Indices of recruitment and effective spawning for tiger prawn stocks in the Northern Prawn Fishery

> David Die, Neil Loneragan, Mick Haywood, David Vance, Fiona Manson, Brian Taylor, Janet Bishop

# **CSIRO** Marine Research

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#### **OBJECTIVES:**

- 1. Define the areas of the tiger prawn fishery in the NPF that can be treated as independent stocks (i.e. areas that respond mainly to local fishing effort and to changes in the local environment);
- 2. Evaluate the use of catch per unit effort (CPUE) as an index of abundance;
- 3. Develop indices of spawning stock and recruitment for each of the above stocks;
- 4. Examine the relationship between spawning stock and recruitment in each of these areas.

## NON TECHNICAL SUMMARY

In the mid to late 1980s NORMAC began to suspect that tiger prawn spawning stocks in the NPF may have been reduced by fishing to levels that reduced recruitment to the fishery. A vessel buy-back scheme and other effort reductions were introduced to reverse this trend but, by the mid-1990s, the desired recovery of tiger prawns had not occurred. To understand the reasons for this, and with the support of FRDC, CSIRO began a 3-year research project in 1995 to improve our understanding of the relationship between the spawning stock and recruitment in the tiger prawn fishery. This project has examined data from the logbook system, collected new information from skippers on where they fish and their patterns of fishing, and developed models to assess the numbers of recruits and spawners, and hence the status of the tiger prawn stocks.

This project has relied heavily on data gathered by the NPF fleet. Some of the data are provided to AFMA as a condition of the NPF permit (logbook data), but other data were provided to us voluntarily by fishers (GPS plotter disks with maps of the fishing grounds and the fishers' trawl tracks). Several fishers also took us on board their vessels to collect information on try net catches and plotter tracks. We have shown how valuable these data are and how much there is to be gained by enlisting the cooperation of the fleet.

One of the main research issues addressed by this project was to understand the spatial dynamics of tiger prawn stocks and the fleet that fishes them. We first developed electronic maps of fishing grounds using data from fishers' GPS-plotter systems. These maps identify

the areas where trawling occurs and the areas where the substrate is such that trawling cannot occur (untrawlable areas). These maps have a resolution of 0.2 km - much finer than the 10.8 km scale provided by the logbooks. Fishing effort and the untrawlable grounds are not distributed evenly throughout the NPF. Some areas within fished logbook grids are intensively fished whereas others are untrawlable. The fishers tend to search for aggregations of tiger prawns early in the night. Once an area of higher catch has been located the vessel targets that same area for the remainder of the night. As a result, some of the fishing ground is trawled several times in the same night but nearby areas may not be trawled. About 10% of the NPF managed area is trawled and only a small proportion of this trawled area is fished heavily (> 100 days of fishing per year). This information is essential for understanding seasonal and historical changes in the efficiency of trawling.

In the past, population indices of spawning stock and recruitment for tiger prawn stocks were assumed to represent the entire NPF stock. However, given the geographical extent of the NPF, it is unlikely that adult prawns would mix thoroughly through the whole area. It was unclear, however, whether water circulation could contribute to the mixing of tiger prawn larvae. To address this question, a simulation model of the currents in the Gulf of Carpentaria and the behaviour of larval prawns was developed. The model was used to predict the offshore spawning regions from which larvae could be expected to reach the seagrass nursery areas along the coast. The model shows that there are large gaps between these effective spawning areas and this suggests limited mixing of tiger prawn larvae within the Gulf of Carpentaria and that there are likely to be several stocks of tiger prawns in the Gulf.

On a large scale, we have used logbook data to examine trends in the spatial extent of the fishery. Although the total area fished has been decreasing since 1983, the area searched continued to increase until 1987. Areas of high catch have remained unchanged throughout the history of the fishery. The area currently fished has contributed to the majority of the historical catches, but in the early 1980s only 60% of the total catch came from this area. Some areas that were fished in the 1980s are not fished today – some because they are now inside trawl closures, but others because of low catch rates. Commercial count data (provided by skippers in their logbooks) for the 3 kg prawn packs is accurate and was used to identify the location and seasonal pattern of recruitment of small prawns onto the fishing grounds. Many of the areas located as recruitment areas are on the edges of current area closures, supporting the hypothesis that these closures are protecting pre-recruits from harvesting. The analyses suggest that October/November tiger prawn catch rates of the 20-30 count category may be a good predictor of recruitment of tiger prawns in the following fishing season.

The analyses of logbook, plotter and larval advection data have led us to propose a new stock structure for tiger prawns inside the Gulf of Carpentaria. Seven new stock areas (NE and SW Groote, Vanderlins, W and N Mornington, Sweers and Albatross Bay) have been defined; some contain a stock of both grooved and brown tiger prawns, and others contain a stock of only one of these species. It is likely that there are additional stock areas for tiger prawns outside the Gulf of Carpentaria. Although we have recognised seven stock areas, the current data and knowledge are unlikely to be able to support stock assessments for these seven areas. For these reasons, more detailed analyses of stock recruitment relationships were carried out for a simpler four stock area model considering the areas of Groote (= NE and SW Groote), Vanderlins, Mornington (= W and N Mornington and Sweers) and Albatross Bay.

Spawning/stock recruitment relationships (SRR) have been defined at two spatial scales: firstly at an NPF-wide scale and secondly for each of the four stock areas of the Gulf of Carpentaria. At the NPF-wide scale, the model suggests a strong influence of spawning stock on recruitment, and also increased recruitment, independent of the spawning stock, every 3 to 4 years. At regional scales, the influence of spawning on recruitment is less apparent. However, the results from simple biomass dynamic models suggest that from 1993 to 1998, tiger prawn stocks in the Gulf of Carpentaria remained below the levels required to produce maximum sustainable yield, thus implying that these stocks were overfished. Similarly, standardised fishing effort for that same period remained above the fishing effort required to achieve maximum sustainable yield, thus implying that overfishing continued to occur. Spatial analysis suggests that there are differences in the levels of overfishing between regional stocks. The assessments seem to confirm the perceptions of some members of the fishing industry who have suggested that the tiger prawn stocks in the Groote Eylandt region have not recovered from the overfishing that occurred in the early 1980s. They also suggest that the stocks in the Vanderlin and Mornington Island areas were further depleted during the later 1980s as the fishing fleet fished more intensively in these areas, in response to the depletion of the stocks around Groote Eylandt.

At smaller spatial scales, our research has shown that fishing is highly aggregated. This reflects differences in the abundance of prawns and the type of bottom present within the fishing grounds. We believe that this knowledge will be critical in supporting the establishment of Marine Protected Areas in northern Australia. To make this information more useful, however, we will need to quantify fishing impacts on prawn populations and benthic habitat at these small scales. This will require further research to characterise the reasons for the aggregations and the relationship between bottom type and prawn populations.

In summary, this project has confirmed that tiger prawn stocks remain overfished at both a large (NPF-wide) scale and a regional scale. This implies that, for NORMAC to put in place management measures that will recover the stocks from their overfished state, these measures will have to be effective in all regions of the fishery.

# **KEYWORDS:** *Penaeus esculentus, Penaeus semisulcatus,* spawning stock-recruitment relationships, patterns of fishing, untrawlable grounds, population dynamics, larval advection

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# 1 BACKGROUND

The Northern Prawn Fishery is Australia's second most valuable fishery, generating around \$150 million annually with most of the catch being exported because of its high value. The fishery has been managed since its beginning by input controls. These have increased in both number and complexity throughout its history (Taylor 1994, Die and Carter in review, Appendix 1). In the early 1960s, the only fishing effort control was the need to hold appropriate licenses, later denoted B-units. In the mid-1980s "A-units" were introduced to control the fishing power of individual vessels by regulating the under-deck tonnage and main engine horse power. Since then the control of the total number of A-units in the fleet has become the main input control in this fishery. Other controls, such as fishing closures and gear restrictions have also been used to achieve the objectives of management.

The Northern Prawn Fishery is generally partitioned into two fisheries: the daytime fishery for banana prawns and the night-time fishery for tiger prawns, each fishery providing about half of the total NPF catch. Incidental catches of other commercial species of prawns, other crustaceans, squid and fish are taken in both the banana prawn and the tiger prawn fisheries (Robins and Somers 1994).

The tiger prawn fishery expanded rapidly in the 1970's but catches declined in the 1980's. This caused economic hardship for fishers and concerns regarding the status of prawn stocks. Managers and scientists concluded that excessive fleet capacity had lowered spawning stocks to levels that led to reduced recruitment (i.e. they assumed recruitment overfishing was occurring). Fishing effort was reduced drastically through gear and fishing time restrictions and by a major restructure of the fleet that cost the industry \$80 million. The buy-back schemes used to achieve this restructure of the fleet reduced the number of A-units by 60%, from a high of 133,000 to the current 52,000. B-units were similarly reduced from 292 to 128. Following these reductions, catches stabilised but they did not increase to the level expected by the fishing industry and the managers of the NPF. This raised questions about the possible causes of the decline in catches and whether the current management, largely aimed at increasing the size of the spawning stock, is the most appropriate method for maximising the value of this fishery. Current restrictions may be inefficient and be unnecessarily costing the industry millions of dollars annually.

In recent years, substantial progress has been made in understanding the dynamics of tiger prawns in the NPF. We have gained considerable knowledge of recruitment processes and the dynamics of various life-cycle stages. The fishing grounds of tiger prawns are largely distinct from those of banana prawns because of the different habitat requirements of the juveniles of the two species-groups. Juvenile tiger prawns prefer seagrasses as nursery areas, whereas banana prawns prefer mangroves (e.g. Loneragan *et al.* 1994, 1996, Haywood *et al.* 1995, Vance *et al.* 1996b, 1998). The most recent major study of nursery habitats in the NPF investigated the role of coastal nursery habitats in determining the long-term productivity of prawn populations in the Northern Prawn Fishery (FRDC 92/45, Loneragan *et al.* 1996). The type of seagrass or mangrove was found to have a significant effect on the juvenile prawn populations. The abundance of juvenile tiger prawns is higher in seagrass beds with high biomass than those with low biomass (Loneragan *et al.* 1998) and predation rates by visual fish predators are lower in high than low biomass seagrass (Kenyon *et al.* 1995). Juvenile

banana prawns are found in higher densities in small mangrove creeks than larger river systems and their pattern of distribution within different mangrove forests depends on whether the forest is located in a small creek or main river (see Loneragan *et al.* 1996, Vance *et al.* 1996a).

As a result of the differences in distribution between different nursery habitats, most fishing grounds for tiger prawns are found in the southern and western Gulf of Carpentaria – regions with extensive coastal seagrass beds. There are also subtle differences in the fishing grounds for the two species of tiger prawns. Adult brown tiger prawns tend to occupy shallower areas than grooved tiger prawns and are more common in the Southern Gulf of Carpentaria. Grooved tiger prawns are more abundant in the northern Gulf and outside the Gulf, off Arnhemland and in the Joseph Bonaparte Gulf. These differences allowed Somers (1994b) to separate the aggregate tiger catch from logbooks into the catch of the two species of tiger prawns on the basis of the location of the catch. Somers' (1994a) work and the fact that the NPF logbook is one of the most complete fishery datasets in Australia, have opened the way for new research into the detailed spatial dynamics of this large fishery.

# 2 NEED

The tiger prawn fishery in the NPF is managed on the assumption that there is a relationship between the size of the spawning stock and recruitment to the fishery. This assumption is essential in the assessment of tiger prawn stock status and has allowed scientists to provide NORMAC with advice on the optimum levels of fishing effort for the NPF and the need to reduce current fishing effort to such levels. In response to this advice, NORMAC has introduced a series of measures that aim to increase the spawning biomass of tiger prawns, but these measures are costly to industry. This cost is exacerbated by the level of uncertainty in the predictions from the stock assessment. This uncertainty forces managers to implement precautionary effort reduction measures thus sacrificing economic efficiency in the process. If scientific assessments were able to explain current stock trends more accurately, the fishery could save millions of dollars by developing a more efficient management regime.

So how can we explain current stock trends better? We believe that there are two priority research areas that can lead to significant reduction in this uncertainty. Firstly, the estimation of regional indices, rather than fishery-wide indices, may allow us to detect a stock recruitment relationship in some regions of the NPF. Secondly, our indices of abundance (mainly based on catch and effort data) need to be re-evaluated because of recent changes in fishing methods (e.g. changes in fishing technology, changes in the spatial distribution of effort). This report summarises the latest advances made on these two research areas.

# **3 OBJECTIVES**

The overall goal of this project was to improve the scientific advice provided to managers of the NPF by obtaining more accurate data on the relationship between the spawning stock and recruitment in the tiger prawn fishery. To achieve this we set up the following objectives:

- a) Define the areas of the tiger prawn fishery in the NPF that can be treated as independent stocks (i.e. areas that respond mainly to local fishing effort and to changes in the local environment);
- b) Evaluate the use of catch per unit effort (CPUE) as an index of abundance;
- c) Develop indices of spawning stock and recruitment for each of the above stocks;
- d) Examine the relationship between spawning stock and recruitment in each of these areas.

# 4 PROJECT DESCRIPTION

In this section we present the data sources, project structure and project components.

## **Data sources**

This project used a number of different data sources. Some, like the AFMA logbook data, were not collected as part of the project although some of the logbook data (shot-by-shot and commercial count data) was entered for the first time into an electronic database. Some of the data were provided to us by commercial fishers (historic plotter data, vessel track and try-shot catch data), and some was collected by project staff.

#### Logbooks

The AFMA logbook program maintains an electronic database of the most important data entered in the logbook.

#### Daily catch and effort

Fishers in the NPF record information on daily catches and location of the highest catch by species group into compulsory logbooks. In the 1990s, catches recorded in the logbooks account for over 95% of the landings from this fishery. Logbooks are therefore a very reliable and precise source of information on the nature of catches and their location (Robins and Somers 1994).

Because logbooks provide a record of daily activity they can be used to estimate fishing effort. In the assessment of the NPF stocks, fishing days are classified as either belonging to the banana prawn fishery or the tiger prawn fishery. Days where the catch of banana prawns exceeds the catch of all other species groups or days where the daily catch is zero (in which case it is assumed that the fisher was searching for banana prawns but did not catch any) are classified as banana prawn fishing days. Any other day is classified as belonging to the tiger prawn fishery. In this project we have only used logbook fdata corresponding to the tiger prawn fishery (Somers 1994a).

#### Fleet characteristics

Vessel and crew characteristics were also obtained from AFMA and CSIRO databases. These data describe characteristics of the gear, vessels, technology and skippers operating in the NPF fleet since the 1980s (Bishop and Sterling 1999).

#### Shot-by-shot

From 1981 to 1993, logbooks also provided the opportunity to voluntarily record catch data for every shot made; however, these data were not entered in the computerised logbook database maintained by AFMA. We have obtained shot-by-shot data from the NPF logbooks

for the period 1991-92 and entered them in an Oracle database. The shot-by-shot data correspond to 20% of the total fishing days of 1991-1992. We have assumed that they represent a random sample of all fishing operations in the NPF.

Shot-by-shot records contain information on the shot number, starting time, ending time and shot duration of each shot made during the fishing day. The number of prawn cartons and/or weight of the catch by species-group are also recorded. The latitude and longitude of each shot are recorded with 1-minute precision.

#### Commercial grades

Since 1986, AFMA logbooks have allowed for the recording of information on the commercial prawn grades (weight classes). This information was not always filled in by fishers and as a result was not entered in the computerised logbook database maintained by AFMA. Logbooks held by AFMA were randomly sub-sampled to determine the best sampling strategy for transcribing commercial grade data. The data for the first 10 days of May, September and November 1985, 1989 and 1994 were entered into a database for analysis. It was estimated from this data that between 30% and 45% percent of the tiger prawn catches recorded in NPF logbooks had information on commercial count. This initial analysis also suggested it would be easier to transcribe data for the whole year rather than subsample some of the records only. As a result all commercial count data from NPF-AFMA logbooks for the period 1989-1995 were entered in an Oracle database. These data represent 64,000 fishing days or 50% of the fishing effort in the tiger prawn fishery for that period.

The A. Raptis and Sons company processes tiger prawns caught by their own large fleet of trawlers working in the NPF, as well as product purchased from other fishers operating in the same area. The company randomly checks the quality of prawn packs entering the factory, including the accuracy of at-sea size grading of prawns into commercial categories. We obtained Raptis quality-control data for the period 1993-1994 to verify the accuracy of the grading information recorded by fishers. The data was collected from 51 different vessels out of the 127 that operated in the fishery during that time. Packs for quality-control assessment were selected at random for every vessel and from all consignments entering the factory. All packs are clearly marked with the vessel's name, the prawn species group, the grade of the prawns, and the date caught. For small 3 kg packs, the quality control sampling records the net weight, the average count and the percentage of misgraded prawns. For larger 9 - 12 kg packs, 2.5 - 3 kg samples were randomly taken from each pack, counted and checked following the same procedure as 3 kg packs.

#### **Historical GPS/Plotter information**

Since 1988, when the first GPS and plotter units were installed in NPF vessels, skippers have been able to electronically record and store navigation and fishing ground information in their plotter units. This information is stored in different files describing GPS fixes, vessel tracks, locations of underwater obstacles, areas of "foul" ground, location of previous good catches etc. In 1995 and 1996, we approached a total of 57 active skippers from the Northern Prawn Fishery requesting copies of their plotter data. Of those, 29 provided us with copies of their

plotter diskettes. During interviews, skippers were requested to interpret the type of symbols and lines they used in their plotters.

The skippers used three different types of plotter units; JRC, Furuno GD188 and Furuno GD180 with the last being by far the most common. We developed a software program that decodes the files from the FURUNO plotters so that the information from the plotter files could be transferred to a computer. Ultimately, this information was loaded onto a Geographical Information System (GIS) for analysis (ESRI 1995). The data loaded into the GIS were displayed in paper form and sent to the skippers to verify that the decoding process transferred the data correctly.

#### Scientific surveys

During this project technical staff went on board research and commercial vessels to collect further catch and fishing effort data.

#### Trawl tracks

GPS plotters can be used to continuously record the position of a vessel during fishing operations. We collected detailed information on the location of trawl shots by logging vessel positions every 1-minute through the plotters used by commercial trawl vessels. These tracks were logged during normal commercial fishing operations. Some correspond to periods when CSIRO staff were on board collecting the data, some were collected by skippers themselves, and stored on disks before being handed to us at the end of the fishing season. Trawl track data were decoded and transferred to the GIS where all track information now resides.

A total of 8 scientific observer cruises were completed in each of the years 1996 and 1997. During these cruises, information was collected on fishing effort (track location) for 70 fishing days. In addition 7 fishers voluntarily provided us with tracks for 729 fishing days. This data represents over 800,000 data points but only 2% of the tiger prawn fishery effort for the years 1996-1997.

Source of data	Number of vessels		Number of nights		Areas fished	
	1996	1997	1996	1997	1996	1997
Scientific observer	6	5	29	41	Albatross Bay Mornington	Mornington Vanderlins
Commencial accord	4	2	490	240	Vanderlins	A lb stas ss
Commercial vessel	4	3	489	240	Albatross Bay	Albatross Bay

Table 4.1 Small scale catch and effort data collected by year and type of vessel.

### Try net catches

In the NPF, fishers sample the catch rates during trawling by using a small beam or otter trawl known as a try net. Try nets are continuously fished and retrieved every 20-30 minutes, whereas the main gear is towed for 3 to 4 hours. Try nets are therefore a source of abundance information at much smaller spatial scales than those provided by main gear catches.

During all trips made by CSIRO scientific observers on board commercial trawlers, we collected data on species composition, sex and size of all prawn species caught in try nets during commercial fishery operations. Additional data on catches from the main trawl nets were collected when catch rates were low. The time and position when try nets were deployed were also recorded.

Two commercial fishers volunteered additional data on try net catches and try net positions that they collected themselves during the 1996 and 1997 fishing seasons.

#### R.V. Southern Surveyor

During 1997 and 1998, the R.V. Southern Surveyor conducted trawl research cruises along the main fishing grounds of the NPF as part of a large project aimed at establishing bycatch sustainability indicators (FRDC 96/257). During these cruises, 534 sites were fished with prawn trawls at night and 27 sites with dredges. Information on species composition, sex and carapace length was collected for all commercially important prawns, including tiger prawns. In addition, the position of the vessel was recorded at 1-minute intervals. The Roxanne acoustic system was used during all Southern Surveyor cruises to obtain relative indices of the hardness and roughness of the seabed.

## **Project structure**

The research conducted during this project had four components:

- 1. defining stocks of tiger prawns;
- 2. evaluating abundance indices for tiger prawns based on catch per unit effort;
- 3. estimating population indices of stock and recruitment for tiger prawns;
- 4. determining the relationship between spawning stock and recruitment.

The methods and results obtained in each component are described in detail below, together with the specific scientific objectives addressed by each component.

# 5 DEFINING STOCKS OF TIGER PRAWNS

#### Objectives

The current assessments of tiger prawn stocks include the assumption that there is a single stock of each of the two species of tiger prawns in the NPF (Die and Taylor 1996, Taylor and Die 1997, 1999). It is unlikely that this assumption is strictly fulfilled because:

- fishing grounds for tiger prawns extend from as far as Albatross Bay to Joseph Bonaparte Gulf and some of the fishing grounds are separated by large areas where tiger prawns are uncommon
- adult tiger prawns have limited dispersal capacity and larvae seem to depend on tidal currents to travel.

To evaluate this assumption we:

- conducted a study of the spatial distribution of catches from logbooks;
- developed a detailed chart of the fishing grounds from plotter information.

#### Methods

#### Defining stocks from commercial logbook information

Logbook data on catch, effort and CPUE were analysed to describe and map areas of similar abundance. The resulting data were incorporated into a Geographic Information System (GIS). To define hypotheses about possible boundaries of stocks, we used location of seagrass beds, catch and effort location and tagging information from previous CSIRO studies. The inter-annual variability in the average spatial distribution of catch was also investigated to assess the permanence of possible stock boundaries.

#### Defining stocks from commercial fishery plotter information

There are considerable differences in the characteristics of the various fishing grounds within the Gulf of Carpentaria. Somers (1987) showed that the species composition of prawn catches within the western Gulf depends on the characteristics of the sediments. In trying to understand the stock structure of tiger prawns it would be useful to describe, classify and characterise the spatial features of tiger prawn fishing grounds. We did this by:

- describing the fishing grounds from plotter information;
- classifying fishing grounds on the basis of their biological and physical characteristics;
- characterising the complexity of fishing grounds by estimating the fractal dimension of the untrawlable areas.

#### Describing fishing grounds

Plotter data were used to develop detailed maps of the current fishing effort distribution and the area of untrawlable grounds (see below). This information was then used to classify fishing grounds according to their physical and biological characteristics.

Skippers define areas of hook-ups, reefs etc, using particular colours and point symbols on their plotters. The data representing these features were extracted from each skipper's files and then pooled. This was loaded into the GIS as point coverages. To allow for the inaccuracy of the GPS units and the fact that different skippers were sharing data that had not been corrected for different datums (specific cartographical coordinate systems), we decided to assume that the accuracy of the data was within about 200 m. Consequently, we created a grid of 200 x 200 m cell size for the whole NPF. If a point lay within a cell, then the whole cell was regarded as untrawlable.

Skippers use the line drawing facility of their plotters to define closures, steaming tracks, and trawling "paddocks" and to record the direction and duration of a trawl track. This kind of record does not reveal how many times that particular area has been trawled by the skipper, only that he has trawled there at least once. We extracted all these "trawls" from all plotter files provided by skippers and pooled them in the GIS. We converted the lines to points by inserting a point every 200 m along each line. We then created a raster grid (hereafter called the line grid) of 1 nautical mile cell size, the value of each grid cell being equal to the number of points lying within it.

The resulting matrix of untrawlable 200 x 200 m cells and all trawl track information collected were then presented to an experienced fisherman. The fisherman was asked to delineate areas (polygons) that were likely to represent large areas of the fishing ground which can be classified as untrawlable. These areas are not strictly untrawlable since some of the plotter data suggested that occasional trawling was conducted within them. They represent, however, large areas with numerous hook-ups, submerged reefs or obstacles that makes trawling hazardous, thus suggesting that most fishers would not venture to fish within them.

#### Classifying fishing grounds

We examined the relationships between the following variables for each statistical grid square for the period 1993-1996: fishing effort, catch and proportion of each tiger and endeavour species caught within each 6 nm x 6 nm grid square, depth, area of untrawlable ground, index of aggregation of effort and the number of boats that recorded catch in each grid for each year, summed over the 4 years.

We obtained data on catch, effort and the number of boats fishing in each grid square for the grids fished during the period 1993-1996 from AFMA. For each 6 nm x 6 nm grid square the mean depth was calculated using a 30 second gridded bathymetry coverage (AGSO 1998).

The extent of untrawlable ground was estimated using the fishers' plotter data as discussed above. The grid coverage of untrawlable ground was overlaid with the 6 nm x 6 nm statistical grid squares and we calculated the area covered by untrawlable ground within each grid square.

The mean *m* and variance  $s^2$  of fishing effort for each 6 nm x 6 nm grid square were estimated from the 36 values available within each cell. These estimates were then used to calculate an index of aggregation for fishing effort (*AE*) using the following formula:

$$AE = \frac{s^2}{m} - 1$$

To categorise the fishing grounds according to these variables we combined two approaches. Firstly, we performed a cluster analysis using the average-linking method (Proc Cluster, SAS Institute 1997). We also examined the data using principle coordinate analysis. The data were all scaled to range between 0 and 1 by dividing by the maximum value of each variable. The similarity matrix was calculated using Euclidean distance. We chose to cut the similarity scale of the dendrogram of the clusters at a point where there were 9 clusters and then performed an ordination on the results.

In order to determine which of the fishing ground variables were most important in determining the pattern shown by the ordination, we calculated Pearson's correlation coefficients (Sokal and Rohlf 1996) between the first three principal components and each of the variables.

#### Complexity of fishing grounds

Fractal-dimension has been found useful in describing the complexity of random spatial patterns (Taylor and Taylor 1991) including benthic habitats (Schmid 2000). To demonstrate how fractal dimension might be used to define the complexity of fishing grounds, we selected a 1 degree square (60 x 60 nautical miles) to the northeast of Vanderlin Island, in the Gulf of Carpentaria. Areas regarded as reef or rough bottom (untrawlable ground) covered 3.5% of the area selected. The sample area was sequentially divided up into 4, 16, 64, 256, 1024 and 4096 boxes with the number of boxes containing fractal elements being (4, 15, 56, 197, 655, 1908). We then applied two different methods to estimate the fractal dimension (Wang *et al.* 1999, Appendix 2).

#### Relationship between catch rates and distance from untrawlable ground

Large areas of the Northern Prawn Fishery are regarded as untrawlable because of the nature of the bottom. Until the advent of GPS fishers were forced to give these areas a fairly wide berth to avoid hooking their nets up. GPS has enabled fishers to navigate around these obstacles much more accurately and many believe that their catch rates are higher when they fish close to untrawlable ground. We tested this idea by examining the try shot catches of three skippers over 160 nights of fishing. There were 3191 try shots taken from areas across most of the NPF including: Melville Island, Croker Island, Cobourg Peninsula, north, east and south of Groote Eylandt, north of the Sir Edward Pellew Group and north and east of Mornington Island.

We used the map of untrawlable ground derived from the fishers' GPS plotter data and created concentric zones around the untrawlable patches. The zones were defined by their distance from the edge of the nearest piece of untrawlable ground (Table 5.1).

The tracks of the fishers' try shots were loaded into a Geographical Information System (GIS) and overlaid with the distance from untrawlable ground zones (Fig. 5.1). The length of each trawl within each zone was then calculated.

Table 5.1Distances from untrawlable ground used in combination with try shot data to<br/>determine whether catch rates of tiger prawns increase close to untrawlable<br/>ground

Zone	Distance from nearest Untrawlable		
	ground (m)		
1	0		
2	0 - 200		
3	200 - 600		
4	600 - 1400		
5	1400 - 3000		
6	3000 - 6500		
7	6500 - 15000		
8	>15000		

Note that for the analysis, Zones 6, 7 and 8 were amalgamated because of a lack of resolution in the data.

If untrawlable grounds act as local sanctuaries for prawns, which naturally re-populate surrounding areas as depletion by trawling occurs, it is intuitively reasonable to suppose that catch rates should decline as the distance from the sanctuary increases. To investigate this possibility we used a statistical modelling approach with try-net data as follows:

The basic data consisted of try-net catches of tiger and endeavour prawns (in numbers of animals), together with an accurate record of where the net had been trawled during the shot.

The grounds were then classified into zones of increasing distance from the untrawlable grounds (Table 5.1).

For each try-net shot, the distances travelled in each zone are measured and we denote these symbolically by  $Z_1, Z_2, \ldots Z_6$ .

Let Y be the number of prawns caught in the try-net shot. The statistical model we use is now specified as follows. Put

$$h = b_1 Z_1 + b_2 Z_2 + \ldots + b_6 Z_6$$

Then Y has a Poisson distribution with mean h. In addition the coefficients,  $b_k$ , are constrained to be non-negative, for obvious consistency reasons.

This kind of model is called a *Poisson generalized linear model with identity link*, but the constraint on the coefficients to be non-negative makes it a non-standard model. This in turn implies that inference is non-standard and standard techniques such as using standard errors to give an indication of estimation errors may be inappropriate. The coefficients,  $b_k$ , may be interpreted as estimates of the mean catch per unit distance spent in Zone k (in units of prawns per metre). The data came from nine regions of the NPF and the same model was fitted in each of them.

#### Results

#### Commercial logbook information

We analysed the 6 nm x 6 nm AFMA logbook data and defined 7 stock-areas that we consider contain separate stocks of either one or both species of tiger prawns (Figure 5.2). A simpler stock structure hypothesis considers only four stock areas. This simpler structure aggregates NE and SW Groote into a single Groote stock, and North Mornington, West Mornington and Sweers into a single Mornington stock. The four stock areas for the simpler hypothesis are therefore Groote, Vanderlins, Mornington, and Albatross Bay. Stocks were defined on the basis of the distribution of average tiger prawn catches over the period 1973-1993, information on movement of tagged tiger prawns and on species composition from previous CSIRO work done in the mid- to late-1980s. Extensive areas with no catches were considered to be possible stock boundaries. Tag returns were then used to group areas into the resulting 7 stock areas. For simplicity, in areas where the two species of tiger prawns coexist, stock boundaries for the two species were considered to be the same.

#### Commercial fishery plotter information

#### Describing fishing grounds

There are large areas of untrawlable ground in all the main tiger prawn fishing grounds of the NPF with the exception of Albatross Bay (Figure 5.3). The most extensive areas occur in the South and Western Gulf of Carpentaria, although some were identified off the Cobourg peninsula and Melville Island. Some of these areas occur close to the shore, like those off the east and north of Groote Eylandt, east of Gove and the North of Mornington Island. Others, like those west of Mornington Island and North and East of the Vanderlins, are far offshore. The total area of untrawlable grounds identified in the initial analysis of 200 x 200 m cells was 1,707 km<sup>2</sup>. The area of untrawlable ground defined by the expert fisherman was 15,994 km<sup>2</sup>. Of the grids fished in 1995, a total of 14,567 km<sup>2</sup>, or 28.1% of the fished grids were untrawlable (Table 5.2). The proportion of untrawlable ground exceeded 34% in North Mornington (44%), Vanderlins (39%) and West Mornington (35%) (Table 5.2). The proportion of untrawlable ground did not exceed 18% in any other tiger prawn stock area and was less than 10% in Weipa (2.8%) and Southwest Groote (6.2%) (Table 5.2).

Stock	Area (km <sup>2</sup> )		
	1995 fishing grounds	Untrawlable	% untrawlable
Weipa	1,866	52	2.8
Sweers	5,949	959	16.1
N. Mornington	6,532	2,878	44.1
W. Mornington	6,882	2,371	34.5
Vanderlins	15,980	6,241	39.1
SW Groote	4,899	304	6.2
NE Groote	9,798	1,762	18.0
Total	51,906	14,567	28.1

# Table 5.2Area of fishing ground in km² (estimated from the number of 6 nm grid<br/>squares with effort reported in the logbooks during 1995) and untrawlable<br/>areas within them for each stock of tiger prawns

#### Classifying fishing grounds

We restricted the cluster analysis to produce nine clusters because the change in the proportion of the total variance accounted for by creating 10 or more clusters was very small compared to that for 9 clusters.

In general the nine clusters had good geographical cohesion (Figure 5.4) with grid cells belonging to the same cluster occurring adjacent to each other or close together. Clusters 1 and 2 contained most of the observations (407 and 372 respectively), clusters 3 to 6 were much smaller with between 23 and 41 observations while clusters 7 to 9 had between 1 and 2 observations each.

The first three principal components accounted for 78.8% of the variation. The variables that were important in determining the clusters were: the species composition of the tiger and endeavour prawn groups, the amount of untrawlable ground, depth and the index of effort aggregation (*AE*). The separation in the first principal component is driven mainly by the species composition (*Penaeus semisulcatus* vs. *P. esculentus* and *Metapenaeus ensis* vs. *M. endeavouri*) and to a lesser extent depth. The separation on the second principal component axis is caused mainly by the amount of untrawlable ground and the index of effort aggregation (Figure 5.5).

Cluster	Characteristics
Number	
1	Dominated by <i>Penaeus esculentus</i> and <i>Metapenaeus endeavouri</i> Small amount of untrawlable ground Moderate depth Moderate AE
2	Dominated by <i>Penaeus semisulcatus</i> Approximately equal proportions of <i>Metapenaeus ensis</i> and <i>M. endeavouri</i> Small amount of untrawlable ground Deep water Moderate AE
3	Dominated by <i>Penaeus esculentus</i> and <i>Metapenaeus endeavouri</i> Large amount of untrawlable ground Moderate depth Moderate AE
4	Dominated by <i>Penaeus esculentus</i> and <i>Metapenaeus ensis</i> Small amount of untrawlable ground Shallow depth Low AE
5	Dominated by <i>Penaeus semisulcatus</i> and <i>Metapenaeus endeavouri</i> Large amount of untrawlable ground Moderate depth Moderate AE
6	Dominated by <i>Penaeus semisulcatus</i> and <i>Metapenaeus endeavouri</i> Moderate amount of untrawlable ground Deep water Moderate AE

Table 5.3Characteristics of clusters 1 to 6. Only the characteristics that were important<br/>in separating the clusters are detailed here. Clusters 7 to 9 are not shown as<br/>they only have 1 or 2 members. AE = Index of Effort Aggregation

#### Complexity of fishing grounds

The regression method and the Quasi-likelihood method estimated the fractal dimension of the untrawlable grounds to the northeast of the Vanderlin Island to be 1.790 and 1.786 respectively. Although these values are similar, simulation results suggest that such a result may not always repeat itself when the analysis is conducted in other areas of the NPF. In addition, the fractal dimension may be different in other areas of the fishery. Differences in fractal dimension will reflect different levels of complexity and could possibly be related to the productivity of different fishing grounds (Wang *et al.* 1999, Appendix 2).

#### Relationship between catch rates and distance from untrawlable ground

There was no clear evidence of any pattern of decline in catch rate with distance from the untrawlable grounds in any of the regions (Table 5.4). For example, at Cobourg, the estimated catch rates were higher in zones 3 and 4 than in zones 1 and 2 (Table 5.4). They were also higher in zones further away from untrawlable grounds (zones 4 to 6) at Croker and

South Groote than those close to untrawlable grounds (zones 1 to 3). At East Groote, catch rates declined away from zone 2 (Table 5.4).

We conclude that the factors determining catch rates are more complex than the simple model we adopted allow us to uncover. The non-negativity constraint for all coefficients has meant that in several cases the best estimate of the parameter is on the boundary of the constraint at zero. This is again more an indication that the underlying model does not adequately capture all forces being exerted on the catch rate (and hence does not fit), rather than that the catch rate in those zones, for those regions, is truly zero. The best unconstrained estimate for these cases is in fact negative, but that could be corrected if suitable additional determining variables could be measured and incorporated in the model.

 Table 5.4
 Estimated catch rates, in prawns.m<sup>-1</sup>, in six proximity zones to untrawlable ground for 9 NPF fishing regions. - = insufficient data to estimate catch rates.

Zone	Cob- urg	Croke r	East Groote	Melville	North East Vanderlins	North Groote	North Mornington	North Vanderlins	South Groote
<i>b</i> <sub>1</sub>	0.000	0.390	0.486	0.000	0.621	0.496	0.000	0.000	0.000
$b_2$	0.560	0.301	0.590	0.000	0.601	0.527	0.000	0.762	0.291
$b_3$	0.675	0.303	0.321	0.376	0.601	0.338	0.569	0.481	0.444
$b_4$	0.619	0.433	0.219	0.000	0.591	0.467	0.345	0.699	0.573
$b_5$	0.625	0.524	0.000	0.443	0.516	0.520	0.345	0.587	0.555
$b_6$	0.602	0.456	-	0.296	0.397	-	0.382	0.641	0.554

#### Summary

- The analysis of logbook data defined 7 separate tiger prawn stock areas in the Gulf of Carpentaria that contain either one or both species of tiger prawns. Both species are found in the stock areas of North Mornington, Vanderlins and NorthEast Groote; *P. esculentus* was the main species in the stock areas of Sweers, West Mornington and SouthWest Groote; and *P. semisulcatus* was the main species caught in Albatross Bay.
- Analysis of the information from Global Positioning System (GPS) plotters showed that extensive areas of the fishing grounds in the Gulf of Carpentaria are untrawlable (total of 28.1%). The proportion of untrawlable grounds varies greatly between the different stock areas, ranging from less than 10% at Albatross Bay and SouthWest Groote, to greater than 30% at West Mornington, Vanderlins and North Mornington. These areas provide potential refuge areas for prawns and other species from trawling.
- The cluster analysis of tiger prawn catch and effort data separated the fishery into nine groups of grid cells, with two major groups: one consisting of grids along the southern and moderate to shallower waters of the western Gulf with catches dominated by *P. esculentus* and *M. endeavouri*; and the other along the eastern and deeper waters of the western Gulf, with catches dominated by *P. semisulcatus*. Both these groups had relatively small areas of untrawlable ground and a moderate aggregation of fishing effort.
- Techniques to estimate the fractal dimension, or habitat complexity, of trawl grounds were developed and applied to an area northeast of Vanderlin Island. Two methods of estimation gave similar results. Given the differences in the extent of untrawlable ground in different stock areas of the NPF, the habitat complexity is also likely to vary greatly between these areas. The calculation of fractal dimension for different stock areas provides a way of examining the links between habitat complexity and the production of tiger prawns in the NPF in the future.
- Analysis of the relationship between distance from untrawlable ground and the catch in try nets for nine regions did not find a consistent pattern of change in catch rates i.e. there was no evident decline in catch rates away from untrawlable ground.

Figure 5.1 An example of an area in the NPF showing the untrawlable ground and distance from untrawlable ground overlaid with a fishers' tryshot tracks.



Figure 5.2 Tiger prawn stock-areas in the Gulf of Carpentaria, derived from an analysis of logbook data



Figure 5.3 Map of the Northern Prawn Fishery with the extent of untrawlable ground, as obtained from skippers' GPS plotters.



Figure 5.4 Map of the Northern Prawn Fishery and its fishing grounds classified according to a cluster analysis. Due to confidentiality requirements, data have been restricted to display grids where the effort per year is greater than 10 days or the number of boats per year is greater than 5.



Figure 5.5 Plot of the NPF grids fished between 1993-1996 in the space of the first two principal components. Each point is labelled with the cluster number determined in the cluster analysis.



# 6 EVALUATION OF ABUNDANCE INDICES BASED ON CATCH PER UNIT EFFORT

#### Objectives

Catch per unit effort (CPUE) has been used as an index of abundance for tiger prawns in the Northern Prawn Fishery. However, this index is based on the assumptions that both fishing effort and the abundance of tiger prawns are randomly distributed through the fishing grounds. With the advent of new technology, such as Global Positioning Systems (GPS), fishing effort may have become much more concentrated in areas of high abundance within the fishing grounds. In discussions with skippers and industry, changes in fishing patterns for tiger prawns are commonly mentioned. It would thus appear that technological change has already lead to changes in fishing patterns and possibly a greater concentration of effort in smaller areas (especially those in proximity to untrawlable ground). CPUE estimates also depend on the accuracy of the recording of catch in logbooks. Although annual catch estimates are validated with owner returns (Sachse 1994), the size composition information (commercial count) data recorded in the logbooks has never been validated.

In this part of the project, we have studied the detailed spatial distribution of fishing effort and catch so that, in the future, abundance estimates for tiger prawns can be more accurate. The objectives of this component of the project were to:

- determine whether there have been significant changes in the spatial distribution of effort in the tiger prawn fishery
- determine the current pattern of fishing effort
- describe the small-scale spatial distribution of tiger prawn catch
- test whether the information stored in plotters is related to the fishing power of individual vessels
- determine whether commercial count data recorded in logbooks accurately represent weight distributions of the catch

#### Methods

#### Historical changes in the spatial distribution of effort

For a number of years, AFMA logbooks provided room for recording shot-by-shot data. These data contain more precise information on the location of catches than that provided by the compulsory daily reporting collected by AFMA. We surveyed the shot-by-shot data present in AFMA logbooks to assess whether it would be possible to use it to test hypotheses about changes in the spatial distribution of fishing effort.

We also analysed AFMA's daily logbook data. We calculated the annual fishing effort and catch for each 6 nm x 6 nm grid in the fishery, and then estimated two indices to define the extent of the fishing grounds. The first index is based on catch per grid. We ranked all grids according to the annual catch and selected those with the greatest annual catch (referred to hereafter as "most productive grids") that produced 80% of tiger prawn catches. The second

index was based on effort; for any given year we define the area of the fishing grounds as those grids with more than 10 fishing days a year (referred to hereafter as "most visited grids"). In contrast, the area encompassing all grids fished at least once is referred to as the "area searched". We further defined the first year that a given grid became part of the fishing grounds as the "year of discovery" of that grid, and the last year the grid was ever fished as the "year of abandonment". Finally, we defined the "currently fished grids" as the combination of all the most visited grids in the period 1993-1997. We then calculated the catch produced by the currently fished grids during the entire history of the fishery.

#### Current spatial pattern of fishing effort

Plotter data obtained from fishermen were used to develop indices of effort at two different spatial scales. The larger scale index ("plotter effort index") was obtained from fisher's plotter disks where skippers had recorded positions of trawls (1 minute of latitude and longitude). When fishing for tiger prawns, fishers record trawl runs on their plotters using a straight line to define the length and direction of the trawl run. We collated all the fishers' trawl run data and converted it to an arc (line) coverage (ESRI 1995). The arcs were converted to points by creating a point every 200m along each arc for its entire length. The point coverage was converted to a grid of cell size 1' (hereafter called the "line grid"), the value of each grid cell being the total number of points within each cell. The cells of this grid were aligned with the 6 nm x 6 nm grid squares, so that each 6 nm x 6 nm grid square contained thirty-six 1' cells of the line grid. To validate these data, we aggregated the 1' line grid data into the same 6 nm x 6 nm grid used for logbook data. We then estimated the correlation between the 1' plotter data aggregated at 6 nm x 6 nm and two effort indices obtained from logbook data:

- 1. the average number of fishing days per year per grid
- 2. the total number of vessels that visited a grid during the entire period 1990-1994

The smaller scale index ("1-minute effort aggregation index") was obtained from continuous trawl track data collected by fishers while trawling. This trawl track information was collected by fishers with their GPS plotters and processed by us with the method described in chapter 5. Skippers set up their plotters to record the vessel position every minute of time. Trawl track data from two skippers fishing in the Vanderlins region were selected to describe the characteristics of trawl tracks from vessels engaged in tiger prawn fishing. For the analysis, 100 fishing days were chosen at random from all those provided by the two skippers. In order to describe the individual characteristics of these tracks, we assumed that the vessel travelled in a straight line between trawl track points. We also assumed the width of the trawl track to be 40m, the estimated width of the two nets fished by these two boats. We then generated a grid of 1/1000 decimal degrees square (approximately 11.7m by 11.7m) and calculated how many times each of these grids were fished by each trawl track. We also calculated the distance and area covered each day, the minimum rectangular area (parallel to meridians) that encompassed each daily trawl track and the percentage of this area that was actually trawled. From this, the mean track area, mean encompassing area, and mean percent area trawled were calculated.

#### Small-scale spatial distribution of tiger prawn catch

About 40 skippers in the NPF were requested to provide details of their try gear catches and locations but we were only able to collect data from 12 skippers. This information was obtained in two ways – by direct collection by CSIRO staff on commercial vessels, and by skippers recording try gear catches and locations for us. A total of 8 trips, of about 10 days each, were made by CSIRO staff on commercial vessels to collect data.

In all cases, the catch of each species group for each try shot was recorded into a logbook and the vessel track as recorded by the GPS plotter for each night was saved onto a diskette. Each individual try shot on the vessel track was identified by a change of colour on the GPS plot or by event marks on the plotter. The GPS plotter tracks were saved into a separate file for each night for further analysis at Cleveland. Here, the try shot catch data were entered into an Oracle database. The GPS plotter files were checked for errors and, when possible, merged with the try shot catch data.

#### Fishing power and plotter data

The incorporation of GPS and plotters by trawl vessels has increased the fishing power of the NPF fleet by between 4% and 6%; furthermore this increase is related to the number of years during which skippers have used GPS and plotters (Robins *et al.* 1998, Bishop *et al.* 2000). These authors hypothesised that these increases may be at least partially explained by the accumulation of fishing ground information. To test this hypothesis, we quantified the information provided by 27 skippers and related it to the fishing power of their vessels. These skippers represent 20% of the total number of skippers who fished the NPF during 1996 and 1997, the years during which we collected the plotter data. The plotter data consisted of "marks" and "lines". Marks represent such events as gear hook-ups, or the locations of large catches. Lines often represent trawl tracks. The relationship between the number of marks and lines to fishing power was investigated by including these terms in a statistical model of fishing power. The catch of tiger prawns in the tiger fishery of the NPF was modelled as a function of effort, vessel and gear characteristics, skipper experience, plotter data and prawn abundance using a generalised linear model (Bishop *et al.* in prep).

#### Accuracy of commercial count data

Prawns landed from the NPF are size-graded at sea because both the demand and price structure differ for product of different sizes. Commercial sizes are based on the number of prawns of the same size per unit weight (per pound), and the sizes are then grouped in a range to constitute a commercial grade. For this project we examined the data for the two pack sizes that were most commonly used during 1993 and 1994 — small packs (3 kg) and large, variable weight packs (12 - 15 kg). A. Raptis and Sons randomly checks the quality of packs entering their factory, including the accuracy of the grading. This company provided us with data on the percentage by weight that were graded correctly and the true grade of those not graded correctly. We used categorical analysis to test for the accuracy of grading and determine whether there were differences by time period or pack size. Details of the method of analysis and data collection can be found in O'Neill *et al.* (1999) (Appendix 3).

#### Results

#### Historical changes in the spatial distribution of effort

Shot-by-shot data was proven to be inadequate in determining historical changes in effort because there were not enough years of data collection to allow conclusions about changes in spatial distribution to be reached. Data for 1990-1992, however, have been entered into a database. Shot-by-shot data can now be used to determine the precision of daily logbook information. Shot-by-shot data for banana prawns have been analysed as part of the project FRDC 95/15 (Population parameters for Australian prawn fisheries).

The shot-by-shot data for 1990-1992 comprise information on 32,000 trawl shots directed at the capture of tiger prawns, representing 8500 fishing days. Of these, only half contained precise location information. Shot-by-shot data for 1991 and 1992 reveal that most vessels fishing for tiger prawns complete 3 or 4 shots per day (Figure 6.1) and most trawls last between 3 and 4 hours (Figure 6.2). This pattern of fishing differs slightly between the early part of the season (April to June) and the later part of the season (August to November). In the early period, more shots tend to be made but these shots are generally shorter. In spite of these differences average fishing times per day are almost identical in the two parts of the fishing season and average 12 hours. The variance of fishing time is smaller in the second part of the season. This is likely to be the result of the fact that during the early part of the season, some vessels may still be searching for banana prawns but do one or two long trawl shots at night targeting tiger prawns. On the other hand some vessels that have stopped searching for banana prawns can trawl longer because there is no daylight fishing ban, as there is in the second part of the year. This is confirmed by our calculations suggesting that, whereas only 2% of fishing in the second season takes place between 6:00 AM and 6:00 PM, during May and June this percentage is 12%. Overall, however, only 4% of the effort directed at tiger prawns in 1991-1992 was conducted during daylight hours, confirming that the tiger prawn fishery predominantly remains a night-time fishery (Figure 6.3).

Annual catch and effort logbook data distributions for each of the banana and the tiger prawn fishery have been entered in a Geographical Information System (ESRI 1995) for the period from 1970 to 1999. We have prepared maps of catch and effort for the tiger prawn and banana prawn fisheries for every four years for the period 1970-1989 and for every year for the period 1990-1999.

Comparisons of the most visited grids suggest that their spatial distribution does not change greatly between years. Correlations of effort per grid for the period 1990-1994 are between 0.86 and 0.92 (Table 6.1), indicating that during the early 1990s the spatial distribution of fishing effort in the tiger prawn fishery did not change much. This is also obvious when comparisons are made of the spatial distribution of effort only between years of poor recruitment 1989, 1993 and 1996, or between years of good recruitment 1987, 1991, and 1995. On the basis of most-visited grids, the area of fishing grounds has been decreasing since 1981 (Figure 6.4). Most grids were discovered during two discovery periods: 1970-74, and 1979-1982. Only about 4% of the grids have been discovered since 1993 (Figure 6.4). The 424 currently fished grids represent more than 95% of the tiger prawn catches for the period 1993-1997. These grids have also contributed the majority of the historical catches, although in the early 1980s they represented only 60% of the total catches (Figure 6.5).

During the 1980s, between 20% and 40% of the catch was coming from grids that are not being fished today. This analysis suggests that the expansion of the tiger prawn fishery at the 6 nm grid level occurred prior to 1987, with few of the current productive areas being discovered since.

Table 6.1	Correlations of annual effort per grid for the most visited grids (those with an
	average of more than 10 days fished per year) for the years 1990 to 1994.

Year		Ye	ear	
	1990	1991	1992	1993
1991	0.89			
1992	0.87	0.89		
1993	0.86	0.90	0.89	
1994	0.88	0.88	0.91	0.92

#### Current spatial pattern of fishing effort

From the plotter data we have obtained detailed information on the relative intensity and degree of aggregation of fishing effort within trawlable areas by developing a relative effort index at 1' scale (the plotter effort index). According to this index, there is considerable aggregation of fishing effort at scales smaller than those provided by the logbook data (Figure 6.6). Most of the historical fishing effort is highly aggregated although it ranges from being almost randomly dispersed (AE = 0) to very highly aggregated (Figure 6.7). At the 6 nm x 6 nm grid level, the index of aggregation is significantly correlated with the amount of untrawlable ground (R = 0.20, P < 0.001) and with the total catch of tiger prawns for the years 1993-1996 (R = 0.346, P < 0.001), although these factors do not explain very much of the variation. The frequency distribution of aggregation indices shows that there is a wide range of levels of aggregation (Figure 6.7). However, in most areas effort appears to be aggregated to some degree.

Our 1-minute effort aggregation index correlated strongly with the mean number of days fished per grid from the logbooks ( $R^2=0.61$ , n=943, p=0.0001). The correlation with the number of vessels that fished each grid was even greater ( $R^2=0.74$  n=943, p=0.0001). Our 1-minute index probably underestimates fishing effort in grids where a single vessel fishes more than one fishing day because skippers are unlikely to draw repeated lines representing several days of fishing if the shots were made in similar locations. This would explain why the correlation between the effort aggregation index and effort was lower for the mean number of days than for the number of vessels.

Trawl tracks tend to show that fishing effort for individual vessels is highly aggregated over very small areas. Commercial trawlers change their trawling strategy depending on the spatial distribution of prawns. Strategies can change from "pattern trawling", where the vessel "combs" an area by conducting more or less parallel trawl shots, to one of "hot spot trawling" where a vessel keeps targeting a small area by intersecting consecutive trawl shots (Figure 6.8).

The trawl tracks were found to vary in shape, length and degree of overlap. A summary for each of the parameters used to characterise the tracks is given in Table 6.2.

Parameter	Mean	Range
	(± 1 SD)	
Track area (km <sup>2</sup> )	$3.92\pm0.44$	2.04 - 4.71
Encompassing area (km <sup>2</sup> )	$164.8\pm206.2$	112.5 – 1197.2
Percentage of encompassing area trawled (%)	$6.83 \pm 7.58$	0.27 - 34.35
Area passed once (km <sup>2</sup> )	$2.84\pm0.63$	1.09 - 4.07
Track area passed once (%)	$73.0 \pm 16.2$	26.6 - 99.9

Table 6.2Summary of daily trawl track parameters.

On average, a trawler covered about  $4 \text{ km}^2$  of fishing ground per day but roamed around an encompassing rectangular area of 165 km<sup>2</sup> (Table 6.2). This indicates that, on average, they cover an area equivalent to four and a half 6 nm x 6 nm grids. Unfortunately, encompassing area depends on the orientation of the tracks. The largest encompassing areas occur when the track is linear and across the diagonal of the rectangle, the smallest when the track is directly N-S or E-W. The parameter "percentage encompassing area is a function of the orientation of the trawling. Because encompassing area is a function of the orientation of the trawl track, a larger percentage area trawled would be expected if frequent overlapping between trawl tracks is occurring. A better index of trawling aggregation is "percentage of the track area passed once". The lower this percentage, the more aggregated the effort. As the table indicates, some trawl tracks showed almost no overlap (percent passed once = 99.9 %), whereas others showed a considerable amount of overlap (percent passed once = 26.6 %).

#### Small-scale spatial distribution of tiger prawn catch

A total of 586 main gear shots were used in the analysis. Shots from the dawn period have not been used, as catches are often lower at that time, presumably due to the increased light. Only main shots that had more than two try shots have been used. Data are from several areas - Cobourg Peninsula, Melville Island, Groote Eylandt, Vanderlins, Tully, Mornington Island, and Weipa (Albatross Bay). Catch per shot varies considerably between shots in a given day. The standard deviation of catch per shot increases as the mean catch per shot increases and is roughly equal to 1/3 of the mean (Figure 6.9). This suggests that for a fishing night with 3 four-hour shots, the shot with the highest catch would contain about half of the total nightly catch.

Most of the variation between try shots seems to be present at the beginning of the night when skippers are still searching. During the first 1/5 of the night, the average catch retained in try shots represents only 15% of the total nights' try shot catch. During the other 4/5 of the night the catches vary less and are more uniformly distributed suggesting that searching is more limited and skippers settle on fishing in a particular area.

#### Fishing power and plotter data

Our analysis provides evidence that the amount of plotter information is related to the fishing power of a vessel (Bishop *et al.* in prep.). This association was detected by comparing catch rates of different vessels, after removing the effects of effort, vessel size and skipper experience. The amount of lines in the plotter data made no difference to catches on their own, but the number of marks did and the impact of marks was modified by the number of lines. Moderate amounts of marks had more benefits than a large or small number of marks, providing there were low or moderate amounts of lines. These results may reflect differences in the quality of information contained in the marks and lines; that is, a large number of marks and lines may be of less use than fewer but well-organised marks and lines. A large number of marks and lines may also be due to the skipper compiling data from several sources without properly having the ability to interpret the data. This suggests that the amount and type of information stored in plotters at least partially explains the increases in fishing power resulting from the adoption of GPS/plotter technology previously reported by Robins *et al.* (1998) and Bishop *et al.* (2000).

#### Accuracy of commercial grade data

Full details of this work are given in O'Neill *et al.* 1999 and Appendix 3. Of the 21,443 tiger prawns contained in the 293 small-packs (3 kg) assessed, an estimated 1937 (9%) prawns in 229 packs were misgraded. There were significant changes in the proportion misgraded with both period of catch and size grade, with higher proportions of misgraded prawns in the small size grades. Overall, grading accuracy tended to increase over the 18 months examined. Samples from 124 large packs (12 - 15 kg), containing an estimated 8210 tiger prawns, were assessed. Of these, an estimated 2914 (35%) prawns in 107 packs were misgraded. Again, there were significant changes in the proportion misgraded with period of catch and size grade, with significant differences in the proportion misgraded. There was a tendency for smaller prawn grade packs to contain larger prawns. These results show that the information contained in the logbooks is very accurate for those catches that were packed in 3 kg packs but less accurate for those packed in bulk trawler cartons.
# Summary

- At the level of the whole NPF, our analysis of the logbook data shows that the spatial pattern of fishing has changed over time. More areas were fished in the later 1970s and 1980s than are currently being fished. However, on the broad scale, the spatial pattern of fishing has been consistent during the 1990s few new grids have been fished and the most visited grids (with more than 10 days of fishing effort) have been consistent between years.
- The more detailed spatial information collected from GPS plotters shows that within the 6 nm x 6 nm grids (used for recording logbook data), effort can be highly aggregated. The trawl tracks from individual vessels in some areas overlap repeatedly showing targeting on aggregations of tiger prawns. Much of the seabed within grids is trawled only once, or not trawled at all. These results are important for estimating indices of abundance for tiger prawns because previously our indices of abundance have been based on the assumption that tiger prawns are randomly distributed within the grids. They also show that for many grids, the impacts of trawling are significant only in small areas.
- The amount of information stored on plotters was related to fishing power, but not in a linear way. Fishing power was higher with a moderate number of marks on the plotter and a low or moderate number of lines, suggesting that it is better to record smaller amounts of well organised information, than lots of detailed information.
- The assessment of grading information in small (3kg) and large packs (12-15kg) packs revealed that prawns are graded quite accurately in the small, but not the large packs. Most of the errors in grading were for the smaller size grades of prawns. The information from small packs, therefore has potential to provide information on the size distribution of tiger prawns and when small prawns recruit to the fishery. The use of the information on prawn size from small packs as an index of recruitment is explored in Chapter 7.



Figure 6.1 Number of shots per day in the tiger prawn fishery during 1991 and 1992.

Figure 6.2 Shot duration (in 15 minute intervals) of trawls targeting tiger prawns during 1991 and 1992.



Figure 6.3 Percent of trawling that takes place during daylight hours (6 AM to 6 PM), as a function of the month of the fishing season.



Figure 6.4 Number of most visited grids (> 10 fishing days per year), grids discovered and abandoned each year.



Figure 6.5 Total annual catch of tiger prawns and annual catch coming from current fishing grounds.



Figure 6.6 One minute grid of historical effort for the SW Gulf of Carpentaria created from 29 fishers' GPS plotter data. The grid of larger squares represents the scale at which the AFMA daily logbook data is collected (6 nm x 6 nm).



Figure 6.7 Frequency distribution of the 1-minute fishing effort aggregation index for the 6 nm x 6 nm grids that were fished between 1993-1996.



Figure 6.8 Shape of a trawl track from a commercial fishing vessel targeting tiger prawns. Note the degree of overlap that can be seen in the frequency distribution of number of passes.





Figure 6.9 Mean main gear catch per shot as a function of standard deviation of catch per shot.

# 7 ESTIMATION OF SPAWNING STOCK AND RECRUITMENT INDICES

# Objectives

Spawning stock and recruitment indices are essential for the assessment of the productivity and status of fished stocks. Because of the large fishing area covered by the NPF, it is costly and difficult to obtain information about such population indices through scientific surveys alone. Historically, these indices were mainly derived from catch information from the commercial fishery. Somers (1990, 1992) used the total catch as an index of recruitment and the catch per unit of fishing effort during the main spawning season as an index of spawning stock. However, recent work suggests that spawning may be more successful close to the shallow water seagrasses that serve as nursery grounds (Crocos and Van der Velde 1995, Haywood *et al.* 1995, Loneragan *et al.* 1998, Condie *et al.* 1999). In this component of the project we therefore aimed to:

- establish the relationship between the abundance of different life-history stages
- define the effective spawning areas
- identify recruits in the commercial catch

## Methods

#### Relationship between the abundance of early life-history stages

Data from Vance *et al.* (1996b) on the log abundance (average count for each date) of postlarval and juvenile tiger prawns collected from three seagrass sites in the Embley River, were analysed by regression on periodic functions of the day of the year. Full details of the approach are given in Thomas (1995; Appendix 5). A general linear model, fitting effects for year, Fourier component 1 (sin and cosine with v = 1), Fourier component 2 (sin and cosine with v = 2) up to Fourier component 4 (sin and cosine with v = 4), and interactions between year and Fourier component, was used in the analysis. With this method, we were able to test for cycles of different amplitudes and frequencies. Since both amplitude and position of the peaks are non-linear functions of the parameters estimated for the Fourier terms, hypothesis tests and confidence intervals were based on bootstrap distributions. Differences in position and size of the peaks indicate that the pattern of abundance varies from year to year. Histograms and kernel density plots of residuals were produced for each site.

In addition, joint analyses were conducted, combining data from all sites (for those years in which data were available at all sites).

## Defining effective spawning areas

Previous research by CSIRO has shown the importance of postlarval behaviour to the fate of migrating postlarvae. We initially developed a model for Albatross Bay (Weipa fishery region) to study the fate of larvae spawned offshore in the north-east Gulf of Carpentaria. We

extended this work later by developing a second model covering the entire Gulf of Carpentaria.

The Albatross Bay model is a 3-dimensional numerical circulation model, linked to four larval/postlarval behaviour patterns. The spatial grid of the model was of variable size, with the finest grids centred within Albatross Bay. Spawning was considered to occur throughout the Gulf of Carpentaria. It was thought that larvae behave like passive particles in the horizontal plane, but actively swim in the vertical plane. Larvae were considered to have a diurnal cycle, and were found in the surface layer during the night and on the bottom during the day. Larval swimming behaviour changed in shallow waters, becoming cued to the tides. Larvae were found on the bottom during the outgoing tide and on the surface during the incoming tide. Larvae were considered to settle when they reached a seagrass bank. Larval advection envelopes were estimated as the area containing the spawning locations from where larvae successfully settled to seagrass banks. Details of the model can be found in Rothlisberg *et al.* (1996).

The second model, covering the entire Gulf of Carpentaria, was also a three-dimensional model but with a constant-size spatial grid. It was forced by the observed tides across Torres Strait and the Arafura Sea and winds as recorded by the European Centre for Medium-Range Forecasting (ECMF). This model differed from the one for Albatross Bay in that modelled depth was continuous rather than a series of depth strata. Details of the model can be found in Condie *et al.* (1999, provided in Appendix 4). To estimate the relevance of the advection envelopes to determine effective spawning, we overlayed the distribution of spawning with the advection envelopes calculated for a range of postlarval transition depths. For each month, the spawning area for each species was assumed to include all grids with the highest catches in that month and that together comprised 80% of the total monthly catch of that species. Any grid within the spawning region containing at least one of the advection envelope points was then defined as forming part of the effective spawning region.

#### Identifying recruits in the commercial catch

Ideally, an index of recruitment should describe the abundance of prawns recruiting in any particular period of time. Because prawns are short-lived animals, the commercial catch tends to be dominated by recruits. Therefore, the total annual catch is often used as an index of recruitment (Somers 1992).

In the NPF, however, prawn trawlers capture a wide range of different prawn sizes. It would be ideal to estimate the catch of "small prawns" as this should give a much better index of recruitment than the total catch. Commercial grade data recorded by fishers in their logbooks offer this chance. We estimated the catch rate of small tiger prawns (in number of cartons of the 20/30 commercial count category per each 100 fishing days) for each 6 nm x 6 nm grid in the NPF. We then looked at the spatial seasonal and inter-annual patterns in catch rate to see whether they were consistent with the recruitment information provided by scientific surveys.

# Results

## Relationship between the abundance of different life-history stages

Both postlarvae and juvenile prawns show a clear seasonal pattern in abundance, with a tendency towards two peaks per year. Although data are very variable, there is clear evidence that both the overall abundance, and the relative magnitudes of the two peaks vary from year to year. Between year differences cannot be accounted for in terms of within year variability. Years differ not only in the amplitude of the annual cycle, but also in the position of the maximum (Table 7.1 and 7.2, Figures 7.1 and 7.2). Both postlarvae and juveniles show complex inter-annual variation, which cannot be summarised by using a small number of parameters.

This complex inter-annual variation has important consequences for sampling. It is not possible to characterise relative abundance between years based on one or a few sampling periods. Any assessment of relative abundance must be based on a regular sampling frame, with multiple samples taken during the course of each year.

There are large differences in abundance between sites. Both the seasonal effects and year differences vary between sites. These differences cannot be accounted for in terms of sample variability. It also suggests that the establishment of relationships between successive life-history stages is highly dependent on whether the sampling is adequate in defining the pattern of abundance in each life-history stage.

Site	Period 1				Period 2			
	Position of Peak		Size of Peak		Position of Peak		Size of Peak	
	Chi Sq	р	Chi Sq	р	Chi Sq	р	Chi Sq	р
C1	49.85	0.000	27.04	0.000	3.31	0.506	73.54	0.000
C5	133.54	0.000	9.98	0.007	9.58	0.008	13.78	0.000
C11	18.90	0.000	2.62	0.269	6.79	0.033	4.04	0.132

 Table 7.1
 Bootstrap test for size and position of peaks - postlarvae all sites

Table 7.2 Between year comparison of peak location and size - juveniles all sites

Site	Period 1				Period 2			
	Position of Peak		Size of Peak		Position of Peak		Size of Peak	
	Chi Sq	р	Chi Sq	р	Chi Sq	р	Chi Sq	р
C1	12.69	0.026	23.61	0.000	3.70	0.448	49.97	0.000
C5	122.66	0.000	11.49	0.003	9.66	0.008	13.90	0.000
C11	69.47	0.000	10.45	0.005	5.76	0.056	8.02	0.018

## Larval advection model

According to the first model, the areal extent from which larvae are expected to successfully recruit into the estuaries of Albatross Bay varies from 500 to 1500 km<sup>2</sup> depending on the behavioural scenario considered and the month when advection is taking place. More details of these results can be found in Rothlisberg et al. (1996). The second hydrodynamic-larval model has resulted in the estimation of advection envelopes for the Gulf of Carpentaria during 1986 to 1990. As shown by the Albatross Bay model, envelopes were mainly tidally driven, and showed a strong seasonal cycle. In Albatross Bay, for example, the envelope is largest during August and September, whereas in Groote Eylandt it is smallest during these months. For all regions the change in size of this envelope throughout the year approaches a factor of two. Broad-scale winds, in contrast, had little effect on larval transport. As a result, the estimated effective spawning envelopes had low levels of inter-annual variability. However, even small changes in the spatial distribution of the envelope may still have a significant impact on recruitment, depending on how they relate to the distribution of spawners. The absolute size of the recruitment envelope is highly dependent on the transition depth (depth at which prawn larvae switch from a day/night behaviour to a tidal behaviour) used in the simulations. Changing the transition depth from 10 to 20 m increases the effective spawning area by 20%. These changes in the envelope create large changes in the catch of effective spawners (Table 7.3) especially for the 20 and 30 m transition depths (Table 7.3). A much higher proportion of the catch was taken within the advection envelope for *P. esculentus* than P. semisulcatus, except at 7 m when only 2% of the catch was within the envelope for both species (Table 7.3). More details of the results from the second model can be found in Condie et al. (1999) (see Appendix 4).

Species and	Catch (tonnes)	Catch (tonnes)	% of catch	
Transition	within envelope	outside envelope	within envelope	
Depth (m)	_	_	_	
P. esculentus				
7	5	199	2	
15	18	186	9	
20	39	164	19	
30	116	88	57	
P. semisulcatus				
7	11	532	2	
15	26	517	5	
20	60	483	11	
30	163	380	30	

Table 7.3Catch for the two species of tiger prawns in October 1990 within ("effective<br/>spawners") and outside the advection envelope for different transition depths.

## Recruitment index from commercial grades

We have produced maps of average catch rates over the whole year for each year and of average monthly catch rates for the period 1991-1995. The areas of greatest catch rates of

20/30 count tiger prawns are quite consistent from year to year. Highest catch rates were observed at the edge of seasonal closures such as the ones east of Mornington Island. Highest catch rates observed in the period 1991-1995 were those during 1995, the year with the highest catches of tiger prawns in the 1990s (Figure 7.3).

The seasonal pattern is consistent across years with the highest monthly average CPUE at the beginning of each fishing season in May and August, and CPUE decreasing thereafter (Figures 7.3, 7.4). During October and November 1994, CPUE tends to increase as the strong wave of 1995 recruits started appearing in the fishing grounds (Figure 7.4). This result is especially interesting and suggests that the CPUE of 20/30 count during October-November could be used as an index of recruitment for the following year, at least during years when recruitment is exceptionally high. This is in spite of the fact that the fishery is operating during the months of lowest recruitment (April to June and August to November, Figure 7.5) to prevent growth overfishing. The peak recruitment from fishery independent survey data is from December until February (Figure 7.5, Wang and Die 1996, Appendix 6).

# Summary

- The models developed for larval advection provide a way of examining where spawners that contribute to subsequent recruitment to the fishery are likely to come from (termed the 'effective spawning area'). The results of these models are very sensitive to changes in the depth where larvae are assumed to change their behaviour from vertical migration during the night, to vertical migration on the flood tide (the transition depth). Changing the transition depth from 10 to 20 m increases the effective spawning area by 20%. These changes in the effective spawning area create large changes in the catch of effective spawners. For example, if the transition depth was assumed to be 15 m, then only 9% of *P. esculentus* and 5% of *P. semisulcatus* commercial catches were taken in the effective spawning area increase to 19% for *P. esculentus* and 11% for *P. semisulcatus*.
- The analysis of postlarval and juvenile tiger prawn data from the Embley River has shown that numbers are highly variable between years, sampling sites and times of peak recruitment. However, there were two broad peaks in numbers of postlarvae arriving on seagrass nursery habitats in 'spring' (September to December) and 'autumn' (February to May). The reliable sampling of these life history stages to estimate relative abundance, therefore requires intense sampling both in time (at least monthly) and space (a number of seagrass beds).
- The information from the small 20/30 count prawns (recorded in logbooks) shows a peak in catches at the start of the fishing season (April/May) and a secondary peak at the end of the year (October/November). This suggests that the CPUE of 20/30 count can be used as an index of recruitment for the following year, at least during years when recruitment is high.



Figure 7.1 Observed and fitted indices of abundance of postlarvae.

Figure 7.2 Observed and fitted indices of abundance of juveniles



Figure 7.3 Catch per unit of effort (cartons per fishing day) of 20 to 30 count tiger prawns.



Figure 7.4 Monthly average catch per unit of effort (cartons per fishing day) of 20 to 30 count tiger prawns.



Figure 7.5 Weekly recruitment pattern estimated from survey data (Wang and Die 1996) compared with average weekly catch per unit of effort of 20 to 30 count tiger prawns (this study).



# 8 RELATIONSHIP BETWEEN SPAWNING STOCK AND RECRUITMENT

# Objectives

Somers (1992) found a relationship between the catch rates of tiger prawns in October/November and the catch in the following season for the northwestern Gulf of Carpentaria (North Groote). He implied that there was a relationship between recruitment and spawning stock for tiger prawns in the NPF. However, this relationship was never demonstrated outside the North Groote region.

The objectives of this component of the project were to:

- test for the presence of a stock recruitment relationship for tiger prawns in the whole NPF
- test whether this relationship also exists in other regions outside North Groote
- develop a spatial population model for tiger prawn stocks in the NPF

### Methods

#### Stock recruitment relationship for tiger prawns in the whole NPF

We have developed a population model to estimate annual spawning-stock and recruitment indices for the whole of the NPF for the period 1970-1998. This model, which required population parameters such as the seasonal patterns of recruitment and spawning, growth and natural mortality, was fitted to weekly catch and effort for brown tiger prawns (*Penaeus esculentus*) and grooved tiger prawns (*P. semisulcatus*). The tiger prawn catch was estimated by adjusting the reported catch from logbooks to match the total landing from processor's returns. Nominal fishing effort was then calculated by assuming that catch per unit of fishing effort for the entire fishery. Catch and effort data was then split by species by using the procedure described in Somers (1994b) which uses the location of the logbook catch to infer its species composition.

The prawn population model is a generalised version of the traditional virtual population analysis when recruitment cannot be treated as a single pulse. It estimates the number of total recruits (annual recruitment index) required to explain the observed weekly catches. The seasonal pattern of recruitment used to distribute these recruits during the year is fixed as an input of the model together with the natural mortality rate and the growth equation. The effective fishing effort is used, together with given catchability estimates, to calculate the fishing mortality for each week of the time series. Once annual recruitment indices are obtained, the model calculates the abundance of prawns throughout the year. These abundance estimates are then used, together with information on seasonal spawning patterns, to develop an annual index of spawning. Two types of Ricker model were fitted to the data: 1. a Ricker type model with an autoregressive component

$$R_{t} = a_{1}S_{t-1}\exp(-b_{1}S_{t-1}) + c_{1}R_{t-1}, \qquad (8.1)$$

2. a Ricker type model with a cyclical component

$$R_{t} = a_{2}S_{t-1}e^{-b_{2}S_{t-1}} + d_{2}\left[\cos(h_{2}t - k_{2})\right]$$
(8.2)

where  $a_1$ ,  $a_2$ ,  $b_1$  and  $b_2$  are the parameters of the Ricker type model,  $c_1$  is the autoregressive parameter,  $d_2$  represents half of the amplitude of the recruitment cycle and parameter  $h_2$  defines the period of the oscillation ( $2\pi / h_2$ ).

The two models above were fitted through non-linear least squares. The adjusted  $r^2$  for these non-linear fits was calculated as:

$$r_{adj}^{2} = 1 - \frac{(n-1)(1-r^{2})}{n-p}$$
(8.3)

where n is the number of observations and p the number of parameters.

In addition to the above stock recruitment models the relationships between the annual number of recruits and the subsequent number of spawners and level of spawning was also estimated. These relationships were then used to estimate reference points of the productivity of the stock: the maximum sustainable yield (MSY), the biomass at MSY and the fishing effort at MSY  $f_{MSY}$ , by using the methods of Wang and Die (1996) (provided in Appendix 6). The ratios of the current spawning stock biomass to the spawning stock biomass at MSY ( $S_y/S_{MSY}$ ) and the ratio of the current effort to the effort at MSY ( $f_y/f_{MSY}$ ) were then derived as reference points to determine the presence or absence of overfishing. Current biomass and fishing effort were estimated as the average over the last five years, 1994 to 1998.

More details of the model can be found in Wang and Die (1996) and Die and Wang (1998a; Appendix 7).

#### Regional stock recruitment relationships

We investigated the relationship between spawning stock and recruitment indices for regional stocks. The stock boundaries used were those developed in Chapter 5 for the four-stock hypothesis that considered the following four regions: Groote (= NE and SW Groote on Figure 5.1), Vanderlins, Mornington (= W and N Mornington and Sweers, Figure 5.2) and Albatross Bay (= Weipa, Figure 5.2). We attempted to directly estimate the spawning stock - recruitment relationship (SRR) by using indices of spawning derived from the larval advection modelling results reported in Chapter 7.

Monthly larval advection envelopes for the months of August to November, using a transition depth of 15 m, were used to delineate the area of the fishery from where effective spawning could occur (see Chapter 7 and Appendix 4). These envelopes were found to vary little from

year to year and thus could be used as a filter for the logbook data over the period 1970-1997. If any part of a 6 nm x 6 nm logbook grid was inside the larval envelope the catch of that grid was selected to reflect the abundance of "effective spawners".

We used the annual catch in year t for the entire stock area as an index of recruitment. We used the catch and the fishing effort inside the larval envelope for each stock area during the months of August to November of year t-1 to develop spawning stock indices. Several stock indices were used:

- $S_{t-1} = Total catch for months 8-11$
- U<sub>t-1</sub> = Average catch per unit of effort
- $M_{t-1}$  = Average catch per unit of effective fishing effort
- $S_{m,t-1} = Total catch for months m$
- $U_{m,t-1} = Average \text{ catch per unit of effort in month } m$
- $A_{m,t-1} = Average catch per unit of effective fishing effort in month m$

To investigate whether there was any relationship between recruitment and spawning stocks, we used the non-parametric method of Myers and Barrowman (1996). This method tries to answer three basic questions:

- 1. Does the largest recruitment occur when spawner abundance is high?
- 2. Does the smallest recruitment occur when spawner abundance is low?
- 3. Is recruitment greater if spawner abundance is above rather than below the median?

To answer these questions, a series of non-parametric statistics were computed. One of these is the ratio of the largest to the smallest spawning stock, referred to as spawning ratio. This ratio describes the range of observations for the spawning stock. The greater the ratio, the greater the range and also the greater the likelihood that if recruitment changes with spawning stock this will be revealed by the data. Another statistic computed is the median spawning stock that is used to calculate the recruitment ratio; this equals the average recruitment for all years where spawning stock was larger than the median spawning stock divided by the average recruitment for all years where spawning stock was smaller than the median spawning stock. The recruitment ratio is 1 when the average recruitment for large spawning stocks (greater than the median spawning stock) equals the average recruitment for small spawning stocks (smaller than the median spawning stock). Ratios greater than one indicate that recruitment is larger when spawner abundance is large. Finally, two other statistics were computed, the rank,  $R_{max}$  of the spawning stock that corresponds to the largest recruitment, and the rank  $R_{min}$  of the spawning stock that corresponds to the smallest recruitment. These ranks are standardised to the total number of observations *n* to estimate relative ranks,

$$r_{\max} = \frac{R_{\max} - 1}{n - 1}$$
;  $r_{\min} = \frac{R_{\min} - 1}{n - 1}$  (8.4)

The closer  $r_{max}$  is to 1, the greater the likelihood that the largest recruitment occurs when spawner abundance is high. The closer  $r_{min}$  is to 0, the greater the likelihood that the smallest recruitment occurs when spawner abundance is low.

#### Spatial population model for tiger prawn stocks in the NPF

Annual biomass dynamic models (Punt and Hilborn 1996) have recently been applied to tropical penaeid stocks (Haddon 1998, Die *et al.* in rev). These models are the dynamic equivalent of equilibrium production models and therefore implicitly assume the presence of a spawning stock - recruitment relationship. Unlike equilibrium production models, biomass dynamic models acknowledge the presence of time trends in stock biomass resulting from the history of exploitation,

$$B_{t+1} = B_t + g(B_t) - C_t \tag{8.5}$$

where  $B_t$  and  $C_t$  are respectively the biomass and catch in year t and where  $g(B_t)$  is the growth in biomass function, which is often defined by the logistic equation,

$$g(B_t) = rB_t \left(1 - \frac{B_t}{K}\right)$$
(8.6)

where *r* is the intrinsic growth rate parameter and *K* is the average unexploited equilibrium biomass. These models have simple data requirements but have the advantage of providing estimates of current stock status, maximum sustainable yield *MSY* and the biomass required to achieve it  $B_{msy}$ ,

$$MSY = \frac{rK}{4} \qquad ; \qquad B_{msy} = \frac{K}{2} \tag{8.7}$$

We used an observation error procedure (Punt and Hilborn 1996) to fit the catch per unit of effort estimated from the model U to the observed catch per unit of effort-  $U_{y,i}$ . This procedure assumes that the model incorporates all factors controlling seasonal changes in biomass, and that the lack of fit between observed and estimated catch per unit of effort is due to measurement error in the observed catch per unit of effort,

$$U_t = q B_t e^{\eta_t} \tag{8.8}$$

where q is the catchability coefficient and  $\eta_t$  is the observation error in year t. The model parameters for equations 8.5, 8.6 and 8.8 were estimated by maximum likelihood as suggested by Punt and Hilborn (1996). This requires the estimation of the biomass at the start of the time series  $B_0$ .

Annual biomass dynamic models have to be interpreted differently when they are applied to short-lived species, like prawns, than when they are applied to long-lived species (Haddon 1998). For long-lived species, there is an expectation that a large part of the biomass survives from one year to the next. The first term in the right hand equation (8.5) represents surviving animals from the previous year. For short-lived species, there is almost no survival from one year to the next, so the same term must be interpreted as a component of recruitment and growth that tends to replace the previous year's biomass. Similarly, the second term in the equation must be interpreted as the growth and recruitment produced beyond just replacement. In a way, when applied to annual species, biomass dynamic models are

spawning stock - recruitment relationships with an additional component representing catch removals. As a result the estimates of biomass from these models should not be interpreted as the biomass of the stock, but rather the biomass of spawners required to explain the observed changes in annual recruitment. For instance, because prawns spawn during the whole year, spawning output depends not only on the initial number of recruits, but also on how many survive to spawn and on the number of spawning output that could be produced by all females present at any point in time during that year.

We applied this model to data for 1975-1997 for each of the regional stocks mentioned in the previous section and assumed that the stock biomass in 1975 was close enough to the unexploited state so that we could assume that  $B_0 = B_{1975} = K$ . We further assumed that the *r* parameter was characteristic of each species and equal for all the stocks of that species. In doing so we fitted the above models to multiple time series for each species as suggested by Punt and Hilborn (1996).

### Results

#### Two-stock model

According to the population model of Wang and Die (1996), over the last 30 years tiger prawn spawning stocks have decreased by about 60% for both species as a result of fishing (Figure 8.1), from around 50 million individuals to about 20 million individuals for *P. esculentus* and from 16 million to about 6 million for *P. semisulcatus*. Similarly, recruitment has decreased from about 500 million to 200 million for *P. esculentus* and from 350 million for *P. semisulcatus*.

The autoregressive stock recruitment relationships explained 49% of the variation in recruitment for P. esculentus and 35% for P. semisulcatus (Table 8.1). The cyclical model explained a greater percentage for both species – 64% for P. esculentus and 53% for P. semisulcatus (Table 8.1). The improvement in the fit for both species with the cyclical model is because this model makes better predictions of the peaks and troughs since 1977 (Figure 8.2). The amplitude of the cycles for both species was estimated to be 3.6 years. This suggests that every 3 or 4 years there is an expectation of high recruitment. The recruitment cycles estimated for the two different tiger prawn species are also almost in the same phase so that, when recruitment of one species is higher than the recruitment that would have been predicted by the spawning stock in the previous year, the recruitment for the other species is The amplitude of the estimated oscillation is 150 million recruits for also higher. P. esculentus and 85 million recruits for P. semisulcatus. Given that the average recruitment for P. esculentus over the period 1993-1998 was 213 million, this suggests predicted oscillations in recruitment ranging from 138 million to 288 million. Equivalent numbers for P. semisulcatus are an average of 183 million, with oscillations ranging from 141 million to 225 million. These predictions, however, have considerable error and the size of some of the residuals was of the same order as the oscillation. Notably, the model underestimates the recruitment of P. esculentus during 1991 and 1995, the last two years of unusually high recruitment. We used the residuals themselves to estimate an empirical distribution of predicted recruitment for 1999. According to this distribution, there is a 90% probability that the recruitment for *P. esculentus* in 1999 will be between 190 million and 330 million with a best estimate of 245 million (Figure 8.3). This value compares with a calculated recruitment for 1999 of 176 million prawns (Dichmont 2000, provided in Appendix 8). For *P. semisulcatus*, the best estimate is 190 million with a 90% probability of being between 150 million and 250 million (Figure 8.3), which compares with a calculated recruitment of 174 million (Dichmont 2000).

The estimated equilibrium production models suggest that over the last five years, both stocks have been overfished (spawning stocks are below  $S_{msy}$ ) and that overfishing has occurred (fishing effort above  $f_{msy}$ ) (Table 8.2, Figure 8.4). At the end of 1998, spawning stocks remained 23-24% below  $S_{msy}$  and fishing effort was 9% greater than  $f_{msy}$  for *P.semisulcatus* and 19% greater for *P. esculentus*. At the end of 1999, spawing stocks of *P. esculentus* were estimated to be about 40% lower than  $S_{msy}$ , while those for *P. semisulcatus* remained about 20% lower than  $S_{msy}$  (Dichmont 2000).

Table 8.1Estimates of parameters of spawning stock recruitment relationships for tiger<br/>prawns stocks in the NPF. Data correspond to the period 1970-1998.

Species and model		I	Paramete	r		SSQ	$r^2$
Penaeus esculentus							
Ricker, with auto- regressive	a <sub>1</sub>	<b>b</b> <sub>1</sub>	c <sub>1</sub>				
	19.19	-0.01	-0.16			173,744	0.49
Ricker, with	a <sub>2</sub>	$b_2$	$d_2$	$h_2$	$\mathbf{k}_2$		
cyclical	15.06	-0.01	76.34	1.74	5.33	109,747	0.64
Penaeus semisulcatus							
Ricker, with auto- regressive	a <sub>1</sub>	$b_1$	c <sub>1</sub>				
-	46.13	-0.05	0.16			66,645	0.35
Ricker, with cyclical	<b>a</b> <sub>2</sub>	<b>b</b> <sub>2</sub>	$d_2$	$h_2$	$\mathbf{k}_2$		
-	44.18	-0.05	42.85	1.75	5.44	44,238	0.53

Table 8.2 Reference points and stock status indicators for tiger prawns

Species	MSY (tonnes)	S <sub>msy</sub> (millions)	$S_{current}/S_{msy}$	f <sub>msy</sub> (standard boat-days)	$f_{current}/f_{msy}$
Penaeus esculentus	1900	24.6	0.76	7300	1.19
Penaeus semisulcatus	1900	8.6	0.77	10100	1.09

## Regional stock models

Because we have no real knowledge of which spawning index is the most appropriate, we present the results from all possible indices. For some of the region/species combinations (e.g. Vanderlins/ *P. semisulcatus*), not all monthly indices were computed because there were no catches made inside the envelope for certain months.

There was little evidence from the data suggesting that the spawning indices derived from advection modelling explain variation in recruitment as measured by the total catch in each stock region. In general, the relative ranks of spawners for the largest recruitment ranged from 0 to 1 without any suggestion that recruitment tended to be greatest in the years where the previous spawning stock was the highest observed (Figure 8.5). The same result was obtained for the relative ranks of spawners for the smallest recruitment, and there is no suggestion that recruitment was lowest in the years where the previous spawning stock was the smallest observed (Figure 8.6).

The only exception to this is for the situation at Groote, where there is some suggestion that the greatest recruitment occurred when the spawning stock was large in both species (Figure 8.5). There is also a suggestion that, for *P. esculentus* at Groote, recruitment was low when spawning stock was low (Figure 8.6). The recruitment ratio, however, did not depart greatly from 1, suggesting that average recruitment was similar for large and small spawning stocks (Figure 8.7). Still, the values obtained for all non-parametric statistics computed for the regional stocks are comparable to the values obtained by analysing the spawning-stock and recruitment indices obtained in the previous section with the autoregressive model (Figure 8.5, 8.6, 8.7).

## Spatial population model for tiger prawn stocks in the NPF

Biomass dynamic models suggest that substantial decreases in biomass have occurred for all 6 stocks considered (Figure 8.8). This decrease was large during the late 1970s and early 1980s but has slowed down since then. For some stocks (*Penaeus semisulcatus* in Albatross Bay and Groote, and *P. esculentus* in Groote), the average stock size has not changed from the mid 1980s. In other stocks, further decreases occurred from the mid-1980s to the present. Parameter estimates obtained for regional stocks were comparable to those obtained by Haddon (1998) in his single stock model for all tiger prawns in the NPF (Table 8.3). Like the Haddon (1998) parameter estimates, ours have large confidence limits. According to likelihood ratios, approximate estimates of 95% confidence limits for *r* (the intrinsic growth rate parameter) for *P. esculentus* are between 0.01 and 0.5 and for *P. semisulcatus* between 0.01 and 0.65.

Table 8.3Parameter estimates for biomass dynamic models for regional prawn stocks<br/>estimated in this project, and parameters estimated by Haddon (1998,<br/>indicated by \*) for a single stock model of the whole NPF. Values in<br/>parentheses show the 95% confidence limits for *r* estimated from likelihood<br/>ratios. Confidence intervals estimated by Haddon (1998) were obtained by<br/>bootstrap.

Species/group	Stock	r	Κ	q	Log L
			(tonnes)		
Penaeus esculentus Penaeus	Groote Vanderlins Mornington Groote	0.17 (0.01-0.5) 0.24	4330 7684 11801 13744	0.000078 0.000059 0.000029 0.000031	0.76 1.19 1.92 0.77
semisulcatus	Vanderlins Albatross Bay	(0.01-0.65)	7730 2707	0.000042 0.000068	1.10 1.22
All tiger prawns*	entire NPF*	0.50* (0.2 –0.96)*	25016*	0.000027*	20.38*

All regional stocks, with the exception of the Albatross Bay stock of *Penaeus semisulcatus*, were overfished (the stock biomass is below  $B_{msy}$ ) during the period from 1993-1997 (Table 8.4, Figure 8.8). During that same period overfishing occurred (fishing effort above  $f_{msv}$ ) for all stocks with the exception of the P. semisulcatus stock in Albatross Bay and the *P. esculentus* stock in Groote. The total MSY for the 6 stocks considered is 2,434 tonnes. The total  $f_{msv}$  for those same 6 stocks is 13,752 standard boat-days. Both these values are lower than we would have expected given these 6 are the largest tiger prawn stocks in the NPF. Still, it must be highlighted that there is considerable uncertainty associated with the estimates. For instance, if r is set to 0.5, the value estimated by Haddon (1998), the MSY for P. esculentus is 1,443 tonnes and that for P. semisulcatus is 1,848 tonnes. Similarly, fmsy for P. esculentus is 6,324 standard boat-days and that for P. semisulcatus is 9,834 standard boatdays. If we consider that a significant portion of *P. semisulcatus* catches occurs outside the three regional stocks considered, the sum of these values are comparable to those obtained by Haddon (1998). On the other hand, given that there are few *P. esculentus* caught outside the three stocks considered here, the sum of these values is considerably lower than the 2-stock estimate of 1,900 tonnes obtained for brown tiger prawns. Values of f<sub>msy</sub>, however, are comparable to those obtained in the two-stock model.

Table 8.4Indicators of stock status for regional tiger prawn stocks obtained from<br/>biomass dynamic models. Bold type is used to highlight those indicators that<br/>suggest overfished stocks (current spawning stocks below S<sub>msy</sub>) or<br/>overfishing (current standard fishing effort over f<sub>msy</sub>). Results from Haddon<br/>(1998) indicated by \*.

Species/group	Stock	MSY (tonnes)	B <sub>current</sub> /B <sub>msy</sub>	f <sub>msy</sub> (standard boat-days)	$f_{current}/f_{msy}$
Penaeus	Groote	179	0.80	1051	0.65
esculentus	Vanderlins	317	0.68	1409	1.43
	Mornington	487	0.88	2815	1.39
Penaeus	Groote	825	0.65	3897	1.02
semisulcatus	Vanderlins	464	0.91	2825	1.07
	Albatross Bay	162	1.14	1755	0.92
All tiger prawns*	entire NPF*	3608*	0.80*		

# Summary

- Spawning stock recruitment relationships (SRR) have been now defined at two different spatial scales. First, at an NPF-wide scale, SRR have been established for each species of tiger prawns. Second, at a regional scale (using the four regions of Groote, Vanderlins, Mornington and Albatross Bay), the presence of SRR is proposed for individual stocks within the Gulf of Carpentaria.
- The incorporation of cycles of recruitment to SRRs markedly increased the amount of variation explained by the SRR model (by about 15%). The cyclical model provided a much better fit to the data in the high recruitment years of 1991 and 1995, and was used to predict the level of recruitment during 1999.
- SRRs at both scales confirm that the biomass of tiger prawn stocks during 1993-1998 remained below the levels required to produce the maximum sustainable yield, thus suggesting that these stocks were overfished. Similarly, standardised fishing effort for that same period remains above the fishing effort required to achieve maximum sustainable yield, thus suggesting that overfishing continued to occur.
- Spatial analysis suggests that there are differences in the levels of overfishing between regional stocks. The tiger prawn stock in Groote has not recovered from the overfishing that occurred in the early 1980s. The stocks in the Vanderlin and Mornington regions were depleted during the late 1980s as the fishing fleet moved more into those areas in response to the depletion of the Groote stocks.

Figure 8.1 Spawning stocks (millions of spawning females) of *Penaeus esculentus* and *P. semisulcatus* in the NPF, estimated by the model of Wang and Die (1996). Also shown are the spawning stock levels that produce the maximum sustainable yield.



Figure 8.2 Annual recruitment estimates for tiger prawns from the population model of Wang and Die (1996). Also shown is predicted recruitment according to two spawning stock / recruitment relationships, one with an autoregressive component and the other with a cyclical component.



Figure 8.3 Empirical estimates of predicted recruitment for tiger prawns for 1999 from the cyclical spawning stock - recruitment model. Distribution of estimates was directly computed from the residuals of the model over the entire time series 1970-1998.



Figure 8.4 Equilibrium production model estimated from autoregressive spawning stock recruitment relationships for tiger prawns (solid lines). Solid squares correspond to historical observations (1970-1992), open squares to recent observations (1993-1998).



Figure 8.5 Non-parametric statistics indicating whether recruitment is related to spawning in regional tiger prawn stocks. Relationship between relative rank of R<sub>max</sub> and the log ratio of largest to smallest spawning stock. Each point represents a different spawning stock index. If the largest recruitment occurs when spawner abundance is high, relative ranks should be greater than 0.5 and approach 1.



Figure 8.6 Non-parametric statistics indicating whether recruitment is related to spawning in regional tiger prawn stocks. Relationship between relative rank of R<sub>min</sub> and the log ratio of largest to smallest spawning stock. Each point represents a different spawning stock index. If the smallest recruitment occurs when spawner abundance is low, relative ranks should be smaller than 0.5 and approach 0.



Figure 8.7 Non-parametric statistics indicating whether recruitment is related to spawning in regional tiger prawn stocks. Relationship between the recruitment ratio (average recruitment above the median spawning stock divided by the average recruitment below the median spawner stock) and the log ratio of largest to smallest spawning stock. Each point represents a different spawning stock index. If, on average, recruitment is greater when spawning stock is large, the recruitment ratio should be greater than one.



Figure 8.8 Biomass dynamic models for regional tiger prawn stocks. Solid lines represent predicted catch per unit of effective fishing effort, whereas squares represent observations. Broken lines represent the catch per unit of effective fishing effort when the stock is in its virgin state and at the level when it is expected to produce maximum sustainable yields. Fits of biomass model were done under the assumptions that *r* was a characteristic of the species and that the stocks were close to their virgin state in 1975.



# 9 SUMMARY OF RESULTS: PERFORMANCE INDICATORS

# Stock structure and characteristics of fishing grounds

- We used historical GPS Plotter data provided by skippers to map the fishing grounds of the entire NPF management area at a finer scale than that provided by logbooks. The maps contain information on the structure of the fishing grounds (i.e. whether they are trawlable or not) and the relative intensity of fishing effort.
- We have classified the fishing grounds according to their biological and fishery characteristics. This classification was done independently of spatial location but showed that the groups identified had considerable spatial cohesion.
- We have developed a method to characterise the complexity of fishing grounds by fractal geometry. This technique has been applied to one area within the Gulf of Carpentaria and could be extended to examine the relationship between complexity of the fishing grounds and the productivity of tiger prawns in the NPF.
- This study has proposed a new stock structure for tiger prawns inside the Gulf of Carpentaria. Seven new stock areas have been defined NE Groote, SW Groote, Vanderlins, W Mornington, N Mornington, Sweers and Albatross Bay. Some contain a stock of each of grooved tiger prawns and brown tiger prawns (NE Groote, SW Groote and Vanderlins) and some contain only a stock of one of the species (W Mornington, N Mornington, Sweers and Albatross Bay). Although seven stock areas were identified, some areas did not contain sufficient data for detailed analyses of spawning stock recruitment relationships. For this reason, a simpler model of stock structure using four regions; Groote (= NE and SW Groote), Vanderlins, Mornington (= N and W Mornington and Sweers) and Albatross Bay, was used for these analyses

## Improvement of abundance indices

- Historical shot-by-shot data collected in the logbooks were shown to be inadequate for describing historical changes in spatial distribution of effort because of the limited number of years for which these data were collected in the logbooks. These data, however, have revealed that the overall amount of time trawled per day, in the tiger prawn fishery, does not change throughout the season. The amount of daylight trawling prior to the daylight ban was small. Therefore, fishing effort units are comparable between months.
- Analyses of logbook effort data have revealed that the areas of high catches have remained relatively unchanged through the history of the fishery. The area of grounds consistently fished has been decreasing since 1983, whereas the area searched continued to increase until 1987. The area currently fished has also contributed to the majority of the historical catches, although in the early 1980s only 60% of the total catches came from this area. There are large areas that were fished during the 1980s and are no longer fished. Some of these areas have been closed to fishing but most have been abandoned by the fleet and were offshore of the current fishing grounds.

- Analyses of try net data, collected from observers and detailed data provided by skippers, have confirmed a daily pattern of effort where fishers search for areas with aggregations of tiger prawns during the early part of the night. Once these have been located, the vessel stops searching and fishes that same area for the rest of the night. This creates a trend in the average catch rate and variance of catch rate through the night. It also suggests that attempts at describing the small scale pattern of abundance on the basis of fishery data may be revealing differences in fishers searching behaviour through the night and not differences in abundance.
- Analysis of data contained in fishers' plotter disks suggests that the amount and quality of the fishing ground information contained on those disks can explain part of the variation in catch rates observed between similar boats. This supports the hypothesis that one of the main sources of the improvement in fishing power caused by the acquisition of GPS and plotters is the ability to record and use precise fishing ground information.
- Analyses of commercial count data have revealed that grading at sea is very accurate, especially for the small 3 kg packs. Grading at sea data therefore contain very accurate information on the size distribution of prawns caught in the fishery. Commercial count data can therefore be used as size-dependent abundance indices and may provide an estimate of the time and size of recruitment to the fishery.
- Reliable abundance indices for juvenile prawns can only be obtained if sampling effort matches the variability in seasonal dynamics. Our analysis suggests that, because of the large inter-annual variability in the timing and amplitude of seasonal cycles, the development of indices for estimating juvenile abundance requires intense and regular sampling at frequent intervals (more frequent than monthly).

## Improvements of spawning stock and recruitment indices

- We have developed a hydrodynamic larval advection model that predicts the areas from which effective spawning can successfully occur within the Gulf of Carpentaria. These areas change considerably through the season, but there is little inter-annual variability. The extent of the area is largely dependent on the assumptions regarding behavioural changes in postlarval prawns. If postlarvae start cuing on tides only at shallow depths (~7 m), the size of the envelopes is very small and extends only over shallow areas. Only if postlarvae start to cue on tides in deep areas (~30 m) would large areas of the current fishing grounds contribute to effective spawning. We have used these larval advection envelopes and logbook data to estimate regional spawning stock indices for tiger prawns in the Gulf of Carpentaria.
- Commercial count data were very valuable for describing the location and seasonal pattern of recruitment of small prawns to the fishing grounds. Many of the areas identified as recruitment areas are on the edges of current spatial closures supporting the hypothesis that these areas are protecting pre-recruits from harvesting. There is a suggestion that the catch rates of small prawns, as identified in the commercial count data by the 20/30 count category, during October and November can be used to predict the recruitment of tiger prawns in the following fishing season.

# Establishment of spawning stock-recruitment relationships

- Spawning stock recruitment relationships (SRR) have been now defined at two different spatial scales. First, at an NPF-wide scale, SRR have been established for each species of tiger prawns. Second, at a regional scale (using the regions of Groote, Vanderlins, Mornington, and Albatross Bay), the presence of SRR is proposed for individual stocks within the Gulf of Carpentaria.
- The incorporation of cycles of recruitment to SRRs improved the amount of variability explained by the SRR model. The cyclical model was used to predict the level of recruitment during 1999.
- SRRs at both scales confirm that the biomass of tiger prawn stocks during 1993-1998 remained below the levels required to produce maximum sustainable yield, thus suggesting that these stocks were overfished. Similarly, standardised fishing effort for that same period remains above the fishing effort required to achieve maximum sustainable yield, thus suggesting that overfishing continued to occur.
- Spatial analysis suggests that there are differences in the levels of overfishing between regional stocks. The assessments seem to confirm the perceptions of some members of the fishing industry who have suggested that the tiger prawn stock in Groote has not recovered from the overfishing that occurred in the early 1980s. The spatial analysis also suggests that the stocks in the Vanderlin and Mornington regions were further depleted during the late 1980s as the fishing fleet moved more into those areas in response to the depletion of the Groote stocks.
# 10 DISCUSSION

Over the last five years scientists from the NPF fishery assessment group (NPFAG) have advised the NORMAC that tiger prawns were overfished during the 1980s and that as a result the biomass of spawners decreased below the levels that would produce the highest average catches in this fishery, referred to as MSY (Die and Taylor 1996, Die and Wang 1996, 1997, 1998b, Die *et al.* 1997, Taylor and Die 1997, 1999, Dichmont 2000). Furthermore, the NPFAG noted that the fleet restructuring that occurred during the late 1980s and early 1990s only helped to stop further declines in biomass but did not rebuild the stocks nor did it completely eliminate overfishing. Analyses of commercial catch rates (Robins *et al.* 1998, Die and Bishop 1998, Bishop *et al.* 2000) have shown that unregulated increases in fishing power have perpetuated overfishing in spite of the intervention of fishery managers.

Although the analyses that provided the above advice represent the best scientific information available at the time, they were not without uncertainty. The assessment of stock status is a complex procedure that relies on accurate data and detailed knowledge of the dynamics of fishery systems. Even in fisheries like the NPF, where considerable research has been carried out and where substantial commercial and research fishery data exist, it can be argued that data and knowledge are limited. As a result, assessment scientists must make assumptions about what the data really represent and about how the fishery system works. Assessment scientists translate these assumptions into specific components of the mathematical and statistical models that they use to provide advice on the status of fishery stocks.

It was the aim of this project to investigate some of these assumptions and attempt to offer alternative ones when necessary. In that respect the project has succeeded in investigating all the assumptions considered during its development, namely:

- whether it was appropriate to consider that there is a single stock of each species of tiger prawns in the NPF
- whether abundance estimates based on catch per unit of fishing effort were robust
- whether spawning stock and recruitment indices based on logbook catch were appropriate
- and whether it was safe to ignore spatial structure during the assessments of stock status

In addition to extending over a very large area, the NPF fishing grounds are very heterogeneous. They support populations of tiger prawns over areas with different hydrographic, coastal and seafloor characteristics. Our analyses suggest there is enough evidence of regional stock separation, at least at the level that is important to managers. Managers are concerned with stock separation at the time-scales of management intervention (i.e. a few years). At these scales, we have found ample evidence from our life-history studies, spatial distribution of catches and larval advection modelling to suggest that there are several stocks within the NPF. Our analyses of the existing logbook and biological data suggest that they are not able to support assessments of seven stock areas within the Gulf of Carpentaria (NE and SW Groote, Vanderlins, W and N Mornington, Sweers and Albatross Bay), but they are able to support assessments of 4 stock areas (Groote, Vanderlins, Mornington, and Albatross Bay).

It is also clear from our analyses that by ignoring spatial characteristics of the fishery system we ignore some fundamental properties of how the system works and may, as result, incorrectly interpret the information contained in the data that we collect. An example of this is highlighted by our work in describing the small-scale characteristics of fishing grounds. We have shown that the information content of fishery data varies between the different fishing grounds in the NPF. For example, 40% of the area around the Vanderlin Islands is untrawlable ground, whereas only 2% of Albatross Bay is untrawlable. This suggests that prawns are more aggregated in the Vanderlins than they are in Albatross Bay. We would therefore expect that the relationship between catch per unit of effort and abundance to vary between these two areas. In fact, for *P. semisulcatus* there is a strong negative relationship between the total effective stock area for regional stocks (after removal of untrawlable grounds) and the catchability estimated from the biomass dynamic model. The highest catchability is found in the stock that occupies the smallest area (Albatross Bay) and the lowest catchability in the one that occupies the largest area (Groote). This could be the simple result of the fact that the area trawled during each fishing day covers a larger portion of the stock when the stock area is small than when it is large. According to our estimates, a fishing day in Albatross Bay covers 0.2% of the stock area but the same fishing day in Groote or the Vanderlins covers only 0.03 to 0.04 % of the area.

The importance of spatial distribution of fishing and prawns is also highlighted by our work on try net catches which suggests that fishers' behaviour may determine differences in catch rate through the night, rather than reflecting abundance. If searching patterns for tiger prawns differed between seasons or areas, they may result in fishing effort units that are not comparable across either seasons or areas. Our analyses of shot-by-shot data, however, suggest that fishing time does not change considerably between seasons. Still, those analyses provide no information regarding searching behaviour. Analyses have shown that logbook data and plotter data give consistent pictures of fishing effort distribution. Thus, at least at time scales longer than days, logbook data should be adequate to describe fleet behaviour. In fact, Ngwenya (1995) has developed a spatially structured fleet dynamics model that attempts to explain fishing strategies of the NPF fleet at scales between that of a region and a 6 nm grid and at monthly time scales. The model can accurately reproduce the spatial distribution of fishing effort from one year to the next by making use of empirical decision functions developed with historical data.

At larger spatial scales, our analysis of historical logbook data has shown that in the 1990s, at time scales of a few years, catch and effort distribution do not change much. Historically, however, large changes have occurred. In fact, although the current fishing grounds have always been the main source of catch, these grounds contributed to less than 2/3 of the early 1980s catch. We have also shown that most of the losses in catch experienced in the last 15 years have occurred through the abandonment of fishing grounds, rather than through decreased production in those grounds that are still fished. This is an extremely important observation because it generates a population recovery scenario that neither managers nor scientists had previously identified. Under such a scenario, any future increases in catch resulting from effective management should come from areas outside the current fishing grounds. Unfortunately, we have no way of knowing whether such phenomena can take place since there have not been any substantial increases in biomass since the fishery commenced. Nor are there any historical records suggesting that the current fishing grounds have ever

produced more than they are producing today. This suggests two alternative hypotheses. One is that the stock contracts and expands depending on overall biomass. The other hypothesis is that only the fleet contracts, also as a function of overall biomass. Whether one or other of these hypotheses is true may determine how likely it is that the current estimates of MSY are achievable by simple effort reductions.

Our inability to directly identify SRR for regional stocks is not an indication that such relationships do not exist. It is well known that even small levels of variability in recruitment caused by environmental changes can make the statistical identification of SRR a very difficult and improbable task, especially with the non-parametric statistics we used. In addition, the current uncertainty in the postlarval behaviour parameters used in the advection model may not be allowing for the effective use of spawning stock indices. Biomass dynamic models, however, clearly suggest that the existence of a SRR could help explain the history of catches and catch rates observed for each regional stock. We therefore strongly believe that SRR should be used in the assessment of regional tiger prawn stocks.

Our estimates of maximum sustainable yield and fishing effort that should produce maximum sustainable yield are consistent with earlier analyses. Regional biomass dynamic models, however, suggest lower values than those obtained for the two-stock model we have developed or the one-stock model of Haddon (1998). This is even true after adjusting for the fact that our regional analyses did not cover all tiger prawn stocks (those outside the Gulf of Carpentaria and a few of the small ones inside this Gulf were excluded). This may be due to several factors, including the fact that we used a shorter time series (1975-onwards rather than 1970-onwards) because not enough data existed at the regional level in the early part of the fishery. Another explanation is that our best estimates of regional MSY are biased. As we said, if the intrinsic growth rate parameter (r) is fixed to the same value obtained by Haddon (1998), our estimates of regional MSY are more comparable with those from Wang and Die (1996) and Haddon (1998).

In summary, the most important thing that we have learned from this research is that improvements of current assessment models may improve our ability to assess the stock, but will not change the basic assessment of current stock status. Tiger prawns remain overfished and overfishing continues to occur. Our analyses also suggest that lower fishing effort will decrease the possibility of overfishing.

# **11 BENEFITS**

The Northern Prawn Fishery (NPF) and prawn fisheries in general have already been large beneficiaries of this research and most of the results presented here have already been presented formally to the NPF fishing industry and its managers (see list of talks and reports in the reference section of this report). The population models and assessments derived from this project constitute the basis for current stock assessments in this fishery and have been used to provide advice on stock status to NORMAC since 1996. The results of those assessments have strongly influenced the management of NPF stocks over the last few years. Current proposed effort reduction and the special seasonal closures imposed in 1997 and 1999 were consequences of the work conducted in this project.

Our evidence that regional stocks are unit stocks also opens up the possibility of managing certain areas of the NPF as independent units. Interestingly, this same analysis suggests that current management, which is not directed at individual stocks, has lead to comparable exploitation of the different stocks. This may have only been possible because the NPF fleet is very mobile.

The data on the distribution of catch by commercial count were provided to NORMAC and to the NORMAC closures sub-committee to document the importance of some spatial closures in the protection of pre-recruit tiger prawns. This same data may be used in the future to predict years of high recruitment a whole season in advance.

We believe that the characterisation of fishing grounds will be of great use to NORMAC in the future. The data we have generated will help NORMAC participate in the process for development of Marine Protected Areas in northern Australia. Analysis of such data has already shown that NPF fishery data can be used to delineate candidate areas and to assess any negative impacts to the fishery of the designation of Marine Protected Areas. In addition, plotter data have been shown to be very useful as a source of fishery data previously untapped by managers. Analyses of plotter data have also quantified for the first time how information can be a powerful determinant of fishing power. Given that input controls remain the main regulatory instrument used by NORMAC to manage this fishery, input control management will need to consider the possible increases in fishing power that can be associated with further increases in fishing knowledge.

# **12 FURTHER DEVELOPMENT**

We believe that further work in the development of spawning stock and recruitment indices is warranted, especially when the results of a current FRDC project on the behaviour of prawn postlarvae (FRDC 97/108) are available. This study should clarify the process by which postlarval prawns switch from diurnal migration to tidally-mediated movement. We also believe that commercial count data collected by the fishery should continue to be analysed to provide a potential recruitment index, independent of the total catch.

Further development of spatial regional stock models is warranted and is part of the work currently being done as a component of the risk assessment project also funded by FRDC (FRDC 98/109). The current project has already provided the basis for much of the data and knowledge for that project. The risk assessment project will, in addition, incorporate the other main prawn species groups into the analyses.

The work on fishing ground characterisation has opened up a whole new area of work; for the first time there is evidence of areas that may be acting as refuges for prawns and bycatch. Our work has not established whether these areas influence how resilient a stock is to exploitation. However, the results certainly suggest that these areas influence how catchable prawns are. Given the increasingly influential role of biodiversity management in fisheries, and its translation into Marine Protected Area management, it seems essential that research is conducted on the characterisation and dynamics of populations that live within untrawlable areas.

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# **Oral presentations**

Die D.J.	July 1996	Can biological research influence management decisions in a trawl fishery for tropical prawns? The Australian Northern Prawn Fishery. World Fisheries Congress Brisbane, Queensland
Die D.J.	June 1997	Uncertainty in assessments, certainty in management: lessons from the Australian Northern Prawn Fishery. International Symposium on objectives and uncertainties in fisheries management with emphasis on three North Atlantic ecosystems. Bergen, Norway
Die D.J.	June 1997	Status of tiger prawns stocks, BRS Sponsored Northern Prawn Fishery Workshop, Canberra, ACT
Die D.J.	May 1998	Underestimation of fishing mortality in penaeid prawns - another northern cod? Stock assessment workshop on the shrimp and groundfish on the Guyana-Brazil continental Shelf. Georgetown, Guyana
Die D.J.	Nov 1998	Modelling the recruitment of tiger prawn larvae ( <i>Penaeus semisulcatus</i> and <i>P. esculentus</i> ) to nursery grounds in the Gulf of Carpentaria, northern Australia: implications for assessing stock-recruitment relationships. Mini-Symposium of crustacean fisheries experts, Perth, Western Australia
Die D.J.	Feb 1999	Status of NPF tiger prawn stocks at the end of 1998. NPF Fishery forum, Cairns.
Haywood M.D.	June 1997	BRS NPF workshop. Spatial dynamics of effort in the NPF. Northern Prawn Fishery Workshop, Canberra, ACT
Wang Y.	Dec 1997	A quasi-likelihood method for fractal dimension estimation. MODSIM 97. International congress on modelling and simulation, Hobart, Tasmania.

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Taylor B.	Marine ecology: collection of historical plotter data and count data	
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Ngwenya E.	Economics : analysis of fleet dynamics	
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Haywood M.	Marine ecology: field collection and analysis of try-net data and plotter	
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Die D.	Population dynamics: project coordination, analysis of commercial count	
	data and stock recruitment relationships, development of spatial model	
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Bishop J.	Statistical analysis: fishing power and plotter data, logbook database	
Andrewartha J.	Physical oceanography: implementation and analysis of advection model	

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- Appendix 3. O'Neill M.F., D.J. Die, B.R. Taylor and M.J. Faddy. (1999) Accuracy of at sea size grading of tiger prawns in the Australian Northern Prawn Fishery. Fishery Bulletin 97(2): 396-401.
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- Appendix 6. Wang Y. and D.J. Die. (1996). Stock-recruitment relationships of the tiger prawns (*Penaeus esculentus* and *Penaeus semisulcatus*) in the Australian Northern Prawn Fishery. Marine and Freshwater Research 47: 87-95.
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- Appendix 8. Dichmont C. (2000). Status of tiger prawn stocks at the end of 1999. NPFAG Working Paper.

**APPENDIX 1** 

Input controls in Australian fisheries:

Ocean & Coastal Management

the never ending of saga of fleet capacity reductions

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## Abstract

Effort controls are the main management tool in prawn trawl fisheries. Although many management initiatives have been used successfully to adjust certain fishing inputs they have been less successful in achieving adjustments in overall fishing capacity. Continued input substitution allows fleets to counteract attempts by management to reduce fishing effort. We discuss the main paradigms that sustain input control management in the Australian Northern Prawn Fishery, and predict the future need for large fishing effort reductions. We suggest that to achieve these reductions it is more important to have a flexible mechanism for effort reduction rather than the most direct mechanism.

### **Keywords:**

Fishery management, input controls, over-fishing

### Introduction

The three main objectives of fishery management are to ensure the sustainability of the resource, optimize its harvest and allocate it fairly between users. The variety of strategies available to achieve these objectives, however, fall into two categories: input and output controls. The former seek to regulate the type of technology (gear and vessel characteristics) used by fishers, the number of catching units (fishers or vessels), and the time and/or place (fishing closures) when fishing is permitted. The latter aims to regulate the amount (quotas) and type (size, species, reproductive state) of catch taken by fishers. Many fisheries have both input and output controls, but often one of the two controls is clearly the main management tool so a fishery is often referred as either "effort-controlled" or "quota-controlled".

In Australia, few fisheries were "quota controlled" until the late 1980s, when the Australian Government introduced the policy that "ITQs (Individual Transferable Quotas) should be the preferred method of managing fisheries" [1]. Today roughly half of the Australian Commonwealth fisheries are managed by quotas [2]. For the others, control of fishing effort remains the main management tool<sup>1</sup>.

The Australian Northern Prawn Fishery (NPF) has been managed since its beginning by input controls. They have increased in both number and complexity throughout its history (for a detailed review see [3]). When the fishery started, in the early 1960s, the only fishing effort control was the need to hold appropriate licenses. These

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licenses, subsequently denoted B-units, were given to both domestic and foreign vessels. By 1979 the fishery became fully Australian, and all foreign fishing ceased. In the mid-1980s a system of "A-units" was introduced to control the under-deck tonnage and main engine horse power. The number of A-units was cut in the late 1980s and early 1990s to reduce fleet capacity. First a voluntary buy-back of A-units was introduced; later a compulsory buy-back of units was imposed. As a result the number of A-units was reduced by 60%, from a high of 133,000 to the current 52,000. B-units were similarly reduced from 292 to 128. Controls on gear were imposed in the late 1960s: a minimum cod-end mesh size and limits on headrope length. In the late 1980s vessels were restricted to two trawl nets each.

The NPF is about to change its system of A-units and replace it by a system of gearunits. These units will regulate the amount of total headrope towed in the fishery rather than the power and size of its vessels. This change is to be accompanied by a reduction in fleet capacity of about 12.5 %, to be achieved by allocating 15% fewer units of net than those presently used in the fishery. This reduction is being used to offset improvements in efficiency that have increased effective fishing effort.

Fishing closures were imposed much earlier than any other input control, initially to prevent growth overfishing (capture of small prawns before they reach their optimum size). At present there is a very complex set of fishing closures. These range from shallow-water permanent closures protecting nursery habitats; seasonal and seasonal-

spatial closures preventing growth overfishing; seasonal closures to reduce fishing mortality on pre-spawners; to daytime closures to reduce fishing effort.

Clearly input controls are the main management strategy in the NPF – but why? Why has the shift in Australian fisheries policy from input controls to output controls not been applied to this fishery, the most valuable of all fisheries managed by the Commonwealth of Australia? To start answering this question we should look at the reasons why output controls, and more specifically ITQs, were chosen as the preferred management tool by the Australian Government. According to the document describing this shift in policy [1], ITQs provide: "autonomous adjustment of fleet and fishing operations" so "less efficient operators leave the fishery, which reduces total fishing capacity". ITQs "give the individual operator much greater opportunity to take advantage of favourable market conditions" and "total allowable catch (TAC) can be readily adjustable to prevent biological over-exploitation".

Output controls were not imposed in the NPF because of:

- the difficulty of determining quotas for stocks of "annual" species such as prawns,
- the cost of surveillance in such a remote area of Australia,
- and the likelihood of discarding of small prawns in favour of large prawns [3].

The document implies that the option of output controls for the NPF was rejected because of the difficulty of defining and policing a system based on total allowable

catch, not because the objectives of Government were different in this fishery. Presumably then input controls were considered to be appropriate for achieving the Government's objective regarding the NPF. Have they worked? We will first investigate the historical performance of these controls and later look at the challenges created by their continued use. To start we examine in detail the performance of each of the four paradigms that traditionally support input control strategies:

- fishing impacts the long-term productivity of fish stocks,
- the catch is a function of fishery inputs,
- managers can control fishery inputs and
- managers can determine the amount of inputs required to achieve management objectives.

## Does fishing impact the long-term productivity of NPF prawn stocks?

For the purposes of stock assessment the Northern Prawn Fishery is partitioned into two fisheries: the banana prawn fishery and the tiger prawn fishery each providing about half of the total NPF catch. Banana prawns are fished mainly during the daytime when vessels target highly aggregated stocks [8] whereas tiger prawns are caught mainly at night. A fishing day is considered part of the banana prawn fishery if half or more of the total prawn catch is made of banana prawns or if the total prawn catch is zero (the trawler was searching); otherwise it is categorised as being part of the tiger prawn fishery. Incidental

catches of other commercial species of prawns, other crustaceans, squid and some fish are taken in both the banana prawn and the tiger prawn fisheries [4]. Formal stock assessments, however, have only been carried out for banana prawns and tiger prawns. These two species groups have, until now, been the focus of all NPF management decisions.

White banana prawn stocks in the Northern Prawn Fishery were assessed as fully exploited in the 1970s [5] but no evidence of recruitment overfishing (reduction in the average number of recruits caused by excessive fishing on the spawner stock) has been found then or since<sup>2</sup>. The estimated median catch over the last 25 years, 4000 t, is used as the target long-term annual catch for management purposes [6]. However, there are large year-toyear variations in annual catches (between 2000 and 14000 t), associated with fluctuations in rainfall in the catchments upstream from the estuarine prawn nursery areas [7] (Figure 1). The fishery for red-legged banana prawns has only recently started to receive attention of managers and scientists, because the NPF catch is between 200 to 1000 t a year, which is a small component of the total catch of prawns<sup>3</sup>.

The first stock assessments of tiger prawn stocks made in the late 1980s suggested [9,10], but did not prove, that the decline in annual catches observed in the mid-1980s was caused by recruitment overfishing. This suggestion, together with the economic problems created by fleet over-capacity, lead to the reduction in fishing effort reductions in the late 1980s and early 1990s. More recently, clear evidence has been obtained of the recruitment

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overfishing of both brown tiger prawn and grooved tiger prawn stocks. Reductions in recruitment observed during the 1980s were indeed caused by reductions of the spawning stock of both species<sup>4</sup> [11].

In summary we can say that there is evidence that fishing affects the long-term productivity of tiger prawns, but so far there is no evidence of an impact on banana prawns.

## Is the NPF prawn catch a function of fishery inputs?

It is clear that, as the NPF fleet grew, catches also grew. However, from very early on it was obvious that these increases were not proportional, especially for banana prawns. In fact previous work suggests that the capacity to harvest the entire annual stock of banana prawns was reached very early in the development of the NPF [5] and that catch fluctuations were mainly due to the environment rather than changes in inputs [7]. Later increases in effort, did not increase the capacity to catch banana prawns, but rather, shortened the season during which the stock could be captured. In the tiger prawn fishery, the first signs of a change in the rate of increase in catch did not appear until mid-way through the 1980s. By then, the reductions in tiger prawn recruitment caused by excessive fishing effort had created an over-capacity problem much more difficult to solve than the one experienced in the preceding decade in the

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banana prawn fishery.

Most of the variation in annual catch in the tiger prawn fishery can be explained by changes in fishing mortality and in recruitment [11]. Increases in fishing mortality were estimated from the observed fishing effort by assuming that the fishing power of the NPF fleet increased by 5% per year (a rate calculated from changes in swept area between 1979 and 1986 [14]). The use of Global Positioning Systems (GPS) alone increased fishing power by 12% over the five years from 1988 to 1992 [15]. Other factors, such as try-net<sup>5</sup> configuration, changes in hull material and shape, engine derating<sup>6</sup> and kort nozzles<sup>7</sup> further increased fishing power [16].

The more recent increases in fishing power attributable to measurable factors can be estimated from the coefficients estimated by other authors [15], some vessel characteristics and the annual fishing effort of each vessel. The result of this analysis suggests that the fishing power increases that can be estimated were: 2% a year between 1988 and 1992; 5% a year between 1992 and 1993; and 1.5% a year since then (Figure 3). This equates roughly to a minimum 2.5% increase per year over the last nine years. It is a minimum estimate because we have no data on other sources of fishing power increases. To accommodate the underestimation and uncertainty in these analyses, and to be precautionary in the management, a 5% annual rate of increase in fishing power is used by scientists during the assessments of this fishery [6, 12].

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Clearly, fishery inputs affect the catches in the tiger prawn fishery. The influence of specific fishery inputs has been well studied in this fishery, but not in the banana prawn fishery. The current perception that the banana prawn fishery is not affected by present fishing practices has resulted in a failure to collect information on how specific inputs affect the catch in that fishery.

## **Can NPF managers control fishery inputs?**

Throughout the 1960s and 1970s, the NPF was managed with minimal controls. The first interim management plan, developed in 1977-1979, limited entry to control overcapitalisation in the fleet. Unfortunately, the need to establish fair entry criteria led to a rush of license applications; by the time the plan was ratified, the number of licenses had grown to 292, although only 145 trawlers had fished in the previous year [3]. The plan allowed vessel licences to be transferred on a like-for-like basis but with a generous 25% tolerance allowance on the comparison of vessel characteristics. These conditions allowed progressive increases in the size of vessels, which subsequent reviews of the plan attempted to control by tightening the input controls. Succesive strategies were tried, each falling short of the fishing effort reduction targets (Table 1). In the end, after only partly successful changes in the vessel replacement conditions and two voluntary buy-back schemes, NPF managers reluctantly agreed to a compulsory surrender of A-units. This surrender happened in 1993, and the fleet was finally reduced to the current 128 vessels.

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The removal of vessels through the buy-back schemes of the 1980s and 1990s cost A\$43 million, of which industry paid more than 80%. Although ultimately successful, the compulsory buy-back of 1993 showed the problems of forcing adjustments based on A-units. As all vessel owners had to surrender 30% of their units, most owners had to decide wether to buy more A-units or leave the fishery; reducing vessel tonnage and/or engine horsepower by 30% was impractical and costly.

The difficulties of a buy-back forced on industry prompted management to consider new options for future effort reductions. After extensive consultation NPF managers, agreed in 1998 to replace the system of A-unit by one based on tradeable gear-units (headrope). The new system will, in theory, enable managers to gradually adjust vessel configuration to accommodate reductions without compromising the vessels' ability to keep fishing<sup>8</sup>. The introduction of this new gear-unit system will also be accompanied by an overall reduction of 15% in the total pool of gear towed, to meet the recommendations made by scientists and to further reduce fishing effort in the tiger prawn fishery. However, some sectors of the NPF fishing industry are resisting adopting this new system. They perceive it will reallocate fishing rights away from the smaller operators to the larger vessel operators. Allocation problems resulting from management changes are not uncommon in fisheries, including tropical prawn trawl fisheries [17].

Can NPF managers determine the amount of inputs required to achieve management objectives?

The initial biological and economic objectives of the first NPF management plan were not expressed in quantitative terms. During the buy-back schemes of the late 1980s, however, managers chose clear targets for A-unit reductions: in 1987, a target of 70,000 A units was set, and in 1989 it was set at 50,000 A-units. The process of translating vague management objectives into precise effort targets probably caused the most problems for NPF managers. This process involved negotiations between industry and government within the northern prawn management advisory committee (NORMAC). Scientists provided information pointing to signs of recruitment overfishing in the tiger prawn fishery [9], although their advice was not clear cut and was vigorously disputed by some sectors of the fishing industry. The government finally agreed to implement the package of effort reduction mostly on economic grounds — to reduce fleet over-capitalization. The judicial process of appeals, however, ensured that the 50,000 A-unit target was only partly met, and by 1996 there were still 52,000 active A-units .

The processes of fishery assessment and development of management strategies are intrinsically linked, and both NORMAC and the NPF Fishery Assessment Group (NPFAG) have negotiated a framework for evaluation of management strategy<sup>9</sup>. This framework specifically aims at developing agreed reference points and procedures to deal with the main uncertainties in stock assessments.

After the experience of the buy-back years, when there were no clear quantitative management objectives, NORMAC and the NPFAG have been trying to develop quantitative reference points for all its management objectives. In 1997 NORMAC agreed to targets for spawning stock status (spawning stock at MSY,  $S_{msy}$ ) and effective fishing effort (fishing mortality at MSY,  $F_{msy}$ ). There are still discussions within NORMAC and the NPFAG on whether these should be considered limit or target reference points. In fact such discussion remains irrelevant while both indicators have been exceeded: current spawning stock biomass is below  $S_{msy}$  and current fishing mortality is above  $F_{msy}$ . NORMAC is trying to overcome this problem but the new effort-reduction package recently negotiated will achieve only half of the reduction recommended by the FAG.

In the assessment of tiger prawn stocks, one of the main sources of uncertainty is the annual rate of increase in fishing power. We can obtain minimum and retrospective estimates of this rate, but canot predict what this rate may be in the future. NORMAC's and NPFAG's solotion has been to negotiate the use of an annual rate of 5% in all tiger prawn stock assessments. When, and if, new information suggests this value is not appropriate it will be changed again through negotiation.

NORMAC is developing reference points for other prawn species and has started developing indicators for bycatch. For example, NORMAC has set an objective of reducing the bycatch of sea turtles to 5% 1989 bycatch.

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The only quantitative reference points currently in operation for prawns are those for tiger prawns. For all other prawn and bycatch species there is still a wide gap between the information collected by scientists and that required by managers to determine the appropriate level of fishery inputs.

### The future: How many boats?

We will now try to review the major challenges for NPF managers and to predict how input controls may be used to meet these challenges. Assessments suggest that the current fleet can produce 25% more effort than is required to achieve MSY. Furthermore, if the annual rate of increase in fishing power does not slow down, it is predicted that this excess capacity will increase by 5% every year. This implies that in the future there will be a need to continually reduce fleet capacity and presumably decrease the number of vessels. Nobody wants to believe, however, that ultimately a single boat will be able to harvest all prawns in the NPF. There must be a limit to the capacity of the fishing industry to keep increasing the fishing power of their vessels! What are the views of scientists and the fishing industry on this? How many boats can we expect to have in the NPF in 20 years time? We now present how the two respective authors answer these questions.

• The view of a scientist

To determine the optimum number of boats required in 20 years time, the most important parameter required is how much the fleet can increase fishing power in those 20 years. We can look at the likely extreme scenarios – no change and same change as in the past (5% per annum) – equating to a range in fleet capacity between today's fleet and a fleet 2.65 more efficient than today's. If we accept the current assessment that today's fleet has already 25% excess capacity, this suggest that the optimum capacity required in 20 years is anywhere between 33% and 75% of today's fleet capacity. With the current mix of vessels this would equate to a fleet of between 43 and 97 vessels.

These calculations have considerable uncertainty, most notably due to the effect of accumulation of change in fishing power over the next 20 years and the current status of stocks. We used MonteCarlo simulation<sup>10</sup> to estimate the uncertainty associated with this prediction by simply looking at the uncertainty in the values of fishing effort at MSY for the two tiger prawn species and the uncertainty in the accumulated change in fishing power after 20 years (Table 2). The simulated distribution (Figure 4) of the optimum number of vessels in 20 years ranges between 50 and 120 vessels with a median of 70. According to this distribution there is an 80% chance that the number of vessels in 20 years should be less than 84, and a 95% chance that the number should be less than 100 boats. Almost 90% of the uncertainty in the appropriate number of boats is associated with the uncertainty in the future increases in fishing power. The current status of stocks contributes the rest of the uncertainty.

### • The view of a fisher

We assume that a single industry owner was given exclusive fishing rights to the resources in the NPF. These rights, however, would be constrained by the requirement to achieve ecologically sustainable development and maximise economic efficiency. How many boats would the owner require in 20 years' time to harvest the MSY levels estimated by scientists? The industry owner's main consideration when making this calculation is to ensure maximum and sustainable prawn production. Maximum sustainable production creates the incentive for the owner to act as a full steward of the stock and to make long-term investment decisions in crew training, market development and efficiency in fishing operations.

We assume the owner agrees with scientific advice on the current status of prawn stocks and the variability of recruitment. The single most important factor in determining an individual vessel's profitability is how much catch it takes each year. If the owner were to try to maximise the profit per boat, then the owner should reduce the fleet dramatically to, say, 6 or 10 boats. Unfortunately this would be likely to reduce "fleet searching-tactics" and "within-fleet competition", two factors that tend to increase fishing performance and therefore enhance efficiency. Therefore maximising profits at the single-vessel level can actually lead to decreases in the effectiveness of overall fishing operations and does not return the maximum benefit from the resource.

To evaluate how to achieve maximum profits for the whole fishery, the industry owner would have to consider a number of variables such as the cost of fuel, efficiency of the fleet, market condition and exchange rates as well as long-term access rights and environmental considerations. Other variables would bear upon judgements about the future; for example the potential for technological innovation in catching, the resilience of the market, the status of the prawn stocks and the variability in catches from season to season. The market economy would drive the operator to make the best use of capital and labour and therefore the fleet would be consist of fewer boats working for a greater part of the year. Ultimately the owner will try to maximise the profit derived from his capital and operating inputs, subject to some operational and social constraints.

However, is very difficult to develop a quantitative model that explicitly includes all these variables. Often, the industry owner will simply avoid complex modelling and take an adaptive approach based on experience, intuition and judgement. According to such an approach, we believe that the fishery should have 80 vessels in 20 years time, although technological advances could lead to an even smaller number of vessels.

### Conclusion

Management of a fishery like the NPF remains a difficult task in spite of the valuable experiences gained in the last 20 years. Input controls are likely to remain as the preferred management tool for this fishery. In practice, however, management through input controls continues to be hampered by the difficulty of implementing the Die D. J. And D. Carter Input controls in Australian fisheries....

controls, the uncertainty associated with biological stock targets and the growing fishing power of the fishing fleet [18, 19].

Two of the four paradigms that are conditions for the management through input controls, discussed in the introduction, clearly apply to the NPF: fishing does impact prawn stocks and the prawn catch is a function of fishery inputs. The other two paradigms, managers can control inputs and determine the appropriate level of inputs, also apply to the NPF but more loosely. Firstly, managers have had some success in controlling inputs, but at very high costs to the industry and the government. In spite of this fishing power and thus effective fishing effort continues to increase. Secondly, defining the amount of these inputs required to achieve the management objectives has not been easy and is still the subject of some contention in sectors of the fishing industry. The partial failure of accepting all four paradigms of input controls has clearly contributed to the difficulty of implementing input controls in the NPF. In the last five years, this has led to tiger prawn stocks again being overfished, despite a very successful effort reduction strategy between 1987 and 1993.

It is encouraging that the views of a scientist and a fishing industry representative are similar in respect to the most likely reduction in fleet size that will be required in 20 years time. Although scientists specifically acknowledge the high uncertainty associated with their predictions, we expect if all members of fishing industry were canvassed on the same question, their predictions would also acknowledge a considerable level of uncertainty.

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The greatest uncertainty facing this fishery, however, is clearly not the status of stocks but rather the extent to which the fishing industry can increase its fishing power in the future. If fishing power continues to increase in the next two decades at the rate estimated for the last 20 years, managers will need to reduce effort again by as much as 50%. The uncertainty regarding the status of prawns stocks is bound to lessen as science refines its methods and as new data become available. The uncertainty about the future changes in fishing power, however, is unlikely to be reduced by the passage of time. Managers must, therefore, face the fact that long-term predictions for effort reductions will be difficult to make. It seems, then, that having the most flexible tool for adjusting fishing effort may be a greater priority than having the most direct tool. Hopefully the new system of gear-units be more flexible than the current A-unit system.

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### Footnotes

<sup>1</sup> Responsibility for management of Australian fisheries is split between the federal and state governments through an agreement that allocates each fishery to the jurisdiction of either the state fishery agencies or the Commonwealth government's Australian Fishery Management Authority.

<sup>2</sup>Recently [8] it has been suggested that the schooling behaviour of common banana prawns makes the model used to assess common banana prawn stocks [5] inappropriate for this type of fishery. There are suggestions that the hypothesis that fishing effort has had no impact on the long-term productivity of white banana prawn stocks should be retested [6].

<sup>3</sup> Current research (David Die, CSIRO unpublished data) suggests that the stock is lightly fished, partly because it is easily accessible to the fleet only during the neap tides, and partly because it is in the most remote and least accessible area of the NPF, in the Joseph Bonaparte Gulf. Annual recruitment, however, seems to fluctuate widely, as does that of common banana prawns. The reasons for such fluctuations are unknown.

<sup>4</sup> The ratio of current biomass to biomass at MSY for both species of tiger prawns is 64% according to results from a biomass dynamic model [13]. The ratio of recent spawning stock index to spawning stock index at MSY estimated is 75% for brown tiger prawns and 79% for grooved tiger prawns (Figure 2) [6,12]. These two sets of
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results have confirmed that tiger prawn stocks in the NPF remain presently overfished.

<sup>5</sup> Try-nets are small otter or beam trawls used ahead or between the main nets to sample the catch and adjust the fishing strategy.

<sup>6</sup>Engine de-rating is the practice of obtaining certificates from engine manufacturers that underestimate the real power of engines. It allows the vessel owner to allocate fewer A-units for the operation of a given vessel.

<sup>7</sup> Kort nozzles increase the thrust produced by the propeller.

<sup>8</sup> Under the current A-unit system any reductions in the total number of A-units will force an owner of a single vessel to stop fishing or purchase more A-units. A similar reduction under the new gear-unit system will let owners fish, but with a smallersized gear. They will not need to sell or re-invest at every effort adjustment.

<sup>9</sup> In 1994 the Australian Fisheries Management Authority established a structure of technical Fishery Assessment Groups (FAGs) to advise each of the fishery Management Advisory Committees (MACs) the status of Australian Commonwealth fisheries. Both the MAC and the FAG have representatives from government, industry and science, but the balance of science and industry is heavily weighted towards science in the FAG and towards industry in the MAC. The main purpose of the FAG is to assess the status of the fishery, and of the MAC to develop management Die D. J. And D. Carter

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strategies. Ultimately it is the role of AFMA to make the decisions and implement any management recommendation made by the MAC.

<sup>10</sup> For convenience, given the lack of knowledge on the probability distributions of any of these parameters, we used triangular probability distributions for all three parameters in the prediction model. Furthermore in the 1000 simulations we assumed there was a 0.8 correlation between the values of  $F_{msy}$  for the two tiger prawns, as it seems that these parameters are strongly correlated [11].

# Table 1.History of main input controls introduced in the NPF. Several seasonal<br/>and spatial fishing closures have been also introduced in the NPF, some<br/>with the specific intention of reducing fishing effort. These closures are<br/>not included in the table.

Year	Input control	Benefits and problems
1977-79	Limited entry - license moratorium	Increase in number of licences as newcomers ensure they establish a stake in the fishery
1980	Vessel licenses (B-units) are transferable like for-like-with 25% tolerance. Vessels <21m can be replaced by boats up to 21m.	Increase in the size of vessels
1985	A-units (under-deck tonnage and engine horsepower) introduced	Vessels hulls modified and engine de- rated to minimise A-unit
1986	Two-for-one A-units when vessel replaced by larger vessels (>375 A)	Small reduction in vessel numbers
1987	Two-for-one vessel licenses (B- units) required upon replacement	Small reduction in vessel numbers
1985- 1989	Voluntary buy-back	License prices sky-rocket; small reduction in vessel numbers (-25%) and total fleet capacity (-15%)
1991- 1992	Accelerated buy-back	25% of capacity removed, fleet reduced by 30%
1993	Compulsory buy-back	30% reduction in capacity
1998	A-units replaced by gear-units	
1999	Reduction in gear-unit pool by 15%	• •

Table 2:Estimates and probability distributions of parameters used to estimate the<br/>optimum number of vessels to be operating in the NPF in 20 years time.<br/> $F_{msy}$  is the standardised fishing effort that would on average produce<br/>maximum sustainable yields.

Parameter	Estimate	Distribution	Minimum	Maximum
F <sub>msy</sub> Brown tiger prawn (boat-	7150	Triangular	6150	8150
F <sub>msy</sub> Grooved tiger prawn (boat days)	9660	Triangular	7660	11660
Current standardised fishing effort (boat-days)	16810	-		
Annual increase in fishing power (percent)	1.8	Triangular	1	2.65

- Figure 1: Observed catches of common banana prawns in the southeastern Gulf of Carpentaria (circles) and mean predicted catches (solid line); and 95% confidence intervals (shaded) according to rainfall model [7].
- Figure 2: Spawning stocks (millions of spawning females) of brown and grooved tiger prawns in the NPF. Also shown are the spawning stock levels that produce the maximum sustainable yield [6,12].
- Figure 3: Estimated change in fishing power (dots) caused by adoption of GPS and increases in gear and vessel size. Other factors increase fishing power, so the total average annual increase is estimated to be 5% (solid line).
- Figure 4: Estimated number of fishing vessels required in 20 years' time to maintain standardised fishing effort at the level that would produce maximum sustainable yields. Results are from 1000 MonteCarlo trials that incorporate uncertainty in the current status of tiger prawn stocks and the future annual increase in fishing power.











**APPENDIX 2** 



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### A quasi-likelihood method for fractal-dimension estimation

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#### Abstract

We propose a simple method of constructing quasi-likelihood functions for dependent data based on conditional-mean-variance relationships, and apply the method to estimating the fractal dimension from box-counting data. Simulation studies were carried out to compare this method with the traditional methods. We also applied this technique to real data from fishing grounds in the Gulf of Carpentaria, Australia.  $\bigcirc$  1999 IMACS/Elsevier Science B.V. All rights reserved.

Keywords: Fractal dimension; Mean-variance relationship; Quasi-likelihood function

#### 1. Introduction

Fractal dimension has been found useful in describing the "complexity" of random spatial patterns [10]. There are various definitions of a "fractal dimension" proposed in the literature, such as box dimension, Hausdorff dimension, capacity dimension and packing dimension. They may or may not have the same value for a given fractal depending on the properties of the fractal (see [1]).

Estimation of the dimension of a fractal has become an important and interesting statistical problem [9]. The box-counting technique is commonly used to estimate the fractal dimension because of its simplicity.

The quasi-likelihood (QL) method has been found useful in parameter estimation, especially when the distributions cannot be fully specified. However, the QL function for the dependent data has probably not received as much attention as it should [11]. This paper proposes a way of constructing QL functions for dependent observations based on conditional moments, which naturally generalizes the original definition of the QL function for independent observations. This approach is then applied with this method to estimate the dimension of a fractal from box-counting data. The principle may be applied to other types of dimensions as well. We have compared the QL with the least-squares method by analysing the simulated data from random fractals. We also analysed a dataset collected from fishers

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in the Gulf of Carpentaria, Australia, to establish the fractal dimension, a relative capacity index, for a selected area.

#### 2. Quasi-likelihood

If *Y* is a random variable with  $E(Y) = \mu$  and  $var(Y) = V(\mu)$  (a known function), the QL function for *Y*,  $Q(\mu; Y)$ , is defined as [8,12]:

$$Q(\mu;Y) = \int_{Y}^{\mu} \frac{Y-t}{V(t)} \mathrm{d}t.$$
(1)

If  $Y=(Y_i)_{n\times 1}$  is a vector of *n* independent observations, the QL function is defined as  $Q(\mu; Y) = \sum_{i=1}^{n} Q(\mu_i; Y_i)$ , where  $(\mu_i)_{n\times 1}$  is the corresponding mean vector of *Y*. The QL approach only requires specification of the mean-variance relationship rather than a full likelihood function. It has been found extremely useful in modelling overdispersion problems, and there has been extensive development in this area, focusing on the case of independent observations.

It is of practical importance to consider the case of dependent data. McCullagh and Nelder ([8], pp. 332–336) constructed a QL function for dependent data. Unfortunately, their QL function, in general, is not uniquely determined, and it depends on the path of a line integral.

In general, if  $Y^{(i)}$  is the vector of the first *i* observations, the log-likelihood function of  $Y=(Y_i)_{n\times 1}$  can be expressed as:

$$\sum_{i=1}^{n} \log\left\{f_i\left(Y_i|Y^{(i-1)}\right)\right\}.$$
(2)

Suppose  $\mu(i)$  is the conditional expectation,  $E(Y_i|Y^{(i-1)})$ , and the conditional variance  $var(Y_i|Y^{(i-1)}) = v_i(\mu(i))$  can be expressed as a function of  $\mu(i)$ . We can then define the following conditional QL (strictly, the quasi-conditional-likelihood) function for  $Y_i$ :

$$Q_i(\mu(i); Y^{(i)}) = \int_{Y_i}^{\mu(i)} \frac{Y_i - t}{v_i(t)} dt.$$
(3)

Using the conditional argument as in (2), the overall QL for Y can thus be defined as:

$$Q(\mu; Y) = \sum_{i=1}^{n} Q_i \left( \mu_i; Y^{(i)} \right).$$

By taking partial derivatives with respect to  $\beta$  the QL function results in the following estimating equations:

$$\sum_{i=1}^{k} \frac{Y_i - \mu(i)}{\upsilon_i(\mu(i))} \frac{\partial \mu(i)}{\partial \beta_j} = 0, \quad \text{for} 1 \leq j \leq p.$$

$$\tag{4}$$

$$D'V^{-1}(Y-\mu) = 0 (5)$$

in which V is a diagonal matrix with *i*th element  $v_i$  and  $\mu$  is the vector of  $\{\mu(i)\}_{n \times 1}$ . Let  $\mathscr{F}_i$  be the standard filtration generated by  $Y_i$ ,  $1 \le j \le i$ , and:

$$Z_i = \frac{Y_i - \mu(i)}{\upsilon_i(\mu(i))}.$$

Clearly,  $(Z_i, \mathcal{F}_i)$  is a martingale difference. Standardizing this martingale difference results in the estimating equations given by (4). Therefore, from the results of Godambe and Heyde ([2], p. 236) and Heyde [4], the QL estimating functions are optimal with respect to both the fixed sample criteria and the asymptotic criterion, and the central limit theorem holds for the estimates under appropriate regularity conditions. Multivariate Gauss approximation can then be used to evaluate the variances of the estimates (see also [2,5–7]).

Let us now consider some examples to see how the proposed QL approach works.

Example 1. First order autoregressive process: Consider a stochastic process of:

$$Y_i = h\left(Y^{(i-1)}, \theta\right) + \epsilon_i$$

where h(.,.) is a smooth function,  $Y_0 = \epsilon_0$  and  $\epsilon_i$  are i.i.d. with mean 0 and variance  $\sigma^2$  (the density function is unknown). The parameter  $\theta$  is of interest. Clearly,  $\mu(1) = 0$  and  $\mu(i) = E(Y_i|Y^{(i-1)}) = h(Y^{(i-1)}, \theta)$  for  $i \ge 2$ . The QL estimating equation corresponding to (4) is thus:

$$\sum_{i\geq 1} \left\{ Y_i - h\left(Y^{(i-1)}, \theta\right) \right\} \partial h\left(Y^{(i-1)}, \theta\right) / \partial \theta = 0.$$

In particular, if  $h(Y^{(i-1)}, \theta) = \theta Y_{i-1}$ , the above equation becomes  $\sum_i Y_{i-1}(Y_i - \theta Y_{i-1})$ , which is the same as obtained by Heyde [4] and McCullagh and Nelder ([8], pp. 340–341). By imposing assumptions on higher moments, Heyde [4] also obtained a combined estimating function for  $\theta$ .

**Example 2.** Bienayme–Galtont–Watson branching process: Let  $Y_0=1$ , and  $Y_{i+1} = Y_{i,1} + Y_{i,2} + \cdots + Y_{i,Y_i}$ , where  $Y_{i,j}, 1 \le j \le Y_i$  are i.i.d., each with the same offspring distribution, and are independent of  $Y_i$ . The offspring distribution has a mean  $\theta$ , which is of interest, and variance  $\sigma^2$ :

The conditional mean  $E(Y_{i+1}|Y_i) = \theta Y_i$  and the condition variance  $var(Y_{i+1}|Y_i) = Y_i \sigma^2$ . Therefore, the estimating equation from the generalised quasi-likelihood becomes:

$$\sum_{i=1}^n (Y_i - \theta Y_{i-1}) = 0.$$

Godambe and Heyde [2] obtained the same result using some optimal estimation criteria. This solution is also the maximum likelihood estimate when the offspring has a power-series distribution [2].

#### 3. Estimation of box dimension

Box dimension, also known as capacity dimension, is the most widely used index for measuring the complexity or irregularity of a fractal. It gives an idea of the relative size of the object which is too irregular to be measured by classical geometry. The dimension has also been described as the amount of Euclidean space that the fractal set fills or a measure of its roughness [3]. Fractal dimension is analogous to the length of a line, or the area of a square and allows comparisons to be made with other fractals and with classical shapes.

For a spatial set the box-counting procedure is carried out by covering the set E with a collection of squares with a small side length  $\delta$ . Effectively, this means laying a grid of side length  $\delta$  over the set and counting the minimum number of squares  $(N_{\delta})$  necessary to cover the set. In general, this number is proportional to the inverse of the grid size [1], that is,  $N_{\delta} \sim (1/\delta)^d$ , as  $\delta \rightarrow 0$ , where d is the dimension of the object. The box-counting dimension  $\beta(E)$ , is defined as:

$$\beta(E) = \lim_{\delta \to 0} \frac{\log(N_{\delta}(E))}{\log(1/\delta)}.$$
(6)

In order to estimate the dimension for a particular set E,  $N_{\delta i}$  may be obtained for a series of  $\delta_i$ ,  $1 \le i \le k$ . Here  $\delta_i$ 's are in decreasing order. When  $\delta_k$  is small, one can rely on the following estimator:

$$\hat{\beta}_1 = -\frac{\log(N_{\delta k})}{\log(\delta_k)}.$$
(7)

This method uses only the last observed number and may not work well especially when the convergence in (6) is slow [3]. An alternative method is to use the regression:

$$y_i = \beta_0 + \beta_1 x_i + \epsilon_i,$$

where  $y_i = \log(N_{\delta_i})$  and  $x_i = \log(\delta_i)$ . The slope  $\beta_1$  represents the box-counting dimension [1].

We now consider the case when  $\delta_i = \delta^i$  for some constant  $\delta$  ( $0 < \delta < 1$ ). We will use  $N_i$  for  $N_{\delta i}$  when there is no confusion. Clearly,  $N_{i+1}$  is generated from a sum of  $N_i$  observations, each taking a value between 1 and  $\delta^{-2}$  (in a 2-dimension space). If we let  $N_0=1$ , we may write  $N_{i+1}$  as  $N_{i,1} + N_{i,2} + \cdots + N_{i,N_i}$ , where  $N_{i,j}$ ,  $1 \le j \le N_i$  are assumed to have the same offspring distribution. This is similar to the well known Bienayme–Galton–Watson branching process. The major difference is that it may be inappropriate to assume  $N_{i,j}$  for  $1 \le j \le N_i$  to be independent of each other. The offspring distribution has a mean  $\theta = \delta^{-\beta}$ , which is of interest, and variance  $\sigma_i^2$ .

If a box is not empty, and when being subdivided into  $m \times m$  sub-boxes, we would expect  $m^{\beta}$  nonempty sub-boxes among these  $m^2$  sub-boxes. This suggests that  $E(N_{i+1}|N_i) = \theta N_i$ , in which  $\theta = \delta^{-\beta}$ . Denote the conditional variance  $var(N_{i+1}|N_i)$  as  $V_i$ . The estimating equation from the generalised quasilikelihood is:

$$\sum_{i=1}^{k} \frac{(N_{i+1} - \theta N_i)N_i}{V_i} = 0.$$
(8)

The conditional variance is:

$$V_i = \sum_{j=1}^{N_i} \operatorname{var}\{N_{i,j}\} + \sum_{j \neq l} \operatorname{cov}\{N_{i,j}, N_{i,l}\}$$

It appears to be appropriate to assume that  $V_i$  is a quadratic function of  $N_i$ . The overdispersion parameters in the quadratic function have to be estimated as well. Iterative procedures can then be used to update the parameter  $\theta$  and re-estimate the overdispersion parameters. If the number of data points is small, such procedures are not possible. A simpler function of  $V_i$  has to be used. In particular, if we assume  $V_i$  is proportional to  $N_i^2$ , we obtain an analytical estimator:

$$\hat{\theta}_{\rm QL} = \frac{\sum_{i=1}^{k} N_{i+1} / N_i}{k-1}.$$
(9)

#### 4. A simulation study

Let us now consider the fractal set generated from a unit square in two dimensions and a vector of probabilities  $(p_1, \ldots, p_9)$   $(\sum_{j=1}^{9} p_j = 1)$ . The unit square is divided into nine smaller squares and the probabilities  $p = (p_1, p_2, \ldots, p_9)$  are assigned to these squares.

The position of a point is determined by an iterative procedure: (i) first randomly select a box of length 1/3 (each with probability  $p_j$ ); (ii) divide the selected box into nine sub-boxes of length  $1/3^2$ ; (iii) randomly select a sub-box among the nine (each with probability  $p_j$ ); and (iv) further divide the selected sub-box into nine sub-boxes with length  $1/3^3$ , and repeat the procedures similar to (i)–(iii) until the length of the sub-box is  $1/3^5$ . We let one, two or three  $p_i$ 's be 0 and the remaining  $p_i$ 's have the same probability. The box-dimension of this type of fractal set is  $\log(9 - n)/\log(3)$  where n=1, 2 or 3 is the number of  $p_i$ 's with zero probability.

Fig. 1 shows three fractal sets with 3000 points corresponding to the cases n=1, 2 and 3. In order to estimate the dimension via the box-counting method, a grid of side length  $1/3^i$  is laid over the fractal set, for each i (i = 1, ..., 5), and the number of non-empty boxes,  $N_i$ , are obtained.

Table 1 shows the mean and standard deviation of the estimates by various estimators based on 100 simulations. The ratio method is based on Eq. (7). Interestingly enough, it works quite well and is better than the LS method in this case. Overall, it appears that the QL method is the best.

Table 1 Actual and estimated fractal dimensions of the fractal sets shown in Fig. 1<sup>a</sup>

n	Actual	Ratio	LS	QL
1	1.893	1.537 (0.7)	1.505 (1.0)	1.602 (1.1)
2	1.771	1.524 (0.9)	1.512 (1.3)	1.559 (1.3)
3	1.631	1.493 (1.2)	1.495 (1.0)	1.500 (1.0)

Standard deviations are multiplied by 1000 and given in brackets.



Fig. 1. Three fractal sets with box-dimension  $\log(9 - n/\log(3))$  each containing 3000 points, n=1, 2 and 3.

#### 5. Data from the Northern Prawn Fishery, Australia

The Northern Prawn Fishery has annual export earnings between \$A100 million and \$A150 million. Some areas in the fishery produce more prawns than others. One of the reasons for this high spatial variation in catches is that survival is related to habitat type. In particular, areas of rough bottom may be associated with higher catch rates. We hypothesise that higher catch rates are related to the complexity of the reef areas rather than just the total area. Fishers in the Northern Prawn Fishery use GPS (Global Positioning System) plotters for navigation and to record features such as areas of high catch, reef, rough bottom, etc. We created a map of untrawlable ground within the fishery by collecting point data representing reef and rough bottom from 30 fishers and converted this data to a grid with a cell size of  $200 \times 200 \text{ m}^2$ . The data covered the whole of the Northern Prawn Fishery. We hope to use boxdimension to measure the complexity for each area, which may be used to explain the variations in catches from different areas.

To demonstrate how this might work, we selected a  $1^{\circ}$  square (60×60 nautical miles) having an area of 12 254 km<sup>2</sup> to the northeast of Vanderlin Island, in the Gulf of Carpentaria, northern Australia (Fig. 2). Areas regarded as reef or rough bottom (untrawlable ground) covered 425 km<sup>2</sup> of the selected study area.

The sample area was sequentially divided up into 4, 16, 64, 256, 1024 and 4096 boxes with the number of boxes containing fractal elements being 4, 15, 56, 197, 655, 1908. The ratio method produces the estimate as  $\log(1908)/(5\log(2)) \approx 1.816$ . The estimates by the regression method and



Fig. 2. The study area divided into 4096 boxes with points showing the reef and rough bottom, in the Northern Prawn Fishery, Australia

the QL method are 1.790 and 1.786, respectively. In this case, these two estimates are not very different. However, we would expect differences to apply to other areas because these two methods differ in general, as the simulation results indicate.

#### 6. Discussion

We have introduced the QL method for dependent data and applied it in the context of fractaldimension estimation. The QL approach allows likelihood inferences because the QL function has likelihood properties. As shown by Lin and Heyde [6], the conditional approach, if the model is correctly specified, is more efficient than the marginal approach. The study presented here is only a preliminary one. Further exploration of the QL approach while accounting for the correlations between observed numbers in each sub-box is of great interest. We intend to establish a fractal dimension for each stock area in the Northern Prawn Fishery, and investigate the possible relationship with the annual catches in these areas.

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**APPENDIX 3** 

## Accuracy of at-sea commercial size grading of tiger prawns (*Penaeus esculentus* and *P. semisulcatus*) in the Australian northern prawn fishery

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The size-frequency distribution of the commercial catch is often used as the basis of fisheries stock assessments (Pauly and Morgan, 1987; Gulland and Rosenberg, 1992) because most dynamic processes of populations (growth, survival, recruitment) are reflected in changes in this distribution. The data are generally collected, often at great expense, by sampling the catch at landing sites and markets, or onboard fishing vessels.

Size-frequency distributions of prawns (*Penaeus esculentus* and *P. semisulcatus*) can also be obtained from fish processors, who grade landings by size. These data are easier and cheaper to obtain than research samples, but unfortunately they are also considered less accurate and lack spatial information. However, they have been used in stock assessment of prawns in Kuwait (Jones and van Zalinge, 1981) and Malaysia (Simpson and Kong, 1978).

It is often difficult to relate size data obtained from a processor to time and place of capture of the prawns, but this is not the case when the product is packed onboard, as in Australia's northern prawn fishery (NPF).

Trawler operators in the NPF have voluntarily recorded size composition since 1985, when provision for this was made in operators' daily logbooks (between 30% and 45% of the tiger prawn catch reported in the logbooks contain size information). These books are therefore the most comprehensive source of information on the spatial and temporal size distribution of the commercial catch of the NPF. Present assessments of the fishery are based on deterministic growth and deterministic seasonal recruitment patterns (Wang and Die, 1996) and do not use size-structured data. If available, these data would help relax the assumption of deterministic recruitment and improve current stock assessments of the NPF.

Before the size data recorded in the logbooks can be used, however, the accuracy of size grading at sea needs to be assessed. This paper examines the accuracy of grading tiger prawns, by using data collected from a private firm, A. Raptis and Sons, that operates a large modern processing factory that regularly assesses the onboard grading of product purchased from NPF trawler operators.

Although the work presented here relates specifically to the NPF, the practice of onboard size grading is widespread in other fisheries around the world. Therefore our methods have potential application to other fisheries.

#### Methods

# At-sea commercial grading procedures

Prawns landed from the NPF are size-graded at sea because both the demand and price structure differ for prawns of different sizes. Commercial sizes are based on the number of prawns of the same size per unit of weight (per pound), and the sizes are then grouped in a range to constitute a commercial grade. For example, "9 to 12 grade" means prawns in a range of sizes individually equivalent to between 9 and 12 per pound.

The size grades (especially for the larger sizes) used for tiger prawns are often more precise than those used for other species, and the grades selected by fishermen at sea vary with operator, pack size, and target market. For this project we examined the data for the two pack sizes that were most commonly used during 1993 and 1994: small packs (3 kg) and large, variable weight (12–15 kg) packs.

**Small packs** Since the early 1990s, the use of accurate digital scales on many vessels has improved the accuracy of procedures for packing prawns into 3-kg or smaller packs, as well as into more conventional larger packs. The sensitivity of

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these digital scales also makes it possible to pack in more precise grades of prawns.

Prawns for these small packs are initially sorted by eye by experienced crew, and many are verified by individual weighing. Those prawns that fall outside a particular size grade are removed and the remainder are graded according to corresponding count-per-unit-of-weight tables.

Large packs Prawns for onboard grading into the large packs are sorted by eye into groups of about the same size (occasionally by counting the number into a unit of weight [often a pound measured on analogue scales] and grouping them accordingly). Very large and very small prawns are removed and regraded.

## Quality control assessment in the factory—source of data for analysis

A. Raptis and Sons process tiger prawns caught by their own large fleet of trawlers working in the NPF, as well as prawns purchased from other fishermen operating in the same area. The company randomly checks the quality of the packs entering its factory, including the accuracy of the grading.

Packs for quality-control assessment were selected at random for every vessel and from all consignments entering the factory. All packs were clearly marked with the vessel's name, the prawn species group, the grade of the prawns, and the date caught.

The selected samples were thawed individually. For the small packs, net weight was recorded, and size grading was checked by counting all prawns from each pack and averaging the count. Large and small prawns that did not fit the grade category were selected by eye, weighed, and graded individually, and the percentage by weight and the true grade of these prawns were recorded along with the percentage of those correctly graded.

With the large packs, a variable 2.5–3 kilogram sample of prawns was randomly taken from each pack, counted, and checked as above. The percentage by weight and the true grade of incorrectly graded prawns in the sample were recorded.

#### **Categorical analysis**

The results of all factory quality-control checks on both the small and large packs between mid-1993 and the end of 1994 were examined. Over this time, samples from 51 of the 127 boats that fished different areas in the NPF had been taken. We split the data into three time periods to find out whether the accuracy of grading early in the year differed from grading

#### Table 1

Commercial size grades (\*) used in grading and qualitycontrol assessments of tiger prawns for two different pack sizes. Also shown are the ranges of carapace lengths (mm) for each size grade.

Grade (prawn count (per lb)	Carapace length (mm)	Small pack	Large pack	Quality control
Under 6	>46	*	*	*
6 to 8	46-42	*	*	*
Under 10	>39		*	
9 to 12	41-36	*	*	*
10 to 15	38-33		*	
13 to 15	35-33	*	*	*
16 to 20	32-30	*	*	*
10 to 20	38-30		*	
Over 20	<29	*		
21 to 25	29–28		*	
26 to 30	27 - 26		*	
21 to 30	29-26		*	*

that took place later in the year when smaller prawns recruited to the fishery. Period one was from July to December 1993, period two from January to June 1994, and period three from July to December 1994.

Data from the large packs, where the grades used were not the same as those for the small packs, were omitted from the analysis because they could not be compared directly. The commonly used size grades for both pack sizes are shown in Table 1, as well as the equivalent carapace length of the prawns.

The number of prawns (n) contained in the small packs was recovered by converting the net weight of the pack to pounds (weight in kilograms divided by 0.45359), and then by multiplying by the count-perpound derived from the quality-control inspection. The number of misgraded prawns (r) in the small packs was estimated by multiplying the number of prawns in the sample by the percentage misgraded in that pack. The numbers misgraded for each period and each size grade were analyzed by fitting binary regression models by means of iterative weighted least squares. The number of misgraded prawns was assumed to have a binomial distribution:

$$Pr = \binom{n}{r} \pi^{r} (1 - \pi)^{n - r}, \qquad (r = 0, 1...n)$$

with  $P(\text{misgraded}) = \pi$  and  $P(\text{correctly graded}) = 1 - \pi$ . The probability  $\pi$  was modelled in terms of the logodds or logistic transformation  $(\log(\pi/(1 - \pi)))$ . The computed deviance statistic, approximately distributed as chi-squared, was used in goodness-of-fit tests.

It was not possible to recover the total number of prawns in the large packs because the variable sample weight (between 2.5 and 3 kilograms) was not recorded in the Raptis database. Therefore estimates of the number of misgraded prawns were derived only for the samples and not for the whole pack. Because these samples were randomly chosen, it was possible to assume that the assessment of grading accuracy was representative of the grading accuracy for the whole pack.

For the large pack samples, the proportion misgraded had a mean (Eq. 1) and variance (Eq. 2) over the different samples

$$Mean = \pi \tag{1}$$

and

0

$$Variance = E\left(\frac{\pi(1-\pi)}{n}\right),$$
 (2)

where  $\pi$  = the misgrading probability; and n =the sample size.

Because the weight range of the samples was small, it was possible to estimate the expected reciprocal sample size



(Eq. 4) by integrating over the sample weight range (assumed for mathematical convience to be uniformly distributed between 2.5 kg and 3 kg) (Eq. 3):

$$E\left(\frac{1}{n}\right) = \int_{2.5}^{3} \frac{0.45359}{\rho w} 2dw$$
(3)  
=  $\left(\frac{0.45359 \times 2 \times \ln(3/2.5)}{\rho}\right)$ (4)

ρ

where 
$$\rho$$
 = count per pound;  
.45359 kg = 1 lb; and

w = sample weight.

The relationship between Equations 1 and 2 here is the same as that for the binomial distribution; therefore the data were analyzed by fitting binomial regression models.

The size of misgraded prawns was examined to determine whether misgrading was a result of including small prawns in large grades or vice versa. The number of size grades in which misgrading occurred was also assessed.

#### Results

#### Small packs

Of the 21,443 tiger prawns in 293 small packs that were assessed, an estimated 1937 (9%) prawns in 229 packs were misgraded. There were significant changes in the proportion misgraded with both period of catch and size grade, with higher proportions of misgraded prawns in the small size grades (Table 2; Fig. 1A). Overall, grading accuracy tended to increase over the 18 months examined (Fig. 1A).

The size of the misgraded prawns over the different grades did not show a consistent pattern, but generally larger prawn grade packs tended to contain smaller prawns (Fig. 1A). The proportion of misgraded prawns that should have been in smaller grades, however, was

- not constant over all size grades within each pe-1 riod of catch (Table 3; Fig. 1A);
- not the same for each size grade over the three 2 periods examined (Table 4; Fig. 1A).

Of the misgraded prawns, 99% were size-graded either one grade larger or one grade smaller. Only grades 9 to 12 and 16 to 20 contained prawns misgraded by as much as two size grades, with no more than 2% so misgraded. Because there was no larger grade, prawns misgraded in the under 6 size, were graded as 6 to 8.

If the proportion of prawns graded size i by fishermen at-sea that were actually size j (i, j=1 for under 6, 2 for 6 to 8, 3 for 9 to 12, 4 for 13 to 15, 5 for 16 to 20, and 6 for over 20 prawns per pound) obtained from the sample data are denoted by  $\theta_{ij}$ , then the proportions,  $p_i$ , of all prawns graded as size i at-sea can be adjusted with the equation:

$$\sum_{i=1}^{5} p_i \theta_{ij} \tag{5}$$

to give a corrected grade size distribution (j=1, 2, ...,6). Shown in Table 5 are the corrected distributions compared with at-sea grading for the small packs. The adjustments can be seen to be quite modest, and the at-sea gradings provide a reliable assessment of the size distribution.

#### Large packs

Samples containing an estimated 8210 tiger prawns from 124 large packs were assessed. Of these samples, an estimated 2914 (35%) prawns from 107 packs were misgraded. Again, there were significant



changes in the proportion misgraded with period of catch and size grade, with significant differences in the proportion misgraded with period of catch, and generally higher proportions of the smaller size grades misgraded (Table 2; Fig. 1B).

There was a tendency for smaller-prawn grade packs to contain larger prawns (Fig. 1B). The proportion of misgraded prawns that should have been in a larger-size grade, however, was

- 1 not constant over all size grades, within any one period of catch (Table 3; Fig. 1B);
- 2 not the same for each size grade, over the three periods examined (Table 4; Fig. 1B).

#### Table 2

Binomial model fits for each period of catch (1: July-December 1993, 2: January-June 1994, and 3: July-December 1994) and pack-size combination. (a, b, c) denote groups of size grades with no significant differences in the proportion of misgraded prawns.

			Size grade					
Time period	Under 6	6 to 8	9 to 12	13 to 15	16 to 20	$\chi^2$ d	df	df P
	а	а	а					
1				b	b	1.517	3	0.68
	a	a						
2			b			0.476	1	0.52
				C	c			
	a							
3		ь	b			3.244	2	0.20
				c	С		<u></u>	-
			a		· •			
1				b		1		
					с			
		a	a	-				
2	b			b	b	2.695	3	0.44
-	a		a					
3		b				2.892	2	0.24
-				с	C			
es of freedom.				· · · ·		-		
	Time period 1 2 3 1 2 3 es of freedom.	Time periodUnder 6a1a2a312ba3es of freedom.	Time periodUnder 66 to 8aaa1aa2ab1aa2ba3bb1aa2ba3bbes of freedom.b	Time periodUnder 66 to 89 to 12aaa1aa2bbaab3bb1aa2ba3bbaaa3bbes of freedom.a	Time periodUnder 66 to 89 to 1213 to 15aaaa1aa2bcabbabcabbcaa1bcabb2bbaaa3bbcaa3bcaaa3bces of freedom.c	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	Time period       Under 6       6 to 8       9 to 12       13 to 15       16 to 20 $\chi^2$ a       a       a       a       a       a       a       a       a       a       a       b       b       1.517         a       a       a       b       b       0.476       c       c       c       a<	Time period       Under 6       6 to 8       9 to 12       13 to 15       16 to 20 $\chi^2$ df         a       a       a       b       b       1.517       3         a       a       a       b       c       c       1         a       a       b       c       c       c       1         a       a       b       b       0.476       1       c       c       c       c       1       <

#### Table 3

Chi-squared statistics for the constant model of misgraded prawn size in each period of catch (1: July-December 1993, 2: January-June 1994, and 3: July-December 1994), for both small and large packs. \* P < 0.0001

Period	Small pack	Large pack
1	45.088 *	17.963 *
2	45.916 *	55.701 <sup>*</sup>
3	32.915 *	83.060 *

Of the prawns misgraded, 92% were sized either one grade larger or smaller. Of those misgraded in the 16 to 20 grade, 11% were misgraded by as much as two grades, whereas less than 2% were so misgraded for the other size grades.

The misgrading proportions can again be used in Equation 5 to obtain the at-sea grade-size distribution for these large packs. Shown in Table 5 are these corrected distributions compared with at-sea gradings; here the adjustments can be seen to be

#### Table 4

Chi-squared statistics for the constant model of misgraded prawn size in each size grade for both small and large packs. \*P < 0.0001, \*\*P = 0.13, \*\*\*P = 0.03.

Size grade	Small pack	Large pack
6 to 8	4.1494 **	14.408 *
9 to 12	33.271 *	4.7639 ***
13 to 15	220.58 *	27.039 *
16 to 20	16.159 <sup>*</sup>	106.83 *

more substantial than those for the small packs, particularly for the smaller grades 13 to 15 and 16 to 20 prawns per pound, owing to the tendency of the fishermen to classify the prawns to smaller size grades.

#### Discussion

Our analysis indicates that small prawns are graded less accurately than large ones. Given that the length

Size	Period 1 (July–December 1993)		Period 2 (January–June 1994)		Period 3 (July–December 1994)	
grade	at-sea	adjusted	at-sea	adjusted	at-sea	adjusted
Small packs						
Under 6 6 to 8 9 to 12 13 to 15 16 to 20 Over 20 Large variable page	0.15 0.16 0.30 0.26 0.13 0	0.14 0.17 0.33 0.23 0.11 0.015	0.012 0.19 0.31 0.28 0.21 0	0.015 0.19 0.30 0.28 0.20 0.014	0.098 0.11 0.32 0.24 0.24 0	0.097 0.11 0.30 0.23 0.24 0.018
Under 6 6 to 8 9 to 12 13 to 15 16 to 20 Over 20	0.079 0.055 0.87 0	 0.12 0.43 0.42 0.030	0.11 0.059 0.12 0.10 0.61 0	0.071 0.11 0.16 0.22 0.38 0.069	0.12 0.17 0.22 0.14 0.36 0	0.15 0.15 0.28 0.21 0.20 0.017

range corresponding to the small commercial grades is narrow (Table 1), it is perhaps not surprising that small prawns tend to be misgraded more frequently. Alternatively the grading of small prawns may be less accurate because they are less valuable than large prawns and therefore less time is spent on grading each individual.

In small packs, misgraded prawns were generally graded into larger categories, whereas in large packs, those misgraded were generally placed into smaller categories.

Incorrectly graded prawns from both pack sizes, however, tend to be incorrectly graded by only one size category, so that all prawns were graded to within three and six millimeters carapace length of their corresponding size grade.

The high proportion of landings graded and the accuracy of some of this grading suggest that size information contained in the NPF logbooks could be valuable for stock assessment. Most prawns sold in small (3-kg) packs have been accurately graded by fishermen, and these gradings could be used as a reasonable measure of the length-frequency distribution of the prawns. However, prawns sold in larger (12–15 kg) packs are graded less accurately, especially for the smaller grade sizes, and it is recommended that data from quality inspections be used to correct fishermen's grade-size distribution.

Although the work outlined in this paper was done for the Australian northern prawn fishery, similar analyses using similar methods could be carried out for other fisheries if comparable data on size gradings were available.

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**APPENDIX 4** 

## Modelling the recruitment of tiger prawns *Penaeus esculentus* and *P. semisulcatus* to nursery grounds in the Gulf of Carpentaria, northern Australia: implications for assessing stock-recruitment relationships

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ABSTRACT: A prawn larval behavioural model was coupled to a hydrodynamic model of the Gulf of Carpentaria in northern Australia to provide estimates of the size of the spawning area from which nursery ground populations are drawn, referred to here as the advection envelope. We have assumed that, during the first 8 d after the nauplii hatch, the larvae undergo a diel vertical migration in the water column, without spending any time on the bottom. After 8 d, larvae in waters shallower than a preset transition depth were assumed to switch to vertical migration cued by the tidal cycles—remaining on the bottom during outgoing tides, and swimming into the water column during flood tides. This tidal behaviour generated a net advection of postlarvae into the coastal zone and local estuaries. The model demonstrated that this mechanism is very efficient at accumulating larvae along the coastal zone. Changes in the timing and magnitude of the tides through the year generated a strong seasonal signal in the size and shape of the advection envelope, with typically a 2-fold difference in the size of the envelope between October and March. However, winds had little effect on the size of the advection envelopes, and interannual variation in the size and shape of the advection envelopes was small (<10%). The model also demonstrated that advection envelopes are very sensitive to the postlarval transition depth, which has not yet been adequately constrained by either field or laboratory studies. For example, changing the transition depth from 7 to 30 m typically resulted in a 2-fold increase in the size of the advection envelope. The results of the model may also have significant implications for the management of the prawn fishery. Comparisons of the advection envelopes with the distribution of tiger prawn catches indicate regions where fishing is most likely to have an impact on the spawning stock and subsequent recruitment to the fishery. The results also suggest that there are 3 discrete substocks of Penaeus esculentus and P. semisulcatus in the Gulf of Carpentaria and, therefore, challenge the assumption that there is a single tiger prawn stock covering the entire region.

KEY WORDS: Larval advection · Penaeid · Postlarvae · Seagrass · Interannual variability · Seasonal variability

#### INTRODUCTION

The relationship between spawning stock and recruitment to the fishery is an important characteristic of exploited fish stocks. Until recently there was little convincing evidence of recruitment overfishing or stock and recruitment relationships for penaeid prawns. This is thought to be due to biological characteristics of prawns, including their short life cycle, high fecundity and response to environmental variation. However, recent studies have established a relationship between spawning stock and recruitment for white shrimp

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Fig. 1. Coastline map of the Gulf of Carpentaria, northern Australia, showing localities mentioned in the text, and the distribution of seagrass beds (areas in black) from Staples et al. (1985) and Poiner et al. (1987). Note that the width of the areas representing seagrass beds is not drawn to scale

Penaeus setiferus (Gracia 1996), brown tiger prawns P. esculentus and grooved tiger prawns P. semisulcatus (Penn & Caputi 1986, Penn et al. 1995, Wang & Die 1996). The last 2 species comprise about 40% of the total catch from Australia's most valuable commonwealth fishery, the Northern Prawn Fishery (NPF). In considering the relationship between spawning stock and recruitment for this fishery, both species of tiger prawns have been assumed to come from unit stocks, despite the fact that this fishery extends across about 6000 km of coastline in northern Australia.

Excessive fishing on tiger prawns by the NPF fleet in the 1980s caused a significant decline in the abundance of spawners and recruits (Wang & Die 1996). The protection of spawning tiger prawns has therefore become a critical issue for the managers of the NPF. On the basis of the information available in the 1980s, the main fishing grounds were thought to coincide with the areas where tiger prawns spawned and hence any substantial reductions of fishing on spawners were thought to be at the cost of closing prime fishing grounds. This led to the present management strategy that seeks to protect pre-spawning tiger prawns from fishing by reducing effort through a seasonal (June-July) closure.

The above conclusions were based on the assumption that all spawning females contributed equally to recruitment. However, recent work suggests that spawning may be more successful close to the shallow water seagrasses that serve as nursery grounds (Crocos & van der Velde 1995, Haywood et al. 1995, Loneragan et al. 1998). The distribution of seagrasses in the Gulf of Carpentaria is limited to the southern and western shorelines, and Albatross Bay in the northeast near Weipa (Poiner et al. 1987, Fig. 1). Only those larvae that reach these beds are likely to survive, grow and eventually recruit to the fishery (Staples et al. 1985). Any index of effective spawning (sensu Crocos & van der Velde 1995) should therefore include the likelihood of larvae recruiting to the shallow seagrass beds.

There is strong evidence that the transport of prawn larvae to coastal nursery habitats in northern Australia is controlled by interactions between tidal flows and the vertical migration of the larvae (e.g. Rothlisberg et al. 1983, 1996). Postlarvae remain close to or on the seabed during outgoing tides and then swim into the water column during the flood tide. This behaviour is presumably triggered by the pressure changes associated with tidal

changes in water depth. It appears to provide an efficient means of transporting larvae toward the shoreline, without the need for chemical cues such as salinity gradients (Hughes 1969, Rothlisberg et al. 1995).

This paper describes a modelling study aimed at identifying the spawning regions from which tiger prawn larvae can be transported to their seagrass bed nurseries in the Gulf of Carpentaria. The results of this study provide one means of identifying stock boundaries for tiger prawns within the NPF, hence enabling the stock-recruitment approach of Wang & Die (1996) to be extended from the whole of the NPF to individual regional stocks.

The general modelling approach is similar to that adopted by Rothlisberg et al. (1996) in that a larval behaviour model has been incorporated into a hydrodynamic model of the Gulf circulation. However, the current model differs from the earlier model in 3 fundamental aspects. Firstly, it extends the coverage of the model from the Weipa region in the northeastern Gulf of Carpentaria to the entire Gulf of Carpentaria. This incorporates the extensive seagrass beds and their associated tiger prawn fisheries in the south and west, and increases the total seagrass area in the bounds of the model by more than 100 times. Secondly, wind forcing has been incorporated into the hydrodynamic model. This introduces interannual variability into the larval advection trends. Thirdly, the vertical migration of larvae in Rothlisberg et al. (1996) consisted of discrete jumps between 2 preset depths. In the current model, larvae swim in a continuous path through the water column, while being advected and dispersed by the prevailing flow. This results in more realistic vertical population distributions.

#### MATERIAL AND METHODS

Hydrodynamic model. Flow in the Gulf of Carpentaria was simulated using the 3-dimensional nonlinear hydrodynamic model referred to as MECO (Model of Estuaries and Coastal Oceans). This model has previously been applied to a range of estuarine and shelf systems, the best documented being Port Philip Bay in southeastern Australia (Walker 1996). The numerical grid was rectangular with 76 by 104 cells in the horizontal and 12 cells in the vertical. Each cell measured 10 km by 10 km in the horizontal, while cell height increased with depth (interfaces at depths of 0, 3, 6, 9, 12, 15, 20, 25, 30, 40, 50, 60, and 70 m). The entire grid was also rotated 30° clockwise in the horizontal to match the geometry of the Gulf and provide straight open boundaries between Cape Wessel and False Cape in the west and Frederick Point and Daru in the east (Fig. 1). Where necessary the coastal geometry was tuned slightly to ensure realistic exchange across the heads of estuaries and inlets into which larvae are advected.

The flow in the Gulf was forced by surface winds, and tidal surface elevations at the open boundaries. Surface heat fluxes were only incorporated in a small number of runs designed to test the influence of temperature stratification. Synoptic winds were interpolated from data from the European Centre for Medium-Range Weather Forecasts (ECMWF). This consists of daily averaged estimates of wind speed with a 2.5° spatial resolution, and therefore does not resolve smaller scale or diurnal processes such as localized storms and sea-breezes. The tides are by far the most significant forcing in the Gulf and their incorporation into the model is now discussed.

Tidal heights incorporating the  $M_2$ ,  $S_2$ ,  $K_1$  and  $O_1$ components were specified across Torres Straight by linearly interpolating from Frederick Point to Daru and across the Arafura Sea by linearly interpolating from Cape Wessel to False Cape. Tidal station data is available at all of these locations except False Cape (Australian National Tide Tables 1996). The tidal harmonic constants at False Cape were therefore adjusted to provide realistic tides at 8 other locations around the Gulf coast. This approach has been adopted in a number of previous studies (Church & Forbes 1981, Wolanski 1993, Rothlisberg et al. 1996). However, the final fit to the observed tides is also dependent on the friction in the model, which is a function of the parameterisation of diffusion and resolution of bathymetry. Any errors from this source cannot usually be corrected by modifying the tides at the station without tidal data, i.e. False Cape. The False Cape harmonic constants which provided the best tidal estimates in MECO (Table 1) are similar to those obtained by Church & Forbes (1981), except that the amplitude of S2 is larger and the phases of M<sub>2</sub> and S<sub>2</sub> lag slightly. The resulting phase difference between Cape Wessel and False Cape is approximately 100°, which falls between the estimates of 130° by Church & Forbes (1981) and 30° by Wolanski (1993).

The advection of penaeid prawn larvae is most strongly influenced by tidal motions within the coastal zone (Rothlisberg et al. 1995). The hydrodynamic model was therefore tuned using tidal measurements from various locations around the coastline. Apart from a slight phase lag, the agreement between tides predicted by the model (tuned using the False Cape harmonic constants: Table 1) and measured tides is very good at Merauke (Fig. 2). While the agreement appears less convincing at Weipa, it should be noted that the gauge is situated within the estuary and may be strongly influenced by local bathymetry and coastline geometry unresolved by the model. This suggestion is supported by the improved agreement at Karumba, in the southeastern Gulf. The tidal signal propagates clockwise around the gulf, and by the time it reaches Milner Bay in the western Gulf, there is a tendency for the model to underestimate tidal amplitudes by around 15%. The agreement improves

Table 1. Tidal amplitudes (H) and phase (g) at False Cape,Papua New Guinea. Numbers in parentheses are values cal-<br/>culated by Church & Forbes (1981)

Constituent	<i>H</i> (m)	g (degrees)
 M2	0.9 (0.9)	320 (340)
S <sub>2</sub>	0.4(0.2)	40 (120)
K,	0.8 (0.8)	125 (125)
$O_1$	0.8 (0.8)	60 (60)





markedly again at Gove Harbour (northwestern Gulf), as the influence of the model boundary forcing at Cape Wessel becomes more significant.

While there have been very few direct observations of currents within the Gulf, the model agrees reasonably well with the observed current signal. For example, time series of model current vectors (not shown) are almost identical to those observed by Wolanski (1993), except that model current speeds are overestimated by 5 to 10%. The low frequency component of the currents is much more difficult to replicate, with model estimates typically a factor of 2 or more smaller than those observed by Wolanski (1993). This is not surprising given the limited resolution of the wind field and the absence of any low frequency component in the boundary forcing. Fortunately, the behaviour of the tiger prawn larvae ensures that their advection is strongly dominated by tidal motions, which, for such a large shallow system, are represented remarkably well.

Larval model. Actively swimming particles representing the prawn larvae were incorporated into the hydrodynamic model. At the start of each month they were seeded onto a regular 5 km grid covering the entire Gulf of Carpentaria. They were then allowed to swim vertically through the water column, while also being advected and diffused by the water circulation. Diffusion was via a random walk process, which was statistically equivalent to a horizontal diffusivity of 1 m<sup>2</sup> s<sup>-1</sup> and a vertical diffusivity dependent on the shear in the water column (Csanady 1982). Based on field measurements, it was also assumed that for the first 8 d the larvae migrate with a diel cycle, swimming gradually toward the bottom from midnight to midday and towards the surface from midday to midnight. This behaviour results in an accumulation of larvae toward the bottom during the day and toward the surface during the night, as found by field sampling (Rothlisberg 1982) and documented for other species such as blue crab megalopae (Olmi 1994). Under the influence of the background flow, a constant vertical swimming speed of 0.4 cm s<sup>-1</sup> resulted in a net migration rate of around 1 m h<sup>-1</sup>, which yielded quite realistic diel trends in vertical larval distribution.

Beginning on the ninth day, the diel migration pattern for all larvae located in water shallower than a specified transition depth was assumed to change to a new swimming behaviour synchronised with the tidal cycle. Specifically, the postlarvae remain on the seabed during the outgoing tide, then swim into the water column at the start of the flood tide in response to increasing hydrostatic pressure. There is significant uncertainty in the duration of each swimming event and we assumed that the postlarvae swim for the entire flood tide before settling on the seabed. The vertical swimming speed for postlarvae was set at 8.0 cm s<sup>-1</sup>, although recruitment envelopes were again insensitive to swimming speed.

The effect of uncertainties in the hydrodynamics on larval advection distances can be estimated as follows.

Run no.	Run period	Winds	Stratification	Transition depth (m)
1	Jan 1986–Dec 1990	ECMWF	None	15
2	Oct 1990	No wind	None	15
3	Oct 1990	ECMWF	Yes	15
3	Oct 1990	ECMWF	None	7
5	Oct 1990	ECMWF	None	20
6	Oct 1990	ECMWF	None	30

Table 2. Summary of parameters for wind, stratification of the water column and the transition depth used in the model runs to calculate larval advection envelopes. Synoptic winds were interpolated from the European Centres for Medium-Range Weather Forecasts (ECMWF)

During the larval stage, advection is determined by low frequency motions (weekly timescale). Beginning with the cross-shore component, weekly averaged velocities are estimated from limited data to be around  $2 \text{ cm s}^{-1}$  in the coastal zone (Wolanski 1993). Over the 8 d of the larval stage, this corresponds to an advection distance of 14 km. Because the model has a quite limited capacity to predict low frequency velocities, a reasonable estimate of the uncertainty in the offshore extent of the envelope during the first 8 d is perhaps 10 km. During the next stage of behaviour (cued by the tidal cycle), mean onshore velocities are less than 10 cm s<sup>-1</sup> and errors should be comparable to those in tidal height (~10%). Therefore, if flood tides operate for half of the time, the uncertainty in advection after 20 d of tidally cued vertical migration is around 9 km, similar to the uncertainty during the first stage of diel behaviour. Since tidal advection is mainly associated with the cross-shore component, uncertainties in the alongshore direction have been based purely on the low frequency motions. For 28 d averaged alongshore velocities, a value of 2 cm s<sup>-1</sup> again appears to be realistic (Wolanski 1993). Assuming that this velocity operates continuously over the first 8 d, and then during flood tide over the following 20 d, gives an advection distance of around 30 km. The limited skill of the model with respect to low frequency motions again suggests that the uncertainty in the alongshore extent of the envelope is not very much less than this value and might be nominally set at say 20 km.

Runs of the combined hydrodynamic-larval model covered the 5 yr period from January 1986 to December 1990. By re-seeding larvae every month, these runs provided information on both seasonal and interannual variability in the size and shape of the advection envelopes. (Table 2). For each month over the 5 yr period, ECMWF winds were used as inputs to the model, the water column was assumed to be homogenous and the transition depth for the change in larval behaviour from vertical migration cued by diel to tidal cycles was 15 m. Sensitivity of the model to specific environmental conditions and behavioural characteristics was tested for 1 mo (October 1990) by using different combinations of wind (ECMWF winds, or no wind), stratification (homogenous or stratified) and transition depths (7, 15, 20 and 30 m) (Table 2). Although some spawning occurs throughout the year, October is the month of consistently high spawning activity in the Weipa region (Crocos and van der Velde 1995).

The advection envelope and effective spawning. The most important aspect of the recruitment issue from a fisheries perspective is identifying the spawning area from which the nursery habitats (seagrass beds and mangroves) draw their maturing larval populations. This is what Rothlisberg et al. (1996) referred to as the advection envelope. While the size of the envelope will clearly grow with time, mortality rates are very high for larvae not reaching the beds within a month after spawning. Most of the results are therefore presented in terms of recruitment envelopes at 28 d. The size of the advection envelopes has been calculated for the 4 main regions of seagrass in the Gulf of Carpentaria. The mean, standard deviation and coefficient of variation for the advection envelopes in each region were calculated for the months of 1 yr (1986), and over 5 yr for 1 mo (October).

The increasing size of the advection envelope over time is not a direct indicator of the number of postlarvae reaching the seagrass beds. Mortality rates also need to be taken into account, including major differences between the offshore and nursery ground rates. Offshore estimates typically exceed 70% wk<sup>-1</sup>, while those in the nurseries fall within the range of 10 to 25% wk<sup>-1</sup> (Dall et al. 1990, O'Brien 1994). Mortality could be crudely represented in the model by assuming that spawning is uniform over the entire advection envelope and multiplying the population in each grid cell by a decaying exponential function based on rates of 70% wk<sup>-1</sup> offshore and 14% wk<sup>-1</sup> on the seagrass.

The NPF fleet targets large mature tiger prawns on the areas of the fishing ground where they are most abundant (Somers 1994). Therefore the distribution of catches reported in the commercial fishery logbooks approximates that of tiger prawn spawners. In the NPF,

daily catches are reported by fishers for  $6' \times 6'$  grids. Commercial fishers do not separate the 2 tiger prawn species, but the catch by species can be estimated from the location of the catch (Somers 1994). For each species of tiger prawn, the spawning area for a specified month (October 1990) was assumed to include all grids with the highest catches in that month. The combined catch within these grids was constrained to be 80% of the total monthly catch of tiger prawns. To determine those areas where spawning was effective, the distribution of spawning was overlayed on the advection envelopes calculated for a range of postlarval transition depths. Any grid box within the spawning region containing at least 1 of the advection envelope points was then defined as forming part of the effective spawning region.

#### RESULTS

#### **Development of the advection envelope**

Postlarval behaviour controlled by tidal cueing was triggered at the start of Day 9 in waters less than the specified transition depth (15 m). This initiated the efficient transport of postlarvae toward the coastline, where they accumulated (Fig. 3). The resulting discon-

tinuity in the concentration of particles at the 15 m depth contour was clearly evident on Day 9 (Fig. 3a). Smaller numbers of larvae from deeper water continued to drift past the transition depth and begin the postlarval migration. This provided a continuously decreasing flux of postlarvae into the nursery grounds (Fig. 3c,d).

The advection envelopes indicate that some larvae had already reached the seagrass beds by Day 9 (Fig. 4a). Between Days 9 and 14, the advection envelopes expanded rapidly away from the seagrass beds in both the offshore and alongshore directions (Fig. 4b). However, by Day 21 most of the postlarvae shallower than the transition depth had reached the coastal zone and further expansion in the advection envelopes tended to be more gradual (Fig. 4c,d).

The area of the advection envelopes for Weipa was very small (<100 km<sup>2</sup>) until Day 8 and then increased to an asymptote of about 1400 km<sup>2</sup> by Day 20 (Fig. 5a). In contrast, the size of the envelopes in the other regions increased more rapidly after Day 8 than that at Weipa, and continued to increase after Day 20, particularly in the Mornington Island region. Thus, the area of the advection envelope in the Mornington Island region increased from about 1000  $\rm km^2$  on Day 8 to 6000  $\rm km^2$  on Day 20 and 8000  $\rm km^2$  on Day 28 (Fig. 5a).

When typical mortality rates were included in the model, the number of individuals in the population on the seagrass beds peaked approximately 10 d after spawning (Fig. 5b), then declined to around 10 to 20% of the zero mortality population after 28 d (cf. Fig. 5a, b). Mortality is relatively higher at Weipa and Mornington Island (Fig. 5b) than in the other regions because the advection envelopes continue to grow over a longer period (Fig. 5a), which exposes more of their larval populations to high offshore mortality rates.

#### Seasonal variability

There was clearly considerable seasonal variation in the 28 d advection envelopes, with envelope areas in all regions varying by almost a factor of 2 (Figs. 6 & 7a). For example, at Weipa the minimum area of the envelope in 1986 was 900 km<sup>2</sup> in January compared with the maximum of 1950 km<sup>2</sup> in September (Fig. 7a). In contrast to Weipa, the maximum area of the advection envelopes in the Mornington Island, Limmen Bight and Groote Eylandt regions were found in December and January (Fig. 7a). The coefficient of variation for



Fig. 3. Distribution of all particles seeded in the Gulf of Carpentaria (a) 9, (b) 14, (c) 21 and (d) 28 d after a spawning in October 1990. Note that particles accumulate on the coastline

the area of the advection envelope in each region was between 15 and 20%.

Envelopes for the 2 main spawning months of March and October also differ substantially. For example, the area of the envelope around Weipa for March (1375 km<sup>2</sup>) was significantly below the annual average, while for October (1700 km<sup>2</sup>) it was above average. This was because the envelope in October extended further to the northwest from Weipa, in agreement with the model of Rothlisberg et al. (1996). In other regions of the Gulf, envelopes extended further offshore on the southern coastline and around Mornington Island in October compared with March. However, around Groote Eylandt, the envelopes were smaller in October than in March. There also appeared to be significant advection of postlarvae from south of Groote Eylandt during March, consistent with strong clockwise circulation during flood tides.

#### Interannual variability

Because the larval advection is forced predominantly by the tides, interannual variation in the advection envelopes for October



Fig. 4. Advection envelopes of postlarvae reaching seagrass beds in the Gulf of Carpentaria (a) 9, (b) 14, (c) 21 and (d) 28 d after a spawning in October 1990. Note that envelopes have not been determined for the northwest Gove region because the extent of seagrass coverage in this region is not known



Fig. 5. (a) Changes in the area of the advection envelopes for each of the major tiger prawn fishery regions in the Gulf of Carpentaria at different times after a spawning in October 1990. Initial envelope area is based on seagrass beds with areas of:  $7 \text{ km}^2$  for the Weipa region;  $170 \text{ km}^2$  in the Mornington Island region;  $280 \text{ km}^2$  for the Limmen Bight-Vanderlins region; and  $440 \text{ km}^2$  for the Groote Eylandt region (Poiner et al. 1987). The area of seagrass is not known for the Gove region. (b) The relative number of individuals in modelled populations within the major tiger prawn fishery regions in the Gulf of Carpentaria at different times after a spawning in October 1990 when larval and postlarval mortality is included. Numbers have been scaled such that Fig. 5a represents the same populations with zero mortality



Fig. 6. Seasonal changes for the 28 d advection envelopes in 1986 illustrated by the advection envelopes for (a) March, (b) June, (c) September and (d) December

was much less than the seasonal fluctuations (cf. Fig. 7a,b). The position of the outer edge of the envelope was always within 5 km of the average position for any given month. The area of the October advec-

tion envelope at Weipa ranged from only  $1575 \text{ km}^2$  in 1990 to  $1800 \text{ km}^2$  in 1988. The coefficient of variation for the envelope size in October was only 4 to 6% in each region and over the Gulf as a whole.

## Sensitivity to wind, stratification and postlarval transition depth

When no winds were used in the model, only minor changes in the size and shape of the advection envelope were found compared with the standard model run (compare Fig. 8a and Fig. 4d). For example, the envelope around Weipa is slightly broader to the north, but still equal in area to the October average.

During summer the central Gulf is characterised by significant levels of stratification (Forbes 1984, Somers & Long 1994). However, because of low turbidity levels, the surface mixed layer generally extends down to 20 or 30 m, so that the coastal zone remains well mixed. The influence of stratification with these characteristics has been examined by incorporating solar radiation and surface heat losses (radiative, sensible and evapora-

tive) into the model. While no changes were made to the specified larval characteristics, stratification tends to reduce turbulent mixing and may enhance wind-driven surface transports. However, these effects do not



Fig. 7. The surface area of advection envelopes associated with each fishery region for (a) each month in 1986 and (b) the month of October from 1986 to 1990



Fig. 8. The 28 d advection envelopes for October 1990 incorporating (a) zero wind, (b) thermal stratification, (c) a transition depth of 7 m and (d) a transition depth of 30 m. The standard October 1990 run is shown in Fig. 4d

appear to significantly affect the size and shape of the advection envelopes (compare Fig. 8b and Fig. 4d). The area of the Weipa envelope is unchanged while there is a contraction in the envelope around Morning-



Fig. 9. Surface area of advection envelopes associated with each fishery region 28 d after an October 1990 spawning, as a function of postlarval transition depth. Error bars are based only on uncertainties in current velocities

ton Island. Less realistic stratification penetrating into the upper few metres and horizontally into coastal zone (not shown) produced a significant expansion of the envelope north of Groote Eylandt, but no other major effects.

The final factor to be varied was the transition depth for postlarval behaviour (Fig. 8c, d). Not surprisingly, the advection envelopes expand offshore to meet the transition depth. Around Weipa this results in the 28 day envelope increasing by around 29 km<sup>2</sup> or 2.5% each time the transition depth is increased by 1 m in the model (Fig. 9). These rates tend to be much higher in the other regions, in some cases exceeding 10%. Changes in the transition depth clearly represent the largest source of uncertainty in model estimates of the advection envelope size.

#### Effective spawning areas

The spawning areas defined by those grids supporting 80% of the catch represented approximately 20% of all grids fished for either species of tiger prawn. This reflects the high degree of aggregation of tiger prawns in the NPF. The area of effective spawning,

based on the overlap of spawning areas and advection envelopes, was very sensitive to the postlarval transition depth (Table 3). Less than 3% of the total tiger prawn catch of October 1990 was caught in this area when the transition depth for postlarvae was set to 7 m. If this depth is set to 30 m, 57% of the catches of *Penaeus esculentus* and 30% of *P. semisulcatus*, are found within the effective spawning area. The effec-

Table 3. Catch of the 2 species of tiger prawns in October 1990 within and outside the advection envelope for different transition depths

Depth (m)	Catch (tonnes) within envelope	Catch (tonnes) outside envelope	% of catch within envelope				
Penaeus esculentus							
7	5	199	2				
15	18	186	9				
20	39	164	19				
30	116	88	57				
Penaeus	semisulcatus						
7	11	532	2				
15	26	517	5				
20	60	483	11				
30	163	380	30				


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tive spawning areas were not, however, uniformly distributed around the Gulf of Carpentaria (Fig. 10). For example, in the northeast, the effective spawning area of *P. semisulcatus* was identified at both shallow and deep transition depths, whereas in the southwest an effective spawning area was only found when the deepest transition depth (30 m) was used.

#### DISCUSSION

#### Variability

The size and shape of the advection envelopes were largely determined by the tidal circulation in the Gulf of Carpentaria. They appear to be relatively insensitive to other aspects of the hydrodynamics. This is further supported by comparisons of our results with those for earlier modelling work in the Weipa region, using similar larval behaviour (Rothlisberg et al. 1996). For example, the envelopes in their Fig. 8c extend offshore and to the north, very similarly to those in our Fig. 4, despite differences between the models in grid resolution, flow dispersion and wind forcing.

The large seasonal fluctuations in the size of the advection envelopes can be attributed to tidal variations. However, the weak interannual variability in the size of the advection envelopes suggests that winds associated with synoptic-scale weather systems have limited influence. Winds during the main October-November spawning period are historically very weak and more variability might be expected in February-March. However, the major interannual fluctuations observed in postlarval numbers entering the Albatross Bay estuaries at Weipa (Vance et al. 1996) must be a consequence of other factors. These may be associated with physical conditions not included in the model, such as localized storms, sea breezes, or unseasonal rainfall and freshwater inflow, or alternatively with biological factors that influence behaviour or mortality. The influence of the latter has been demonstrated by field experiments in Albatross Bay near Weipa, where the survival of Penaeus merguiensis larvae varied between 30 and 60 % over a single 3 d period (Preston et al. 1992).

The very limited influence of wind contrasts sharply with other species which experience extended periods of non-tidal advection. For example, spring winds can explain the cross-shelf distribution of the Dungeness crab *Cancer magister* larvae, including their onshore transport to favourable settling areas (Botsford & Hobbs 1995, McConnaughey et al. 1995).

#### The role of larval behaviour

The largest sources of uncertainty in predicting the size and shape of the advection envelopes are associated with the larval behaviour. The estimates of the size of the advection envelopes from the model were very sensitive to the choice of transition depth. The only constraints currently available are observations of the eastern king prawn *Penaeus plebejus* on the subtropical east coast of Australia which suggest that the transition depth for this species is less than 20 m (Roth-lisberg et al. 1995). However, this limited data set is for a different species from a different region. Field and laboratory experiments are now being used to refine our estimates of the transition depth for tiger prawn postlarvae (D. J. Vance, CSIRO Marine Research, pers. comm.).

Following the change in behaviour from vertical migration cued by a diel signal to that cued by the flood tide, an additional uncertainty is associated with the time that postlarvae remain active during the flood tide. We assumed that they remain active for the entire flood tide, thereby maximizing the larval advection. This behaviour requires the larvae to start swimming in response to the increasing hydrostatic pressure at the start of the flood tide, then settle rapidly under the reduced turbulence conditions during the change of tide. However, it is equally plausible that they swim to the bottom after a certain period of activity. Rothlisberg et al. (1996) examined scenarios for 3 and 6 hourly activity around Weipa. They found that while the shorter activity period slowed the growth rate of the advection envelope, the growth continued for longer so that the envelope size after 28 d was similar in both scenarios. The main effect of a reduced activity period is therefore likely to be increased exposure to the higher offshore mortality.

Even after the larvae reach the nursery grounds, their behaviour can still influence the advection envelope. We assumed that the tidal swimming behaviour continues over the seagrass beds. In most regions, this simply clusters the larvae more tightly along the coastline without affecting the envelope. However, in a few locations, such as the northwest corner of Groote

Fig. 10. Distribution of spawning (6' grids representing 80% of the commercial catch) and effective spawning (spawning grids within the advection envelope) for (a) *Penaeus esculentus* and (b) *P. semisulcatus* and a range of transition depths

Eylandt, the flood tides remove postlarvae from the seagrass beds. Laboratory studies have shown that postlarvae become more benthic once they reach a certain size and hence this assumption may not apply to large postlarvae (>1.6 mm carapace length, Liu & Loneragan 1997).

#### **Effective spawning areas**

Because the area of effective spawning was partially defined by the larval advection envelopes, it was also highly sensitive to the transition depth of postlarvae. In some regions of the Gulf of Carpentaria, the distributions of catches overlapped with those of the advection envelopes only for the deepest transition depth (30 m). This suggests either that the real transition depth is relatively deep ( $\geq$ 30 m), or that a high proportion of the successful spawners are found closer to the coast, in regions outside the major fishing grounds.

It is well established that large tiger prawns, particularly grooved tiger prawns Penaeus semisulcatus, are not confined to the main fishing grounds and occur throughout the Gulf of Carpentaria, albeit in low densities (Crocos & van der Velde 1995). There are also large areas of untrawlable ground, particularly around the islands of the western Gulf, such as the Vanderlins archipelago. Spawning tiger prawns may be abundant in these areas that are not accessible to the fleet and, therefore, do not appear in the catch or estimated spawning distributions. Shallow waters are closed to commercial fishing and may also contain some spawning prawns that are safe from fishing (e.g. Somers et al. 1987). Both the untrawlable grounds and the shallow areas would act as ecological refuges for spawning tiger prawns.

The main evidence against effective spawning being concentrated within untrawlable or shallow waters is that in the past fishing has strongly affected the recruitment of tiger prawns to the fishery (Wang & Die 1996). While this does not preclude unfished areas from contributing significantly to the effective spawning population, it means either that the fishing grounds contribute to a large portion of the effective spawning or that fishing impacts spawning populations outside the trawling grounds. The latter can only occur if the population of spawners is thoroughly mixed in the areas within the advection envelopes. Unfortunately there is little information on mixing other than that obtained from tag-recaptures, which only applies to movements within the fishing grounds. Alternatively, if mixing within the advection envelopes was limited, then it would support the hypothesis that the transition depth is likely to be relatively deep (>30 m).

The distribution of effective spawning shown in Fig. 10 suggests that there is more than a single stock of tiger prawns in the Gulf of Carpentaria. There are large gaps in the effective spawning distribution for all the fishing grounds, and those in the northeast are particularly well isolated. The only mechanism for effective mixing of prawn populations would have to be the migration of adults across these gaps. There is strong evidence that the majority of prawns migrate over distances smaller than the width of the gaps (Somers & Kirkwood 1991) and there is no evidence of excursions approaching the apparent separation of the effective spawning distributions. Our results suggest that there may be 3 main stocks of each of the 2 species of tiger prawns in the Gulf of Carpentaria. For Penaeus semisulcatus, the first stock is found in the northeast around Weipa, the second in the southwest, south of Groote Islandt, and the third to the northwest of Groote Eylandt. Penaeus esculentus would also have a northwest and southwest stock, with a third one in the southeast near Mornington Island.

### CONCLUSION

The coupled hydrodynamic-larval model has provided advection envelopes for the entire Gulf of Carpentaria within the 5 yr period from 1986 to 1990. The tides were by far the major hydrodynamic influence on the size and shape of the advection envelopes, and the seasonal cycle of the tides generated substantial seasonal variability in the advection envelopes. This contrasts with the effects of the broad-scale winds, which had a very limited influence on larval transport, resulting in low levels of interannual variability. Alternate explanations, presumably based on variation in mortality rates, are therefore required to account for the large interannual variability observed in postlarval numbers (Vance et al. 1996). Realistic levels of summertime stratification in the Gulf tend to maintain a well-mixed coastal zone and also have relatively little influence on postlarval advection. While the model was relatively robust to changes in the hydrodynamics, it was very sensitive to changes in the values of the parameters for larval behaviour. For example, it has been assumed that postlarvae remain within the water column for the duration of the flood tide. Shorter periods of activity will reduce the growth rate of the advection envelopes (Rothlisberg et al. 1996). However, by far the most sensitive and poorly constrained behavioural parameter is the transition depth at which larvae switch from vertical migration cued by the diel cycle to that cued by the tides. Improved estimates of this parameter are required to predict the advection envelopes with greater confidence.

The present work challenges the current management dogma that the best way to reduce the impacts of fishing on spawning tiger prawns is to use seasonal closures. It may be possible to protect a large portion of the effective spawning stock by closing selected inshore areas within the main fishing grounds. It also questions the assumption that there is a single stock of each species of tiger prawns in the NPF. We suggest that in the Gulf of Carpentaria alone there are at least 3 substocks for each of the 2 species.

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CSIRO IPP&P Biometrics IPPP/BU/9?/??

# Analysis of Seasonal Patterns of Prawn Abundance: Albatross Bay

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### Introduction

This report describes an analysis of seasonal variation in prawn abundance at three sites in Albatross Bay: C1, C5 and C11. Data are available fortnightly over a period of several years (6 for site C1, 3 for site C5 and 3 for site C11). Later years at all sites do not have records for every fortnight. No samples were taken during periods during which prawn numbers are known to be almost zero.

The objective of this study was to establish:

- 1. Are there differences in prawn abundance between years?
- 2. What is the seasonal pattern of prawn abundance, and does the pattern remain constant across years?
- 3. Given the yearly and seasonal effects, what is the sampling distribution of prawn numbers?
- 4. Is the seasonal pattern of prawn abundance constant across sites?

Data were available for approximately 20, 1 cm size classes. Size classes 1-2 were summed to form "Post Larvae", and size classes 3 onwards were summed to form "Juveniles". Analyses were repeated for "Post Larvae", Post Larvae Size Class 1", "Post Larvae Size Class 2" and for "Juveniles".

### **Methods**

Preliminary residuals were generated by removing year and month means. Histograms and density plots of residuals suggested a highly skewed distribution, which was normalised by a logarithmic transformation. All subsequent analyses and diagnostics were performed on log transformed data. Analyses were based on average counts for each date. Data for sites C5 and C11 were standardised by distance. Data for site C1 were not standardised because distance was fixed.

The seasonal pattern of prawn abundance was investigated by regression on periodic functions of day of the year (day of year equals 1 for Jan 1st and 365 for December 31st). Sin and cosine functions were generated with 1,2,3 and 4 cycles per year. Both sin and cosine terms were required to fit phase and amplitude of each period (Chatfield,

1975). Sin and cosine terms were defined as:  $\sin\left(2\pi v \frac{d}{365}\right)_{\text{and}} \cos\left(2\pi v \frac{d}{365}\right)_{\text{, for } v=1..4.}$ 

Log transformed prawn abundances were analysed using the general linear model, fitting effects for year, fourier component 1 (sin and cosine with v = 1), fourier component 2 (sin and cosine with v=2) up to fourier component 4 (sin and cosine with v=4), and interactions between year and fourier component. An analysis of variance was conducted, and residuals and predicted values were generated.

Although both a sin and cosine term are used for each period (1 to 4 cycles per year), these terms are used to capture both phase and amplitude of a single periodic term. If the coefficients for sin and cosine terms at a given frequency are  $\beta$  and  $\alpha$  respectively, then the amplitude and phase of the cycle may be written as:

Amplitude = 
$$\sqrt{\alpha^2 + \beta^2}$$
  
Phase =  $\tan^{-1}(-\beta/\alpha)$ 

Note that the amplitude term in a given year measures not the overall abundance at the peak, but the difference between maximum and minimum abundance for the component

at this frequency. A phase of zero indicates that the maximum abundance in this cyclic component is found at day 0 (January 1st), whilst a phase angle of  $\pi$  indicates maximum abundance at July 1st.

Where there were differences between years in fourier terms, these differences were characterised by considering the height, position and existence of the two peak abundances which may occur in each year (one in the period January to June, and one in the period July to December). Since both amplitude and position of the peaks are non linear functions of the parameters estimated for the fourier terms, hypothesis tests and confidence intervals were based on bootstrap distributions. For each peak and year, bootstrap distributions of amplitude and phase were generated. Differences in amplitude and position of the peaks between years were tested using a Chi Square statistic, based on the bootstrap mean and variance for each distribution. In addition, for each year the proportion of bootstrap realisations which exhibit a peak was recorded for each period.

Differences in position and size of the peaks indicate that the pattern of abundance varies from year to year. If the pattern of abundance varies, then it may be necessary to conduct an intensive sampling each year in order to estimate stocks and recruitment; for example, a sample taken each December might be near a peak in incidence in some years, but near a trough in other years.

The maximum predicted abundance for each site and year was calculated, using the model which included interaction terms between year and the fourier components. Predicted abundance at 1st September, October, November and December was also calculated. The maximum predicted abundance was compared with the abundance predicted for each date. High correlations between the maximum abundance (which occurs at a varying date) and the fixed date abundances indicate that despite any differences between the fourier terms, the abundance pattern is sufficiently stable to enable each year's population to be characterised by a single sample time. Low correlations, however, indicate that the pattern varies too much between years to allow each year to be characterised from a single sample.

Histograms and kernel density plots of residuals were produced for each site.

In addition, joint analyses were conducted, combining data from all sites (for those years in which data were available at all sites). Analyses of variance of log transformed data were generated, with site, year and two fourier component effects. The site differences were decomposed into two single degree of freedom comparisons. "Between types" (Sites C1 and C11 vs. Site C5) which measures the difference between mangrove and non mangrove sites, and within types (site C1 v Site C2) which measures differences within mangrove sites.

### Results

### Post Larvae All Size Classes

The analyses of variance for Post Larvae in total are shown in table 1.

In general, the first and second fourier terms (1 year and 6 month cycles) and their interactions with year, were statistically significant. This indicates that there are up to two peaks in abundance each year, and that the phase or relative magnitude of the peaks varies from year to year. To aid interpretation, fitted values were calculated from a model including year, the first two fourier terms, and year by fourier term interaction.

Fitted values were plotted against sample date, and observed values were superimposed on the plot. Figure 1 shows this result for site C1 and figures 2 and 3 show similar plots for sites C5 and C11. Histograms and kernel density estimates of the residuals are plotted in figure 4. The residuals are seen to have a similar distribution across sites, though there is some suggestion that the variance is smallest in site C1 and greatest in site C5.

Figures 5, 6 and 7 show box plots of the bootstrap distribution of peak position and size by year, for each part of the season. The bootstrap test for differences in peak position and size between years is shown in table 2. The location of the first peak abundance differs between years for all sites, and the size of the peak differs between years for sites C1 and C5. Similarly, the location of the second peak abundance differs between years for sites C5 and C11, and the size of the peak differs between years for sites C5 and C11. Site C1 also showed marked differences between years in the proportion of bootstrap realisations which showed a peak in period 2. Only 0.6% of realisation showed a second peak in other years. The Chi square tests for the second peak at site C1 were therefore performed excluding this year.

To summarise, all sites showed marked variation in both the timing and extent of maximum abundance between years.

The relationship between abundance at fixed sample dates and maximum predicted abundance is displayed in figure 11. Here the maximum predicted abundance is plotted against abundance predicted at a range of sample dates. Each point represents a particular site and year combination. Correlations are poor for all reference dates, the best correlation is between October abundance and maximum fitted abundance, with an  $R^2$  of 49%.

The analysis of variance across sites is shown in table 3. The site, year and fourier effects are all statistically significant, and all two way interactions are statistically significant. That is, there are differences between site and year, and the seasonal pattern differs between sites and years.

Effect		C1			C5			C11	
	df	Mean	F	df	Mean	F	df	Mean	F
		Sq			Sq			Sq	
Year	5	17.1	13.6**	2	16.6	12.4**	2	4.4	6.4**
f1	2	12.2	9.7**	2	4.7	3.5*	2	66.7	95.5**
f2	2	12.9	10.2**	2	10.7	8.0**	2	10.2	14.6**
f3	2	1.9	1.5NS	2	0.7	0.5NS	2	1.2	1.8NS
f4	2	4.1	3.2*	2	4.0	3.0NS	2	0.9	1.2NS
Year by f1	10	6.8	5.4**	4	2.7	2.0NS	4	4.1	5.8**
Year by f2	10	4.3	3.4**	4	4.7	3.5*	4	4.5	6.4**
Year by f3	10	1.3	1.1NS	4	2.8	2.1NS	4	3.0	4.3*
Year by f4	10	1.6	1.3NS	4	0.7	0.6NS	4	0.8	1.1NS
Residuals	74	1.3		19	1.3		20	0.7	

Table 1: Analysis of	Variance for	Post Larvae
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		Peri	od 1		Period 2				
	Position	of Peak	Size o	f Peak	Position	of Peak	Size of Peak		
Site	Chi Sq	p Value	Chi Sq	P Value	Chi Sq	p Value	Chi Sq	P Value	
C1	49.85	0.000	27.04	0.000	3.31	0.506	73.54	0.000	
C5	133.54	0.000	9.98	0.007	9.58	0.008	13.78	0.000	
C11	18.90	0.000	2.62	0.269	6.79	0.033	4.04	0.132	

Table 2: Bootstrap test for Size and Position of Peaks All Post Larvae

	Df	Mean Sq	F Value	p Value
site	2	25.19	17.85	0.000
site: between.types	1	25.03	17.74	0.000
site: within.types	1	25.35	17.97	0.000
year	5	24.69	17.50	0.000
f1	2	45.86	32.50	0.000
f2	2	20.42	14.47	0.000
year:site	4	3.50	2.48	0.046
year:site: between.types	2	4.70	3.33	0.038
year:site: within.types	2	2.29	1.63	0.200
year:f1	10	8.94	6.34	0.000
year:f2	10	7.41	5.25	0.000
site:f1	4	11.62	8.23	0.000
site:f1: between.types	2	11.63	8.24	0.000
site:f1: within.types	2	11.61	8.23	0.000
site:f2	4	6.02	4.27	0.003
site:f2: between.types	2	5.54	3.92	0.022
site:f2: within.types	2	6.51	4.61	0.011
year:site:f1	8	2.01	1.42	0.190
year:site:f1: between.types	4	0.55	0.39	0.818
year:site:f1: within.types	4	3.47	2.46	0.047
year:site:f2	8	0.87	0.61	0.766
year:site:f2: between.types	4	0.85	0.60	0.664
year:site:f2: within.types	4	0.89	0.63	0.643
Residuals	161	1.41		

Table 3 : Analysis of Variance for Post Larvae All Sites

### Post Larvae Size Class 1

The analyses of variance for Post Larvae in size class one are shown in table 4.

There was a statistically significant interaction between year and at least one of the fourier terms for all sites. This indicates that the recruitment profile changes from year to year.. To aid interpretation, fitted values were calculated from a model including year, the first two fourier terms, and year by fourier term interaction. Fitted values were plotted against sample date, and observed values were superimposed on the plot. Figure 8 shows this result for site C1 and figures 9 and 10 show similar plots for sites C5 and C11

Figures 11, 12 and 13 show box plots of the bootstrap distribution of peak position and size by year, for each part of the season. The bootstrap test for differences in peak position and size between years is shown in table 5. The location of the first peak abundance differs between years for all sites, and the size of the peak differs between years for sites C1 and C5. Similarly, the location of the second peak abundance differs between years for sites C5 and C11, and the size of the peak differs between years for sites C5 and C11.

To summarise, all sites showed marked variation in both the timing and extent of maximum abundance between years.

The relationship between abundance at fixed sample dates and maximum predicted abundance is displayed in figure 11. Here the maximum predicted abundance is plotted against abundance predicted at a range of sample dates. Each point represents a particular site and year combination. Correlations are poor for all reference dates, the best correlation is between October abundance and maximum fitted abundance, with an  $R^2$  of 49%.

The analysis of variance across sites is shown in table 6. The site, year and fourier effects are all statistically significant, and all two way interactions are statistically significant. That is, there are differences between site and year, and the seasonal pattern differs between sites and years.

Effect		Site C1			Site C5			Site C11		
	df	Mean	F	df	Mean	F	df	Mean	F	
		Sq			Sq			Sq		
Year	5	14.3	6.088	2	16.9	10.1**	2	2.0	1.8NS	
f1	2	12.8	5.4**	2	3.6	2.1NS	2	41.8	36.0**	
f2	2	6.6	2.8NS	2	4.9	2.9NS	2	6.8	5.9**	
f3	2	1.8	0.8NS	2	1.4	0.8NS	2	0.1	0.1	
f4	2	9.1	3.9*	2	6.6	4.0*	2	0.1	0.1	
Year by f1	10	5.5	2.3*	4	2.3	1.4NS	4	4.3	3.7*	
Year by f2	10	5.8	2.4*	4	5.6	3.4*	4	3.3	2.9	
Year by f3	10	2.3	1.0NS	4	4.2	2.5NS	4	1.7	1.4	
Year by f4	10	1.9	0.8NS	4	0.5	0.3NS	4	1.4	1.2	
Residuals	74	2.4		19	1.7		20	1.2		

### Table 4: Analysis of Variance for Post Larvae Class 1

		Peri	od 1		Period 2				
	Position	of Peak	Size o	f Peak	Position	of Peak	Size of Peak		
Site	Chi Sq	p Value	Chi Sq	P Value	Chi Sq	p Value	Chi Sq	P Value	
C1	54.71	0.000	16.31	0.006	23.81	0.000	30.96	0.000	
C5	20.21	0.000	4.41	0.110	13.20	0.001	5.69	0.058	
C11	14.1	0.001	0.97	0.616	5.93	0.051	1.81	0.404	

Table 5: Bootstrap test for Size and Position of Peaks Post Larvae Size Class 1

	Df	Mean Sq	F Value	p Value
site	2	19.34	9.17	0.000
site: between.types	1	30.43	14.42	0.000
site: within.types	1	8.25	3.91	0.050
year	5	19.54	9.26	0.000
f1	2	38.07	18.04	0.000
f2	2	12.38	5.87	0.004
year:site	4	4.28	2.03	0.093
year:site: between.types	2	5.20	2.46	0.088
year:site: within.types	2	3.35	1.59	0.207
year:f1	10	5.95	2.82	0.003
year:f2	10	8.68	4.11	0.000
site:f1	4	6.48	3.07	0.018
site:f1: between.types	2	9.17	4.35	0.015
site:f1: within.types	2	3.78	1.79	0.170
site:f2	4	4.64	2.20	0.072
site:f2: between.types	2	1.58	0.75	0.475
site:f2: within.types	2	7.69	3.65	0.028
year:site:f1	8	2.98	1.41	0.195
year:site:f1: between.types	4	1.27	0.60	0.662
year:site:f1: within.types	4	4.69	2.22	0.069
year:site:f2	8	1.15	0.55	0.821
year:site:f2: between.types	4	1.79	0.85	0.496
year:site:f2: within.types	4	0.51	0.24	0.915
Residuals	161	2.11		

Table 6 : Analysis of Variance for Post Larvae Size Class 1All Sites

### Post Larvae Size Class 2

The analyses of variance for Post Larvae in size class one are shown in table 7.

There was a statistically significant interaction between year and both of the fourier terms for sites C1 and C11, but not for Site C5. This indicates that the recruitment profile changes from year to year for sites C1 and C11.. To aid interpretation, fitted values were calculated from a model including year, the first two fourier terms, and year by fourier term interaction. Fitted values were plotted against sample date, and observed values were superimposed on the plot. Figure 14 shows this result for site C1 and figures 15 and 16 show similar plots for sites C5 and C11

Figures 17, 18 and 19 show box plots of the bootstrap distribution of peak position and size by year, for each part of the season. The bootstrap test for differences in peak position and size between years is shown in table 8. The location of the first peak abundance differs between years for all sites. Similarly, the location of the second peak abundance differs between years for site C1, though the difference is not statistically significant for sites C5 and C11.

To summarise, all sites showed marked variation in both the timing of maximum abundance between years.

The analysis of variance across sites is shown in table 9. The site, year and fourier effects are all statistically significant, and all two way interactions are statistically significant. That is, there are differences between site and year, and the seasonal pattern differs between sites and years.

Effect		C1			C5			C11		
	df	Mean	F	df	Men	F	df	Mean	F	
		Sq			Sq			Sq		
Year	5	20.0	14.8**	2	14.9	10.2**	2	4.0	6.1**	
f1	2	6.2	4.6*	2	4.6	3.1NS	2	50.0	76.0**	
f2	2	16.8	12.5**	2	15.1	10.3**	2	9.5	14.4**	
f3	2	5.3	3.9*	2	0.5	0.3NS	2	2.2	3.4*	
f4	2	4.9	3.6*	2	2.5	1.7NS	2	2.0	3.0NS	
Year by f1	10	8.3	6.1**	4	2.8	1.9NS	4	3.0	4.5**	
Year by f2	10	4.8	3.6**	4	2.9	2.0NS	4	4.2	6.4**	
Year by f3	10	1.1	0.8NS	4	1.7	1.2NS	4	3.3	5.1**	
Year by f4	10	2.4	1.8NS	4	0.5	0.3NS	4	0.7	1.1NS	
Residuals	74	1.3		19	1.5		20	0.7		

Table 7: Analysis of Variance for Post Larvae Class 2

		Peri	od 1		Period 2				
	Position	of Peak	Size o	f Peak	Position	of Peak	Size of Peak		
Site	Chi Sq	p Value	Chi Sq	P Value	Chi Sq	p Value	Chi Sq	P Value	
C1	31.49	0.000	8.38	0.137	6.18	0.289	70.51	0.000	
C5	8.29	0.016	1.46	0.481	2.47	0.291	2.96	0.228	
C11	13.08	0.001	2.43	0.296	2.60	0.261	2.72	0.257	

Table 8: Bootstrap test for Size and Position of Peaks Post Larvae Size Class 2

	Df	Mean Sq	F Value	p Value
site	2	17.16	11.14	0.000
site: between.types	1	24.85	16.13	0.000
site: within.types	1	9.46	6.14	0.014
year	5	26.39	17.13	0.000
f1	2	32.40	21.03	0.000
f2	2	19.93	12.93	0.000
year:site	4	2.61	1.69	0.154
year:site: between.types	2	2.78	1.80	0.168
year:site: within.types	2	2.44	1.58	0.209
year:f1	10	9.67	6.28	0.000
year:f2	10	6.38	4.14	0.000
site:f1	4	10.07	6.53	0.000
site:f1: between.types	2	9.18	5.96	0.003
site:f1: within.types	2	10.95	7.11	0.001
site:f2	4	7.91	5.13	0.001
site:f2: between.types	2	9.27	6.02	0.003
site:f2: within.types	2	6.54	4.24	0.016
year:site:f1	8	2.78	1.81	0.079
year:site:f1: between.types	4	0.50	0.33	0.860
year:site:f1: within.types	4	5.06	3.29	0.013
year:site:f2	8	1.11	0.72	0.671
year:site:f2: between.types	4	0.93	0.60	0.661
year:site:f2: within.types	4	1.30	0.84	0.500
Residuals	161	1.54		

Table 9 : Analysis of Variance for Post Larvae Size Class 2All Sites

### Juveniles

The analyses of variance for sites C1, C5 and C11 are shown in table 10. Site C1 shows statistically significant fourier terms for 1,2 3 and 4 cycles per year, with a statistically significant fourier term by year interaction for 1 and two cycles. F values for the 1st and 2nd fourier terms are VERY much larger than for the 3rd and 4th components. There is clear evidence of two peaks in abundance per year, and that the relative magnitude or phase of these peaks varies from year to year. To aid interpretation, fitted values were calculated from a model which included year, the first 4 fourier terms, and an interaction of the first 2 fourier terms with year. Fitted values were plotted against sample date, and observed values were superimposed on the plot. Figure 21 shows this result for site C1 and figures 22 and 23 show similar plots for sites C5 and C11. Histograms and kernel density estimates of the residuals are plotted in figure 24. Residuals generated for all sites have a similar distribution.

Table 12 shows the joint analysis across sites.

The bootstrapped tests for differences in peak location and size between years are given in table 11. There are clear differences between years in both the location and size of the first peak in abundance for all sites. Similarly, all sites show between year differences in the size of the second peak abundance, and site C5 shows clear between year differences in the location of the peak. The bootstrapped distributions are shown for all sites in figures 13, 14 and 15.

The relationship between abundance at fixed sample dates and maximum predicted abundance is displayed in figure 16 . Here the maximum predicted abundance is plotted against abundance predicted at a range of sample dates. Each point represents a particular site and year combination. Correlation between maximum fitted abundance and abundance at each reference date is better than for the post larvae, but is not impressive. The highest correlation ( $R^2$  of 72%) is between maximum fitted abundance and fitted abundance during December.

Effect		C1			C5			C11		
	df	Mean	F	df	Mean	F	df	Mean	F	
		Sq			Sq			Sq		
Year	5	5.4	11.3**	2	9.6	24.1**	2	4.9	8.5**	
f1	2	62.5	130.0**	2	12.8	32.0**	2	55.4	95.8**	
f2	2	17.9	37.3**	2	17.6	44.0**	2	16.4	28.3**	
f3	2	1.9	3.9*	2	0.5	1.3NS	2	0.1	0.1NS	
f4	2	3.4	7.0**	2	0.7	1.9NS	2	1.5	2.6NS	
Year by f1	10	3.5	7.2**	4	1.1	2.7NS	4	3.6	6.2**	
Year by f2	10	1.7	3.5**	4	2.8	7.0**	4	3.1	5.3**	
Year by f3	10	0.3	0.7NS	4	0.1	0.3NS	4	0.1	0.2NS	
Year by f4	10	0.3	0.5NS	4	1.0	2.6NS	4	1.4	2.5NS	
Residuals	74	0.5		19	0.4		20	0.6		

Table 10: Analysis of Variance for Juveniles

		Perio	od 1		Period 2			
	Position	of Peak	Size of Peak		Position of Peak		Size of Peak	
Site	Chi Sq	p Value	Chi Square	P Value	Chi Sq	p Value	Chi Square	P Value
C1	12.69	0.026	23.61	0.000	3.70	0.448	49.97	0.000
C5	122.66	0.000	11.49	0.003	9.66	0.008	13.90	0.000
C11	69.47	0.000	10.45	0.005	5.76	0.056	8.02	0.018

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Table 11 : Between Year Comparison of Peak Location and Size - Juveniles All Sites

 Table 12 : Analysis of variance for site and year
 : Juveniles

	Df	Mean Sq	F Value	p Value
site	2	18.76	33.60	0.000
site: between.types	1	19.92	35.70	0.000
site: within.types	1	17.59	31.50	0.000
year	5	18.49	33.10	0.000
f1	2	63.66	114.10	0.000
f2	2	43.79	78.50	0.000
year:site	4	3.02	5.40	0.000
year:site: between.types	2	3.19	5.70	0.004
year:site: within.types	2	2.85	5.10	0.007
year:f1	10	6.36	11.40	0.000
year:f2	10	5.63	10.10	0.000
site:f1	4	12.18	21.80	0.000
site:f1: between.types	2	7.20	12.90	0.000
site:f1: within.types	2	17.16	30.80	0.000
site:f2	4	2.65	4.70	0.001
site:f2: between.types	2	2.18	3.90	0.022
site:f2: within.types	2	3.12	5.60	0.005
year:site:f1	8	0.70	1.30	0.272
year:site:f1: between.types	4	0.69	1.20	0.295
year:site:f1: within.types	4	0.70	1.30	0.287
year:site:f2	8	1.09	1.90	0.057
year:site:f2: between.types	4	1.13	2.00	0.095
year:site:f2: within.types	4	1.05	1.90	0.118
Residuals	161	0.56		

### Discussion

Both Post Larvae and Juvenile prawns show a clear seasonal pattern in abundance, with a tendency towards two peaks per year. Although data are very variable, there is clear evidence that both the overall abundance, and the relative magnitudes of the two peaks vary from year to year. Between year differences cannot be accounted for in terms of within year variability. Years differ not only in the amplitude of the annual cycle, but also in the position of the maximum. Both post larvae and juveniles show complex inter annual variation, which cannot be summarised in a small number of parameters.

This complex inter annual variation has important consequences for sampling. It is not possible to characterise relative abundance between years based on one or a few sampling periods. Any assessment of relative abundance must be based on a regular sampling frame, with multiple samples taken during the course of each year.

There are large differences in abundance between sites. Both the seasonal effects and year differences differ between sites. These differences cannot be accounted for in terms of sample variability.

### Figures

### Figure 1: Post Larvae Observed & Fitted C1



### Post Larvae Site C1



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Post Larvae Site C5



Post Larvae Site C11



### Figure 4: Post Larvae Residuals All Sites





Figure 5: Post Larvae Size and Position of Peaks in Abundance by Year - Site C1



Period 1 Position by Year

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Period 2 Position by Year





Figure 7: Post Larvae Size and Position of Peaks in Abundance by Year - Site C11







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Figure 12:Post Larvae Class 1 Size and Position of Peaks in Abundance by Year - Site C5

Period 1 Position by Year

Period 2 Position by Year







Post Larvae

Post Larvae Period 2 Power by Year



Post Larvae

## Figure 13: Post Larvae Class 1 Size and Position of Peaks in Abundance by Year - Site C11







Post Larvae Class 2

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C5: Fitted Values by Date



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c11: Fitted Values by Date





Figure 18: Post Larvae Class 2 Size and Position of Peaks in Abundance by Year - Site C5

Period 1 Position by Year



Post Larvae

Period 1 Power by Year



Post Larvae

Period 2 Position by Year



Post Larvae

Period 2 Power by Year



Post Larvae



# Figure 19: Post Larvae Class 2 Size and Position of Peaks in Abundance by Year - Site C11

Figure 20 : Comparison of Maximum Fitted Abundance with fixed Date Abundance



### Figure 21 : Juveniles Site C1





Figure 22 : Juveniles Site C5

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Juveniles C5



Analysis of Seasonal Patterns of Prawn Abundance: Albatross Bay

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### Figure 24: Distribution of Residuals by Site - Log Juveniles

Figure 25: Bootstrap Distribution of Size and location of Peak Abundance by Year - Site C1

Period 1 Position by Year



Juveniles





Juveniles











Juveniles

## Figure 26: Bootstrap Distribution of Size and location of Peak Abundance by Year - Site C5



Figure 27: Bootstrap Distribution of Size and location of Peak Abundance by Year - Site C11

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Period 2 Position by Year





Period 2 Power by Year



Juveniles

Juveniles





**APPENDIX 6** 

# Stock–Recruitment Relationships of the Tiger Prawns (*Penaeus esculentus* and *Penaeus semisulcatus*) in the Australian Northern Prawn Fishery

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Abstract. This paper investigates the stock-recruitment and equilibrium yield dynamics for the two species of tiger prawns (Penaeus esculentus and Penaeus semisulcatus) in Australia's most productive prawn fishery: the Northern Prawn Fishery. Commercial trawl logbooks for 1970–93 and research surveys are used to develop population models for these prawns. A population model that incorporates continuous recruitment is developed. Annual spawning stock and recruitment indices are then estimated from the population model. Spawning stock indices represent the abundance of female prawns that are likely to spawn; recruitment indices represent the abundance of all prawns less than a certain size.

The relationships between spawning stock and subsequent recruitment (SRR), between recruitment and subsequent spawning stock (RSR), and between recruitment and commercial catch were estimated through maximum-likelihood models that incorporated autoregressive terms. Yield as a function of fishing effort was estimated by constraining to equilibrium the SRR and RSR. The resulting production model was then used to determine maximum sustainable yield (MSY) and its corresponding fishing effort ( $f_{MSY}$ ).

Long-term yield estimates for the two tiger prawn species range between 3700 and 5300 t. The fishing effort at present is close to the level that should produce MSY for both species of tiger prawns. However, current landings, recruitment and spawning stock are below the equilibrium values predicted by the models. This may be because of uncertainty in the spawning stock-recruitment relationships, a change in carrying capacity, biased estimates of fishing effort, unreliable catch statistics, or simplistic assumptions about stock structure.

Although our predictions of tiger prawn yields are uncertain, management will soon have to consider new measures to counteract the effects of future increases in fishing effort.

#### Introduction

The Northern Prawn Fishery (NPF) is one of Australia's most important fisheries: its yearly exports earn between \$100 million and \$150 million (Dann *et al.* 1994). The commercial fishery catch is made up of eight prawn species, but three of them—the banana prawn (*Penaeus merguiensis*), the brown tiger prawn (*Penaeus esculentus*) and the grooved tiger prawn (*Penaeus semisulcatus*)—make up almost 80% of the annual average catch (Somers 1994a).

Operationally, the fishery has two components: a daytime fishery for banana prawns, which targets schooling prawns, and a night-time fishery for tiger prawns. The fleet starts fishing for banana prawns at the beginning of the fishing season (mid March to mid April) and then progressively changes to tiger prawn fishing as banana prawn catch rates decline. At present the banana prawn fishery lasts only about three to four weeks, and the tiger prawn fishery lasts eight months but is interrupted by a one-month trawl closure in July.

The recruitment of banana prawns is strongly linked to the amount of rainfall during the annual wet season, and this is especially evident in the south-east of the Gulf of Carpentaria (Vance *et al.* 1985). There is no evidence that fishing affects banana prawn recruitment, so management of the banana prawn fishery focuses on maximizing short-term (annual) yields by adjusting the opening date of the fishing season (Somers 1990*a*).

The recruitment of tiger prawns appeared to be declining in the mid 1980s, but no clear reason for this decline was identified (Somers 1990b). Worried by the lack of knowledge on the cause of the decline in recruitment, fishery managers decided, as a precaution, to decrease fishing effort in the tiger prawn fishery (Fig. 1). This management decision recognized implicitly that fishing was possibly one of the factors responsible for the decline in recruitment and therefore that there was a relationship between stock size and recruitment in tiger prawns, albeit undetected (Somers 1990b). Regardless of how difficult it is to prove statistically the existence of such relationships for penaeid prawns, research on stock-recruitment dynamics can provide the basis for sound management decisions (Caputi 1993). This type of research is still a priority for the NPF (Ferguson 1994).

Almost 10 years have passed since the first evidence of decline in tiger prawn recruitment surfaced. In those 10 years the fishery has endured a vessel buy-back scheme that



Fig. 1. Historical (a) fishing effort and (b) landings for the two species of tiger prawns (*Penaeus esculentus* and *P. semisulcatus*) in the Northern Prawn Fishery.

reduced boat numbers by 50%, and other restrictions on fishing effort. These reductions in fishing effort have not resulted in the expected increases in landings, and it is now time to revise the long-term yield predictions made five years ago for the tiger prawn fishery (Somers 1990*a*). We have therefore re-examined the relationships between spawning stock and recruitment and between recruitment and the subsequent catch. We have also made new long-term average yield predictions for tiger prawns in the NPF. All analyses are made on the assumption that catches of these two tiger prawn species come from single stocks within the bounds of the NPF (Fig. 2).

At present both species are managed as a single stock; however, there are management measures that affect more than one species of tiger prawns. For instance, the main effect of the mid-season closure is to reduce fishing effort on brown tiger prawns. In fact, because of the spatial and seasonal separation of the two species, it would be possible to implement management measures that target a particular stock or species of tiger prawns. This paper aims to provide information on the status of tiger prawn stocks so that managers of the Northern Prawn Fishery can evaluate the benefits of fishery regulations aimed at individual tiger prawn species.

#### Materials

#### Commercial Catch and Effort Data

The catch and effort data set consists of two parts: fishers' daily logbooks and processors' landing returns, both held by the Australian Fisheries Management Authority. The logbook data are claimed to be the most complete and comprehensive of all the federally managed fisheries in



Fig. 2. Main tiger prawn fishing areas in the Northern Prawn Fishery (6-min grid squares in which fishing effort was >50 boatdays over 1970-93).
Table 1. von Bertalanffy growth parameters  $(l_{\infty}, k)$ , weight-length relationship  $(W = al^b)$  parameters (W is total weight in g, l is carapace length in mm), length at recruitment  $l_r$ , natural mortality (M) and catchability (q) by sex and by species for tiger prawns

	P ser	nisulcatus	P. esculentus		
	Female	Male	Female	Male	
k (week <sup>-1</sup> )	0.043 <sup>A</sup>	0.062 <sup>A</sup>	0.041 <sup>B</sup>	0.034 <sup>B</sup>	
$l_{\infty}$ (mm)	51.6 <sup>A</sup>	37.5	44.8 <sup>0</sup>	37.5°	
a	0.00265	0.00195	0.00373	0.00207- 0.764D	
b	2·048°	2.740° 268	2.5/4- 288	2.704 26A	
$t_{\rm r} ({\rm mm})$	20 <sup>10</sup>	20 0.045 <sup>F</sup>	0.045 <sup>F</sup>	0.045 <sup>F</sup>	
$q$ (boat-day) $\times 10^5$	8-8 <sup>E</sup>	8-8 <sup>E</sup>	8.8 <sup>E</sup>	8.8 <sup>E</sup>	

<sup>A</sup>Somers and Kirkwood (1991). <sup>B</sup>Kirkwood and Somers (1984). <sup>C</sup>Farmer (1980). <sup>D</sup>Penn and Hall (1974). <sup>E</sup>Y. Wang, CSIRO Division of Fisheries, unpublished data. <sup>F</sup>Assumed.

Australia (Sachse 1994). Both data sets are broken down by commercial species groups ('tiger prawns', 'banana prawns', 'king prawns' and 'endeavour prawns') and therefore do not distinguish between the two species of tiger prawn.

#### Research Survey Data

Monthly length-frequency distributions of *P. semisulcatus* were obtained from surveys carried out between 1986 and 1992 in the northeastern Gulf of Carpentaria, around Albatross Bay (Crocos and van der Velde 1995). Monthly length-frequency distributions of *Penaeus* esculentus were obtained from surveys of the north-western Gulf of Carpentaria, around Groote Eylandt, carried out for 18 months between 1983 and 1985 (Somers et al. 1987).

#### **Biological Parameters**

Growth and length-weight parameters, size at recruitment, and catchability were all obtained from previous studies (Table 1). The lifehistory characteristics of tiger prawns suggest that their natural mortality is lower than that of banana prawns (Dall *et al.* 1990). Therefore, the instantaneous natural mortality coefficient, M, was assumed to be 0.045 (week<sup>-1</sup>) for tiger prawns, which is smaller than the value of 0.05 estimated for *P. merguiensis* (Lucas *et al.* 1979) and equivalent to the value of 0.2 (month<sup>-1</sup>) used in previous assessments of tiger prawns stocks in the NPF (Somers 1990*a*).

*P. semisulcatus* spawns year-round, with a major spawning peak between August and October and, in most years, a secondary peak between January and February (Crocos 1987*a*; Crocos and van der Velde 1995). *P. esculentus* has a similar pattern, but with smaller peaks (Crocos 1987*b*).

The sex ratio (males: females) at recruitment was assumed to be 1:1.

#### Methods

The analysis is based on weekly catch and effort data to reduce the variations between successive daily catches. The biological year is assumed to start in November, when recruitment of both species is low, and finish in October.

#### Catch and Effort Estimates

The tiger prawn catch was estimated by adjusting the reported catch from logbooks to match the total landing from processors' returns. The ratio of logbook catches to processor landings varies from 50% in the early 1970s to over 95% in the 1990s (Sachse 1994). Nominal fishing effort was then calculated as the ratio between processor landings and catch per unit of fishing effort (from logbook data). This assumes that catch per unit of fishing effort estimated from logbook data is an unbiased estimate of the

average catch per unit of effort for the entire fishery. Catch and fishing effort were then assigned to each of the two tiger prawn species according to the geographical distribution of the logbook catches and the geographical distribution of the species (Somers 1994b). Somers (1994b) showed that at the scale at which logbook data is collected ( $6 \times 6$  min grids), the two species have almost mutually exclusive distributions. Effective fishing effort was calculated by assuming that average fishing power increases constantly every year. A 5% rate of increase in fishing power was estimated by Buckworth (1992) and has since been adopted in all assessments of the NPF fishery (Somers 1994a). In addition to the 5% rate, we use a 2% and 10% rate for sensitivity analysis.

#### Annual Recruitment Pattern

The average fortnightly length-frequency distribution of each species was estimated from the research survey data by pooling the monthly data over the length of the survey. The number of recruits in each month was calculated as the sum of all prawns smaller than or equal to the size at recruitment  $l_r$  (Table 1). This number of recruits was then used to calculate each month's proportion of the annual recruits. Because monthly sampling effort was constant during the surveys, each month's proportion of the annual recruits represents catch per unit of effort and can be considered as an index of abundance for monthly recruits. The proportion of annual recruits  $\alpha_i$  recruiting each week *i* was calculated by linear interpolation of the monthly proportions.

#### **Population Model**

Annual recruitment and spawning stock indices were calculated from the estimates of weekly catches, the annual recruitment pattern, and a model of the prawn population. Weekly catches in weight were converted to catches in number by estimating the average weight of individual prawns for each week. Average weight was estimated from the proportions of prawns in each age (length) group in each week obtained in the prawn population model. This prawn population model is presented below; it can be regarded as a generalized version of the traditional virtual population analysis when recruitment cannot be treated as a single pulse.

Given  $\alpha_i$  (the proportion of annual recruits *R* coming to the fishing ground during week *i*), let  $N_i$  be the cumulative number of prawns surviving up to the beginning of week *i*, including those from previous years, and let  $Z_i$  and  $F_i$  be the instantaneous total mortality and fishing mortality in week *i*, respectively. Fishing mortality was estimated as the product of effective fishing effort and catchability. If it is assumed that a recruit can appear any time during that week, the probability of a recruit from week *i* surviving to the end of week *i* is  $[1-\exp(-Z_i)]/Z_i$  (which is denoted as  $P_i$  for convenience), and therefore the probability that recruits from week *i* are caught in week *i* is  $(1-P_i)F_i/Z_i$ . The recurrence equation of abundance can thus be written as

$$N_{i+1} = N_i \exp(-Z_i) + P_i \alpha_i R, \tag{1}$$

where  $P_i \alpha_i$  is the discounted proportion at the end of week *i* of recruits arriving that week. The expected catch  $C_i$  is then (cf. Gulland 1983, pp. 99-105)

$$C_i = N_i P_i F_j + [\alpha_i (1 - P_i) F_j / Z_j] R.$$
<sup>(2)</sup>

Note that the catch (the right-hand side of Eqn 2) is made up of two components, corresponding to the catch of prawns recruited before and during week i, respectively.

From the recurrence equation (Eqn 1), we have

$$N_{i+1} = \gamma_i R + N_1 \exp(-U_{1,i}),$$

where

$$V_i = \sum_{j=1}^{i} \alpha_j P_j \exp\left(-U_{j+1,i}\right)$$

and  $U_{j,i}$  is the cumulative total mortality from week *j* to week *i*, i.e.

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$$\sum_{k=j}^{\prime} Z_k$$

if  $j \le i$  (and 0 otherwise). Here,  $N_1$  is the surviving population from previous years and can be obtained when the annual recruits of those years are evaluated. From Eqns 2 and 3, we obtain

$$C_i = \beta_i R + N_1 P_i F_i \exp(-U_{1,i-1}), \qquad (4)$$

where  $\beta_i = \gamma_{i-1} P_i F_i + \alpha_i (1-P_i) F_i / Z_i$ .

Therefore, the total annual recruits R can be estimated by

$$R = \left[\sum C_i - N_1 \sum P_i F_i \exp(-U_{1,i-1})\right] / \sum \beta_i.$$
(5)

The annual spawning stock indices were estimated as the average number of spawning females per week in the population model. The number of spawning females in a given week i was calculated as the product of the abundance of females times the proportion of spawning females in each month obtained from Crocos (1987*a*, 1987*b*).

Estimates of recruitment and spawning stock indices were obtained by fitting the population model, with maximum likelihood, to the weekly history of landings and fishing effort estimated above for each tiger prawn species. This method requires an estimate of the value of  $N_1$  for the first year (1970), which was initially assumed to be equal to zero. The model was then fitted to the data, and preliminary estimates of  $N_1$  for the rest of the data series were obtained. The preliminary survival rate for 1970 was then used to obtain an initial value of  $N_1$  for 1970 during the final fit of the model to the data. The resulting indices were then fitted to relationships—presented below—representing the spawning stock, recruitment and equilibrium yield dynamics of tiger prawn stocks in the NPF.

#### Spawning Stock-Recruitment Relationship (SRR)

Spawning stock-recruitment relationships were modelled according to Ricker's equation:

$$R_{t} = a_{1}S_{t-1}\exp(-b_{1}S_{t-1}), \qquad (6)$$

where  $R_t$  is the total number of recruits produced in year t and  $S_{t-1}$  is the spawning stock index of the previous year.

#### Recruitment-Spawning Stock Relationship (RSR)

The spawning stock  $(S_t)$ , resulting from the recruitment  $R_t$  of the same year, depends on the weekly pattern of fishing effort (Eqn 3) but is well approximated (Penn *et al.* 1995) by

$$S_t = a_2 R_t \exp(-b_2 F_t), \tag{7}$$

where  $F_{t}$  is the fishing mortality of year t.

#### Catch-Effort Relationship

The annual catch  $C_i$  in tonnes is approximated by

$$C_{l} = a_{3}R_{l}[1 - \exp(-b_{3}F_{l})].$$
 (8)

Note that the catch increases asymptotically to the maximum of R as fishing effort tends to infinity.

#### Fitting Procedures

(3)

Time series of recruitment and spawning stock indices, catch and fishing effort are strongly autocorrelated (for a review, see Hilborn and Walters 1992). To account for the possible correlation in the error terms over years, log-linear, first-order autoregressive time-series models were developed for each of the last three relationships (Eqns 6 to 8). The annual recruits were estimated from Eqn 5 first. PROC MIXED and PROC NLIN (SAS 6.07) were used to obtain estimates of  $a_i$  and  $b_i$ . The residual v. predicted plots were examined and did not have any systematic patterns.

#### Equilibrium Yield and Biological Reference Points

Eqns 6 and 7 can be solved for a given fishing mortality to give the equilibrium spawning stock and recruitment, i.e. the recruits that survive fishing replace, on a one-to-one basis, the adults that spawn them. Furthermore, if equilibrium recruitment and fishing mortality are incorporated in Eqn 8, the equilibrium yield can be estimated at different levels of fishing mortality. The relationship between fishing mortality and fishing effort (f) is assumed to be F = qf. The resulting relationships between equilibrium yield and fishing effort are thus analogous to surplus production models. The maximum sustainable yield (MSY) and the corresponding fishing effort ( $f_{MSY}$ ) are then obtained.

We also estimated two additional biological reference points from levels of fishing effort. The first one is  $f_{0.9}$ , an effort that is lower than  $f_{MSY}$ but that still yields 90% of MSY, which could be considered a target reference point (sensu Anon. 1993) for management of this fishery. The second,  $f_{rep}$ , represents the fishing effort associated with the median RSR, where half of the data points fall on each side of the curve (Sissenwine and Shepherd 1987). This reference point is appropriate for stocks where there is little evidence of density dependence between spawning stock and recruitment because  $f_{rep}$  corresponds to a level of fishing effort such that the population will fluctuate in size without a trend (equal probability of increasing or decreasing). Any fishing effort higher than  $f_{rep}$  will lead to lower recruitment and spawning stock size. We therefore propose that  $f_{rep}$ be used as a limit reference point (sensu Anon. 1993) for fishing effort: management would have to react if it is surpassed.

To describe the impact of data from different years in the estimates of MSY and  $f_{MSY}$ , the effect of each data point on the SRR was investigated by a procedure similar to the jackknife or cross-validation techniques (Miller 1974). One data point at a time was left out, resulting in *n* samples of n - 1 data points each, where *n* is the number of data points in the original sample (n = 23). Parameters of the SRR were obtained for each subset of the data and used to estimate MSY and  $f_{MSY}$ .

#### Results

#### Annual Recruitment Pattern

For both tiger prawn species the peak in recruitment was between December and February. For *P. esculentus*, however, there was a secondary peak in April. Recruitment was low for both species between May and September (Fig. 3).

#### Recruitment and Spawning Stock Indices

In comparison with other years in the period 1985 to 1993, recruitment of *P. esculentus* was high in 1991 and hence spawning stock was high in 1991 (Fig. 4*a*). Over the last 10 years, however, neither recruitment nor spawning stock have increased to the levels of the 1970s. Estimates of recruitment indices show that recruitment and spawning



Fig. 3. Annual recruitment pattern—proportion of prawns under the size at recruitment  $l_r$ —for the two species of tiger prawns (*Penaeus esculentus* and *P. semisulcatus*) in the Northern Prawn Fishery. Data are from trawl surveys in the north-eastern (Crocos and van der Velde 1995) and the north-westerm (Crocos and Kerr 1983) Gulf of Carpentaria.

stock size have been fairly stable for *P. semisulcatus* since 1985 (Fig. 4b).

The 1993 spawning stock of *P. esculentus* is about 60% smaller than in the mid 1970s, and the *P. semisulcatus* stock is about 50% smaller. Similarly, recruitment has decreased by 50% for *P. esculentus* and 30% for *P. semisulcatus*.

#### Spawning Stock-Recruitment Relationship (SRR)

The autocorrelation estimated in the SRR was greater for *P. esculentus* than for *P. semisulcatus*, but the evidence of density dependence was clearer in *P. semisulcatus* than in *P. esculentus* ( $b_1$  is closer to zero for *P. esculentus*) (Table 2).

For both species of tiger prawns the stock-recruitment relationship shows significant variability (Fig. 4), but this variability was greater for *P. esculentus* ( $R^2 = 0.23$ ) than for *P. semisulcatus* ( $R^2 = 0.52$ ). Statistical residuals between the estimated indices and the predicted SRR are larger for the early years of the fishery than for recent years. This is likely to be the result of the correlation between the error in those estimates and the value of the estimate.

#### Recruitment-Spawning Stock Relationship (RSR)

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In the case of both P. esculentus and P. semisulcatus, these relationships approximated the data very well, and



Fig. 4. Indices of spawning stock and recruitment and stock-recruitment relationships in the Northern Prawn Fishery over 1971–93 for (a) Penaeus esculentus and (b) P. semisulcatus. Dotted lines represent the recruitment-spawning stock relationships at the current levels of fishing effort (7500 boat-days for P. esculentus and 8700 boat-days for P. semisulcatus).

recruitment and fishing mortality explained most of the variability in subsequent stock size ( $R^2 = 0.96$  for *P. esculentus* and  $R^2 = 0.95$  for *P. semisulcatus*). As in the case of the SRR, the autocorrelation was greater for *P. esculentus* than for *P. semisulcatus* (Table 2). It is worth mentioning that these  $R^2$  values overestimate the goodness of the models because the annual recruitment indices were estimated from the catch and effort data.

Table 2. Maximum-likelihood parameter estimates for spawning stock-recruitment relationship  $(a_1 \text{ and } b_1, Eqn 6)$ , recruitment- spawning stock relationship  $(a_2 \text{ and } b_2, Eqn 7)$ , and modified catch-effort relationship  $(a_3 \text{ and } b_3, Eqn 8)$  for the two tiger prawn species of the NPF

Species	<i>a</i> <sub>1</sub>	b <sub>l</sub>	ρ	a2	b <sub>2</sub>	ρ	a <sub>3</sub>	b <sub>3</sub>	ρ
P. esculentus	14.41	0.0096	-0.52	0.111	0.354	-0.62	14.08	0.494	-0.44(
P. semisulcatus	45.96	0.0548	0.16	0.047	0.302	0.25	15-18	0.544	0.004

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## Catch-Effort Relationship

The data fitted the model very well; however, unlike the SRR and the RSR, the estimated parameters for the catch and effort relationships were quite similar for both species of tiger prawns (Table 2). This is not surprising given that catchability is assumed to be the same for both species and that there is less uncertainty in the estimates of catch than in the estimates of spawning stock size.

## Equilibrium Yield and Biological Reference Points

The intersection of the SRR and the RSR provides predicted equilibrium recruitment for a given fishing effort. The recruitment of *P. esculentus* in 1993 was 20% below the predicted equilibrium recruitment—at a fishing effort of 7500 boat-days (Fig. 4a). Recruitment of *P. semisulcatus* in 1993 was 25% below the expected equilibrium value—at a fishing effort of 8700 boat-days (Fig. 4b).

The MSY for both species of tiger prawns was estimated to be well below the historic maxima in landings, especially for *P. esculentus*. The MSY estimate for *P. esculentus* was estimated as 1900 t and for *P. semisulcatus* as 2200 t. To these estimates correspond  $f_{\rm MSY}$  values of 7300 boat-days for *P. esculentus* and 12800 boat-days for *P. semisulcatus* (Fig. 5). Both of these values are in 1993 boat-day units.

A yield only 10% lower than MSY can be obtained at a substantially lower fishing effort  $(f_{0.9})$ . This fishing effort is 4900 boat-days for *P. esculentus* and 8300 boat-days for *P. semisulcatus*. Estimates of  $f_{rep}$  are 3700 boat-days for *P. esculentus* and 8300 boat-days for *P. semisulcatus*.

This analysis shows strong yearly correlations between the observations, and jackknife resampling is therefore inappropriate for variance estimation; however, jackknife resampling can be used to highlight the influence of individual years on the overall analysis. The jackknife estimates of MSY were equally variable for *P. esculentus* (1600–2000 t) and *P. semisulcatus* (2000–2500 t). Jackknife estimates of  $f_{MSY}$ , however, were less variable for *P. esculentus* (6300–8000 boat-days) than for *P. semisulcatus* (10800–16000 boat-days) (Fig. 6).

Those years that change MSY and  $f_{MSY}$  the most when excluded are 1975, 1977, 1983, 1986 and 1991 for *P. esculentus* and 1971, 1972, 1974, 1975, 1979 and 1982 for *P. semisulcatus* (Fig. 6).

The estimated MSY for both species of tiger prawns was 4100 t, but according to the jackknife results this estimate ranged from 3600 to 4500 t. Similarly, the best estimate of  $f_{\rm MSY}$  for both species was 20100 boat-days, but jackknifed estimates ranged between 17100 and 24000 boat-days.

Equilibrium yield results are very sensitive to the rate of increase in fishing power used in the analysis (Fig. 5). If the rate of increase was 2%, MSY for *P. esculentus* would be 2200 t and fishing effort over the period 1989–93 would have been below  $f_{MSY}$ . If the rate of increase was as high as



Fig. 5. Equilibrium yield estimates in the Northern Prawn Fishery for (a) *Penaeus esculentus* and (b) *P. semisulcatus* derived from the spawning stock-recruitment relationships. Fishing effort is standardized to 1993 units by assuming three rates of annual change in fishing power: 2%, 5% and 10%. Shaded boxes represent the range of landings and fishing efforts estimated from logbooks for 1989–93 and reflect the uncertainty in the rate of annual change in fishing power.



Fig. 6. Jackknife estimates of maximum sustainable yield (MSY) and corresponding fishing effort  $f_{MSY}$  for the two tiger prawn species (*Penaeus esculentus* and *P. semisulcatus*) in the Northern Prawn Fishery. Solid square and solid circle represent non-jackknifed estimates. Data-point labels correspond to the year excluded in the estimation of parameters of the spawning stock-recruitment relationships. Only those data points that depart the most from the non-jackknifed estimate are labelled.

10%, then the MSY would be 1600 t and fishing effort over the period 1989–93 would lead to severe overfishing. In fact, under such a high rate of increase in fishing power the equilibrium model would have predicted a complete collapse of the brown tiger prawn stock.

For a 2% rate of increase in fishing power the MSY for *P. semisulcatus* is 2100 t, the same as for a 5% increase. For such a low rate of increase in fishing power, though, fishing effort over the period 1989–93 would have been below  $f_{\rm MSY}$ . If the rate of increase in fishing power was 10%, then MSY would be as large as 3100 t and fishing effort over the period 1989–93 would have been close to  $f_{\rm MSY}$ .

#### Discussion

The population model developed here is inherently complex because it incorporates the observed weekly patterns of fishing effort, recruitment and proportion of females spawning. Models of stock-recruitment dynamics can be incorporated in such a population model to estimate the stock-recruitment parameters directly. This approach, however, requires specifying the exact form of the SRR, before the population abundance indices are estimated. In this paper we chose the simpler approach because of the historical difficulties of establishing such a relationship (Somers 1990b, 1994a).

The RSR and the catch-effort relationship used here can be considered as empirical approximations of the dynamics of the stock expressed in Eqns 1 to 5. Such relationships, as reported elsewhere (Penn *et al.* 1995), explain most of the variability in the dependent variable (spawning stock and catch respectively). That is why the uncertainty associated with the above two relationships was not considered in the estimation of the variability associated with the estimates of biological reference points and equilibrium yield.

In the Northern Prawn Fishery, tiger prawn recruitment has decreased from its historic peak by around 40-50%, which is significantly less than the 80% reductions reported for the *P. esculentus* fisheries of Shark Bay and Exmouth Gulf in Western Australia (Penn *et al.* 1995). However, reductions in fishing effort instigated by NPF management have not led to significant increases in recruitment, as has occurred in Exmouth Gulf (Penn *et al.* 1995).

In the Northern Prawn Fishery, spawning stock size and recruitment of tiger prawns have not varied greatly over the past 10 years. As a result, the new relationships developed here confirm the work on recruitment overfishing in the NPF done in the mid 1980s (Somers 1990*a*) and on the SRR of tiger prawns in the western Gulf of Carpentaria (Somers 1992). These studies used the total catch as an index of recruitment and the catch per unit of fishing effort during the main spawning season as an index of spawning stock.

The present study confirms the results of Somers (1990a, 1992), who identified the possibility of recruitment

overfishing of *P. esculentus* from 1978 and of *P. semisulcatus* from 1983. Interestingly, recruitment of *P. semisulcatus* has decreased less than recruitment of *P. esculentus*, even though fishing effort directed to *P. semisulcatus* has been maintained at high levels during the past 10 years whereas fishing effort directed to *P. esculentus* dropped considerably in the mid 1980s. This may be a result of the differences in the migratory behaviour of the two species: *P. semisulcatus* moves out of the fishing grounds for a few months of the year, whereas *P. esculentus* does not (Somers and Kirkwood 1991).

The present analysis suggests that effective fishing effort on *P. semisulcatus* grew until 1989 and started to decrease only after 1990. Since 1990, effective fishing effort directed to *P. semisulcatus* has dropped by 30%. However, according to the present analyses, such a drop would lead to only a small change in equilibrium yield (Fig. 5b). The fact that in 1993 recruitment of *P. semisulcatus* was 25% lower than the equilibrium recruitment predicted by the model cannot be easily explained. The next few years of tiger prawn data will be critical to determine whether this level of recruitment remains depressed, as has been the case with *P. esculentus*.

Effective fishing effort directed at *P. esculentus* decreased by almost half between 1983 and 1987. It increased again between 1987 and 1989; however, in 1993 it was still 30% lower than the 1983 maximum. Over the last 10 years, recruitment and spawning stock have varied by 40-50%. In spite of the short lifespan of penaeid prawns, because of the continuous fluctuations in fishing effort it is unlikely that the *P. esculentus* stock would reach or remain in equilibrium for very long. It is therefore possible that the large changes in fishing effort have resulted in the observed fluctuations in recruitment and spawning stocks of *P. esculentus*.

Recent tiger prawn yields, however, have been consistently lower than the equilibrium yields predicted by our models. Several hypotheses can be proposed to explain this. The first hypothesis is that the true SRR is more linear than the ones estimated here. A small decrease in the curvature, i.e. the degree of density dependence, of the SRR would lead to a substantial decrease in the SRR equilibrium point (Fig. 4b).

A second hypothesis is that recent yields reflect changed environmental conditions for the *P. esculentus* stock. Poiner *et al.* (1989) reported how in March 1985 Cyclone Sandy destroyed 20% of the seagrasses within the Gulf of Carpentaria. Recent data suggest that it has taken 10 years for those areas to recover to the state they were in before Cyclone Sandy (R. Kenyon, CSIRO Division of Fisheries, unpublished data). How such substantial losses of seagrass affected the SRR is difficult to say, but it is possible that they were responsible for a drop in carrying capacity of juvenile prawn nursery areas and a decrease in abundance of *P. esculentus.* Given that those seagrass beds are now back to their pre-Cyclone Sandy state, the magnitude of recruitment of brown tiger prawns over the next few years could confirm or reject this hypothesis.

The amount of recruitment variability not explained by the levels of spawning stock in the *P. esculentus* fisheries of Exmouth and the NPF is remarkably similar (Fig. 4a of this study; and Penn *et al.* 1995). Given that environmental factors have been shown to explain a significant fraction of this unexplained variability in Exmouth Gulf (Penn and Caputi 1986; Caputi 1993), it is possible that similar environmental factors affect recruitment of *P. esculentus*. These environmental factors affecting recruitment of *P. esculentus* and are the subject of current research.

Yet another hypothesis is that there is more than one stock in the NPF for each of the two tiger prawn species. Some of the tiger prawn fishing grounds are separated by large distances (e.g. the Albatross Bay area and the rest of the tiger prawn fishing grounds in the Gulf of Carpentaria, Fig. 1). In fact, the historic patterns of tiger prawn landings are quite different in the various regions of the NPF (Robins and Somers 1994). Several of these areas may function as independent stocks and recruitment might therefore be mainly determined by local fishing effort and spawning stock. In such a case, SRRs may have to be defined for each of these areas before the true relationships between spawning stock and recruitment can be understood for the whole fishery.

There are other uncertainties in our estimates of population indices and equilibrium yield that have not yet been considered. The effects on yield predictions of model uncertainty (e.g. Ricker v. Beverton and Holt stockrecruitment model), of uncertainty in population parameters, and of errors in landing and effort estimates are unknown and should be quantified in further analyses. Regardless of these uncertainties, however, some important conclusions can be reached from this study. The 1993 fishing effort directed towards P. esculentus (7500 boat-days) seems close to the estimated  $f_{MSY}$  (7300 boat-days) but well above  $f_{0.9}$  (4900 boat-days) and  $f_{rep}$  (3700 boat-days). It is often argued that the economic optimum is always obtained at a fishing effort lower than  $f_{MSY}$  (for a review, see Anon. 1993). The value of  $f_{rep}$ , however, suggests that the present effort will lead to decreased recruitment and stock size. It must therefore be concluded that the present data on spawning stock and recruitment dynamics for P. esculentus suggest that present fishing effort is excessive.

For *P. semisulcatus*, however, the 1993 fishing effort was 8700 boat-days, closer to the 8300 boat-days corresponding to  $f_{0.9}$  and  $f_{rep}$  than to the 12800 boat-days corresponding to  $f_{MSY}$ . In such a case, present fishing effort should be close to the optimum.

Our predictions of equilibrium yield as a function of fishing effort are very sensitive to the rate of increase in fishing power, especially for brown tiger prawns. Depending on what value of the rate of increase in fishing power is used, the model would suggest that during 1989–93 brown tiger prawns were either severely overfished (fishing effort was much higher than  $f_{MSY}$ ) or slightly underfished. The assessment of the status of stocks of grooved tiger prawns during 1989–93 is not as sensitive to this rate of increase in fishing power as the assessment for brown tiger prawns. During 1989–93 grooved tiger prawns were either fully fished or slightly underfished.

As shown above, it is critical to determine the rate of increase in fishing power. The incorporation of new technology such as plotters and global positioning systems (GPS) between 1988 and 1990 is thought to have dramatically increased fishing power. If the increases were as high as 40%, as suggested by some NPF operators, population estimates derived by assuming rates of increase of 2% or 5% would be biased. However, preliminary analysis of the effects of such technological changes suggests that the increase in fishing power was closer to 10% (C. Robins, CSIRO Division of Fisheries, personal communication). In the Western Australian rock lobster fishery, the adoption of GPS increased fishing power by 12% and colour echo-sounders by 15% (Brown et al. 1995). In fact, the 5% annual increase in fishing power adopted in the present analysis would represent a 25% increase in fishing power between 1989, the year that GPS started to be commonly used by the NPF fleet, and 1993. We therefore believe that a rate of increase of 10% per annum is unlikely to have occurred and that the sensitivity analysis results for such a rate of increase should be considered as a 'worst-case scenario'. On the other hand, the rate of increase in fishing power must be greater than zero, therefore 2% should be considered as a 'best-case scenario'.

Let us now assume that fishing power keeps increasing by 5% every year and that there will be no further changes in the number of boats after 1993 (the last year of the accelerated boat buy-back scheme instituted by the managers of the fishery). By 1995 effective fishing effort will have reached 5700 boat-days for *P. esculentus* and 12700 boat-days for *P. semisulcatus*. That means that in less than two years the fishery will be operating at levels of fishing effort that are likely to be excessive for both species. It is therefore necessary, as suggested by certain sections of the NPF industry (Ferguson 1994), to urgently consider new management options to control the likely increases in fishing effort in the tiger prawn fishery and to further protect the spawning stock.

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**APPENDIX 7** 

# Notes on methodology used for stock assessments of the Tiger Prawns (*Penaeus esculentus* and *Penaeus semisulcatus*) in the Australian Northern Prawn Fishery

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## Introduction

This document contains details of the methods used to assess the status of tiger prawn stocks not contained in Wang and Die (1996). For details on the results of the assessment or its management implications refer to Wang and Die (1996) , Die (1995) and Die and Taylor (1996).

#### Materials

## Commercial Catch and Effort Data

The catch and effort data set consists of two parts: fishers' daily logbooks and processors' landings returns, both held by the Australian Fisheries Management Authority. The logbook data is claimed to be the most complete and comprehensive of all the Commonwealth-managed fisheries in Australia (Sachse 1994). Both data sets are broken down by commercial species groups ('tiger prawns', 'banana prawns', 'king prawns' and 'endeavour prawns'), and therefore do not distinguish between the two species of tiger prawn.

### Research Survey Data

Monthly length-frequency distributions of *P. semisulcatus* were obtained from surveys carried out between 1986 and 1992 in the north-eastern Gulf of Carpentaria, around Albatross Bay (Crocos and van der Velde in press). Monthly length-frequency distributions of *Penaeus esculentus* were obtained from surveys of the north-western Gulf of Carpentaria, around Groote Eylandt, carried out for 18 months between 1983 and 1985 (Somers <u>et al.</u> 1987).

#### **Biological Parameters**

Growth and length-weight parameters, size at recruitment, and catchability were all obtained from previous studies (Table 1). The life-history characteristics of tiger prawns suggest that their natural mortality is lower than that of banana prawns (Dall <u>et al.</u> 1990). Therefore, the instantaneous natural mortality coefficient, *M*, was assumed to be 0.045 (week  $^{-1}$ ) for tiger prawns, which is smaller than the value of 0.05 estimated for *P. merguiensis* (Lucas <u>et al.</u> 1979) and equivalent to the value of 0.2 (month  $^{-1}$ ) used in previous assessments of tiger prawns stocks in the NPF (Somers 1990<u>a</u>).

*P. semisulcatus* spawns year-round, with a major spawning peak between August and October and, in most years, a secondary peak between January and February (Crocos 1987<u>a</u>; Crocos and van der Velde in press), *P. esculentus* has a similar pattern, but with smaller peaks (Crocos 1987<u>b</u>).

The sex ratio (males / females) at recruitment was assumed to be 1:1.

## Catch and Effort Estimates

The analysis is based on weekly catch and effort data in the tiger prawn fishery to reduce the variations between successive daily catches. The catch and effort of a vessel is assigned to the tiger prawn fishery if its catch of banana prawns is less than the catch of all other species combined.

The tiger prawn catch was estimated by adjusting the reported catch from logbooks to match the total landing from processor's returns. The ratio of logbook catches to processor landings varies from 50% in the early 1970s to over 95% in the 1990s (Sachse 1994). It has been 100% since 1994. Nominal fishing effort was then calculated as the ratio between processor landings and catch per unit of fishing effort (from logbook data). This assumes that

catch per unit of fishing effort estimated from logbook data is an unbiased estimate of the average catch per unit of effort for the entire fishery.

Catch (in weight) and fishing effort were then assigned to each of the two tiger prawn species according to the geographical distribution of the logbook catches and the geographical distribution of the species (Somers 1994<u>b</u>). Somers (1994b) showed that at the scale at which logbook data is collected (6x6 minute grids) the two species have almost mutually exclusive distributions. CSIRO has developed a species composition database with the proportion of each species within each species group found for each 6x6 min grid of the NPF. These database is updates each time new information is obtained for a particular area through research cruises. These proportions are used to calculate the catch of each tiger prawn species in each grid and then summed over all grids to obtain the catch per week for each of the two tiger prawns.

The above proportions are also used to estimate the effort directed at each of the two tiger prawn species. Effort in the tiger prawn fishery, in a given 6x6 min grid is associated only to the species of tiger prawns with the highest proportion in the species composition database.

Effective fishing effort was calculated by assuming average fishing power increases constantly every year. A 5% rate of increase in fishing power was estimated by Buckworth (1992) and has since been adopted in all assessments of the NPF fishery.

### Annual Recruitment Pattern

The biological year is assumed to start in November, when recruitment in both species of tiger prawns is low, and finishes in October.

The average fortnightly length-frequency distribution of each species was estimated from the research survey data by pooling the monthly data over the length of the survey. The number of recruits in each month was calculated as the sum of all prawns smaller than or equal to the size at recruitment  $l_r$  (Table 1). This number of recruits was then used to calculate each month's proportion of the annual recruits. Because monthly sampling effort was constant during the surveys, each months's proportion of the annual recruits represent catch per unit of effort, and can be considered as an index of abundance for monthly recruits. The proportion of annual recruits  $\alpha_i$  recruiting each week *i* was calculated by linear interpolation of the monthly proportions.

### Population Model

Annual recruitment and spawning stock indices were calculated from the estimates of weekly catches, the annual recruitment pattern and a model of the prawn population.

Weekly catches in weight were converted to catches in number by estimating the average weight of individual prawns for each week. Average weight was estimated from the proportions of prawns in each age (length) group in each week obtained in the prawn population model. This prawn population model is presented below; however it can be regarded as a generalised version of the traditional virtual population analysis when recruitment cannot be treated as a single pulse.

Let i be the week in the biological year (from 1 to 52)

j be the cohort of recruits that enter the fishery in week I

s be the sex

Let  $(Z_i, F_i)$  be the instantaneous total mortality and fishing mortality in week <u>i</u>, respectively and let M, the natural mortality be assumed to be constant and known (Table 1). The number of prawns at week i of cohort j and sex s is

$$N_{ijs} = N_{i-1js} e^{-Z}$$

The length of prawns at week *i* is

$$L_{ijs} = L_{\infty} \left( 1 - e^{-k_s i + a_s} \right)$$

where as is the age in month of recruits.

And given the length weight relationships of the form

 $W_{iis} = a_s L_{iis}^{b_s}$ 

The average weight of prawns in the catch for week *i* will be:

$$w_i = \frac{\sum_{ijs} N_{ijs} W_{ijs}}{\sum_{ijs} N_{ijs}}$$

Fishing mortality was estimated as the product of effective fishing effort and catchability, where catchability is assumed to be constant and known (Table 1).

We further assume that all recruits are fully selected so that fishing mortality is neither dependent on size nor sex.

Now let's just express the dynamics of recruitment for a single cohort of either sex:

Given  $\alpha_i$  (the proportion of annual recruits R coming to the fishing ground during week <u>i</u>), let  $N_{ij}$  be the cumulative number of prawns of cohort j surviving up to the beginning of week <u>i</u> including those from previous years, If we assume that a recruit can appear any time during that week, the probability of a recruit from cohort j (and where j=i) surviving to the end of week <u>i</u> is  $\{1 - \exp(-Z_i)\} / Z_i$  (which will be denoted as P<sub>i</sub> for convenience), and therefore the probability that recruits from cohort j are caught in week <u>i</u> is  $(1 - P_i)F_i / Z_i$ . The recurrence equation of abundance can thus be written as

$$N_{i+1} = N_i \exp\left(-Z_i\right) + P_i \alpha_i R, \qquad (1)$$

where  $P_i\alpha_i$  is the discounted proportion at the end of week <u>i</u> of recruits of cohort j (and where j=i). The expected catch  $C_i$  is then (cf. Gulland 1983, pp.99-105)

$$C_{i} = N_{i}P_{i}F_{i} + \{\alpha_{i}(1 - P_{i})F_{i} / Z_{i}\}R_{1}$$
(2)

Note that the catch (the right-hand-side of equation 2) is made up of two components, corresponding to the catch of prawns recruited before and during week i, respectively.

From the recurrence equation (1) we have

$$N_{i_{+}1} = \gamma_{i}R + N_{1} \exp(-U_{1,i}), \qquad (3)$$

where  $\gamma_{i} = \sum_{j=1}^{7} \alpha_{j} P_{j} \exp(-U_{j+1,j})$ , and  $U_{j,i}$  is the cumulative total mortality from week *j* to week *i*, <u>i.e.</u>,  $\sum_{k=j}^{i} Z^{k}$  if  $j \le i$  (and 0 otherwise). Here  $N_{1}$  is the surviving population from previous years and can be obtained when the annual recruits of those years are evaluated. From equations (1) and (2) we obtain,

$$C_{i} = \beta_{i}R + N_{1}P_{i}F_{i}\exp(-U_{1,\underline{i}}), \qquad (4)$$

where  $\beta_i = \gamma_{i-1} P_i F_i + \alpha_i (1 - P_i) F_i / Z_i$ .

Therefore, the total annual recruits R can be estimated by

$$R = (\sum C_{i} - N_{1} \sum P_{i} F_{i} \exp((-U_{1,i-1}))) / \sum \beta^{i}.$$
 (5)

Equations (1) to (5) can be extended to all j cohorts and both sexes to obtain the entire population of prawns at any time i.

The annual spawning stock indices were estimated as the average number of spawning females per week in the population model. The number of spawning females in a given week *i* was calculated as the product of the abundance of females times the proportion of spawning females in each month obtained from Crocos (1987<u>a</u>; 1987<u>b</u>).

## Population model: Fitting Procedure

Estimates of recruitment and spawning stock indices were obtained by fitting the population model, with maximum likelihood, to the weekly history of landings and fishing effort estimated above for each tiger prawn species.

This method requires an estimate of  $N_1$  for the first year (1970), which was initially assumed to be equal to zero. The model was then fitted to the data and preliminary estimates of population size were obtained for the rest of the data series. The preliminary survival rate of 1970 was then used to obtain an initial value of  $N_1$  for 1970 during the final fit of the model to the data. The initial estimates of survival rates for 1970 were 0.6 and 0.52 for P. esculentus and P.semisulcatus respectively. Fitting was implemented in SAS (See Appendix 1).

The resulting indices were then fitted to relationships -- presented below -- representing the spawning stock, recruitment and equilibrium yield dynamics of tiger prawn stocks in the NPF.

#### Stock-Recruitment Relationship (SRR)

Spawning stock and recruitment relationships (SRR) were modelled according to Ricker's equation:

$$R_{t} = a_{1}S_{t-1}\exp(-b_{1}S_{t-1}), \qquad (6)$$

where  $R_t$  is the total number of recruits produced in year <u>t</u>, and  $S_{t_1}$  is the spawning stock index of the previous year.

#### Recruitment to Spawning stock Relationship (RSR)

The spawning stock  $(S_i)$ , resulting from the recruitment  $R_i$  of the same year, depends on the weekly pattern of fishing effort (equation 3) but is well approximated (Penn *et al.* in press) by:

$$S_t = a_2 R_t \exp((-b_2 F_t)), \qquad (7)$$

where  $F_t$  is the fishing mortality of year t.

## Catch-Effort Relationship

When the recruitment is continuous and fishing mortality is not a constant, the traditional catch equation is not valid. In such case the annual catch  $C_{r}$  in tonnes is well approximated by the equation (cf. Penn *et al.* in press)

$$C_{\prime} = a_3 R_{\prime} F_{\prime} \exp (-b_3 F_{\prime}). \tag{8}$$

#### SRR, RSR and Catch and Effort Relationships: Fitting procedures

Time series of recruitment and spawning stock indices, catch and fishing effort are strongly auto-correlated (for a review see Hilborn and Walters 1992). To account for the possible correlation in the error terms over years, log-linear, first-order autoregressive time series models were developed for each of the last three relationships (equations 6 to 8). Parameters of these models were estimated by the method of maximum likelihood. The adjusted  $R^2$  values( from the ordinary linear fit to the equations 6 to 8) were also calculated to show the goodness of fit. This model was implemented in SAS (Appendix 2).

## Equilibrium yield and biological reference points

Equations (6) and (7) can be solved for a given fishing mortality to give the equilibrium spawning stock and recruitment, i.e., the recruits that survive fishing replace one to one the adults that spawn them. Furthermore, if equilibrium recruitment and fishing mortality are incorporated in equation (8), the equilibrium yield can be estimated at different levels of fishing mortality. The relationship between fishing mortality and fishing effort (f) is assumed to be F=qf. The resulting relationships between equilibrium yield and fishing effort are thus analogous to surplus production models. The maximum sustainable yield (MSY) and the corresponding fishing effort (f<sub>MSY</sub>) are then obtained.

We also estimated two additional biological reference points from fishing effort levels. The first one is  $f_{0.9}$ , a level of effort lower than  $f_{MSY}$  but that still yields 90% of MSY, which could be considered a target reference point (sensu FAO 1993) for management of this fishery. The second,  $f_{rep}$ , represents the fishing effort associated with the median RSR, half of the data points fall in each side of the curve (Sissenwine and Shepherd 1987). This reference point is appropriate for stocks where there is little evidence of density dependence between spawning stock and recruitment because  $f_{rep}$  corresponds to a level of fishing effort such that the population will fluctuate in size without a trend (equal probability of increasing than of decreasing). Any fishing effort higher than  $f_{rep}$  will lead to lower recruitment and spawning stock size. We therefore propose that  $f_{rep}$  be used as a limit reference point (sensu FAO 1993) for fishing effort: management would have to react if it is surpassed.

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Table 1. Von Bertalanffy growth parameters  $(l_k, k)$ , weight - length relationship  $(W = a l^b)$ parameters (W = total weight in g, l = carapace length in mm), length at recruitment  $l_r$ , natural mortality (M) and catchability (q) by sex and by species for tiger prawns.

	P. semisulcatus		P. esci	ılentus
	Female	Male	Male Female	
k (weekly <sup>-1</sup> )	0.043 <sup>A</sup>	0.062 <sup>A</sup>	0.041 <sup>B</sup>	0.034 <sup>B</sup>
$I_{\infty}$ (mm)	51.6 <sup>A</sup>	37.5 <sup>A</sup>	44.8 <sup>B</sup>	37.5 <sup>B</sup>
а	0.00265 <sup>C</sup>	0.00195 <sup>C</sup>	0.00373 <sup>D</sup>	0.00207 <sup>D</sup>
b	2.648 <sup>C</sup>	2.746 <sup>C</sup>	2.574 <sup>D</sup>	2.764 <sup>D</sup>
<i>l<sub>r</sub></i> (mm)	28 <sup>A</sup>	26 <sup>A</sup>	28 <sup>A</sup>	26 <sup>A</sup>
M (weekly <sup>-1</sup> )	0.045	0.045	0.045	0.045
q (boat-day)∞10 <sup>5</sup>	8.8 <sup>E</sup>	8.8 <sup>E</sup>	8.8 <sup>E</sup>	8.8 <sup>E</sup>

A Somers and Kirkwood (1991); <sup>B</sup> Kirkwood and Somers (1984); <sup>C</sup> Farmer (1980); <sup>D</sup> Penn and Hall (1974); <sup>E</sup> Y. Wang CSIRO Division of Fisheries, unpublished data. **APPENDIX 8** 

## Status of tiger prawn stocks at the end of 1999

C. Dichmont Northern Prawn Fishery Assessment Group

## Summary

Nominal fishing effort directed to tiger prawns during the 1999 fishing season decreased by 5,240 fishing days in comparison to 1998 mainly due to an extended seasonal closure in 1999. As a result of this, during 1999, effective fishing effort decreased by 15% on grooved tiger prawns and by 40% on brown tiger prawns with respect to 1998. Effective catch-per-unit of effort for both species declined between 1998 and 1999 and was well below the average of the last 7 years.

According to the assessment carried out with the model of Wang and Die (1996), the recruitment of brown and grooved tiger prawns in 1999 declined from 1998 by 9% and 11% respectively. The spawning stock present in late 1998 early 1999 decreased by 2.5% for brown tiger but increased by 26% for grooved tiger prawns from the previous year.

The estimates of Maximum Sustainable Yield (MSY), Spawning stock which produces maximum yields (S<sub>MSY</sub>) and fishing effort which produces maximum yields (E<sub>MSY</sub>) have slightly changed from those estimated over the last few years. The estimates of MSY for the period 1970-1998 are therefore 1800 t (as opposed to 1900t for previous years assessments) for brown tigers prawns and 1900 t for grooved tiger prawns. The associated E<sub>MSY</sub> are respectively 6,999 (7150 in 1998) and 10,428 (9,660 in 1998) standard boat-days.

Effective fishing effort in 1999 was 18% below  $E_{MSY}$  for brown tiger prawns and 7% above  $E_{MSY}$  for grooved tiger prawns. Therefore, for all tiger prawns, the 1999 effective fishing effort was 3% below  $E_{MSY}$ . The main reasons for this decrease in effort were the time closure and movement of effort to the banana and other fisheries.

In late 1998 early 1999 brown tiger spawning stocks were 63% of the  $S_{MSY}$  and grooved tiger prawns were 82% of the  $S_{MSY}$ , therefore spawning stocks remain below the levels that will produce MSY.

In conclusion:

- 1. Spawning stock levels for both tiger prawn species as at the end of 1999 are below the target levels of S<sub>MSY</sub> (brown tiger 63% and grooved tiger 82% of S<sub>MSY</sub>).
- 2. Both tiger species stocks remain over-exploited as at the end of 1999 and any rebuilding of spawning stocks to  $S_{MSY}$  requires effort levels of  $E_{MSY}$  or less along with average recruitment. The lower the level of effort, the faster rebuilding will occur.
- 3. The reduction of effort in 1999 is due to the extended temporal closure and other factors.

## Catch and effort data

Data for 1999 was extracted from AFMA logbooks and processed as in previous years to provide catch and nominal fishing effort for each tiger prawn species per week. Annual 1999 catch of brown and grooved tiger prawns declined by 45% and 25% respectively relative to the 1998 fishing year (Table 1). Nominal fishing effort was 5,240 days less than in 1998. The effort reduction was mainly due to the 1999 temporal closure and displacement of effort to the banana and other fisheries. Most of the effort reduction was in the south-east Gulf of Carpentaria region, a predominantly brown tiger area.

	Catch		Nomina	al effort	Totals		
	(tons)		(boat	days)			
	Brown	Grooved	Brown	Grooved	Catch	Effort	
1993	1284	1230	7504	8682	2514	16186	
1994	1387	1774	8045	10524	3161	18569	
1995	2569	1555	8512	8292	4124	16804	
1996	1165	1143	7146	9406	2308	16552	
1997	1271	1393	6300	9083	2664	15383	
1998	1542	1713	7527	10311	3255	17838	
1999	849	1284	4293	8305	2133	12598	

**Table 1.** Catch (tonnes) and nominal effort (boat-days) for the two species of tiger prawns in the NPF during the last 6 years.

If, as previously agreed by NORMAC, we assume that fishing power increased by 5% in 1999, then effective effort decreased from 1998 by 40% on brown tiger prawns and 15% on grooved tiger prawns. This compares to a 25% effective effort increase on brown tiger prawns and 19% increase on grooved tiger prawns between 1997 and 1998. However, effective CPUE for both species (Table 2) declined between 1998 to 1999 and was well below the average of the last seven years.

**Table 2.** Effective effort (standardised boat-days) and effective catch-per-unit of effort (cpue in kg per standardised boat-day) for each species of tiger prawns in the NPF during the last 6 years.

	Effective effort (standardised boat- days)		Effective cr standardisec	<b>bue</b> (kg per l boat days)	Totals		
	Brown	Grooved	Brown Grooved		Effective	Effective	
					effort	Cpue	
1993	7504	8682	171	142	16186	155	
1994	8447	11050	164	160	19497	162	
1995	9384	9142	274	170	18526	223	
1996	8272	10889	141	105	19161	120	
1997	7658	11040	166	126	18698	142	
1998	9607	13160	161	130	22766	143	
1999	5753	11129	148	115	16883	126	

## **Recruitment and spawning stocks**

The model of Wang and Die (1996) was used to assess the status of the resource by estimating recruitment and spawning stock indices. The model uses weekly catch and effort data from 1970 to 1999. In each year's assessment, the model parameters are re-estimated with all previous and new data.

The estimated recruitment for brown tiger prawns during 1999 was 176 million animals and grooved tiger prawns 174 million (Figure 1). This is a 9% and 11% decline in recruitment compared to 1998 for brown and grooved tiger prawns respectively. The 1999 recruitment level of brown and grooved tiger prawns is below the 10 year average of 217 and 188 million prawns respectively.



Figure 1. Recruitment indices of brown and grooved tiger prawns.

Spawning stock indices for the year represent the number of female prawns in spawning condition during the biological year. This means that because spawning occurs at the end of one year and at the beginning of the next, the latest index that could be estimated at the end of the 1999 fishing season, was that of 1998/1999 (Figure 2).

The spawning stock index in late 1998 early 1999 of brown tiger prawns declined by 2.5% (to 15.8 million) in comparison to that of the previous year. However, that for grooved tiger prawn increased by 26% (to 6.8 million). Stock levels for grooved tiger prawns are above average for the last 10 years (average of 6.7 million), whereas stock levels for brown tiger prawns are still below the 10 year average (18.3 million).



Figure 2. Spawning stock indices for brown and grooved tiger prawns.

Recruitment and stock indices were then used to estimate stock-recruitment relationships (Figure 3 and 4). The 1999 stock and recruit value is highlighted in the graphs and demonstrates the low stock and recruitment levels mentioned above.



**Figure 3.** Estimated annual recruits and spawners (millions) and fitted stock recruitment relationship of brown tiger prawns.



Figure 4. Estimated annual recruits and spawners (millions) and fitted stock recruitment relationship of grooved tiger prawns.

The relationship between the survival of recruits and subsequent spawners, as a function of fishing effort, were then estimated. From these relationships, the long-term equilibrium (sustainable) yield was estimated for different levels of effective effort (Figure 5 and 6). The estimated maximum sustainable yield and effective effort at the maximum sustainable yield are shown on the graphs. The position of the 1999 catch and effective effort are also shown therein. As in previous assessments, the new indices for 1998 and 1999 did not significantly change the parameters of any of the relationships mentioned above. Indicators of Maximum Sustainable Yield, effective effort at the Maximum Sustainable Yield, spawning stock and virgin stock levels are presented in Table 3. It is important to note that stock levels for both species are below the stock at the Maximum Sustainable Yield.

**Table 3.** Indicators (millions of individuals) of spawning stock status. All indicators estimated with 1970-1999 data.  $S_{vir}$  = average spawning stock in the absence of fishing,  $S_{MSY}$ =spawning stock that would on average produce Maximum Sustainable Yield and Ave.  $S_{95-99}$  = Average spawning stock over the last 5 years (1995-1999).  $S_{99}$  = Spawning stock in late 1998 and early 1999.  $S_{99}/S_{MSY}$  is the ratio of spawning stock in late 1998 and early 1999 to the spawning stock size at the maximum sustainable yield.  $E_{MSY}$ =effective fishing effort at the maximum sustainable yield.  $E_{1999}$ =effective effort in 1999.

Prawn species	$S_{vir}$	Smsy	Ave.	<b>S</b> 99	S99/Smsy	Emsy	E1999
			S95-99		(%)		
Brown tiger	48.2	25.0	18.0	15.8	63	7000	5753
Grooved tiger	15.2	8.35	6.6	6.8	81	10428	11129



**Figure 5.** Equilibrium yield and effective effort for brown tiger prawns showing the Maximum sustainable yield (MSY) and the effort at MSY. The point on the graph is the 1999 effective effort and yield.



**Figure 6.** Equilibrium yield and effective effort for grooved tiger prawns showing the Maximum sustainable yield (MSY) and the effort at MSY. The point on the graph is the 1999 effective effort and yield.

Due particularly to high levels of fishing effort that existed in the early to mid 1980s, the historical catch and effort data for the tiger prawn fishery are consistent with the assessment that both tiger prawn species have been over-exploited (Figure 7 and Figure 8). The substantial effort reductions that occurred in the late 1980s and early 1990s did not decrease effective fishing effort below E<sub>MSY</sub> levels as would have been desirable. On the other hand, the extended temporal closure during the 1999 season was effective at cutting effort on both tiger species. In addition, effort was reduced by vessels moving to the banana and other fisheries. The result is that effort is below that at E<sub>MSY</sub> for brown tigers for the first time in a decade. However, it does not mean that the resource is underexploited. Both tiger species stocks have not recovered from overfishing as spawning stock levels for 1999 are still below the stock levels at the Maximum Sustainable Yield. With effort levels at E<sub>MSY</sub>, recovery would be slow (and no recovery if effort is above E<sub>MSY</sub>).



**Figure 7.** Effective fishing effort directed to brown tiger prawns and effort that would, on average, produce the Maximum Sustainable Yield.



**Figure 8.** Effective fishing effort directed to groove tiger prawns and effort that would, on average, produce the maximum sustainable yield.

Over-exploitation is the most likely but not the only hypothesis consistent with the historical data on tiger prawn stocks. Another possible explanation is that recruitment had been determined by as yet unidentified environmental factors that affect larval dispersal and/or productivity in nursery areas. A detailed description can be found in CSIRO (1993) and in the results of a fishing industry workshop on the same topic (AFMA 1995).

## Conclusion

- 1. Spawning stock levels for both tiger prawn species as at the end of 1999 are below the target levels of S<sub>MSY</sub> (brown tiger 63% and grooved tiger 82%).
- 2. Both tiger species stocks remain over-exploited as at the end of 1999 and any rebuilding of spawning stocks to S<sub>MSY</sub> requires effort levels of E<sub>MSY</sub> or less along with average recruitment. The lower the level of effort, the faster rebuilding will occur.
- 3. The reduction of effort in 1999 is due to the extended temporal closure and other factors.

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