	-	-	-
B	0.39 (0.26; 0.59)	0.56 (0.12; 0.67)	128 (25; 162)
C	0.52 (0.31; 0.88)	0.52 (0.13; 0.63)	138 (36; 175)
D	0.45 (0.28; 0.72)	0.54 (0.13; 0.66)	132 (35; 170)
E	0.41 (0.34; 0.5)	0.46 (0.13; 0.55)	119 (85; 138)
F	0.5 (0.33; 0.74)	0.54 (0.18; 0.64)	133 (68; 168)

Gladstone

Run	Steepness (fixed)	B_{2004}/B_0	MSY
A	0.5	0.19 (0.15; 0.24)	62 (59; 67)
B	0.5	0.45 (0.36; 0.52)	88 (78; 99)
C	0.5	0.47 (0.38; 0.56)	89 (75; 104)
D_1	0.5	0.46 (0.37; 0.53)	87 (76; 100)
D_2	0.7	0.51 (0.43; 0.58)	119 (103; 134)
D_3	0.4	0.41 (0.33; 0.49)	68 (59; 78)
E	0.5	0.45 (0.37; 0.53)	87 (77; 100)
F	0.5	0.46 (0.38; 0.54)	87 (77; 101)

Burnett

Run	Steepness	B_{2004}/B_0	MSY
A	0.57 (0.44; 0.74)	0.34 (0.25; 0.37)	110 (85; 128)
B	0.58 (0.37; 0.95)	0.51 (0.38; 0.56)	125 (75; 200)
C	0.62 (0.35; 1)[NS]	0.56 (0.38; 0.63)	176 (73; 271)
D	0.58 (0.36; 0.96)[NS]	0.55 (0.39; 0.61)	165 (62; 240)
E	0.43 (0.34; 0.54)	0.49 (0.28; 0.56)	121 (81; 148)
F	0.7 (0.42; 1)[NS]	0.56 (0.44; 0.63)	193 (82; 270)

Moreton

Run	Steepness	B_{2004}/B_0	MSY
A	0.56 (0.51; 0.62)	0.53 (0.45; 0.56)	99 (91; 106)
B	0.44 (0.39; 0.51)	0.61 (0.47; 0.65)	96 (79; 108)
C	0.49 (0.42; 0.57)	0.61 (0.45; 0.66)	102 (80; 116)
D	0.46 (0.4; 0.53)	0.61 (0.44; 0.66)	99 (78; 112)
E	0.45 (0.38; 0.52)	0.58 (0.38; 0.63)	106 (82; 121)
F	0.47 (0.42; 0.55)	0.63 (0.52; 0.68)	90 (75; 102)

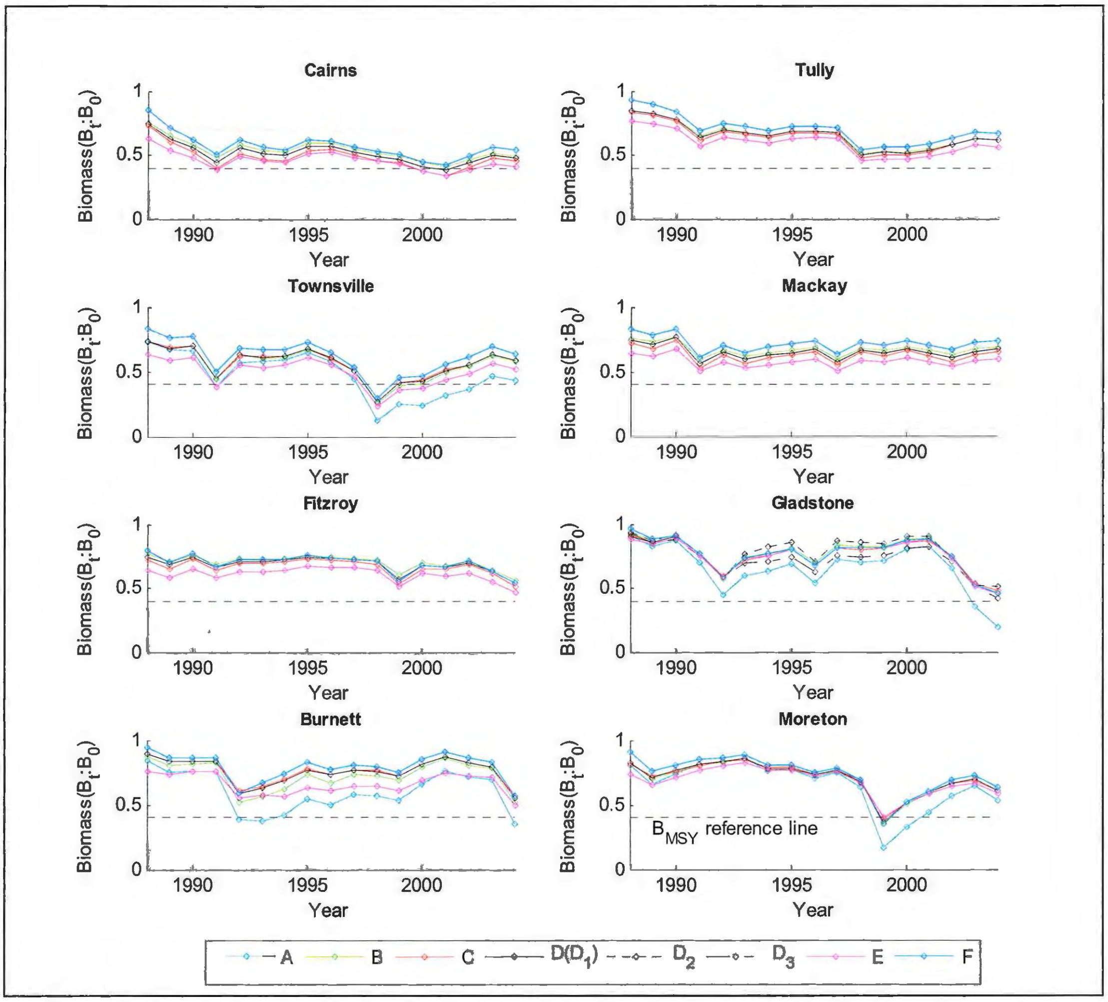

Figure 5.5 The predicted exploitable biomass ratio (annual biomass to virgin biomass) between 1988 and 2004 for the different sensitivity runs.

Figure 5.6 and Figure 5.7. show the age-structured base model (Model D) fits to the standardised CPUE data in each sub-stock area, and goodness-of-fit-plots of the corresponding age-structured model were located in APPENDIX 6. As seen from the goodness-of-fit plot, the log-scaled standardised residuals generally followed normal distribution without any extreme error, thus the use of log-normal residuals was considered to be adequate.

The fits were relatively good for the beam trawl fishery with the exception of the Cairns and Tully areas where there were very few beam trawl catch and effort data, compared to the otter trawl fishery (Figure 5.6 and Figure 5.7). The restricted nature of the selectivity for each fishing method and the limited number of parameter estimates may have caused interactions between the predicted catch rates for each fishing method which resulted in the model tuning to one catch rate data source.

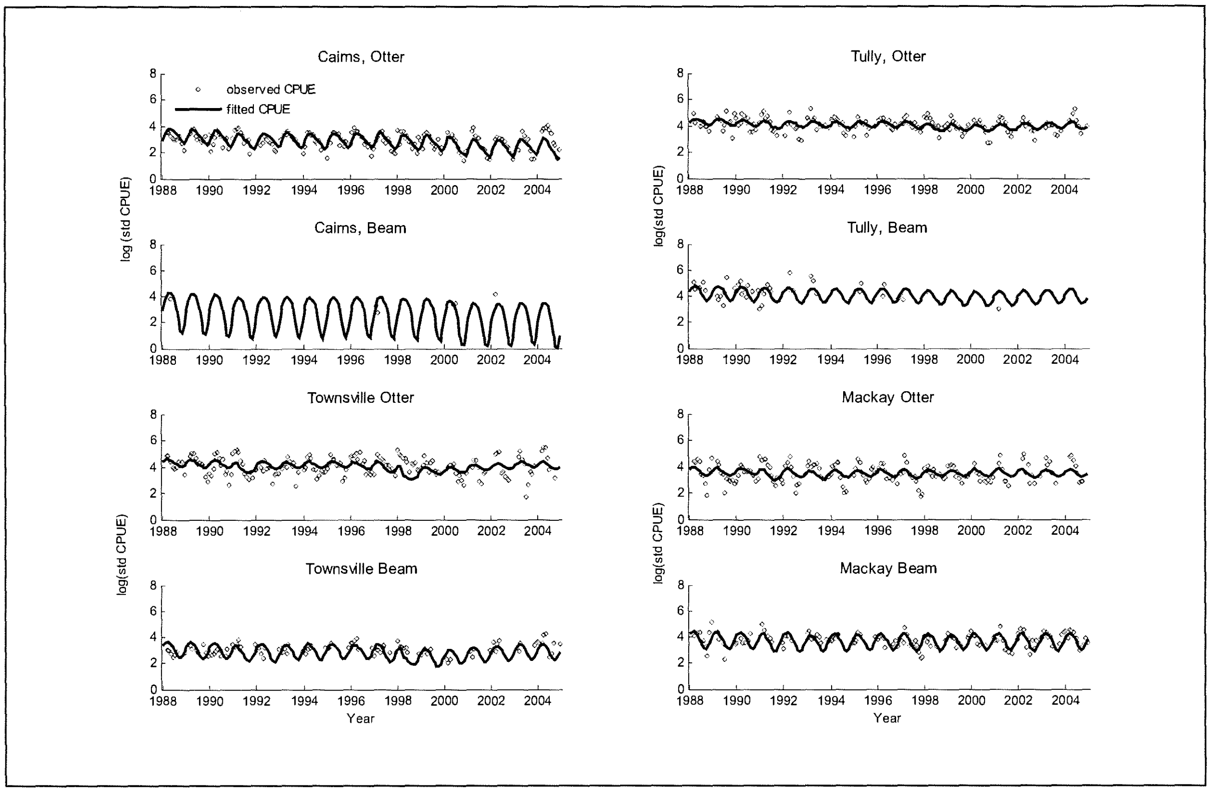

Figure 5.6 Observed (circles) and predicted (lines) standardised (log-scaled) CPUE from age-structured base model (Model D) in northern region (Cairns to Mackay).

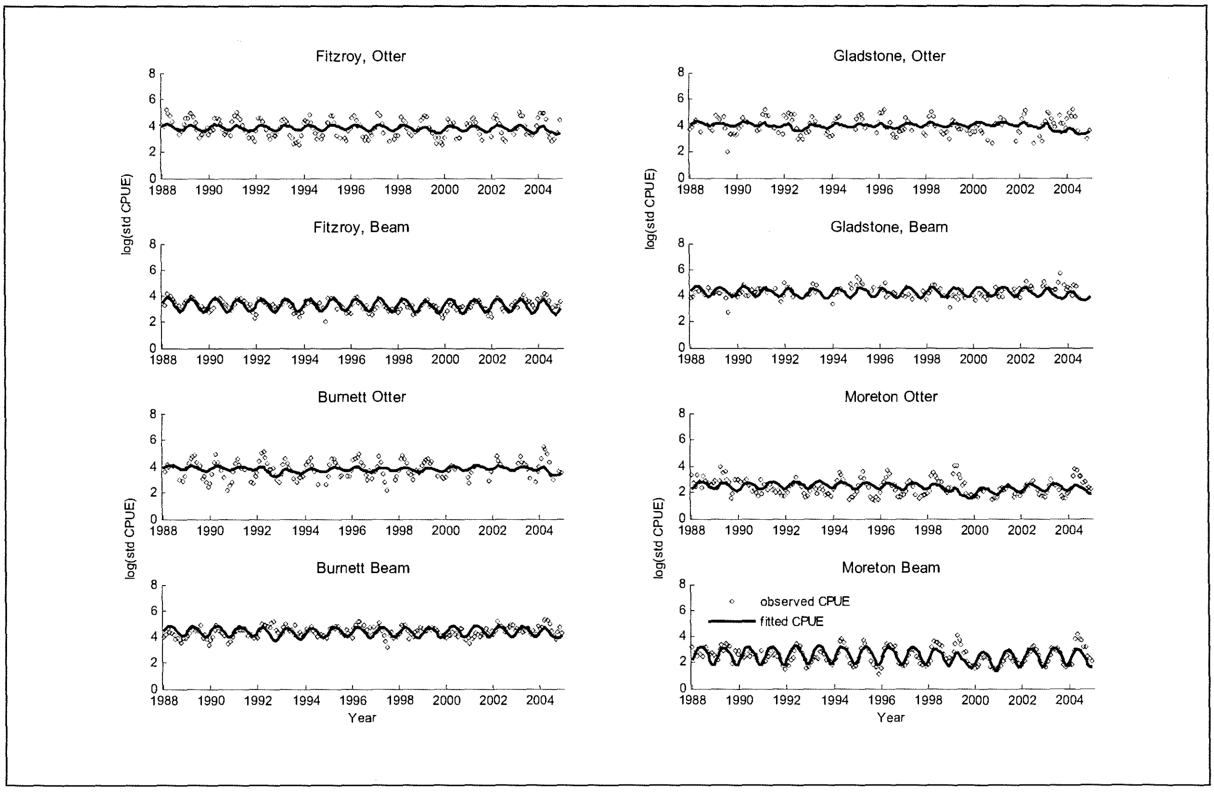

Figure 5.7 Observed (circles) and predicted (lines) standardised (log-scaled) CPUE from age-structured base model (Model D) in southern region (Fitzroy to Moreton).

5.3 Discussion

Stock assessment and sensitivity analysis

The age-based stock assessment model showed that the standardised CPUE in the Townsville, Gladstone, Burnett and Moreton areas did not have enough temporal contrast to obtain realistic parameter estimates, and therefore the second penalty function was applied to these areas. Despite the application of the penalty functions, the model for Gladstone converged to unrealistic parameter estimates, including an unrealistically high steepness value of 1. The fixed steepness values (Table 5.3) were therefore applied for the Gladstone area. Due to the application of the penalty function which restricted the direction of the optimisation procedure, the range of confidence intervals of the steepness estimates for the constrained areas may be smaller than those without the penalty function.

With the exception of the Gladstone area and some sensitivity scenarios for the Burnett area, steepness estimates were statistically significant. This indicated that a relationship between stock and recruitment is present for all sub-stock areas, even though natural variations in this relationship were expected to be high. According to Vance *et al.* (2003), the steepness of the stock recruitment relationships for banana stocks in the Gulf of Carpentaria is likely to be low (0.25–0.52). The low steepness appears to apply to the Queensland stocks at least in the *unconstrained* areas (steepness estimates in the *constrained* areas were influenced by the exploitation rate). It is important to note that Vance *et al.* (2003) obtained extremely high steepness for one of the regions in the Gulf of Carpentaria, which they suggested was due to a small population that was influenced by environmental changes. Cairns was also found to have relatively high steepness values, and because reported annual landings from this area were relatively small (i.e. around 50 t), the population seems likely to be characterised by a relatively small spawning stock.

The assessment assumed that the catchability of the prawns remained constant through time. This assumption may be violated if the average fishing power of banana prawn vessels has changed (i.e. 1988–2004). We were aware of this possibility and in recent years the Department of Primary Industries and Fisheries, Queensland (DPI&F) has undertaken surveys and analyses to quantify annual change in fishing power for the state's major trawl sectors (i.e. eastern king prawn, scallop, tiger/endeavour prawn and Torres Strait tiger prawn sectors) (O'Neill *et al.* 2005; O'Neill and Leigh 2006; O'Neill and Turnbull 2006). However, very few banana prawn vessel owner/operators were included in these surveys, which focused on the larger more valuable sectors, and as such any change in the fishing power in the banana prawn fleet, and its subsequent effect on catchability, remains unquantified.

Effects due to changes in fishing power were not completely omitted from the standardisation process because 'vessel ID'—which does capture differences *between* vessels—was included in the process. Differences *within* vessels were not captured. If fishing power in the banana prawn fleet has increased over time, and therefore catchability has increased over time, then the overall effect is such that the true biomass trends are likely to be more pessimistic than the estimated trends determined here.

Future assessments of the banana prawn stock should attempt to quantify annual changes in fishing power and incorporate their effects in the standardisation of catch rates. If this is undertaken then the assumption that catchability is constant would be valid.

Biomass trends

The high reported catches in 1991 for the northern region (i.e. Cairns, Tully, Townsville and Mackay), which all exceeded the MSY estimates (Figure 4.3 and Table 5.4), contributed to the marked declines in biomass in the same year. These high catches were likely affected by the severe flood that occurred in the Townsville (Burdekin River and Haughton River) and Tully (Tully River and Herbert River) areas in 1991. There were no severe flooding events for the Mackay and Cairns catchments in 1991, but the highest annual river flow in Mackay between 1988 and 2004 was in 1991. The total river flow in the Cairns area was also relatively high in 1991. The following year's total catches decreased significantly in the Cairns, Townsville and Tully areas, and were some of the lowest annual catches for banana prawns recorded in the CFISH database. The biomass levels in 1992 in the northern region improved, possibly as a result of the reduced catches in that year. Interestingly, very low river flows were recorded in these areas in 1992. The extensive flooding that occurred in the Fitzroy River in 1991 (Figure 3.5) was not associated with a significant concurrent decline in biomass (Figure 5.5), possibly because the catches from the area were not as large as those in the northern areas.

While very low catches were observed for the northern areas in 1992, the Burnett area recorded its highest annual catch of 269 t (Figure 4.3), which was about 100 t more than the MSY estimated from the base model D (165 t). The Burnett area also recorded its highest total river flow for 17 years in 1992 due to the flooding in the Burnett and Kolan Rivers from tropical Cyclone Fran (Bureau of Meteorology 2005). This large catch, which was likely due to the extremely high river flow, contributed to a decline in biomass of about 25% at the time.

In the Gladstone area, biomass declined by about 30% from 1990 to 1992 with increased reported annual catches. In 1992 the reported catch was large and exceeded the estimates of MSY for all sensitivity runs (62–119 t). Although the high catches were likely affected by high river flows during these years, the amount of water was very small compared to the other sub-stock areas, due to the relatively small size of the catchment.

Biomass in the Moreton area remained relatively stable (70–80% of virgin biomass) until the late 1990s, but declined rapidly from 1998 to 1999 to less than 40% B_0 in 1999. This marked decline followed the high catches recorded in 1998 and 1999 (143 t and 275 t, respectively), which exceeded the estimated MSY upper confidence intervals for all sensitivity runs (102–121 t).

Biomass declined from 1995 to 1998 in the Townsville area to below the 40% B_0 limit reference point. This decline was reflected by the increased total catches at the same time, which exceeded the MSY upper confidence intervals for all sensitivity runs (151–173 t). CPUE trends were relatively stable despite the decline in biomass during this period (Figure 5.6), which suggests that the standardised catch rates may not adequately represent the abundance of the stock. The stable CPUEs may be indicative of hyperstability due to the schooling behaviour of the banana prawns and the improved fishing power of the vessels. In order to overcome this problem the logbook data recording system should be altered (see details in Section 5.4).

River flow effects

The standardisation of the CFISH catch rates showed that recent river flow events (i.e. those that occur within 60 days prior to the catches) have a) a positive effect on the otter trawl catch rates and b) a generally negative effect on beam trawl catch rates. This suggests that flows promote the downstream movement of individuals to offshore areas, and increase the catchability of sub-adults and adults to the otter trawl fleet. The movement of juveniles and sub-adults is likely to lower their catchability to the beam trawl fishery, which may explain the negative effect in this sector.

The standardisation of the CPUEs also suggested that long time lagged flows (i.e. those that occur 61 to 90 days prior to the catches) affect the productivity of the banana prawn populations; however, this effect is largely limited to the beam trawl fishery (Table 3.8). There was very little evidence of long time lagged flows affecting otter trawl catch rates. The assessment model developed by Vance *et al.* (2003) for banana prawn stocks in the Gulf of Carpentaria examined a large number of time-lagged effects for rainfall, temperature and wind but found only a small number significant effects. The stock assessment model developed here incorporated flow parameters for the prediction of recruitment, but no significant correlations between the two were obtained. This result should be considered preliminary and further modifications to the model may be required to elucidate the relationship between flow and recruitment.

Conclusion

The biomass in the northern region (i.e. Cairns, Tully, Townsville and Mackay) declined from the late 1990s to 2000 but has since recovered. In contrast, biomass estimates for the southern areas, with the exception of the Moreton area, have generally declined since 2000. The recovery of the biomass in the northern region is likely to be at least partially attributed to the reduction in fishing effort due to a) a number of vessels exiting from the fishery after the *Fisheries (East Coast Trawl) Management Plan* was introduced in 2000 and b) the introduction of the annual northern closure (15 December to 1 March) in 2000 (Figure 2.9).

The model suggests that the banana prawn fishery was unlikely to be overfished (i.e. where the biomass has fallen below 40% B_0 limit reference point) in any sub-stock area in recent years (i.e. 2000–04). However, the model has also indicated that very high annual catches (i.e. those that exceed MSY) can lead directly to significant reductions in biomass which result in the biomass falling below 40% B_0. For example, the high catches in Townsville in 1998 (Figure 4.3) contributed to the marked decline in biomass (Figure 5.5). It is important to note that:

- banana prawn landings in 2004 exceeded those required to achieve B_{MSY} (using the base model D) for all areas except Mackay

- current biomass levels (i.e. for 2004) for all areas are relatively low at about 50 to 60% of B_0.

It is therefore quite feasible that large catches from any sub-stock area in the immediate to short-term (i.e. within the next two years) could easily result in a marked decline, with biomass falling below the 40% B_0 limit reference point. Areas in the southern region may be of particular concern because biomass estimates in these areas have been in decline since 2002.

The study has highlighted differences between the sub-stock areas, the need to examine the areas separately, and the possibility of sub-stock area based management intervention in the future. Management that is based on the entire east coast catches may overlook the status of regional stocks. Trends in the biomass for the northern region (i.e. Cairns, Tully, Townsville and Mackay) suggest that the northern annual closure has reduced effort and catch on the banana prawn stocks, and contributed to an increase in biomass in recent years. This is likely to be fortuitous as the northern closure was implemented mainly to reduce the risk of growth overfishing of tiger prawns (*Penaeus esculentus* and *Penaeus semisulcatus;* see Draft Management Plan and Regulatory Impact Statement (1999)). In contrast, there is no evidence to suggest that the annual southern closure, which takes place from 20 September to 1 November, has any effect on the effort, catch or biomass of banana prawn stocks in the southern region (i.e. Fitzroy, Gladstone, Burnett and Moreton areas). This is likely because the closure occurs when there is very little catch and effort directed at the banana prawn stocks (Figure 2.6). Note that Moreton Bay is exempt from the southern closure. In the Gulf of Carpentaria the main management objective for banana prawn stocks is the prevention of growth overfishing by controlling the start of the fishing season. No attempt is made to control the level of fishing effort directed at banana prawn stocks in the Gulf.

5.4 Further research and recommendations

1. **Further biological research**. Due to the very limited research on the biology and population dynamics of banana prawns on the Queensland east coast, this assessment used parameter estimates that were derived from the Gulf of Carpentaria stocks. It is unknown whether these parameters accurately reflect the population dynamics of the east coast stocks and therefore further studies of the Queensland populations are required. Specific parameters that need to be measured include: a) mortality rates, including natural mortality and fishing mortality, b) spawning stock dynamics and c) growth rates.
2. **Recreational data.** The recreational catch survey data are very sparse. Further research on the recreational fishery is required, specifically to quantify the recreational catch rates, recreational effort and total catch of banana prawns in each sub-stock area. These data would help reduce the uncertainty associated with the total annual recreational catch estimates.
3. **Amendments to data recording in logbooks.** It is recommended that logbooks are altered to record: a) target species, b) zero catches, c) searching effort and d) information on fishing gear and technology. The species that the fisher was targeting could be recorded on a shot-by-shot or daily basis. Zero catches should also be recorded; however, this could be achieved simply by recording the targeted species and automatically assuming zero catch if no

catch of the target species is recorded for that shot or day. Searching effort may take the form of recording the number of hours the vessel 'steamed around' each day in search for 'boils' of banana prawn schools. These changes, together with records on fishing gear and technology, will allow the aggregation dynamics of the prawns and changes in fishing power to be quantified and, consequently, will improve the standardisation of CPUE.

4. **Reference points.** At present the *Fisheries (East Coast Trawl) Management Plan 1999* contains no specific target or limit reference points for banana prawns. The Plan does refer to a CPUE (limit) Review Event of 70% for several principal target species, but does not specifically address banana prawns. While monitoring catch rates is important and recommended, we also recommend that formal assessments of the banana prawn stock include commenting on the status of the biomass. We are not aware of the underlying biological or economic basis for the 70% CPUE Review Event. Given that it appears to have been arbitrarily chosen and that it is unlikely to perform any better than other percentage-based CPUE reference points (i.e. 60% or 80%), we question any benefit from retaining such a strategy. In the current assessment estimates of the Maximum Sustainable Yield (MSY) were identified for each sub-stock area. Ratios of the biomass to virgin stock biomass were also presented for each year and sub-stock area and a limit reference point aimed at maintaining biomass to achieve MSY (B_{MSY}) was suggested. This limit reference point equates to approximately 40% B_0. If it is deemed that 40% B_0 is inappropriate then a thorough discussion of alternative reference points should be undertaken by the trawl fishery Management Advisory Committee (Trawl MAC). (A brief discussion of alternative reference points for the fishery was included in the Independent Review by Ass. Prof. Malcolm Haddon and is provided in APPENDIX 1.)
5. **Frequency of stock assessments for the Queensland banana prawn fishery**. The priority is to undertake the biological research identified in (1). Once this research has been undertaken it would be prudent to undertake a formal assessment of the Queensland banana prawn fishery once every three to four years. This would allow managers, fishers and other stakeholders to examine the performance of the stock in relation to biomass levels, and specifically reduce the likelihood of the biomass falling below the limit reference point suggested herein (i.e. 40% B_0) or some other biomass limit. Standardised catch rates should be monitored annually for each sub-stock area and reported to the TrawlMAC and the trawl fishery Scientific Advisory Group (SAG). Examining the catch rates on an annual basis will be relatively cost effective, and although informative, it will not provide detailed information on biomass trends.
6. **The northern and southern closures**. The study suggested the northern closure, which takes place in coastal waters north of 22°S from 15 December to 1 March may have reduced the banana prawn catch and effort in the northern region and subsequently had a positive effect on biomass trends. There is no evidence of the southern closure affecting the biomass of banana prawns in the southern region. If closures are to be used to optimise the value of the banana prawn catch, in the southern region or elsewhere, then a range of closure scenarios should be investigated and their effects on biomass simulated before they are implemented. Because of the mixed-species nature

of the trawl fisheries it would also be necessary to investigate the impacts and benefits on other species.

7. **Regulating the banana prawn fishery in real-time**. The banana prawn fishery is a cyclic fishery operating on a short-lived species. The most effective management arrangement would therefore be to monitor and control catch or effort in real time. VMS information could be used to monitor effort in the fishery. Differentiating banana prawn fishing effort from other spatially overlapping stocks such as tiger prawns would be relatively straightforward as the banana prawn fishery operates predominantly during daytime, while king and tiger prawns are caught at night. When effort levels are deemed to be approaching or exceeding those associated with MSY, fishers would have to be instructed to reduce or cease fishing.

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APPENDIX 1 Review by Associate Professor Malcolm Haddon, Tasmanian Aquaculture & Fisheries Institute

18th May 2006

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Review of Queensland Banana Prawn Assessment Document

Dear Mai,

Your assessment strategies, with respect to reconstructing the time series of data, both commercial and recreational appear to be as good as you are going to be able to get. The methods you have used to generate the data series appear robust, adequate and generate plausible time series. The sensitivity tests obviously assist in any interpretation.

The data standardization is interesting. I wasn't sure why you treated the three way interaction as a random effect in one model and then as a fixed effect in another. Whether a factor is fixed or random is always cause for debate but the debate is missing from this document (which is one of the most open and detailed I have read in a while). It would be useful to discuss this and possibly compare the outcomes with simpler statistical models. Most standardizations of catch rates are conducted in such a manner that the parameter estimates for the time step of interest (in this case the monthly figures) constitute the standardized catch rate relative to a reference value (either the first or last date is common). However, the approach you have used is equally valid.

The failure of some regions to be fitted to the model either reflects inherent problems with the data (too little, or internally inconsistent, or other problems such as the data not be representative of the area) or that the regions are not representing coherent stocks. By using parameters from adjacent stocks you are effectively combining the regions while keeping them separate - which strategy is best here would need to be explored.

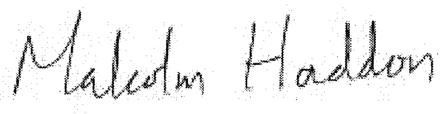
In terms of diagnostics it would have been useful to have seen residual plots of the residuals against month/year (the equivalent to Figs 5.6 and 5.7). Looking at the fit of the model to the CPUE series I imagine I can see patterns in the residuals but I cannot be sure. Such residual plots may well be informative about whether the model is succeeding in capturing the stock dynamics. Without them we can see you have a reasonable statistical fit but we cannot see whether there are patterns in the dynamics that may lead to better ideas.

Then there is the idea of using Bmsy as a limit reference point. This approach seems ok as long as the inherent variation in the banana prawn stocks is recognized. Obtaining a precise estimate of the production curve for banana prawns is ambitious and difficult depending on your data. It essentially relates to the production of a precise spawner recruit relationship. So what is needed if Bmsy is to be used as a limit reference point is a probabilistic interpretation. That is the use of the limit reference point should be couched in terms such as there is a 70% chance that the spawning stock biomass (SSB) will fall below the median estimate of Bmsy. For that you would need to develop the use of maximum likelihood methods at least (to provide the option of generating likelihood profiles). Or, better still, perhaps it would be better to have a limit reference point that was reached if the SSB fell below the optimum estimate of Bmsy for X years. Whichever way you go towards making this limit reference point operational I think you will need a risk assessment of some kind. I totally applaud the idea of including limit reference points. Ideally one should also have target reference points but here in Australia these often seem to default to any level above the limit reference point.

Because of the operational difficulties involved with applying Bmsy as a reference point I would recommend caution in trying to apply it strictly for a while. For example, off Townsville the model suggests (Figure 5.5 page 68) that the stock was below (possibly well below) 40% Bmsy in 1998 and 1999, yet is still recovered with no management action. It is possible that 40% is over cautious and maybe you might contemplate some other biological bottom line below which you would not want to go below. Off Townsville you have evidence that you could go as low as ~30% Bmsy and still recover in only one or two years. On the other hand there is security in being cautious, though it depends on what management levers you have available to pull.

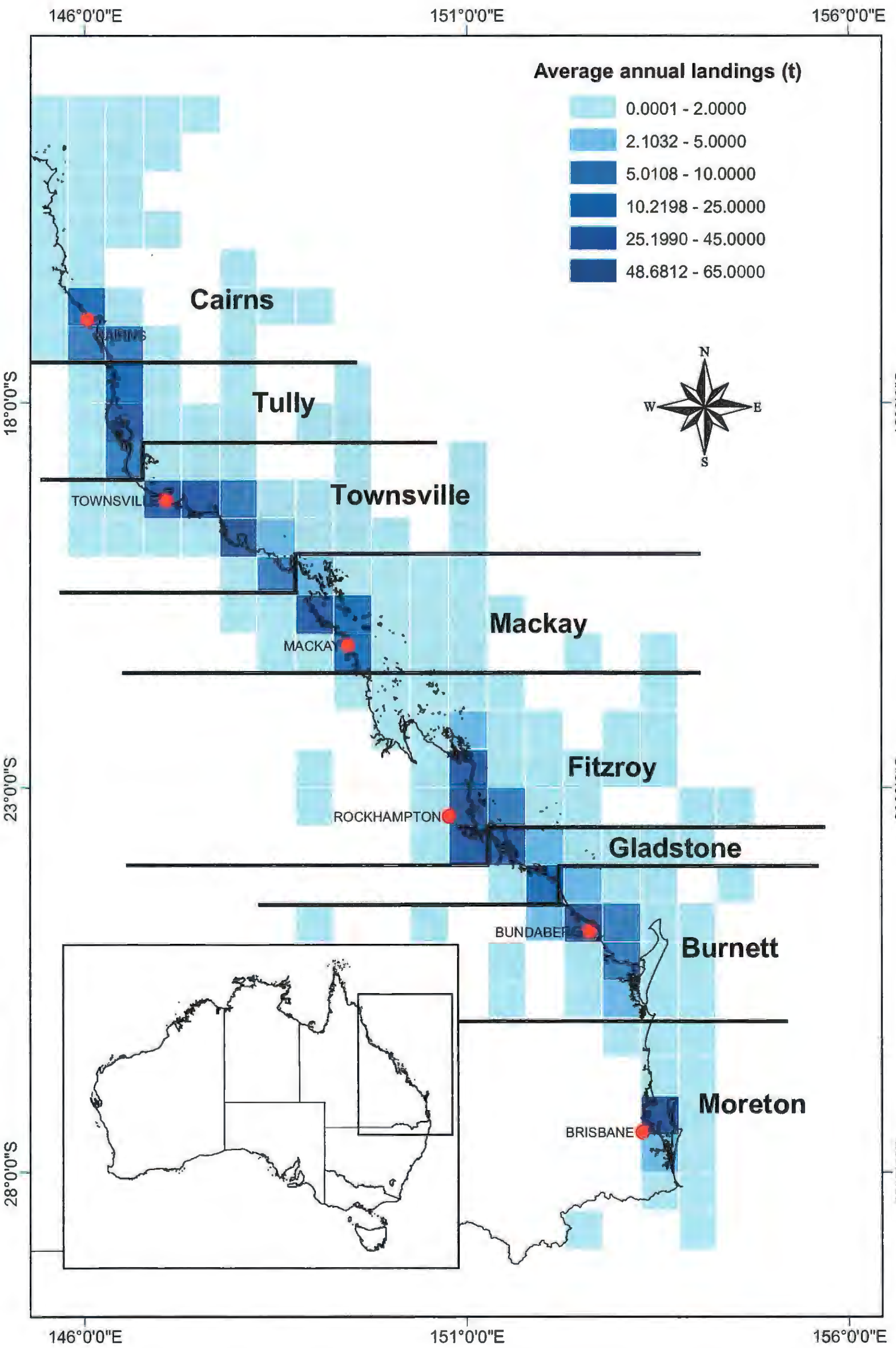
But all of that is for the next assessment. As your recommendations point out there is much to learn about the biology of the banana prawns off the east coast of Queensland before your confidence in the model becomes strengthened. I see nothing especially wrong with the assessment. The data re-construction is about as good as you are likely to get. The indices of the relative abundance are standardized and while the exact method could be debated there does not appear to be anything invalid or incorrect in the methods used. It may be worth conducting some alternative standardizations for comparison but there is no reason not to use the ones you have. The model design seems perfectly appropriate and provides the results you need. A small amount of work is required to develop the diagnostics. The big area of debate will be how finally to use the outcomes of the assessment. I can only comment briefly on that (see above) as this will be a matter for the managers in Queensland. Having a limit reference point is better than not having one (these review events can sound good but it basically says let us have a meeting and doesn't really lead to the possibility of fishery control rules). There may need to be debate on how best to implement or use Bmsy as a limit reference point off the east Queensland coast. The implications of how it is used should be made clear to the managers as should how one might react to the limit reference point being breached (if one does nothing it can hardly be called a limit reference point—which is why they have to be designed carefully and defensibly).

Yours sincerely

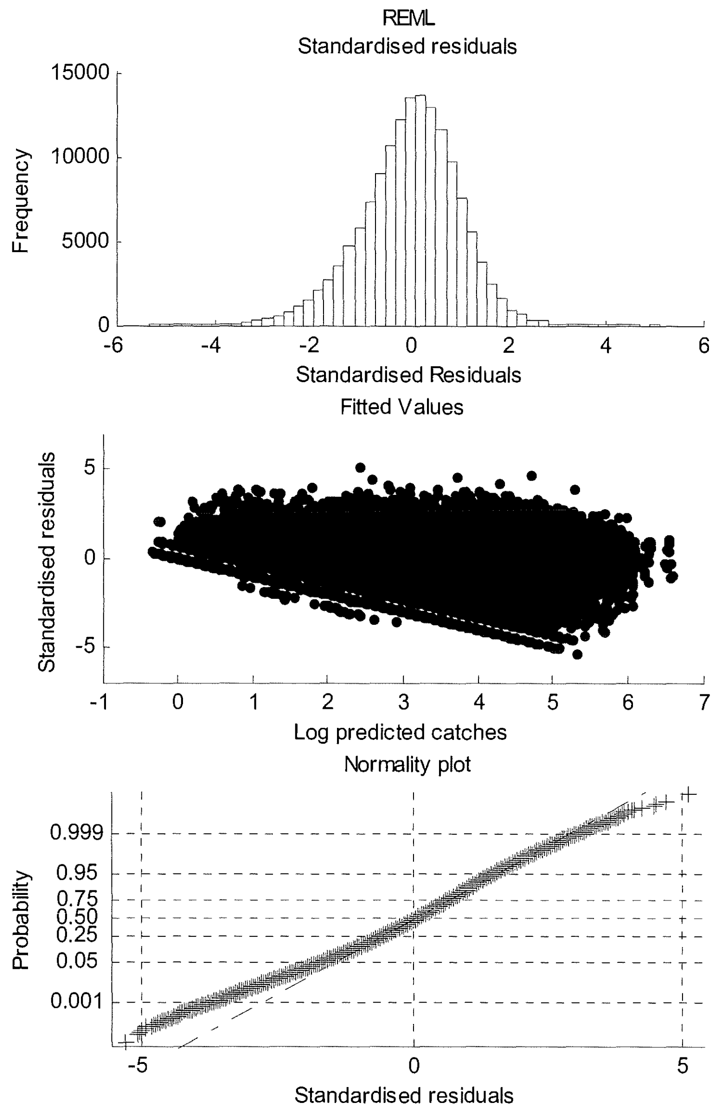


Malcolm Haddon
Resource Modeller
Tasmanian Aquaculture and Fisheries Institute.

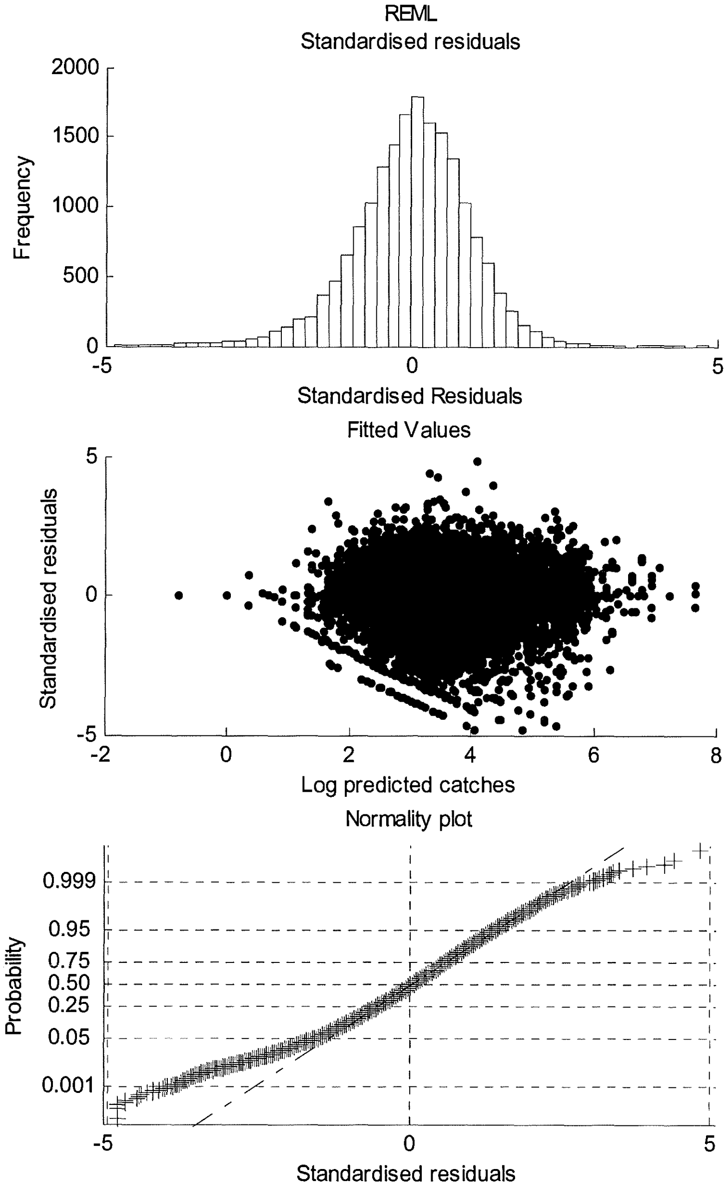
APPENDIX 2: 30' × 30' grids included to calculate total banana prawn catches in each sub-stock area. Note that the banana prawn catches in the Cooktown area were included as catches in the Cairns area, because there was no standardised catch rate available in the Cooktown area.



APPENDIX 3: Residual plot of REML analysis (Flow Model) for CFISH logbook data (1988–2004)



APPENDIX 4: Residual plot of REML analysis for historical trawl data (1968–1987)



APPENDIX 5: Results of logistic regression to estimate proportion of otter trawling

Regression analysis

Response variate:	otter
Binomial totals:	total
Distribution:	Binomial
Link function:	Logit
Fitted terms:	Constant + area + area.month + year.area

Summary of analysis

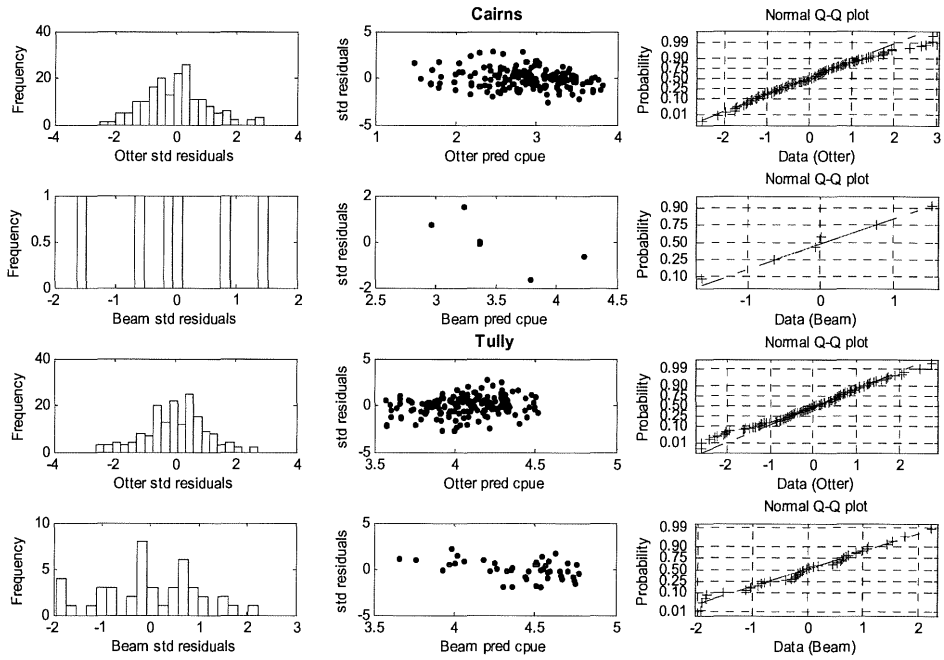
Source	d.f.	deviance	mean deviance	deviance ratio	approx chi pr
Regression	103	1685153.	16360.7	16360.71	<.001
Residual	760	724544.	953.3		
Total	863	2409697.	2792.2		

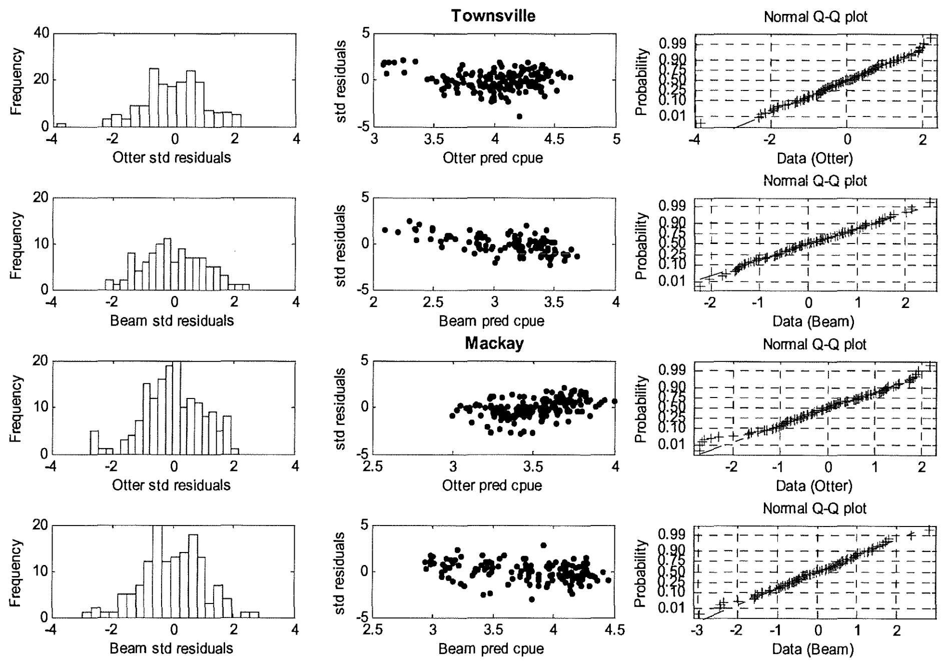
Estimates of parameters

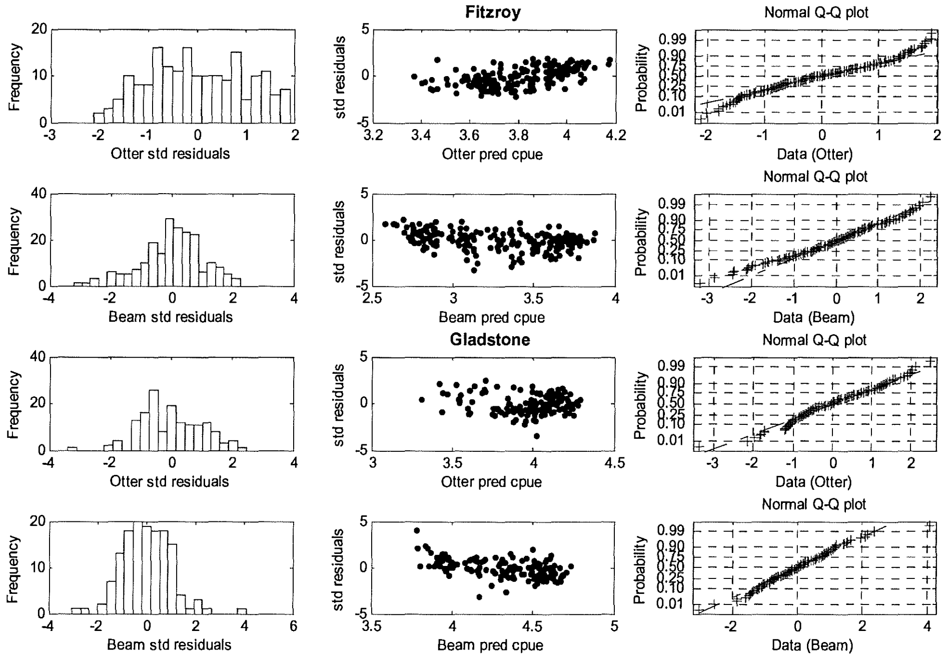
Parameter	estimate	s.e.	t(*)	t pr.	antilog of estimate
Constant	-1.08	1.83	-0.59	0.555	0.3395
area Cairns	-19.18	3.61	-5.31	<.001	4.673E-09
area Fitzroy	71.29	2.57	27.74	<.001	*
area Gladstone	308.28	4.67	65.99	<.001	*
area Mackay	260.59	3.24	80.33	<.001	*
area Moreton	162.09	2.76	58.69	<.001	*
area Townsville	194.81	2.91	66.89	<.001	*
area Tully	-40.28	4.79	-8.41	<.001	*
area Burnett .month 2	0.6475	0.0120	53.87	<.001	1.911
area Burnett .month 3	1.3205	0.0111	119.29	<.001	3.745
area Burnett .month 4	1.5740	0.0110	142.80	<.001	4.826
area Burnett .month 5	1.3772	0.0114	121.24	<.001	3.964
area Burnett .month 6	0.5803	0.0127	45.80	<.001	1.787
area Burnett .month 7	-0.5484	0.0155	-35.42	<.001	0.5779
area Burnett .month 8	-0.1532	0.0178	-8.60	<.001	0.8580
area Burnett .month 9	0.4239	0.0221	19.21	<.001	1.528
area Burnett .month 10	0.6002	0.0178	33.68	<.001	1.822
area Burnett .month 11	0.2149	0.0216	9.96	<.001	1.240
area Burnett .month 12	-0.9019	0.0200	-45.06	<.001	0.4058
area Cairns .month 2	0.1811	0.0457	3.96	<.001	1.199
area Cairns .month 3	-0.0946	0.0382	-2.48	0.013	0.9098
area Cairns .month 4	-0.5215	0.0374	-13.96	<.001	0.5936
area Cairns .month 5	-0.5786	0.0372	-15.55	<.001	0.5607
area Cairns .month 6	-0.4209	0.0379	-11.10	<.001	0.6565
area Cairns .month 7	-0.8582	0.0387	-22.16	<.001	0.4239
area Cairns .month 8	-1.3158	0.0417	-31.52	<.001	0.2683
area Cairns .month 9	-0.8387	0.0413	-20.31	<.001	0.4323
area Cairns .month 10	-1.1635	0.0422	-27.59	<.001	0.3124
area Cairns .month 11	-1.4969	0.0474	-31.55	<.001	0.2238
area Cairns .month 12	-0.7714	0.0929	-8.30	<.001	0.4624
area Fitzroy .month 2	0.6932	0.0142	48.91	<.001	2.000
area Fitzroy .month 3	0.5178	0.0129	40.08	<.001	1.678
area Fitzroy .month 4	0.2417	0.0128	18.90	<.001	1.273
area Fitzroy .month 5	-0.6767	0.0131	-51.69	<.001	0.5083
area Fitzroy .month 6	-1.2331	0.0140	-87.81	<.001	0.2914
area Fitzroy .month 7	-2.4123	0.0179	-134.78	<.001	0.08961
area Fitzroy .month 8	-2.2619	0.0198	-114.49	<.001	0.1042
area Fitzroy .month 9	-2.4563	0.0225	-109.10	<.001	0.08575
area Fitzroy .month 10	-2.7119	0.0248	-109.39	<.001	0.06641
area Fitzroy .month 11	-1.8123	0.0213	-85.23	<.001	0.1633
area Fitzroy .month 12	-0.7506	0.0241	-31.16	<.001	0.4721
area Gladstone .month 2	0.9329	0.0182	51.19	<.001	2.542
area Gladstone .month 3	1.3236	0.0168	78.93	<.001	3.757
area Gladstone .month 4	1.7497	0.0185	94.34	<.001	5.753
area Gladstone .month 5	0.7208	0.0229	31.47	<.001	2.056
area Gladstone .month 6	1.2817	0.0520	24.62	<.001	3.603
area Gladstone .month 7	1.5934	0.0836	19.06	<.001	4.921

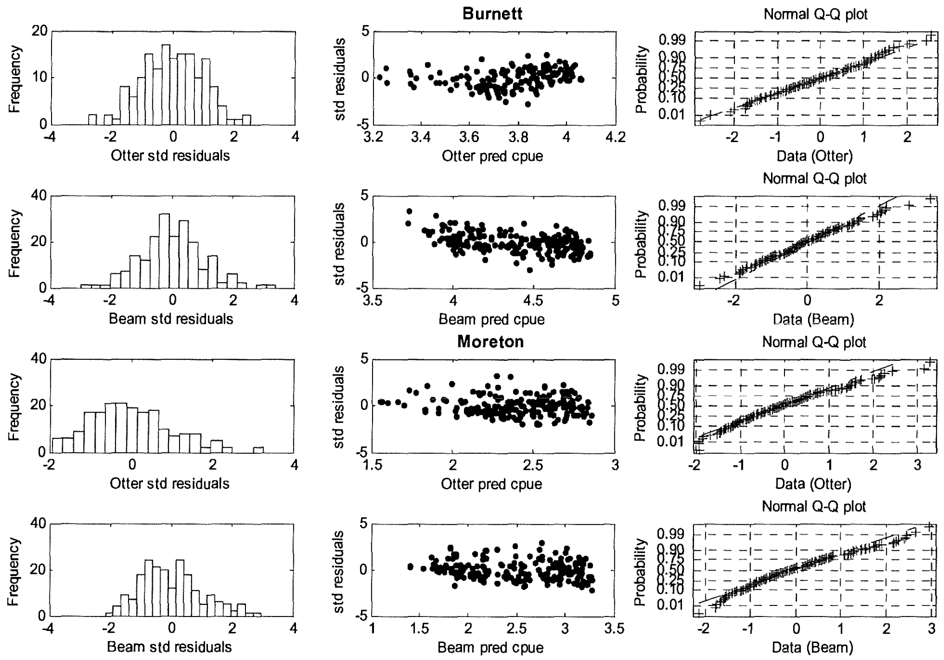
area Gladstone .month 8	-0.4467	0.0541	-8.26	<.001	0.6397
area Gladstone .month 9	-2.2072	0.0938	-23.52	<.001	0.1100
area Gladstone .month 10	-2.3887	0.0620	-38.52	<.001	0.09175
area Gladstone .month 11	-0.5629	0.0454	-12.41	<.001	0.5695
area Gladstone .month 12	-0.2156	0.0372	-5.79	<.001	0.8060
area Mackay .month 2	0.8332	0.0161	51.80	<.001	2.301
area Mackay .month 3	0.5786	0.0143	40.51	<.001	1.783
area Mackay .month 4	0.4078	0.0147	27.70	<.001	1.504
area Mackay .month 5	0.4331	0.0155	28.01	<.001	1.542
area Mackay .month 6	0.7192	0.0204	35.24	<.001	2.053
area Mackay .month 7	0.0772	0.0239	3.23	0.001	1.080
area Mackay .month 8	-0.8445	0.0316	-26.73	<.001	0.4298
area Mackay .month 9	-1.9320	0.0397	-48.65	<.001	0.1449
area Mackay .month 10	-0.8422	0.0393	-21.42	<.001	0.4307
area Mackay .month 11	-0.8702	0.0279	-31.23	<.001	0.4189
area Mackay .month 12	-0.4836	0.0236	-20.47	<.001	0.6165
area Moreton .month 2	-0.0012	0.0275	-0.05	0.964	0.9988
area Moreton .month 3	0.0074	0.0222	0.33	0.738	1.007
area Moreton .month 4	1.0428	0.0203	51.44	<.001	2.837
area Moreton .month 5	1.5323	0.0203	75.39	<.001	4.629
area Moreton .month 6	1.4690	0.0207	70.81	<.001	4.345
area Moreton .month 7	0.0603	0.0240	2.51	0.012	1.062
area Moreton .month 8	-1.3119	0.0361	-36.32	<.001	0.2693
area Moreton .month 9	0.5996	0.0308	19.46	<.001	1.821
area Moreton .month 10	-0.0692	0.0328	-2.11	0.035	0.9331
area Moreton .month 11	0.1137	0.0322	3.53	<.001	1.120
area Moreton .month 12	0.0263	0.0323	0.82	0.415	1.027
area Townsville .month 2	0.6677	0.0118	56.75	<.001	1.950
area Townsville .month 3	1.2652	0.0108	117.18	<.001	3.544
area Townsville .month 4	1.4044	0.0113	123.96	<.001	4.073
area Townsville .month 5	1.2822	0.0124	103.73	<.001	3.604
area Townsville .month 6	1.4316	0.0154	92.83	<.001	4.185
area Townsville .month 7	1.2074	0.0218	55.31	<.001	3.345
area Townsville .month 8	1.5439	0.0283	54.50	<.001	4.683
area Townsville .month 9	1.6375	0.0381	42.93	<.001	5.142
area Townsville .month 10	1.1304	0.0399	28.30	<.001	3.097
area Townsville .month 11	1.4004	0.0541	25.89	<.001	4.057
area Townsville .month 12	-3.2276	0.0470	-68.74	<.001	0.03965
area Tully .month 2	0.1611	0.0444	3.63	<.001	1.175
area Tully .month 3	0.1030	0.0382	2.69	0.007	1.108
area Tully .month 4	0.1513	0.0385	3.93	<.001	1.163
area Tully .month 5	0.3440	0.0385	8.94	<.001	1.411
area Tully .month 6	-0.4426	0.0388	-11.40	<.001	0.6423
area Tully .month 7	-0.2195	0.0426	-5.15	<.001	0.8029
area Tully .month 8	0.5587	0.0476	11.75	<.001	1.748
area Tully .month 9	0.4402	0.0606	7.27	<.001	1.553
area Tully .month 10	0.2377	0.0799	2.97	0.003	1.268
area Tully .month 11	-1.693	0.107	-15.78	<.001	0.1839
area Tully .month 12	0.1692	0.0733	2.31	0.021	1.184
year.area Burnett	0.000047	0.000918	0.05	0.959	1.000
year.area Cairns	0.01112	0.00156	7.12	<.001	1.011
year.area Fitzroy	-0.034682	0.000906	-38.27	<.001	0.9659
year.area Gladstone	-0.15364	0.00216	-71.20	<.001	0.8576
year.area Mackay	-0.12961	0.00134	-96.39	<.001	0.8784
year.area Moreton	-0.08169	0.00104	-78.56	<.001	0.9216
year.area Townsville	-0.09665	0.00114	-84.93	<.001	0.9079
year.area Tully	0.02186	0.00222	9.83	<.001	1.022

APPENDIX 6: Residual plots of monthly age-structured models (Model D)






Fitzroy
Gladstone
Normal Q-Q plot
Frequency
std residuals
Probability
Otter std residuals
Otter pred cpue
Data (Otter)
Beam std residuals
Beam pred cpue
Data (Beam)


Burnett
Moreton
Normal Q-Q plot
Frequency
std residuals
Probability
Otter std residuals
Otter pred cpue
Data (Otter)
Beam std residuals
Beam pred cpue
Data (Beam)