# Recruitment Processes in Commercially Important Prawn Species

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# Causes of declines in stocks of commercially important prawns in the Northern Prawn Fishery

**Final Report to the Fisheries Research & Development Corporation (FRDC Project 85/85 & 89/13)**

CSIRO

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**Division of Fisheries**

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CSIRO Division of Fisheries

Cleveland Marine Laboratories


## Final Report: FRDC 85/85 & 89/13

# Contents

# 1. SUMMARY

The following report is a description of the two FIRTA projects (85/85 & 89/13) which examined recruitment processes in penaeids at Albatross Bay in the northeastern Gulf of Carpentaria over the years 1985 to 1992. The aim of the first of the two projects was to identify the main factors which control the recruitment of prawns, while the aim of the second project was to build on the results on the first to provide managers with explanations for declines in commercial catches that had been experienced in the fishery.

The work was focused in three main areas: measuring year-to-year variation in numbers of the main life history stages (eggs, larvae, juveniles and adults in the Albatross Bay region) and correlating the abundances with changes in the environment; measuring the year-to-year variation in the extent of predation by fish on juvenile and adult prawns; and examining relationships between commercial fishery catches throughout the Northern Prawn Fishery and meteorological data.

The results of the projects have enabled us to better define the life history dynamics of the banana prawn *Penaeus merguiensis* and, to a lesser extent, the grooved tiger prawn *Penaeus semisulcatus*. Life cycles of both species were found to be based on two cohorts per year. Comparison with *P. merguiensis* life cycles throughout the Indo-West Pacific region has shown that two cohorts per year was the common pattern, and that the relative contribution to offshore commercial fisheries of each cohort in the various regions was governed to a large extent by the local pattern of rainfall. In the case of *P. merguiensis* in Albatross Bay, differential mortality results in only one of these cohorts contributing significantly to the commercial fishery.

Like *P. merguiensis*, two cohorts per year was also found to be the more typical recruitment pattern for *P. semisulcatus* in Albatross Bay. However, unlike *P. merguiensis*, both cohorts may contribute to the annual commercial fishery, though the respective contributions may fluctuate from year to year.

For banana prawns, the population models developed in the south-eastern Gulf have now been fine-tuned for the north-eastern Gulf environment and we have been able to explain, and even predict, the interannual variation in banana prawn commercial catches to a reasonable degree. However, the work on *P. semisulcatus* has not yet progressed to the stage where we can unequivocally separate the environmental and fishery-induced effects on recruitment. Nevertheless, the advances made during these two projects have enabled us to contribute significantly to management of the fishery at a time of major structural change within the fishing industry. In particular, our estimates of average long-term sustainable yields have been very important in the fleet-rationalisation process, while our understanding of life-cycle timing and migration patterns was critical in setting seasonal closures to optimise size composition of the catch.

## 2. HISTORICAL PERSPECTIVE

CSIRO began intensive multidisciplinary prawn research in northern Australia in 1975. The period 1975-1980 was directed towards banana prawns and the results of that work received world-wide recognition (Garcia 1988, Gulland and Rothschild 1984)). The tide and current analysis produced models and data of the physical circulation and showed how prawn larvae are transported by currents (Rothlisberg *et al.* 1983). This research was combined with that on adults to show that larvae from the heavily fished population in March-May were not major contributors to the stocks of prawns in the following year. Research on juvenile prawns enabled catches to be predicted in the southeastern Gulf based on rainfall (Vance *et al.* 1985). Quantitative prediction has rarely been achieved in any fishery and never previously for penaeid prawns. Results from banana prawn stock assessment were used to develop a yield-per-recruit model and this in turn was used to advise seasonal fishing patterns to maximise the value to the catch. (Lucas *et al.* 1979)

By 1980, tiger prawns had become a major component of the catch, and research switched to them. A serious problem that made analysis of commercial fishery data difficult, was that the two species of tiger prawns were not distinguished by the industry. A one year pilot project was carried out in 1980-81 (FIRTA and NTFIRDT), to estimate population parameters (growth, migration, mortality) for tiger prawns in the western Gulf of Carpentaria. Tagging showed that the two species separated as they migrated offshore suggesting that they inhabited different areas, and emphasising that detailed knowledge of each species is essential for proper management of the fishery (Somers and Kirkwood 1984). This work was successful in providing useful growth information for the two species of tiger prawn (Kirkwood and Somers 1984) but was unsuccessful in obtaining reliable estimates of mortality rates because of inherent problems of tag-induced mortality. In addition to this, a complimentary study (FIRTA 1981/14) was set up in 1981-82 in the north-eastern Gulf to establish what areas are used as nursery grounds and seagrass beds were found to be a critical habitat for both species (Staples *et al.* 1985).

Information from these two pilot studies was used to design a major study of the two tiger prawn species in the western Gulf of Carpentaria (FIRTA 82/13). Amongst the achievements of this extremely successful program was the mapping of seagrass beds in the entire western and southwestern Gulf, enabling the various government agencies to protect these areas by closing them to trawling (Poiner *et al.* 1987). The distribution of the adults of the two species of tiger prawns were successfully separated on the basis of substrate and depth preferences (Somers 1987) and this has enabled CSIRO to apportion the two species in the Western Gulf in 20 years of commercial logbook data. Growth data were refined and spawning periods were described for each species (Crocos 1987a 1987b). Based on the 18 months of sampling, a simple life history model was constructed with associated stock-recruitment curves (Somers 1990b). Based on the above information, CSIRO was able to provide advice on the best ways of reducing effort in the tiger prawn fishery when in 1986, the industry faced decreasing catch rates and total landings.

However, two of the shortcomings of the western Gulf of Carpentaria study were the lack of (i) complete information of all life history stages and (ii) information on year-to-year variation in life history dynamics. To overcome these shortcomings, CSIRO with FIRTA assistance (FIRTA 85/85), started a study of recruitment processes in penaeids at Albatross Bay in the northeastern Gulf of Carpentaria in 1985. The primary objective of this study was to identify the main factors which control the recruitment, and hence the abundance of prawns in the commercial fisheries of the north-eastern Gulf of Carpentaria. The effects due to both natural and man-induced changes were to be examined. The study concentrated on banana prawns, brown and grooved tiger prawns.

- To identify the main causes of mortality and the factors which significantly affect growth of each of the major stages in the life history of prawns (larvae, postlarvae, juvenile, pre-adult and spawning stages).

- Establish a long-term sampling program of juvenile and adolescent prawns to determine the extent to which the above factors and stages may limit the fishable stock

- To develop quantitative models of recruitment in the three major commercially important species and describe the form of stock-recruitment relationships in each species.

Building on the results of this three-year study, the north-eastern Gulf research program was revised and continued in 1989 (FIRDC 1989/13), focussing on possible reasons behind a decline in commercial catches. The primary objective of the new project was to provide managers with models to explain declines in commercial catches of prawns in the Northern Prawn Fishery (NPF). This was to be achieved by modelling the relative influences of environmental changes (climate and predation) as well as fishing pressure on the recruitment of prawns throughout the NPF. Specific objectives were:

- To measure year-to-year variation in numbers of the main life history stages in Albatross Bay region (eggs, larvae, juveniles and adults) and to examine how their abundance is affected by changes in the environment (e.g. temperature, rainfall, food, water movement).

- To measure the year-to-year variation in the extent of predation by fish on juvenile and adult prawns.

- To estimate recruitment to the commercial fishery using existing commercial catch data and to examine how this correlates with fishing effort and environmental factors.

These studies allowed for the first time, the simultaneous examination of spawning stock, larvae, postlarvae, juveniles and recruits to the subsequent fished stock. No one else in the world has ever attempted such an ambitious undertaking for penaeid prawns. Australia, FIRDC and CSIRO have been widely applauded for the approach they have taken and the information they have gained.

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# 3. DESCRIPTION OF THE PROJECT

The field component of the project was located in the Gulf of Carpentaria, with the detailed work on recruitment of the various life history stages being carried out in Albatross Bay in the north-eastern Gulf (Fig. 1). The project was split into several components based on the sampling methods and/or life history stage: (a) Offshore sampling of adult and larval prawns in Albatross Bay (b) Inshore sampling of juvenile prawns in the Embley River and Groote Eylandt nursery grounds (c) sampling of predators of prawns in the Gulf of Carpentaria in the Embley River estuary, the Norman River estuary, the inshore waters of Groote Eylandt, and the offshore waters of Albatross Bay and (d) a logbook study of recruitment to the commercial fishery in the Gulf.

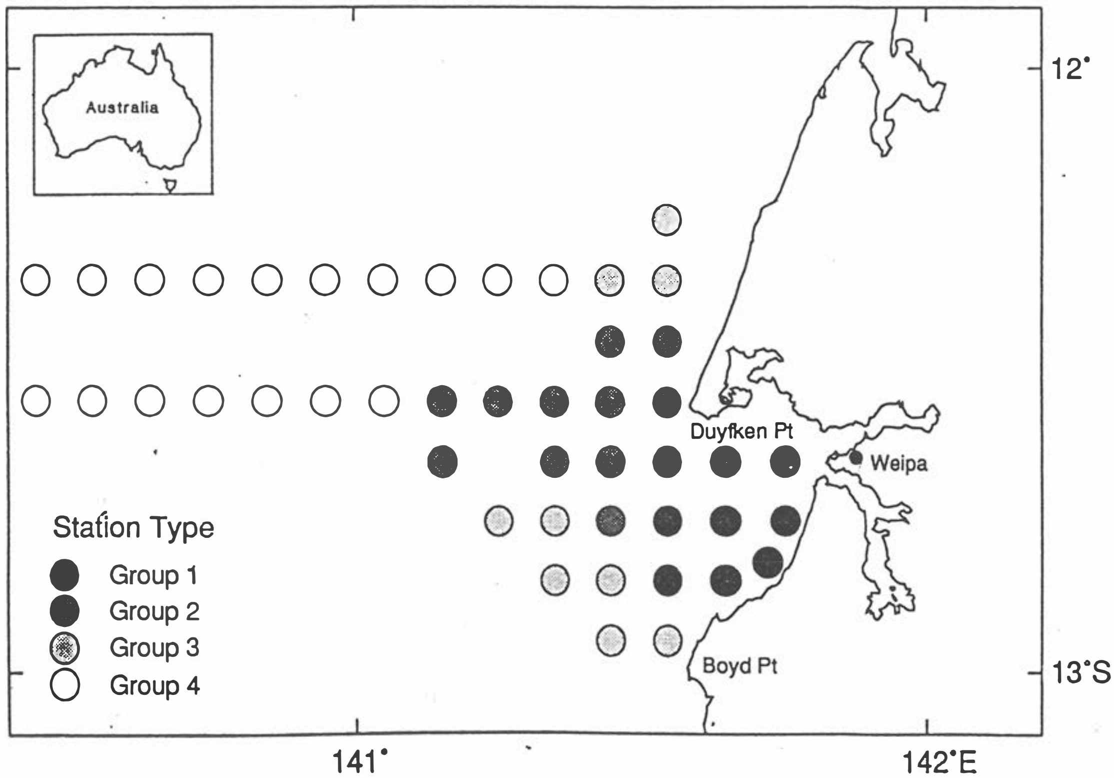


Fig 1. Albatross Bay study area showing station locations and station type relevant to sampling stratification. See text for explanation of groups.

### (a) Offshore sampling of adult and larval prawns - Albatross Bay

Adults and larvae were sampled on a lunar monthly basis at selected stations on a six nautical mile grid pattern in Albatross Bay (Fig.1), using a chartered commercial prawn trawler. The study area bounds were initially chosen in relation to the known distribution of penaeids in the region, based on commercial fishery log-book data. Sampling cruises were typically of 3 to 5 nights duration and were centred on the date of the new moon.

During the first phase of the project, March 1986 to December 1987, all stations in Groups 1, 2 and 3 were sampled each lunar month, with trawl sampling carried out at each station and larval sampling carried out at alternate stations. For the second phase, between January 1988 and April 1992, the sampling regime was changed to concentrate on critical periods for the offshore stages of the life history, so sampling was restricted to the months from August through to to April in each year. Sampling intensity was also increased on shallow-water stations (Group 1) in Albatross Bay to increase the sampling effort on the banana prawn spawning and recruitment phases. Throughout this 3.5 year period, the Group 1 stations were sampled 3 times (on separate nights) on each lunar monthly cruise between August and December, and were sampled twice on cruises between January and April. Both trawl sampling and larval sampling were carried out at every station. For the same period, the Group 2 stations were sampled once on each cruise, with trawl sampling at every station and larval sampling at alternate stations. The Group 4 stations were sampled on four cruises (May, July and November 1987, and February 1990), to examine the offshore seasonal distribution of *P. semisulcatus*.

Trawls for adults were typically of 15 minutes duration using four 5 fm (headrope length) nets towed at 3.2 knots. All trawls were carried out in the hours of darkness. Abundance (CPUE, standardised to number caught per 60 net-minutes), size composition data and reproductive parameters were recorded for each species. In the laboratory, ovarian tissue samples were taken from adult females to provide a histological description of maturity. The description of spawning seasonality and spawning location was based on a calculated index of population fecundity (Crocos and Kerr 1983, Crocos 1987).

Larvae were sampled with a stepped oblique tow of 5 to 9 minutes duration using a single net with a 0.25 $m^2$ mouth area. A 142 μm mesh net was used from March 1986 to February 1988 and a 250 μm mesh net used from March 1988 to April 1990. Plankton samples were quantitatively split and fractions sorted, then penaeid larvae were identified to species using numerical taxonomic techniques developed by Rothlisberg *et al.* (1983,1985). Throughout the sampling program salinity and temperature profiles were measured at approximately 2 m depth intervals at all larval sampling stations using a submersible data logger (CSIRO/Yeokal SDL).

Seasonal and interannual variation in primary and bacterial production were measured on nine of the cruises between 1989 and 1992. Gulf-wide measurements were taken in the summer of 1988 on board R.V. Franklin.

### (b) Juvenile prawn sampling

Sampling for banana and tiger prawns was carried out every 2 weeks, centred around the spring tides, between September 1986 and March 1990. After that, sampling was not done during the winter months, but we sampled every 2 weeks from September to March and once a month from April to May for the last 2 years of the project. One CSIRO employee lived at Weipa while sampling was being carried out and he was assisted with sampling by local contractors and CSIRO staff who flew from Cleveland once a month.

*Banana prawns*

All sampling for resident juvenile banana prawns was carried out on mangrove-lined sloping mud banks as previous work had shown that juvenile banana prawns were most abundant in these areas (Staples et al. 1985). In earlier projects, banana prawns had been sampled only in the main river systems but in this project we also wanted to assess the importance of smaller creeks so we sampled at 1 site in the main river and 3 sites in a nearby creek. Prawns were sampled at all sites using a small 1.0 by 0.5 m beam trawl fitted with a 2 mm mesh net and 1 mm codend. At the main river site, a larger 2.0 by 1.0 m beam trawl with 28 mm mesh and 12 mm codend was also used to check that the smaller net was catching the full size range of prawns present in the river. Trawls were made on the last third of ebb tides during the day or night as we had earlier shown that the largest catches were taken around this time (Staples and Vance 1979, Vance and Staples 1992). A trawl parallel and close to the water's edge in about 0.5 m of water was made at each site on the ebb tide within 2 h of low water; trawls in the river were 200 m long but trawls in the creek were reduced to 50 m. At each site 4 random trawls, each of 10 m length, were also made at right angles to the bank, from the water's edge towards the middle of the river or creek (as postlarvae tend to concentrate very close to the water's edge, their abundance is underestimated by parallel trawls. Catches from the parallel and perpendicular trawls were combined to give abundance estimates for each site. Prawns were measured to the nearest 0.1 mm carapace length.

Banana prawns emigrating from the Embley River were sampled using 2 set nets moored in the middle of the river near the main river trawl site: a 1.0 by 0.5 m frame with 2 mm mesh net and a 2.0 by 1.0 m frame with 28 mm mesh net with a 12 mm mesh codend cover. The nets were set each fortnight for 1 ebb tide.

*Tiger prawns*

For the first 3 years of the project, sampling was carried out at 1 site in the Embley River; an intertidal seagrass flat dominated by *Enhalus acoroides*, a large strap-like seagrass. Trawls were made with the same large and small nets which were used on the main river banana site, and were always made at night as close as possible to high tide.Trawls were made at right angles to the shore and were 200 m in length. For the last 3 years of the project we sampled a second seagrass site which was mostly small seagrasses, *Halodule* and *Halophila* species.

During the project we discovered that there was other subtidal vegetation in the Weipa rivers, transient algae and sparse small seagrasses which seemed to support low densities of tiger prawns but , nevertheless, made up a large area of habitat. For the last 2 years of the project we included another 2 algal and sparse seagrass sites in the regular tiger sampling program.

*Environmental data*

Salinity, temperature, turbidity, water depth, sea and weather conditions were recorded at the time of each sample. Other environmental data such as rainfall, wind speed and direction, barometric pressure and sea level variations were obtained from the Meteorological Bureau and the Port Authority. We tried to relate changes in abundance of the juvenile prawns to variations in the environmental variables.

In the last year of sampling, automatic logging systems were developed to measure changes in salinity, water temperature, rainfall and water depth over short time scales (15 minutes). The loggers were set up near the upstream banana sampling site in the small creek and on the seagrass bed where tiger prawn sampling was carried out. We aimed to get more information on the short-term environmental variations which might affect abundances of juvenile prawns in their nursery areas.

## (c) Predators of prawns

*Study areas*

This was undertaken in four areas: the Embley estuary, the Norman estuary, the inshore waters of Groote Eylandt, and the offshore waters of Albatross Bay.

*Embley estuary:* this estuary in the eastern Gulf of Carpentaria is almost entirely mangrove-lined. Extensive intertidal mudflats and areas of seagrass in shallow water are found on the south side of the lower reaches. Intertidal sandy mud beaches occur on the north side of the lower reaches and on both sides at the mouth. Open-water channels and small mangrove creeks occur throughout the estuary but are the only habitats in the middle and upper reaches. There is a maximum tidal range of about 2.6 m.

*Norman estuary:* In contrast to the Embley this south-east Gulf estuary has less diversity of habitats. The predominant habitat is open water channels. The banks are steep and hence the mud intertidal areas are small and largely restricted to the lower reaches. The extensive fringe of mangroves is everywhere narrow (< 20m wide).

*Groote Eylandt:* Sampling was undertaken at three localities: in sheltered Northwest Bay; in the less sheltered Bartalumba Bay and on the exposed west coast. Seagrasses were mapped using SCUBA as part of another study (CSIRO unpublished data). The community composition and structure of the seagrass varied considerably and sample sites were chosen to cover the following categories:

a) Tall, dense seagrass areas in depths between 1 and 3 m. In Northwest Bay and Bartalumba Bay these beds consisted mainly of *Cymodocea serrulata, Enhalus acoroides* and *Thalassia hemprichii.* In the subtidal zone of the west coast they consisted of *C. serrulata, C. rotunda, T. hemprichii* and *Syringodium isoetifolium.*

b) Tall, dense seagrass areas in depths less than 1 m. These beds were dominated by *C. serrulata* and *E. acoroides* and were all in Northwest Bay.

c) Short, sparse seagrass areas in depths between 1 and 4 m. These consisted mainly of *Halophila ovalis, Halodule uninervis* and *T. hemprichii*; all were in Northwest Bay.

d) Short, sparse seagrass in less than 1 m depth. These were dominated by *H. uninervis* and *H. ovalis*, and sampled in the intertidal of sand beaches on the west coast and in Northwest Bay.

e) Intertidal areas of short, dense mixed-seagrass with patches of bare muddy substrate were sampled on the west coast. The seagrass was mainly *H. uninervis*.

f) Non-seagrass control sites were sampled (i) in deep water (4 - 7 m), (ii) at intermediate depth (1 - 4 m) and (iii) in shallow (<1 m) intertidal sandy-mud pools. The deeper control sites were located in Northwest Bay (4 - 7 m) and Bartalumba Bay (1 - 4 m), while the shallow control sites were sampled in both Bartalumba Bay and on the west coast. These control sites were chosen because they were adjacent to seagrass areas and similar to them in terms of substrate and depth.

*Albatross Bay:* This is a fully marine coastal embayment on western Cape York into which the Embley and Mission estuaries open. It has a gently shelving bottom of soft sandy mud that reaches a depth of 50 m at a distance of 72 km from the mouth of the Embley estuary. The shores consist mainly of sandy beaches with a few rocky outcrops. Salinity varies little with season except in the immediate vicinity of the estuary mouth.

*Fish sampling methods*

The equipment and sampling methods were similar for the Embley and Norman estuaries and at Groote Eylandt. Where differences occurred they are noted below. The different physical nature of the types of habitat made it necessary to sample each by different methods. The methods used were the most effective and those most likely to produce the least biased estimates of fish abundance for each habitat.

a) *Open-water:* Areas in the lower, middle and upper reaches of the estuaries and along the shores of Groote Eylandt with depths down to 5 m, were sampled with a fleet of 60 m monofilament gill nets of 50, 75, 100, 125 and 150 mm stretch mesh. Sampling was undertaken over all tides and day and night at each site. Seagrass areas with depths greater than 1 m and up to 7 m were also sampled both day and night with the same 330 m fleet of gill nets.

b) *Intertidal sandy mud beaches (with or without seagrass)* : these were fished with a 60 m x 2 m seine net of 25 mm stretch mesh fitted with a 25 mm cod-end. Netting took place at all stages of the tide.

In addition in the Embley estuary and at Groote Eylandt a stake net was used to isolate areas. An intertidal/subtidal area of about 11,000 $m^2$ adjacent to the shore and not more than 2 m deep, was enclosed by a stake net 260 m long and 2 m deep with 25 mm multifilament stretch mesh. All fish within the netted area were either collected at low tide or caught with gill nets.

c) *Shallow seagrass areas:*

(i) *in the lower reaches of the Embley estuary* : A 2 m x 1 m beam trawl with 28 mm stretch mesh fitted with a 12 mm mesh cod-end was towed at 5 km $h^{-1}$ through a seagrass area site in the lower Embley River estuary. The maximum depth was 2 m at high tide and hence trawling could only occur at high tide. Samples of smaller, cryptic species, were obtained from 20 $m^2$ areas of seagrass isolated with 2 mm mesh netting and treated with a piscicide (rotenone).

(ii) *at Groote Eylandt*:: Sites less than 1 m deep, adjacent to mangroves and in intertidal pools at low tide were enclosed with 2 mm mesh netting and all fish within the area killed with the piscicide rotenone. This method was used in tall dense seagrass, short dense seagrass and control sites.

d) *Small mangrove creeks and inlets (< 2 m deep) in the estuaries:* These were sampled by blocking the mouths with 2 mm mesh netting and collecting all fish after treating the water with rotenone. A Fyke net with a 1 $m^2$ mouth and 3 m long wings was also used in the mouth of a short, steep creek in the lower reaches of the Norman estuary.

*Albatross Bay*: All sampling took place using the chartered trawler "Jacqueline D". The bay was divided into 11 $km^2$ grids, from which a 26 grid sampling area was chosen. The grids were divided into four depth strata (7-10, 11-20, 21-30, >31 m).

Each cruise consisted of consecutive legs each of four stations. Stations from each of the four depth strata were sampled on each leg, with no station being sampled twice within the first four legs. The stations were trawled between 0700 h and 1730 h. A restricted randomised sampling scheme was used. To ensure that the stations could be sampled in a four day cruise, the legs were paired and the strata sampled in order of increasing distance from the coast on the first leg, and in the reverse order on the second leg, and so on. Limits were imposed on the steaming distance between stations (25 km = 2.35 grids) and on the total steaming distance of each leg (58 km = 5.35 grids). For each cruise a sampling plan was chosen at random from 17 computer-generated possible random station sequences. The probability of selecting a plan was weighted inversely with the frequency with which the grid points in it appeared in the plans. The weighting was approximate but was designed to give each grid point within a stratum, as close as possible to equal selection. Despite the restrictions on the randomisation, the scheme resulted in the sampling of the grids being as random as possible with regard to both position and time.

In addition to 97 daylight trawls, a total of 21 night (1900 - 0500 h) trawls were shot outside the random sequence when time permitted.

Fish were captured with a Frank and Bryce demersal wing trawl of the following dimensions: 26 m headrope and 32 m footrope fitted with chain. The stretched mesh of the wings was 225 mm, of the body 150 mm gradually reducing to 100 mm, and of the cod-end 50 mm. The net was rigged with 50 m bridles and otter boards. Tows were either of 15 or 30 min duration, timed from completion of warp out to commencement of hauling.

The weight of the entire catch from each trawl was recorded and all fish longer than about 500 mm were sorted, identified and weighed on board. A sub-sample of between 5.5% and 77% (dependent on the size of the catch) of the remainder was frozen for subsequent analysis. Where the total catch was less than about 75 kg it was frozen entire after the larger fish were removed.

The numbers and weights of each species in the sub-sample were determined in the laboratory. The numbers and weights of each species in the total sample were then calculated from the proportion the sub-sample represented of the catch, plus all the larger fish not included in the sub-sample.

The biomasses of the fishes were calculated from the wingspread of the net, the towing speed and catchability coefficients. The wingspread of the net at depths between 10 and 45 m was measured with surface buoys; it remained constant at 15.6 m (60% of headrope length). The net was towed at an estimated speed of 5.76 km $h^{-1}$ (3.2 knots), thus resulting in a swept area of 0.0225 $km^2$ for a 15 min tow.

The species caught in Albatross Bay were divided into three groups in terms of their catchability coefficients (q). For all small species q = 0.3, for larger species (> 225 mm) q = 0.47 and for very large, slow-moving species q = 1.0. The use of these three q factors is more realistic than the practice of incorporating a single q such as 0.5 (Pauly 1983) or 1.0 (Gulland 1979)(see May and Blaber 1989). The coefficients used in this study were derived from formulae obtained from experiments with a Frank and Bryce trawl on the North West Shelf of

Australia (K.J. Sainsbury pers.comm. and in prep.). These indicate that the majority of small species (< 225 mm) have a q of 0.3 (0.47 entering net, of which 0.64 are retained by the meshes; hence 0.3). For larger species, such as *Caranx bucculentus*, we have assumed minimal escapement through the meshes and hence a q of 0.47. The initial reduction from 1.0 to 0.47 is caused by fish moving out of the path of the trawl. However, for very large and relatively slow species, such as Dasyatidae and Pristidae, we have assumed minimal avoidance and retained a q of 1.0.

*Sampling dates*

*Embley estuary*: Sampling was undertaken over three-week periods in October/November 1986 (pre-wet season), February 1987 (wet season), August 1987 (dry season), November 1987 (pre-wet season), February 1988 (wet season) and July 1988 (dry season). Due to extreme flood conditions no sampling was undertaken in the upper reaches in February 1987.

*Norman Estuary*: Sampling was undertaken in April (wet season), July (dry season), October (pre-wet season) 1991 and in February 1992.

*Groote Eylandt:* Sampling was undertaken over eight three-week periods in January, May, August and December 1989 and February, May, August and October/November 1990.

*Albatross Bay:* Seven sampling cruises took place over five day periods in August and October 1986, March, August and November 1987, and February and November 1988.

*Diet analyses*

In the first year of sampling at each site stomachs from all predators likely to be feeding on penaeid prawns were taken for analysis, but in the second year, only known penaeid predators were sampled. All fish were weighed and measured (standard length (SL) for teleosts, total length (TL) for sharks and disc width for rays) and the stomachs preserved in 4% formaldehyde or frozen.

Stomach contents were analysed mainly by the gravimetric method of Hyslop (1980). In addition the frequency of occurrence of prey categories was measured by Hyslop's (1980) method.

All penaeid prey were identified to species (where possible) and their size measured as carapace length. Adult commercially important penaeid species are larger than 150 mm total length (about 30 mm carapace length), whereas commercially unimportant species are all less than 120 mm T.L. (about 23 mm C.L.)(Grey et al., 1983). The juveniles of commercially important species occur only in the estuaries and not in Albatross Bay. However, sub-adult commercially important penaeids (<150 mm) are found in Albatross Bay at certain times of the year.

Prey from the stomach contents were categorised as benthic, bentho-pelagic or pelagic, with a various category for prey that belonged in more than one category. This provided information on the feeding behaviour of the penaeid-eating fishes.

*Measuring predation impact*

An index of predation impact was measured as the weight of penaeids taken by each species per hectare per day, and can be calculated as the product of (i) the abundance of each fish species (kg $ha^{-1}$) (ii) weight of food eaten per day, calculated as a proportion of the predator body weight and (iii) the proportion of penaeid prey in the diet of a fish species. The lack of information on meal size and consumption rates of tropical fishes has led us to assume a constant daily food ration of 3% of total body weight. This figure is consistent with temperate studies and is probably an underestimate for tropical fish species. Work on consumption rates was initiated and is still continuing.

## Recruitment of adults to the commercial fishery

To carry out an analysis of recruitment to the commercial fishery in relation to environmental variables, it was necessary to first refine the fishermen's logbook data to individual species. Catch per unit effort (CPUE) for each species in each year (January to December) was then statistically analysed in relation to meteorological data (temperature, rainfall, wind speed and direction) for corresponding biological years (July to June). The rationale for the chosen time frames was that any environmental events that might determine year class strength would most likely take place in the period before recruitment to the fishery.

*Species composition data*

Species composition data from research sampling were available from three surveys conducted in different parts of the Gulf at different times. Between them, these data covered the north-western and most of the eastern Gulf at various times between 1976 and 1992.

Three additional data sets were available as a result of sampling of commercial catches in the Gulf of Carpentaria. The first of these was collected by officers from the Northern Territory Fisheries Division in the western Gulf in 1979 as an aid in planning a biological research program in the early 1980s. The second set was made available by a commercial fishing company, Newfishing Australia Pty Ltd., which employed quality-control officers on board some of its vessels. These officers, who were able to identify the various species, monitored the composition of catches regularly. The third set of data came from a joint CSIRO/industry catch-sampling program conducted from 1988 through 1990, for which 31 fishermen were trained in techniques of species identification and random sampling of catches (Somers and Taylor 1990). All trainees were tested before taking part in the data collection program. During the fishing season, these fishermen would analyse and record the species composition of samples of their own catches. Market sampling of product from the Gulf was considered but not adopted, because there is usually some preliminary sorting of product at sea, and because it is difficult to trace the origin of the catch.

For each datum used in the amalgamation, there is a record of its source location (with a precision within 3 nautical miles), date, and number of each species in the sample. These data were collated to six-nautical-mile grid squares to integrate with commercial fishery logbook data, which give the catch in species groups.

*Commercial catch and effort data*

The main source of catch and effort data for the Gulf fishery is the Australian Fisheries Management Authority's program of processors' landings returns and fishermen's logbooks, which cover the whole Northern Prawn Fishery and the Kimberley region of north-western Australia (Somers and Taylor 1981). The landings returns provide estimates of annual catches by species group for the entire fishery, while the logbooks indicate the spatial and temporal distribution of the catch and effort for the fishery (Somers 1989). Logbook records give daily information on catches by species group, fishing ground and, sometimes, a more precise position (six-nautical-mile grid square) denoting the central location of catch for the day. Because logbooks only account for between 40 and 98% of annual catches, estimates of the annual landings by species group from the Gulf of Carpentaria were obtained by multiplying the total landings for the fishery by that fraction of the total logbook catch that was recorded within the Gulf.

*Species composition of commercial catches*

To convert commercial fishery data on catch by species group to catch by species, the logbook and species composition data sets were integrated at the level of six-nautical-mile grid squares. The procedure adopted to obtain estimates of annual catch by species was as follows:

(i) Calculate the annual landings by species group for the Gulf as outlined above.

(ii) For logbook data recorded with six-nautical-mile positions, convert the catch by species group to catch by species using the independent estimates of species composition for that location.

(iii) Accumulate the logbook catch by species and calculate the proportion of each species in each species group.

(iv) Calculate the annual landings by species for the Gulf by multiplying the species group landings from (i) above by the species proportions from (iii) above.

*Species distribution and abundance*

The spatial distribution and abundance of the species groups was assumed to be reflected in the distribution of logbook catch-per-unit-effort (CPUE; kg/day) in each of the six-nautical-mile grid squares. The distribution and abundance of individual species was obtained by integrating the logbook catch data for the species group with the species composition data for each grid. For the few grids where there were commercial catches but no species composition data, the latter were interpolated from adjacent grids.

*Climate data*

Information on rainfall, ambient temperature, wind speed and direction, and atmospheric pressure for the period January 1968 to December 1991 were obtained from the Australian Bureau of Meteorology for various coastal recording stations around the Gulf. Data were collated to monthly means. Rainfall data were in the form of daily totals; temperature and wind speed and direction were from recordings taken each day at 0900 and 1500 h. Mean wind speed and direction were obtained by using simple vector arithmetic to calculate net displacement per day; component wind vectors were calculated from the wind speed and the sine and cosine of the wind direction.

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# 4. RECRUITMENT PROCESSES & YEAR-TO-YEAR VARIATION

The six years data collected during the study have provided the linkages and relationships between the different life history stages. Estimates of the abundance of each stage show the extent of interannual variation in the life history dynamics. Most importantly, we have established that the earlier life history model, derived from the results of the western Gulf of Carpentaria study, over-simplified the real situation.

## Banana prawns (*Penaeus merguiensis*)

### (a) Life History Dynamics

*Life History Patterns and Linkages*

Mean monthly abundance data over 6 years for each of the life history stages (spawning index, larvae, benthic postlarvae, juveniles, emigrants, sub-adults and adults) shows distinct seasonality of abundance at each stage (Fig. 2).

Two seasonal cohorts are clearly apparent, one arising from the spring spawning (Aug-Nov) and one arising from the late summer-autumn (Jan-March) spawning. In both cohorts the modes can be traced clearly from one stage to the next. However only the spring cohort contributes to the subsequent adult stock. Differential survival between the two cohorts occurs principally at the transition between two life history stages (arrows, Fig. 2). In spring, spawners and larvae are in relatively low abundance, but benthic postlarvae in the estuary are much more abundant than would be expected from the spawner and larval abundance. The dominance of the spring cohort is apparent from this stage onwards, through to the commercially fished stock in April. The autumn cohort, derived from the very large number of eggs and larvae in February/March, is not the dominant postlarval or juvenile cohort. Further, these autumn cohort juveniles apparently do not leave the estuary in large numbers to become later recruits to the fishery.

Several explanations are possible for the differential survival of eggs, larvae and benthic postlarvae between the two cohorts. Physical changes such as temperature, or variation in the nutritional environment for spawning females or larvae, may result in differential larval survival. Seasonal changes in water circulation in Albatross Bay may affect the delivery of larvae and postlarvae to the estuary. As rainfall, salinity and temperature all vary seasonally, the suitability of the estuary as a habitat for postlarval survival and growth may differ between the two cohorts. The apparent lack of emigration by the autumn juvenile cohort to the offshore fishery is more easily understood; it is probably due to the low levels of rainfall and runoff at that time.

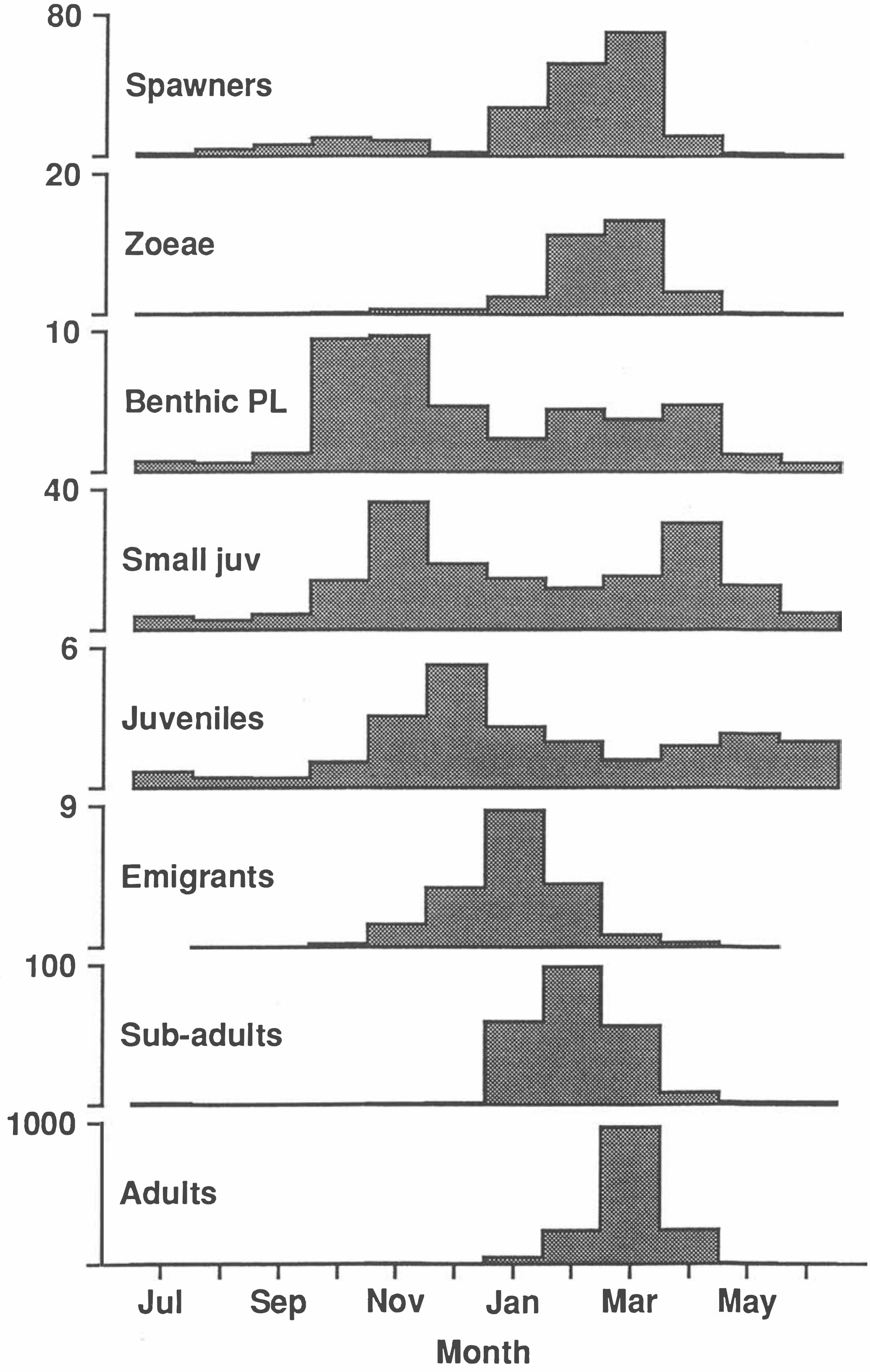



Figure 2. Monthly mean abundance of each life history stage for banana prawns *Penaeus merguiensis* over 6 years.

*Interannual variability in recruitment.*

Focussing on the spring cohort only, the 6 years of data on abundance of each of the life history stages show variability among years at each stage and also show that the relative abundance between one stage and the next is not always consistent; that is a mismatch (Fig. 3). Further, there are mismatches at different stages of the life history in different years. In three of the five years, the spawning index and larval abundance match, but in 2 years there is a major mismatch, in a different direction each year, suggesting different factors affecting survival in each year. In four of the five years, the abundance of benthic postlarvae reflects larval abundance, which suggests that the supply of larvae will determine benthic postlarval abundance. However, in 1987/88 larval abundance is below average and benthic postlarval abundance is above average, so factors other than supply will affect abundance of benthic postlarvae in some years. We have not identified a simple environmental relationship to explain these mismatches.

At the later life history stages, comparisons between benthic postlarvae and juveniles show matches in abundance in four of the five years; but in 1990/91 an above average abundance of benthic postlarvae was followed by below average juvenile numbers. Juvenile and subadult abundances match in four of the five years, with only a low-level mismatch for the 86/87 year. Again, subadult and adult (not shown) abundances follow the same pattern as juveniles and subadults.

*Levels of variability between stages.*

The variability observed in abundance patterns across the life history stages and between years indicates a very dynamic system responding to many environmental variables relating to survival at each stage.

Comparison of the maximum extent of variability above and below the 6 year mean for each life history stage indicates those life history stages which are most variable (Fig. 4). The trend is for greatest variability in the early life history stages (eggs and larvae), reduced variability in the estuarine juvenile phase, and increased variability in the emigrant, subadult and adult stages. The greatest variability is apparent in the number of emigrants, which for *P. merguiensis* is related to rainfall/salinity regimes associated with the wet season. Factors driving the variability of the early stages have not yet been identified.

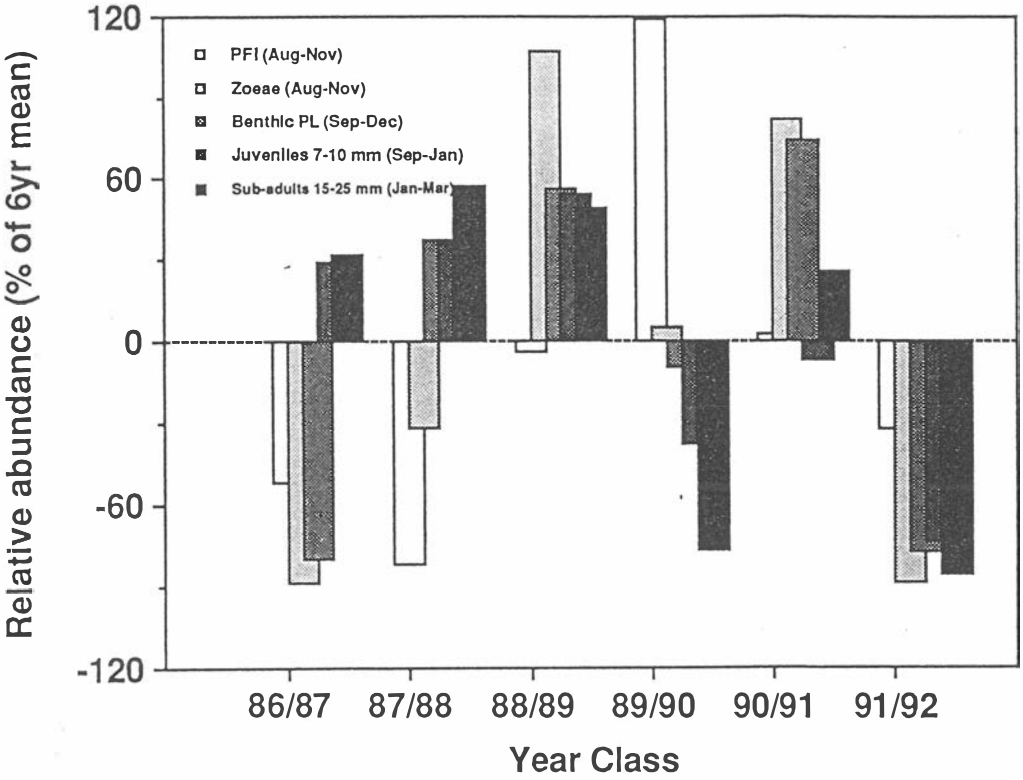



Figure 3. Abundance of banana prawn life history stages: Deviation from 6 year mean for each year class.

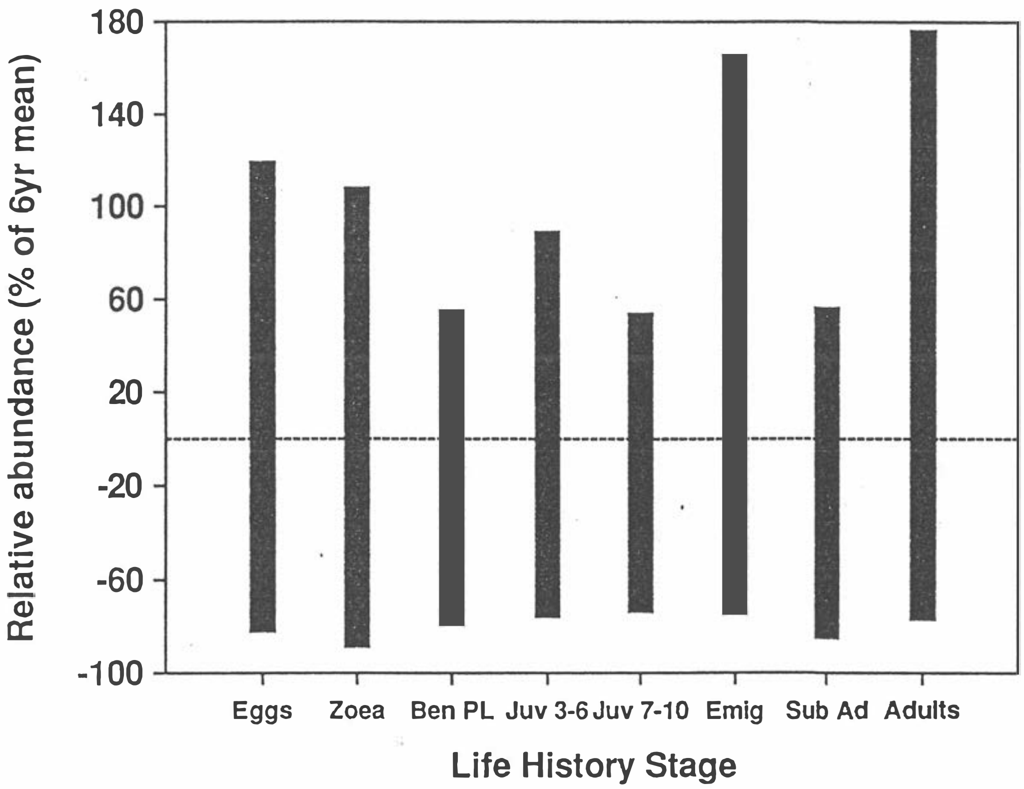



Figure 4. Maximum variability of each banana prawn life history stage over 6 years.

### (b) Ability to forecast catches

*History of prediction 1970 to 1990*

Since the inception of the Gulf of Carpentaria banana prawn fishery in the early 1970s there have been noticeable fluctuations in catches which mirrored fluctuations in rainfall. No event was more dramatic than the record high rainfall in 1974 (ca 2000 mm) and the attendant record catch (ca. 4000 t) in the southeastern Gulf (Fig. 5a). The very next year rainfall was about 800 mm and catches plummeted to about 800 t. Because of this sudden decline in a newly developed fishery, CSIRO began the Tropical Prawn Research Project to try and understand the factors that affected the fluctuations in population size. Working in the Norman River in the southeastern Gulf, we found a relationship between the amount of rainfall in the Norman River catchment and the number of adolescent banana prawns that emigrated and hence the size of the catch 1 to 3 months later. This led to a predictive model which forecasts catches for the southeastern Gulf (Karumba region), based simply on rainfall.

The model that was developed has a relatively good fit between catches in the southeastern Gulf and rainfall – 74% of the variation in catch can be explained by rainfall alone (Fig. 5a) and therefore, has a predictive capacity. However, in the northeastern Gulf (Weipa region) the predictions have never been good – only 4% of the variation in catch is explained by rainfall (Fig. 5b).

*Predictions for 1991 and 1992*

In 1991 very high rainfalls immediately following a record low catch in 1990, allowed us to test hypotheses about spawning stock and recruitment relationships – could the prawn stocks respond from a very low spawning biomass to very high environmental stimulus? Based on rainfall alone, we predicted a catch of 2000 t for the southeastern Gulf and the catch for the region was 2114 t (Fig. 5a). This indicates that the banana prawn recruitment to the fishery in the southeastern Gulf, over the range of spawning biomasses encountered, is largely determined by environmental factors – in this case affecting adolescent emigration. In 1992, annual rainfall dropped to well below average and the commercial catch was only about 420 t which was, in fact, higher than the predicted catch of 190 t.

In the Weipa region there is still no reliable predictive model based on a simple rainfall relationship (Fig. 5b). An assessment of the rainfall patterns and catchment areas suggests the rainfall impact in Weipa is less variable from year-to-year and therefore, is not as important in inter-annual variability in recruitment to the offshore prawn fishery. However, from the data collected over the 6 years of the Albatross recruitment study, we have made catch predictions for the first time; but based them on two biological parameters: numbers of emigrants leaving the estuary and subadults caught offshore prior to the opening of the season. This led to two predictions for 1991: 1100 t (based on emigrants) and 890 t (based on subadults) – the resultant catch was 1173 t, suggesting that model had good predictive value. In 1992, predicted catch was 815 t (based on emigrants) and 838 t (based on subadults) but the resultant catch was only 369 t. This lower than predicted catch highlights the need for caution when using models based on only a few years data which may not be entirely representative of the full range of natural variation in the environment and in prawn abundance.

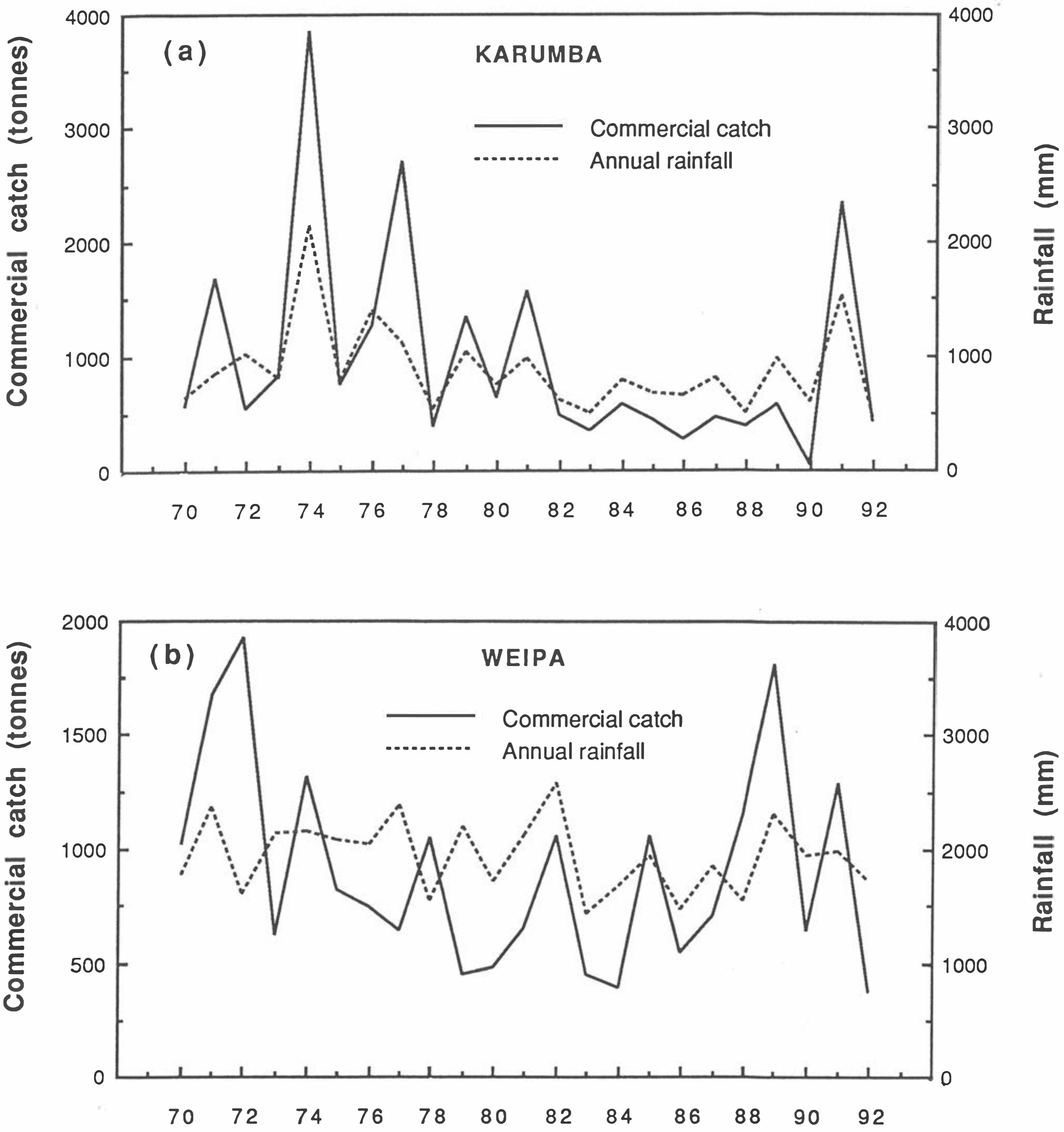



Figure 5. Commercial catch (t) of banana prawns and rainfall (mm) from 1970 to 1991. (a) Southeastern Gulf of Carpentaria (Karumba region). (b) Northeastern Gulf of Carpentaria (Weipa region).

## Tiger prawns (*Penaeus semisulcatus*)

### (a) Life history dynamics

The grooved tiger prawn *Penaeus semisulcatus* represents more than 90% of the tiger prawn population in the Albatross Bay region and as a result, has been the tiger species most intensively studied.

The annual year class typically consists of two main cohorts; one is born in spring (August to October) while the other is born in late summer (January and February). Although data for individual years does not show strong links between successive stages, when the data for five years is combined on a monthly scale, the two cohorts are evident in all life history stages, with the exception of subadults (Fig. 6). The generation born in spring leaves the estuarine nursery grounds in November-December, moves rapidly through the fishing grounds and disperses in the deeper offshore waters. These animals appear to spawn for the first time (about 6 months of age) during this migration and spawn again in late winter and spring (about 12 months of age) at which time they appear to move shoreward and congregate on the fishing grounds. The generation born in late summer appears to over-winter in the estuarine nursery grounds and moves offshore onto the fishing grounds in spring (September). The coincidence of the two cohorts on the fishing grounds is one of the reasons for the peak in commercial catch rates of tiger prawns at this time of the year. The relative contribution of each cohort varies from year to year (Fig. 7). For example, the spring cohort represented less than 25% (by number) of the adult catch between June and October in 1986 compared to about 50% in 1988.

For each of the two cohorts, the survival between successive stages varies both from year to year and from stage to stage – the direction of variation is not the same for all of the stages (Fig. 8a and 8b). For example, in 1986/87 the spawning index in spring was about 50% below average but the relative abundance of early larval stages, benthic postlarvae and small juveniles were all above average (Fig 8a). Following this, the relative abundance of the larger juveniles, subadults and adults were all below average. In none of the years since 1986/87 has there been a generation that has been consistently above average or consistently below average for all life history stages. Thus, as with banana prawns, the relationship between the levels of spawning and subsequent recruitment to the commercial fishery appear to be largely influenced by external factors that vary markedly from year to year. Although no single environmental factor has yet been found that explains the variation in survival between any of the successive stages over the duration of the current study, the dataset has provided the basis for formulating hypotheses which can now be tested. e.g.

- Interannual variation in survival of juvenile stages may be determined by the amount of subtidal, estuarine and coastal algae.

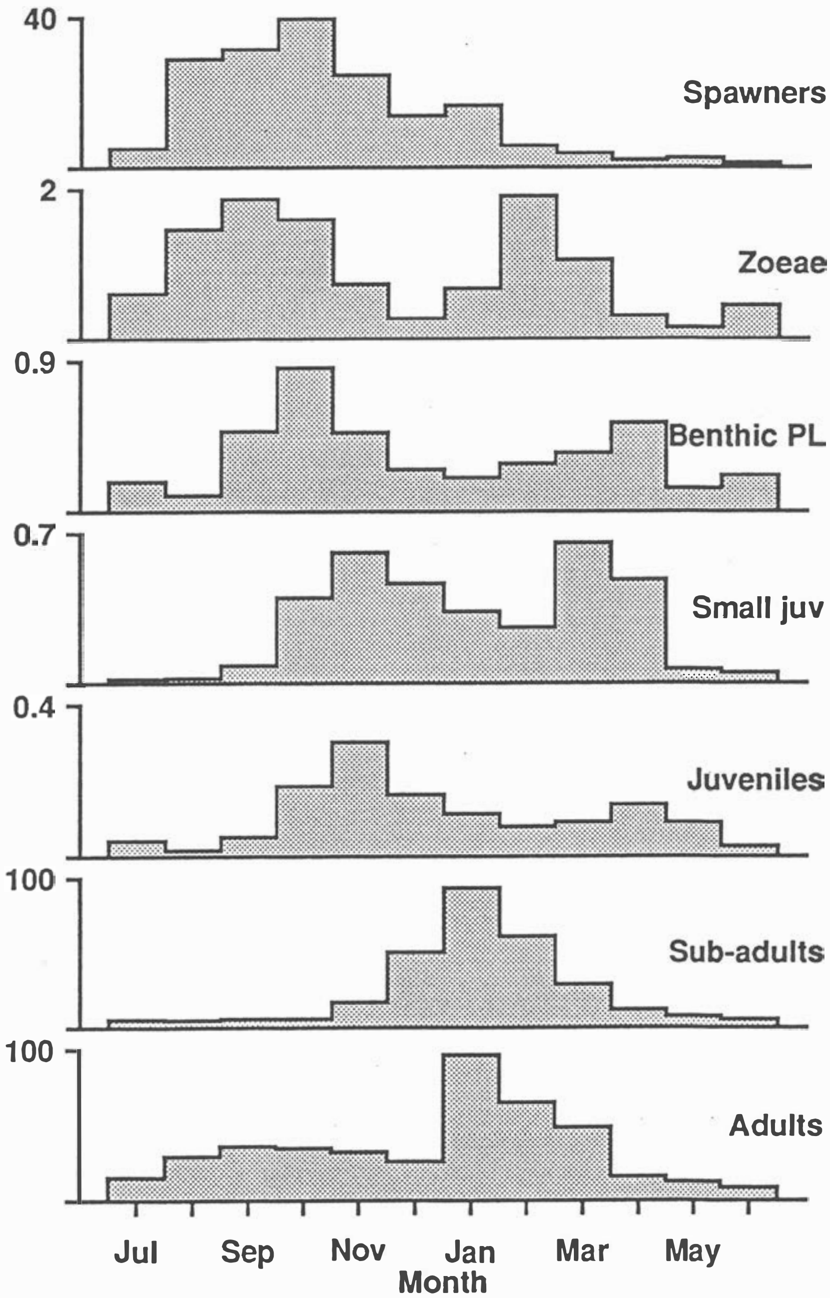



Figure 6. Monthly mean abundance of each life history stage for grooved tiger prawns *Penaeus semisulcatus* over 6 years.

- Interannual variation in survival of juvenile stages may be determined by the biomass of predators in the estuary.
- Interannual variation in the recruitment of postlarval prawns to the estuarine nursery grounds may be determined by hydro-meteorological events that affect the strength and direction of larval advection from the offshore spawning grounds to the nearshore.
- Seasonal and interannual variation in larval survival in Albatross Bay may be determined by the number and suite of planktonic predators and/or the amount and type of food available in the phytoplankton.
- Seasonal and interannual variation in the larval numbers in Albatross Bay may be determined by factors affecting benthic egg survival between the time of spawning and hatching.

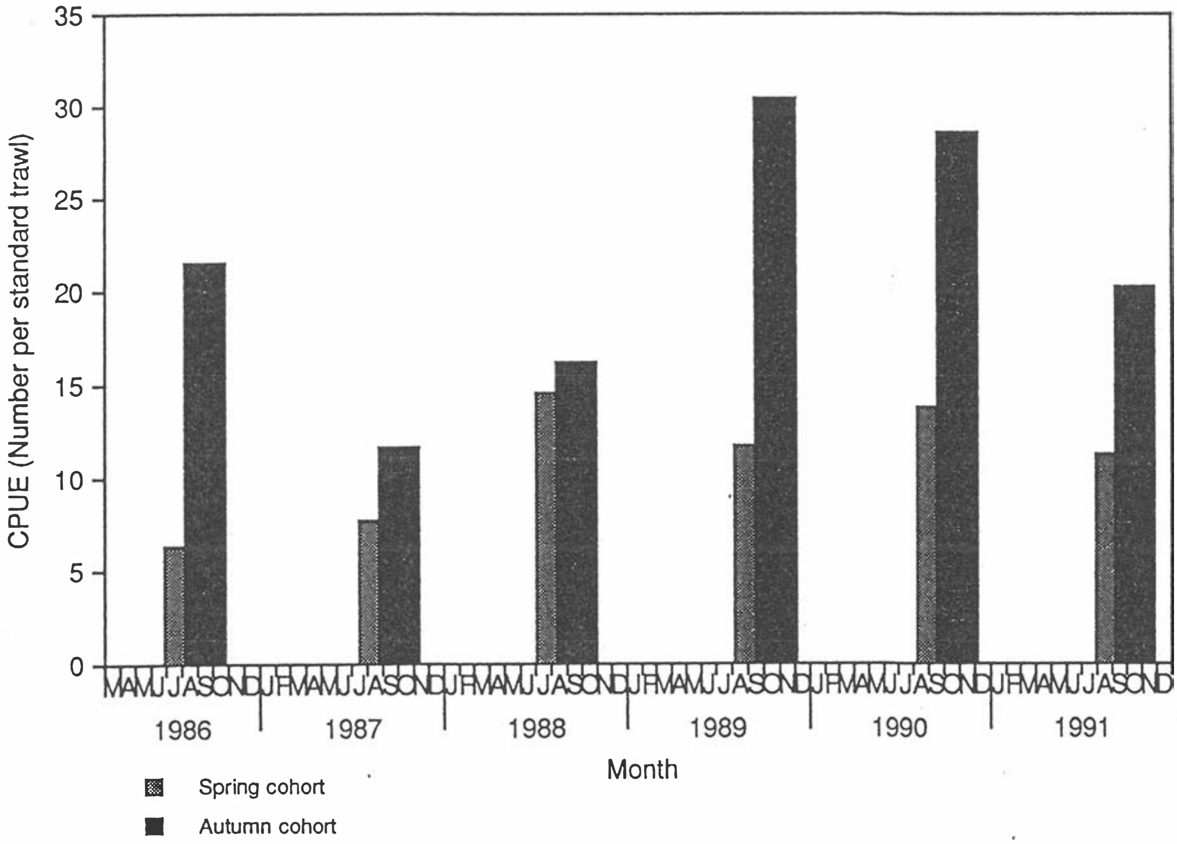
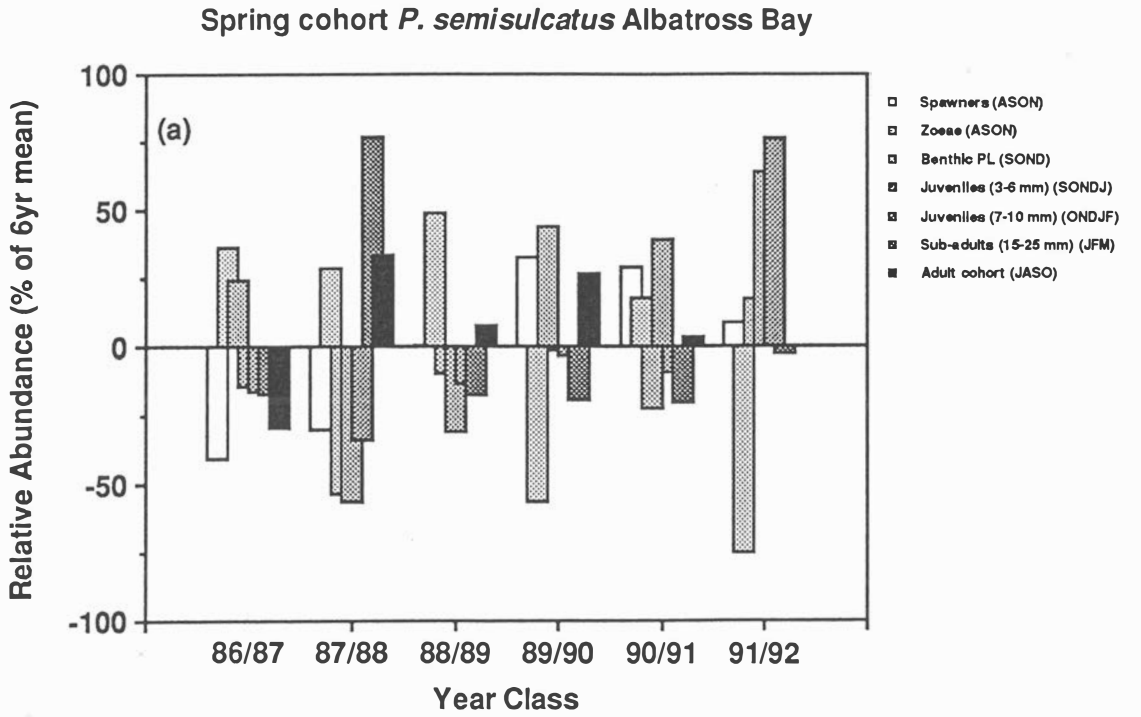



Figure 7. Relative abundance of spring (12 month old) and autumn (6 month old) generations of grooved tiger prawns to offshore population in spring.



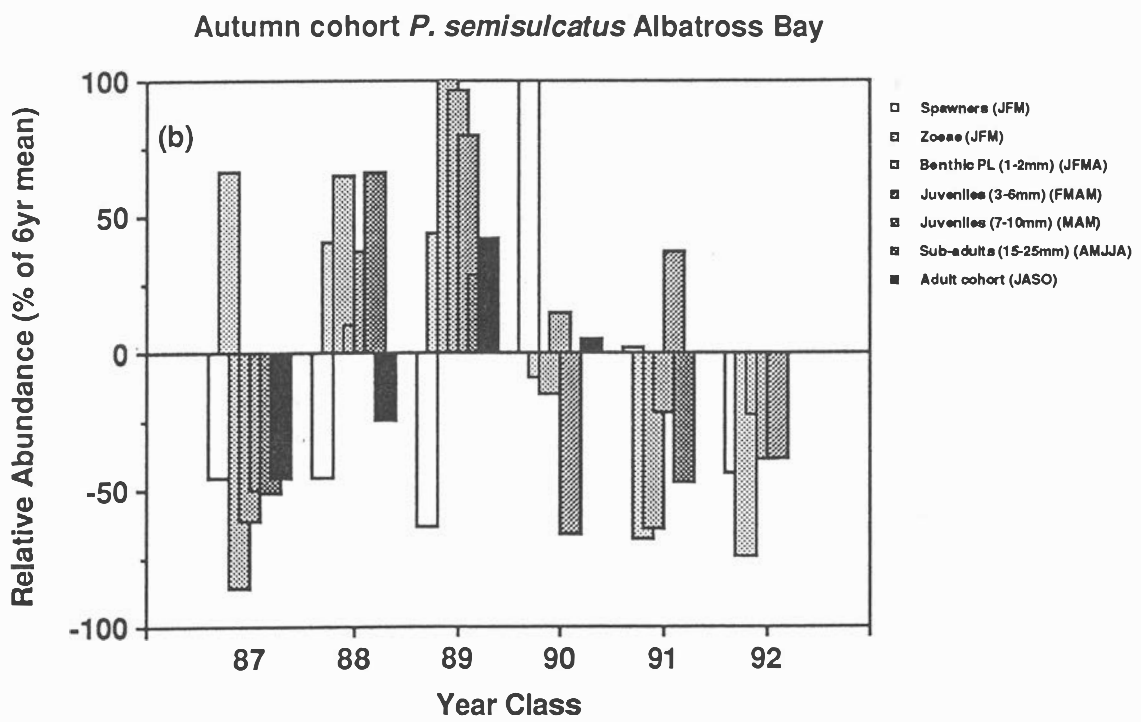




Figure 8. Abundance of grooved tiger prawn life history stages: Deviation from 6 year mean for each year class for (a) the spring generation and (b) the autumn generation.

### (b) Ability to forecast catches

We do not yet have the ability to forecast annual catches of tiger prawns in the Northern Prawn Fishery with any degree of confidence. However, we are at the stage where we can forecast the species composition of the tiger prawn catches throughout most of the fishery. Thus we can now extract catch-per-unit-effort data for each of the two tiger prawn species from the commercial fishery logbook data for most of the important tiger fishing grounds, even though the original data were recorded only as tiger prawns (two species combined). However, initial analysis of these data in relation to meteorological variables have not shown any consistent relationships across regions.

A model of the tiger prawn fishery was constructed which included a stock-recruitment relationship. The model assumed that annual recruitment was entirely determined by the population of spawners during spring (August to October) of the previous year, which in turn was determined by the recruitment in the previous year and the level of fishing effort in between. Although it is a multi-species fishery, for simplicity, the various minor species were assumed to be biologically similar to that of the grooved tiger prawn. This simple model was able to simulate the history of the fishery reasonably well when fitted to the commercial fishery data for the years from 1970 to 1986 (Fig. 9). However, it has been largely unsuccessful in forecasting catches for the years since 1986. Possible reasons for this may be the fact that the model does not account for differences between the various species caught as part of the tiger prawn fishery; nor does it account for the two separate cohorts (at least for the grooved tiger prawn) contributing to the fishery each year. Another and more likely reason is that unidentified environmental factors play a significant role in determining year class strength.

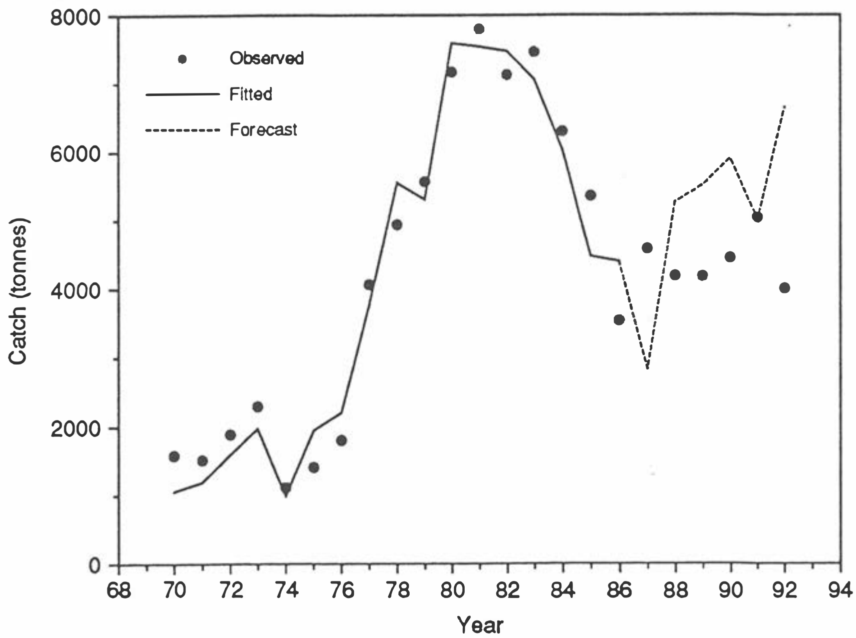



Figure 9. Simulation model of the mixed-species tiger prawn fishery of the Northern Prawn Fishery fitted to catch and effort data from 1970 to 1986. Observed catches together with those predicted by the model are given for the years 1987 to 1990.

# 5. MANAGEMENT IMPLICATIONS

Various effort-reduction measures have been introduced in the Northern Prawn Fishery over the years in response to advice from research agencies. One of the measures introduced in 1987, on CSIRO advice, was a mid-year closure to restrict the fishing effort on tiger prawns before the start of their main spawning season in August. The reasoning behind this closure was an assumption that the decline in tiger prawn catches from 1981 to 1986 was a direct result of over-exploitation and reduction in spawning stocks.

In the absence of any direct evidence to support this assumption, it seemed prudent to be conservative until such time as another more plausible explanation could be found. In addition to this assumption, based on limited data at the time, it was thought that the fishery was based on a single cohort in each year class, and the timing of the closure was designed to protect the spawning success of this cohort. However, since 1987 when the mid-season closure was first imposed, the catches in the fishery have not returned to the levels of the early 1980s as predicted by the simple stock-recruitment model for tiger prawns.

The results of the six years of information collected from the CSIRO/FIRTA penaeid recruitment studies in Albatross Bay may explain the inadequacy of the simple single-cohort, single-species model. The simultaneous sampling of all the different life history stages of the commercially important penaeids has not shown any consistent link between spawning stocks in spring and recruits in the following year.

One reason for the lack of an obvious spawner-recruit relationship may be that we have been using an inappropriate measure of annual spawning. We have been using the entire population of spawners in spring as our measure of annual spawning, whereas it is possible that only a subset of this spawning population (i.e. the *effective* spawning stock) may be contributing to recruitment. Further, it appears that there may be another effective spawning period in late summer that ultimately contributes to annual catches, and that its contribution varies from year to year. Clearly, a better understanding of these complex reproductive processes are needed if we are to establish any firmer links between spawning and recruitment.

The results of the projects have been communicated directly to NORMAC through CSIRO's representative, and to the industry through CSIRO Information Notes, Australian Fisheries articles and presentations at pre-season workshops. In addition, there have been a number of papers published in scientific journals and many more in preparation. A full complement of these papers will be submitted to FR&DC once they are completed and published.

# 6. KEY ACHIEVEMENTS

The following is a list of the key outcomes from the project. Although most of them relate directly to the main objectives of the project, many were quite unexpected.

*Adult prawn ecology*

- **Identification of factors that determine spatial distributions of species**

The spatial distributions of individual species in the Gulf of Carpentaria are related to depth and/or sediment type (Somers 1993). The brown tiger prawn *P. esculentus* was most abundant in the southern Gulf and shallower parts of the western Gulf (<35 m deep), where sediments were sand or muddy sand. In contrast, the grooved tiger prawn *P. semisulcatus* was most abundant in the north-eastern Gulf and the deeper parts of the western Gulf (>35 m deep) where sediments were mud or sandy mud. The blue-tailed endeavour prawn *M. endeavouri* was the most widespread of the species in the Gulf but, like *P. esculentus*, it was most abundant in the south-eastern Gulf and shallower parts of the western Gulf, where sediments were either sand or muddy sand. The red endeavour *M. ensis* was more limited in its distribution, with highest abundance in the north-eastern Gulf and in the deeper parts of the western Gulf (35-45 m). Here the sediments were more than 60% mud.

- **Offshore migration of grooved tiger prawns**

Studies in the western Gulf suggested an offshore migration of grooved tiger prawns during autumn to beyond the commercial fishing grounds, with the population contracting shorewards in spring (Somers and Kirkwood 1991). The Albatross Bay study confirmed this offshore migration of young adult grooved tiger prawns in the north-eastern Gulf from February each year, with the stock widely dispersed to depths of 65 m by July (Somers and Crocos 1987). This same cohort apparently began moving back into Albatross Bay in spring, mixing with a younger cohort that had newly recruited from nursery grounds (Crocos and Van der Velde, in prep b).

- **Spatial and seasonal egg production in grooved tiger prawns**

We found that peak egg production for *P. semisulcatus* in the north-eastern Gulf was in a depth range of between 15 and 30 m (Crocos and Van der Velde, in prep b.). Egg production was highest in spring, gradually declining through summer and autumn. There was a slight secondary peak in late summer.

- **Age structure of grooved tiger prawn population**

In contrast to earlier studies in the western Gulf, we found that recruitment to the adult population was bimodal, with prawns recruiting to the fishing grounds in both autumn and spring (Loneragan *et al.* in prep). The stock at any time was made up largely of two generations that were 6 months different in age. The spawning stock during spring was made up largely of spring generation females (12 months old), but by late summer, females from the autumn generation formed the majority of spawners (Crocos and Van der Velde, in prep b).

- **Age structure of banana prawn population**

We confirmed that there was a single pulse of *P. merguiensis* recruitment per year despite bimodal seasonal patterns of spawning, larval and juvenile abundance (Crocos 1992, Crocos *et al.*, in prep).

- **Spatial and seasonal egg production in banana prawns**

Egg production was highest in autumn (6 months old) but peaked again in spring (12 months old). Although the number of 12 month old spawners was always very low, these were largely responsible for the single annual pulse of recruitment to the commercial fishery in autumn. This spring spawning was in shallower inshore waters (<15 m deep) than that of the spawning at other times of the year (Crocos and Van de Velde, in prep. a).

- **Spawner-recruit relationship for banana prawns**

There was no well defined spawner-recruit relationship between years. Survival both between life history stages and between years varied significantly. Interannual variation in relative abundance was at a minimum in the larger estuarine juvenile stages, suggesting that nursery habitat may be one factor limiting annual production of banana prawn stocks.

- **Forecasting banana prawn catches**

We established a reasonable relationship between the abundance of recruiting sub-adults in January/February and the subsequent commercial catches in April (Vance *et al.* in prep c). Although the relationship is based on just six years, it has been useful in forecasting catches in Albatross Bay.

- **Feeding by Penaeids**

Analysis of diets has shown differences between juveniles of the two species of tiger prawns and changes in diet through the life cycle of both tiger (Wassenberg and Hill 1987) and banana prawns (Wassenberg and Hill in press). Factors that affect diet include habitat and moult stage (Hill and Wassenberg 1992, 1993). Penaeids were found to be selective in their feeding and could distinguish and had preferences for particular species of crustaceans and molluscs (Hill and Wassenberg 1987).

- **Emigration of juvenile banana prawns**

Experimental studies showed that juvenile banana prawns in constant salinity tended to move against the current. When salinity dropped, this behaviour changed and they swam with the current when the water level was falling and against the current when the water level was rising. This behaviour may explain the emigration of juvenile banana prawns from estuaries in the rainy season.

• **Emergence behaviour**

The emergence behaviour of eight commercially important penaeid species has now been described (Wassenberg and Hill in prep a). Most of the species examined emerged at night only and could be split into three groups based on their sensitivity to light. The king prawns *P. plebejus* and *P. latisulcatus* were most sensitive while the banana prawn *P. merguiensis* was least sensitive. The tiger prawns *P. semisulcatus* and *P. esculentus* , the endeavour prawns *M. endeavouri* and *M. ensis* , and the greasyback prawn *M. bennetae* were intermediate in their reaction to light. As well as light, emergence was also found to be a function of moult stage and prawn size (Wassenberg and Hill in prep b).

*Juvenile prawn ecology*

•**Utilisation of seagrass and algae by juvenile tiger prawns**

Earlier work of Staples *et al.* (1985) established the importance of seagrass as a juvenile nursery habitat for both brown (*P. esculentus*) and grooved tiger prawns (*P. semisulcatus*). The current study confirmed this link but also established the importance of seasonal algal beds as nursery habitats for *P. semisulcatus* (Haywood *et al.* in prep, Vance *et al.* in prep a).

Whereas seagrass sites supported both species of juvenile tiger prawns from September to April/May each year, upstream algal sites only supported *P. semisulcatus* postlarvae and only from September to December . Low salinities at the onset of the wet season resulted in a marked decrease in the algal biomass, rendering this habitat unavailable for the postlarvae.

• **Growth and mortality of juvenile tiger prawns**

Growth rates for grooved tiger prawns were estimated using length frequency analysis and ranged from 0.53 - 1.99 mm CL $wk^{-1}$ (Vance *et al.* in prep b). Weekly natural mortality rates ranged from 0.139 - 1.456 and varied between sites. Juvenile grooved tiger prawns only spent between 4 to 10 weeks on the seagrass habitat.

• **Environmental effects on the abundance of juvenile tiger prawns**

River salinity was the only environmental factor to be significantly correlated with the abundance of juvenile tiger prawns. Decreased salinity was associated with a decrease in the numbers of larger juvenile *P. semisulcatus*, presumably due to emigration of prawns from the nursery areas (Vance *et al.*, in prep a).

• **Relationship between juvenile grooved tiger prawns and adults**

Any relationship between juvenile and adult populations of *P. semisulcatus* is complicated by their 6-month generation time and their 18-20 month longevity. The adult population in spring has a higher proportion of 6-month than 12-month old individuals and consequently the abundance is more closely related to juveniles in the river in the previous autumn (i.e. 6 months old) than the previous spring (Vance *et al.* in prep a).

**• Utilisation of mangrove habitats by juvenile banana prawns (*Penaeus merguiensis*)**

Strong links were found between juvenile banana prawns and mangroves, with highest survival in the upstream reaches of small mangrove-lined creeks (Vance *et al.*, 1990). Although postlarval banana prawns settle on most habitats found in the Embley River, largest catches of juveniles were taken from the steeply sloping mudbanks adjacent to mangroves. The upstream limit of distribution of banana prawns coincided with the distribution of broad bands of mangrove forests.

**• Growth and mortality of juvenile banana prawns**

Length frequency analysis was used to estimate growth and natural mortality rates and how long juvenile banana prawns remained in the river (Haywood and Staples, in press). Growth rates ranged from 0.63 to 1.65 mm CL $wk^{-1}$ and increased with temperature and decreased with increasing prawn density. Natural mortality rates ranged from 0.63 to 0.94 per week, being highest during the pre-wet (October to December) and wet seasons (January to March) and lowest during the dry season (July to September). Banana prawns spent between 6 and 20 weeks in the river before emigrating to Albatross Bay.

**• Forecasting the commercial catch of banana prawns**

The number of juvenile prawns emigrating from the river was correlated with rainfall, the salinity of the river and the number of juveniles present in the river at any particular time (Vance *et al.*, in prep c). The commercial catch of banana prawns was significantly correlated with emigrants and the number of juveniles in the river (Vance *et al.*, in prep d). Whereas there is a close relationship between annual rainfall and commercial banana prawn catch in the southeastern Gulf, there is only a weak relationship in the Weipa region. However, we have shown that emigration of juvenile prawns is correlated with subsequent commercial catch at Weipa and that the factors determining the numbers of prawns emigrating each year are the same as in the southeastern Gulf rivers. The lack of a rainfall / commercial catch relationship in the Weipa region was due to different levels of rainfall and different catchment areas of the rivers in the two regions (Vance and Loneragan, in prep).

*Larval Ecology*

**• Natural diet of larval prawns**

Variation in larval food supply was examined for its possible role in mortality of *P. merguiensis* larvae in Albatross Bay. Using *in situ* rearing (Preston 1992), we demonstrated that higher larval survival in spring was not caused by seasonal differences in food abundance (Preston *et al.* 1992a). However, recent laboratory work has shown that larval survival may depend on the nutritional quality of the algal species available (Burford and Preston 1992). Cyanobacteria, which, at times, are a dominant component of the Gulf of Carpentaria phytoplankton, could not be digested by prawn larvae (Preston and Burford 1992, Preston *et al.* in prep a), resulting in starvation (Preston *et al.* in prep b). The techniques that were developed for examining the natural diet of prawn larvae have also provided useful information for the aquaculture industry (Preston *et al.* 1992b).

- **Design, construction and testing of the Larvatron.**

The Larvatron is an innovative device which enables sophisticated experiments on the salinity, temperature and feeding requirements of prawn larvae and other planktonic animals (Jackson et al., 1992). The Larvatron is currently being used to study the salinity and temperature requirements of Penaeus semisulcatus (Jackson and Rothlisberg, in prep a).

- **Identification of larval tiger prawn species.**

Laboratory-based spawning and larval rearing has enhanced our larval taxonomy reference collection for *Penaeus esculentus* and *P. semisulcatus*. This has improved the accuracy of our numerically-based identification scheme for these larvae and allowed us to describe the spatial, seasonal and interannual variation in abundance of *Penaeus semisulcatus* in Albatross Bay (Jackson et al, in prep b).

- **Postlarval recruitment mechanisms**

Collaborative work with physical oceanographers has recently focused on nearshore changes in larval behaviour of *Penaeus plebejus* (Rothlisberg and Church in press; Rothlisberg *et al.* submitted). By monitoring postlarval activity patterns and physical gradients, we have discovered the cues that allow postlarvae to enter their estuarine nursery grounds. Postlarvae change from diurnal to a tidal activity activity rhythm in response to relative changes in water pressure as they are moved into shallow water (<20 m). This process both concentrates ('traps') the postlarvae in the coastal zone and delivers them to their estuarine nursery grounds regardless of the horizontal physical gradients.

- **IOC/FAO Penaeid Recruitment Project (PREP)**

CSIRO scientists involved in penaeid research in the Gulf of Carpentaria have been responsible for instigating a regional study of penaeid recruitment in southeast Asia under the auspices of the Intergovernmental Oceanographic Commission (IOC) and the United Nations Food and Agricultural Organisation (FAO). The Penaeid Recruitment Project (PREP) aims to describe the recruitment dynamics of *Penaeus merguiensis* in seven countries: Australia, Brunei, China, Indonesia, Papua New Guinea, the Phillipines and Thailand. By comparing the level of recruitment, environmental parameters and fishing pressures across this region, it should give a more rapid insight into physical and man-induced factors that affect recruitment. Towards this end, there have been three training workshops (Staples *et al.* 1988; Staples *et al.* 1989; Staples *et al.* in press). The regional comparisons in recruitment and rainfall regimes for one year have also been described (Staples and Rothlisberg, 1990). Although complicated, the life cycle of *P. merguiensis* was found to be based on two cohorts per year in all of the study sites. However, in most areas, differential survival resulted in only one of the cohorts contributing to the offshore fishery. Evidence suggests that rainfall is one of the major factors which control the extent to which a particular cohort recruits offshore and contributes to the commercial fishery.

- **Larval ecology of tiger prawns in Albatross Bay.**

The larval *Penaeus semisulcatus* are very widespread. The larvae are found in two seasonal peaks (spring and autumn) and these peaks are usually about equal in height (Jackson *et al.* in prep b).

- **Larval ecology of banana prawns in Albatross Bay.**

The larval ecology of *Penaeus merguiensis* in Albatross Bay is much better understood than that of *P. semisulcatus.* We have been able to describe the spatial, seasonal and interannual variation in its distribution and abundance (Jackson et al, in prep c). Larval abundance usually mirrors adult egg production with two peaks per year with the spring peak, which produces the majority of recruiting postlarvae in the estuary, being much smaller than the autumn peak.

- **Larval ecology of endeavour prawns in the Gulf of Carpentaria.**

Further development of our numerically-based larval identification scheme has allowed the identification of larvae of the two major commercial species of *Metapenaeus* in the Gulf of Carpentaria. *M. ensis* larvae were widely distributed, in both coastal and offshore areas, and were present in significant numbers throughout the year. Larvae of *M. endeavouri* were found in coastal regions only (Jackson and Rothlisberg, in prep b).

*Abiotic environment*

- **Long term database of salinity and temperature in Albatross Bay.**

Depth profiles of salinity and temperature at 10-20 locations within Albatross Bay were taken each month for a period of six years (Jackson et al, in prep a). This data allows us, for the first time, to relate variations in recruitment and survival of various prawn life history stages to seasonal and interannual variation in physical conditions.

- **Physical environment Gulf of Carpentaria**

The climate, hydrology and sediments of the Gulf of Carpentaria have now been described (Somers and Long 1993), facilitating a correlative analysis of abiotic factors that might affect the spatial, seasonal and interannual variation in prawn abundance (Somers and Wang, in prep).

*Biotic environment*

- **Spatial and temporal variation in phytoplankton biomass and community structure**

Within Albatross Bay, seasonal phytoplankton biomass was highest in summer whereas no seasonal trends in biomass were observed offshore (Burford and Rothlisberg in prep). Standard analytical techniques for measuring algal biomass were improved as a result of the study (Burford and Pollard, in prep). The phytoplankton community was dominated by diatoms, with green algae, golden brown flagellates, chrysophytes and cyanobacteria also present (Burford and Rothlisberg, in prep). Nutrient concentrations (nitrate, phosphate and silicate) were variable but did not appear to be linked to rainfall events. The phytoplankton within the Bay was well mixed with little or no vertical stratification.

- **Primary productivity**

We found that, in summer, the Gulf was divided into two biologically independent water masses: a well-mixed coastal boundary layer and a vertically stratified water mass in the central Gulf. In the upper layer of the central Gulf, we found light to be the most important factor in controlling the level of primary productivity, with a peak in a particular range of light intensities (Rothlisberg *et al.*, in prep.). In the lower layer, productivity was low because of low light even though nutrient concentrations were highest closest to the bottom. Primary productivity in the Gulf was highest in Albatross Bay, where nutrients were were well mixed throughout the water column (Pollard *et al.* , in prep). For the phytoplankton communities in Albatross Bay, highest productivity was at the surface.

- **Identification of the main predators on juvenile prawns**

In studies in the Embley and Norman River estuaries and in the inshore waters around Groote Eylandt, about 50 fish species were found to be significant predators of juvenile prawns (Brewer *et al.* in prep; Salini *et al.* 1990; Salini *et al.* 1992; Salini *et al.* in prep.).

- **Estimation of biomass of predators on juvenile prawns**

Within the estuaries and inshore around Groote Eylandt, the fish biomasses varied between 1 and 30 g $m^{-2}$ but were much lower in seagrass habitats than in mangrove habitats (Blaber *et al.* 1989; Blaber *et al.* 1992; Blaber *et al.* in prep.).

- **Identification of the main predators on sub-adult and adult prawns**

In a study in Albatross Bay, about 34 species of fish were identified as significant predators of prawns. Of these, the trevally *Caranx bucculentus* and four species of elasmobranch had the greatest impact on prawn populations. An estimated 2950 t/yr of commercial penaeids are eaten by fishes in Albatross Bay (Brewer *et al.* 1989; Brewer *et al.* 1991; Salini *et al.* 1993).

- **Estimation of biomass of predators on sub-adult and adult prawns**

A preliminary standing stock estimate of fish, of which about 25% are prawn predators, in Albatross Bay was 93 000 tonnes, with mean densities of between 128 and 297 kg $ha^{-1}$ (Blaber *et al.* 1990a; Blaber *et al.* 1990b).

- **Bioenergetics of teleost prawn predators**

Estimation of food intake, consumption rates and growth of important teleost prawn predators was completed (Smith *et al.* 1991; Smith *et al.* 1992). Consumption rates averaged between 6-8% of body weight per day which, for the biomass of *Caranx bucculentus* in Albatross Bay, corresponds to about 10 g of prawns per hectare per day.

- **Effect of habitat structure on predation by fishes on tiger prawns**

Soft substrates, in which prawns can bury, and seagrass habitats reduce predation rates by fish during daytime (Laprise *et al.* 1992). However, the protection offered by burying during daytime disappears at night when the prawns become active. Seagrass habitat structure offers the same protection during both day and night.

*Stock assessment*

- **Estimates of long-term sustainable yields for the NPF**

Estimates of the average long-term sustainable yields (8 000 - 10 000 t) for the Northern Prawn Fishery (NPF) were made using simple fishery models based on our knowledge of banana and tiger prawn life cycles (Somers 1988, 1990, 1992). The fishery is fully exploited.

- **Spatial distribution of commercial species in the Gulf of Carpentaria**

The spatial distribution of the six main commercial species have been described in detail for the Gulf of Carpentaria (Somers 1993). The distribution of sibling species was sufficiently distinct to enable interpretation of the large 22-year commercial fishery data set to the individual species level. Over the last nine years, the biomass of the Gulf catch has been made up of about 41% banana prawns *P. merguiensis*, 24% grooved tiger prawns *P. semisulcatus*, 23% brown tiger prawns *P. esculentus*, 8% blue-tailed endeavour prawns *M. endeavouri*, 3% red endeavour prawns *M. ensis*, and 1% king prawns *P. latisulcatus*.

- **Model for maximizing long-term bioeconomic viability of prawn fisheries**

We were able to examine the long-term implications of manipulating both the level and pattern of fishing effort for a prawn fishery where there is a knowledge of growth, mortality and stock-recruitment relationships (Somers 1990b). The work was based on our understanding of the life cycle dynamics of banana and tiger prawns and has been an important factor in setting seasonal closures in the NPF.

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