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Contraction of the banana prawn (*Penaeus merguiensis*) fishery of Albatross Bay in the Gulf of Carpentaria, Australia

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Abstract. When the biomass and area occupied by a stock decline together, catch rates can remain high (hyperstability) and management with effort controls may be ineffectual. Banana prawn (*Penaeus merguiensis*) catches declined from 2000 until 2005 in the Albatross Bay area in the Gulf of Carpentaria (GOC), Australia. Data from commercial logbooks were used to investigate historical changes in the banana prawn fishery in this and other regions of the Northern Prawn Fishery to infer the potential causes of this decline. Data since 1970 were analysed using: (*1*) the mapping of catch and effort; and (*2*) normalised rank order catch curves, to determine the distribution of catches across fishing areas. These analyses show that there has been a marked contraction of the Albatross Bay fishery over 33 years of fishing into the centre of a stable 'hotspot', suggesting a potential mechanism for the observed negative relationship between catchability and biomass. We believe this is the first observation of a *Penaeus* prawn fishing ground contracting as biomass declines, supporting the view that the contraction of an area occupied by a stock as biomass declines, is a generalised phenomena observed widely across fisheries resources and not a dynamic confined to certain finfish and molluscs.

Additional keywords: catchability, hyperstability, penaeid, recruitment overfishing, shrimp, stock contraction.

Introduction

Since the seminal paper of Paloheimo and Dickie (1964) the relationship between the areal extent and biomass of a stock has been a subject of growing interest in fishery science because of its potential to bias indices of stock abundance based on catch rate (Arreguin-Sanchez 1996) and make management with effort controls ineffectual (Crecco and Overholtz 1990; Walters and Maguire 1996; Walters and Martell 2004). Based on studies of a relatively few pelagic fish species, Winters and Wheeler (1985) postulated that the area occupied by a fished stock generally contracts as biomass declines, leading to a focusing of fishing pressure within the reduced area and thus an increase in fishing power and catchability. This dynamic also naturally results in the maintenance of high catch rates as the biomass declines, termed 'hyperstability' of catch rates (Hilborn and Walters 1992). Harley *et al.* (2001) apparently confirmed the common nature of this dynamic for finfish with a meta-analysis of 297 finfish stocks with parallel time series of catch per unit effort (CPUE) and biomass surveys, finding that most cases indicated hyperstability.

Winters and Wheeler (1985) noted the paucity of studies examining the area occupied by stocks as biomass changes for species other than pelagic fish. Since that time, studies have been published for a wider range of finfish and molluscan species (e.g. Crecco and Overholtz 1990; Prince 1992; Swain and Sinclair 1994; Orensanz *et al.* 1998; Petitgas 1998). In the present study, we provide what we believe to be the first description of long-term spatial dynamics for a stock of *Penaeus* prawns in Australia's Northern Prawn Fishery (NPF), which usefully broadens the information of stock area and biomass relationships across the field of fisheries ecology.

The NPF (Fig. 1) catches nine species of prawns (shrimp) in two linked sub-fisheries that target different groups of species – banana prawns (*Penaeus merguiensis*, *Penaeus indicus*) and tiger prawns (mainly *Penaeus esculentus*, *Penaeus semisulcatus*) (Dichmont *et al.* 2007). Some species of prawns, including the banana prawn (*P. merguiensis*), form large free-swimming aggregations, which commercial fishermen target with their trawl nets (Munro 1975; Somers 1977; Dall *et al.* 1990; Wassenberg and Hill 1993). Fisheries for aggregating prawns are apparently prone to decline (Kristjonsson 1969; Penn 1984; Van Zalinge 1984; Mathews and Abdul-Ghaffar 1986). In some parts of the NPF, schools of banana prawns are spotted for the fishing fleet by light aircraft. Albatross Bay, the focus area of the present study, is characterised by turbid waters and aerial spotting is not practiced there. Instead the fishers search the fishing grounds

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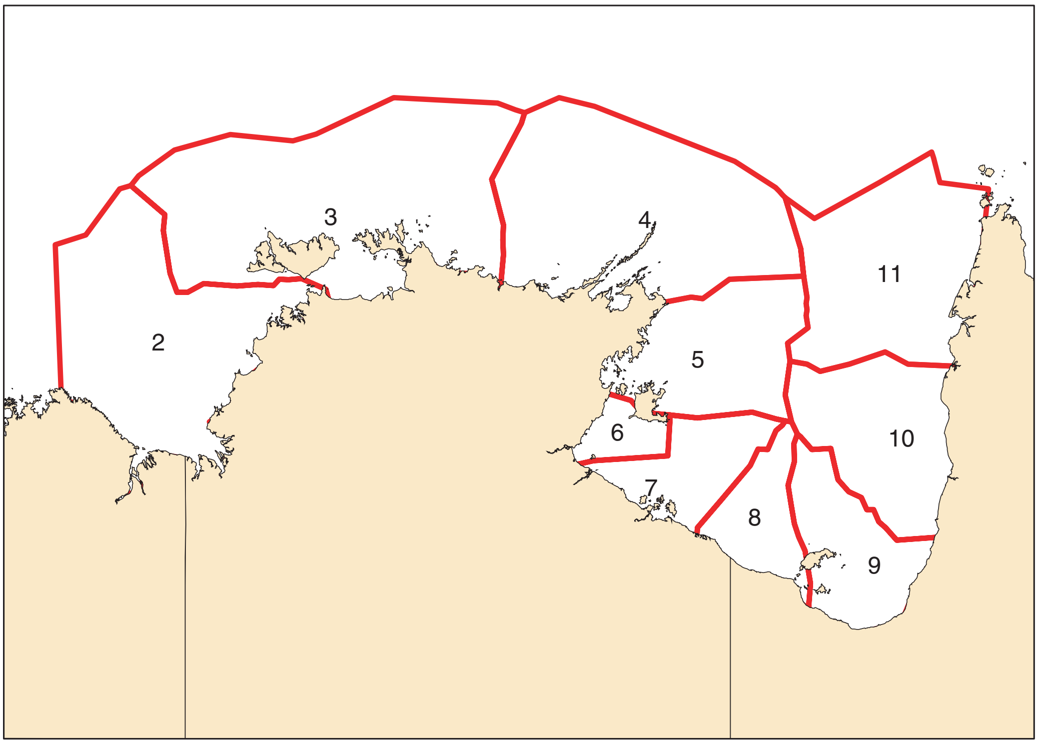

Fig. 1. Map of 10 of the eleven statistical regions for banana prawns in the Northern Prawn Fishery. The Albatross Bay or Weipa region is zone 11 at the far top right.

with the echo-sounders in their vessels looking for the acoustic 'marks' on the bottom indicating schools of prawns.

Banana prawns have been regarded as fully or over-exploited since the early 1970s (Lucas *et al.* 1979). Catches have fluctuated greatly among years, and in some regions of the fishery they have been correlated with rainfall and river flow (Vance *et al.* 1985, 1998; Loneragan and Bunn 1999). Although the fishery is managed through the control of fishing effort, fishing efficiency has been increasing over time as technology has improved (Robins and Sachse 1994; Robins *et al.* 1998). The time taken to catch 90% of the banana prawn catch has decreased considerably over the history of the fishery, declining from many months in the 1960s, to a few months in the 1970s to just over 1 month in the 1990s (Somers and Wang 1997).

Until the late 1990s, the Albatross Bay (Weipa statistical area 11) and Karumba regions (statistical area 9) (Fig. 1), were the two most important areas for banana prawn fishing in the NPF, with long-term average annual catches of ~650 t for Albatross Bay and 900 t for Karumba (Fig. 2*a*), valued at over AUD $12 million. However, from 2000 until 2005, the annual catch from Albatross Bay declined markedly, with an average of ~56 t per annum being landed during that period. Fishing effort also collapsed during this period from around 900 boat days per annum during the 1970s, to 136, 156, 75, 31, 122 and 92 boat days for the respective years from 2000 until 2005 (Fig. 2*b*). In 2006, catches recovered to 398 t, still well below the historical long-term average (643 t), before falling back to 202 t in 2007. In contrast to the trends in catches at Albatross Bay since 1999, good catches continued in other regions of the NPF, e.g. catches from Karumba were at least double the long-term average for the region in 2001 (2114 t) and 2002 (1743 t) (Fig. 2*a*).

Several hypotheses have been proposed by members of the fishing industry and researchers to explain this catch decline in the Albatross Bay prawn fishery, and these fall into four categories:

1. The recent reductions of fleet size and season length led to a loss of searching capacity preventing the detection of schools;
2. Recruitment to the fishery failed as a result of a change in environmental conditions;
3. Recruitment to the fishery failed as a result of overfishing; and
4. Prawns declined as a result of indirect trophic effects of environmental change or fishing.

The analyses described here, and those by Zhou *et al.* (2007, 2008), were conducted as part of a broader exploration of fisheries data for Weipa that was undertaken with the aim of trying to distinguish between these hypotheses. A description of the other aspects of these broader analyses, including the development of an ecosystem model for the Albatross Bay region, is provided by Rothlisberg and Okey (2007). In this paper, we confine ourselves to describing the geographic contraction of the banana prawn (*P. merguiensis*) fishing grounds that has occurred in the Albatross Bay area over a period of 34 years of fishing.

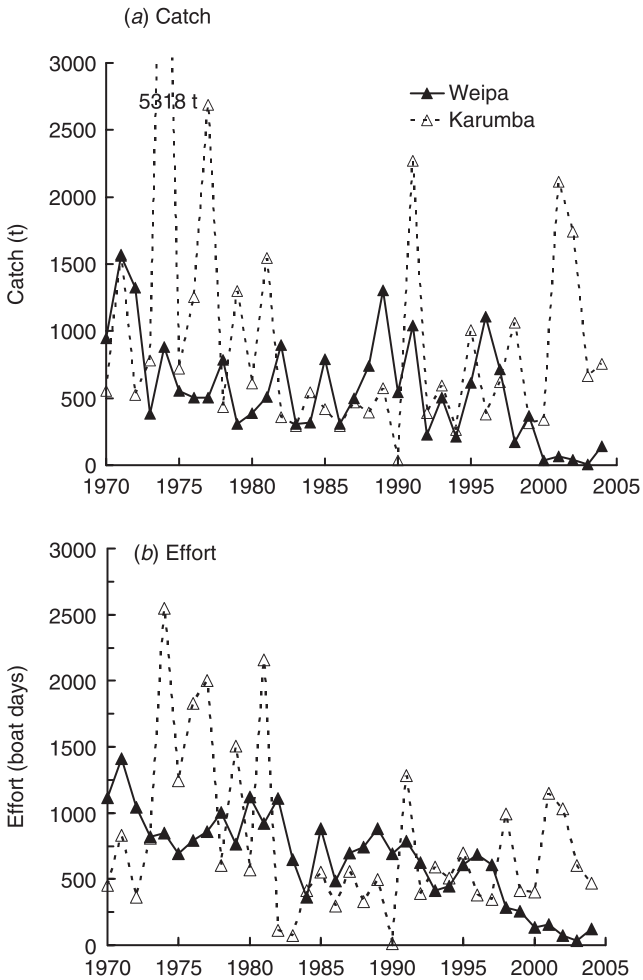

Fig. 2. Comparative catch (*a*, t) and effort (*b*, boat days) trends from 1970 to 2004 for Weipa (black triangles, GoC statistical area 11) and Karumba (open triangles, GoC statistical area 9).

Materials and methods

The analyses undertaken in the present study were prompted by discussions with an experienced ex-fisher (Mr Nick Laird) about the spatial dynamics of the NPF. Two relatively simple analyses of spatial trends over time in the Albatross Bay area were performed on reported catch and effort trends for banana prawns (*Penaeus merguiensis*). Three components made up the analyses for each year of the fishery: a spatial examination of catch and effort; calculation of a normalised rank-order curve (NROCs); and an estimate of the area under the curve. The results of the analysis for each year were then presented as a time series of changes in the spatial characteristics of the fishery. Estimates of the area under the NROC curves over time were also made for each region of the NPF where banana prawns are caught, in order to compare the dynamics of the fishery at Albatross Bay with the dynamics elsewhere.

Logbook data

We used daily logbook data for each vessel that fished in the NPF from 1970 to 2004, held by the Australian Fisheries Management Authority (AFMA) in our analyses. These data include the location of catch and effort (6 × 6 nautical mile grid), total banana prawn catch (kg), and the identity of the banana prawn stock to which the catch had been attributed. Eleven statistical areas were originally defined for the NPF, containing 10 banana prawn fishing areas, which correspond to purported separate 'stocks' for assessment and statistical analysis (Fig. 1). We extracted the logbook data for the Albatross Bay (i.e. Weipa) 'stock' identified in the database as banana prawn 'stock' 11 and analysed the data using a Microsoft Access database, Microsoft Excel spreadsheets, and an ArcView Geographic Information System.

Spatial trends

The spatial distribution of fishing effort and catches in each year of our time series was mapped using ARCVIEW. However, only a tabulated summary of these results is presented because of requirements for data confidentiality by the AFMA.

Normalised rank order curves

An alternative view of these spatial trends can be derived through the use of 'normalised rank order curves' (NROCs), a commonly used technique for analysing spatial-temporal trends. The same approach has various names in parallel fields; ecology (rarefaction curves, originally), economics (Gini indices and the Lorenz curve), geostatistical theory (selectivity curve), fisheries surveys (geostatistical aggregation or concentration curves), and resource management (cumulative concentration profiles) (see Orensanz *et al.* 1998 and Petitgas 1998).

These curves were derived for each year by sorting the grid cells by the magnitude of their catch and then plotting the cumulative catch against their rank order. These plots will tend towards a diagonal (45°) straight line when the catch is evenly distributed across all statistical cells, and towards a 90° angle as the catch becomes increasingly concentrated in a limited number of cells. For our purposes, these individual annual curves (NROC) were then converted into a one dimensional 'area index' for each year, which is simply the total area under the 'NROC' of each year. A larger area index indicates greater dispersion of the catch across the area of the fishery. The area index was also calculated for each year in each of the 10 banana prawn stock regions of the NPF.

Results

From the 1970s until the mid-1990s, the annual catches at Weipa ranged from 200 to 1500 t (Fig. 2*a*). Between 1997 and 2005, annual catches declined relatively smoothly, with an average annual landing of ~56 t being recorded from 2000 to 2005, and a minimum of 3 t being recorded in 2003. The reported effort at Weipa declined from around 900 boat days per annum during the 1970s, to 136, 156, 75, 31, 122 and 92 boat days for the respective years from 2000 until 2005 (Fig. 2*b*). In contrast, both catch and effort remained high at Karumba during the same period (Fig. 2).

Mapping catch and effort shows that from 1970 to 2003, the fishery has varied around a stable core area within the Albatross Bay fishing grounds (Fig. 3). Since 1970, >95% of the historic catch has come from 28 of the 62 statistical cells (6 × 6 nautical miles) in the Weipa statistical region (shaded in Fig. 3). Catch and effort data have been reported from these 28 cells for at least 20 years of the 34 year time series. Within these cells are 12 cells

Years with reported catch

1	1			1	6	4		
1	4	2	5	5	12	11		
	2	3	5	8	18	25		
2		7	9	18	29	29		
2	6	13	13	24	33	23		
10	4	19	26	32	33	20		
5	8	18	24	30	33	30	24	17
5	14	25	27	33	34	34	23	
3	4	18	22	30	32	31	9	
7	8	18	26	27	27	12	2	

Fig. 3. A figure showing the 62 statistical cells (6 × 6 nm) for the Albatross Bay statistical region in the Northern Prawn Fishery, bounded by latitudes 12.25°S to 12.95°S and longitudes 141.25°E to 141.85°E, in which catch and effort data have been reported during the 34 years from 1970 to 2003. The number in each cell indicates the number of years for which catch and effort data have been reported. Shaded cells indicate the 28 cells with catches reported for ≥20 years and which comprise >95% of historic banana prawn catches from the Albatross Bay statistical area.

(dark shading and black in Fig. 3) from which data have been reported for at least 30 years and these cells comprise >68% of the historic catches. At the core of the Weipa area are two cells for which catch and effort data have been reported in each of the 34 years of the time series and they contribute ~16% to the total historic catches.

The normalised rank order curves (NROCs) summarised with the 'area index', which is the index of the area under each NROC, formalise the spatial trend described above. Plotting this 'area index' over time indicates a clear, large spatial contraction of the Albatross Bay fishery (Fig. 4). Although the area index shows considerable inter-annual variation, this does not obscure the long-term decline, which commenced during the 1970s and continued through the present, accelerating during the most recent decade (Fig. 4).

The plot of area index and catch provides an alternative striking view of the inter-annual variability (Fig. 5). Visually, larger catches appear to have some tendency to be dispersed over a broader area of the fishery. However, over periods of 5 to 6 years, the area index appears to have varied less inter-annually than has the catch. The area index has declined relatively steadily through the time series, with each successive decade having a characteristic lower area index. Some relatively large catches (>1000 t) were recorded in each decade until 2000. When the 34 years of data are considered, despite the inter-annual variability in catch

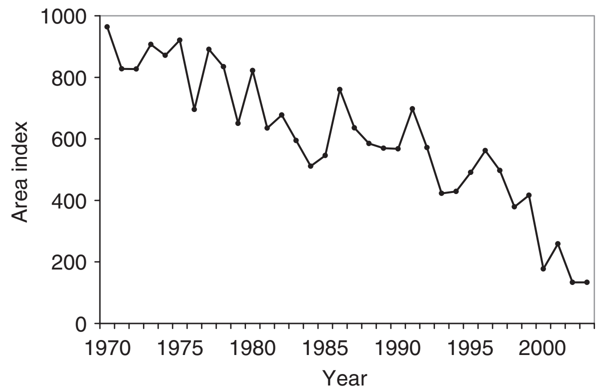

Fig. 4. The trend in 'area index' for the Albatross Bay statistical region from 1970 to 2003. The 'area index' for each year is the area under the 'normalised rank order curve' (NROC) for each year. The size of the area index indicates the dispersion (large) or concentration (small) of the reported catch.

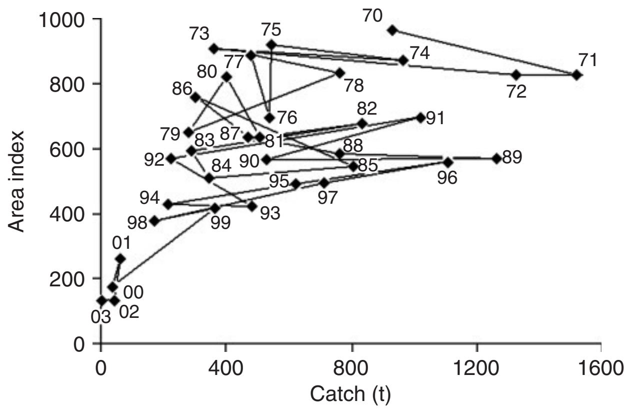

Fig. 5. A plot of the 'area index' (area under the 'normalised rank order curve') for each year against total catch for the Albatross Bay statistical region 1970–2003.

and area, the progression towards smaller catches and smaller area is conspicuous (Figs 4, 5). The years of widespread fishing in the Albatross Bay area have become less frequent. In recent years, low catches have been taken consistently from a very small area of the fishery at the core of the original fishing grounds (Fig. 3).

Our analysis of NROCs and area index for each of the other statistical zones of the NPF banana prawn fishery, followed by plotting the area index, shows that after their initial expansion, these other grounds have followed similar, though less pronounced trends in area index over time to those in Albatross Bay, particularly for stock regions 2, 3, 4, 5, 8 and 10 (Fig. 6).

Discussion

The quality of the data from the NPF logbooks has improved considerably over time. Originally, fishing locations were determined visually and data were recorded by fishing ground or by statistical cell. Later, fishing within statistical cells was

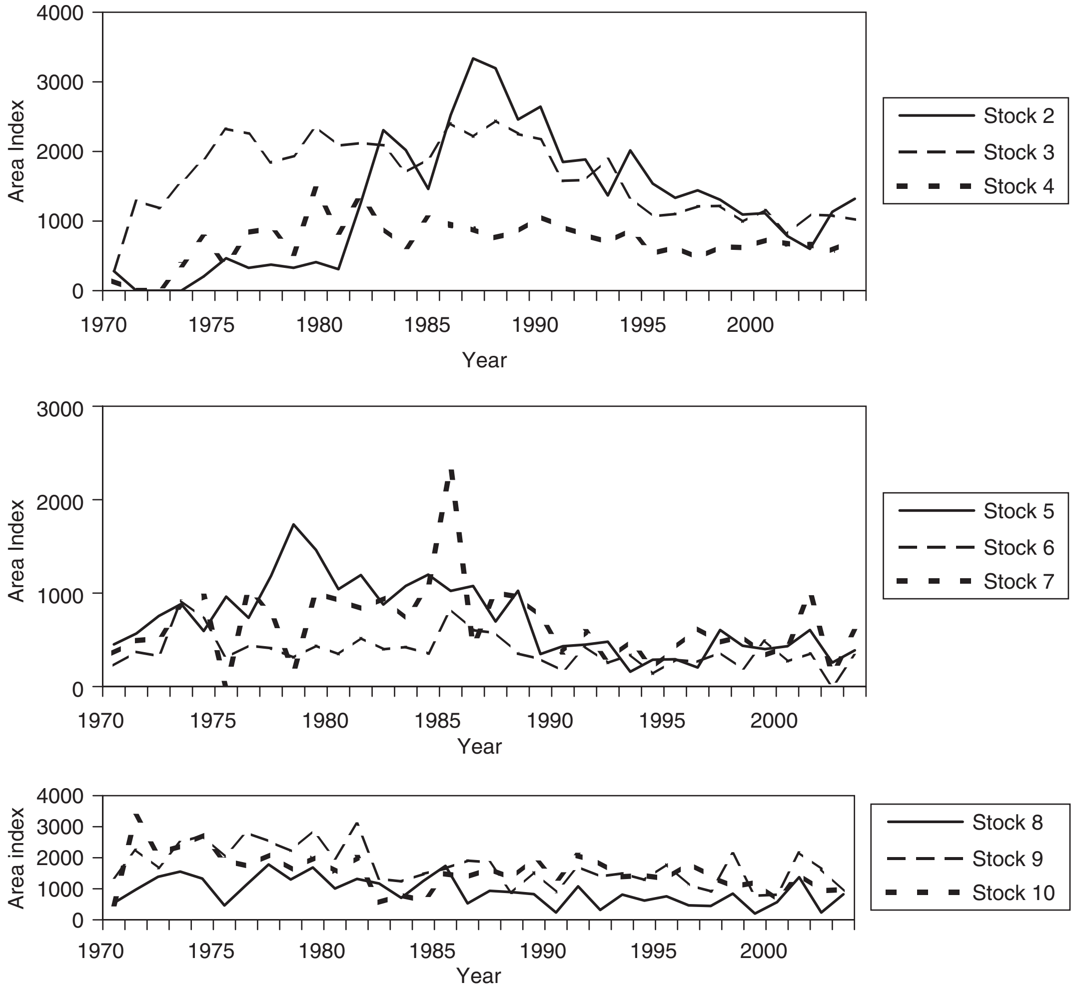

Fig. 6. Trends in 'area index' for statistical zones 2–10 of the Northern Prawn Fishery 1970–2003. As in Fig. 4 the 'area index' has been calculated from the total area under the 'normalised rank order curve' for each year.

determined with radar and period fixes with satellite navigation. Most recently, positions are determined with high precision using GPS technology and data are recorded with longitude and latitude for every shot (Bishop and Die 2001; Dichmont *et al.* 2001). Some of the broader spread of catches in the earlier years might be attributable to errors in position fixing and data recording. However, the long-term decline in the area index of the fishery continued consistently through the four decades of the fishery and several epochs of data improvement (Figs 3 to 5). This suggests a gradual but real spatial contraction in the Albatross Bay banana prawn fishing area that began slowly soon after the fishery began and has continued at an increasing rate until recently.

Our analysis of the 1970–2003 time series revealed three broad features for the Albatross Bay banana prawn fishery:

1. Considerable inter-annual variability of fishing over a large area interspersed with years of fishing over a smaller area. However, the area fished has diminished greatly since the late 1990s (Figs 4, 5).
2. There is a small predictable core of fishing activity through time (12 central cells of Fig. 3), despite annual variability of the spatial extent of the main catching area.
3. There has been a marked contraction of the Albatross Bay fishery into this stable centre of the fishing area (Figs 3 to 5).

The predictability of the location and timing of aggregations in a fishery can reduce the need for searching a large area and lead to an increase in the overall catchability (q) of the stock when the stock size is small (Paloheimo and Dickie 1964; Winters and Wheeler 1985; Crecco and Overholtz 1990; Hilborn and Walters 1992; Prince 1992; Orensanz *et al.* 1998; Petitgas 1998). In fisheries that display an inverse correlation between catchability and stock size, fishing pressure can remain high even when fishing effort is reduced; i.e. catch rates remain high as biomass declines – so called hyperstability (Hilborn and Walters 1992).

For much of the history of the Northern Prawn Fishery, stock assessments on tiger and banana prawns have tended to assume that catchability has been relatively constant and independent of stock size. However, in an analysis of data from individual trawls during 3 years, Die and Ellis (1999) concluded that within a season, the catchability of banana prawns was likely to decline with decreasing stock size. In their analysis, they observed that, 'searching time is the main component of fishing effort, and that within a season the area to be searched remains constant'. They concluded that the fishery's ability to target aggregations of banana prawns each season is likely to decline with smaller stock sizes, resulting in a positive relationship between stock size and catchability. Vance *et al.* (2003) conducted the first stock assessment of banana prawns based on Die and Ellis's suggestion of a power analysis and estimated that a positive within year correlation between biomass and catchability existed in three of seven NPF stocks. More recently, Zhou *et al.* (2007, 2008) applied depletion estimators to the daily CPUE data from three of the Gulf of Carpentaria banana prawn fisheries to estimate catchability. They detected no clear pattern in the within season relationship between catchability and stock abundance to support the suggestion of Die and Ellis (1999) and Vance *et al.* (2003).

This hypothesis of a within-season positive correlation between stock abundance and catchability has been used subsequently to support the notion that management driven reductions in nominal fishing effort in the NPF over the last decade resulted in a loss of searching power, such that in recent years the industry has been unable to find the banana prawn biomass in Albatross Bay. It has been argued that because of the inability to find prawns in this region, the fleet has chosen to fish other areas of the NPF, where with the aid of spotter planes, banana prawns are more easily found. In this view, banana prawn stocks in the Albatross Bay area might have remained high and the recent declines in catch have been occurring independently of actual stock trends.

Stock assessments, based on this assumption that catchability has been declining or has not changed over time, support this view and predict that the recent (after 2000) low levels of fishing should be contributing to stock rebuilding. This argument has apparently been bolstered by an analysis of a recent time series of fishery independent surveys at Albatross Bay that compares them to a previous series of surveys (1986 to 1992) of a slightly different design. The results of that analysis have been taken to suggest that the biomass of banana prawns in Albatross Bay in 2003 and 2004 was similar to that in the previous surveys (Ye *et al.* unpubl. data), though this result contradicts the biomass estimates presented by Zhou *et al.* (2008; Fig. 1), who suggest that the average biomass from 1987 to 1992 was ∼850 t compared with 110 t from 2000 to 2004.

Using sophisticated stock depletion estimators, Zhou *et al.* (2007, 2008) have noted that among years, a negative power function between abundance and catchability exists in the three stocks they analysed; i.e. catchability increases as stock size decreases. Our observations on the spatial extent of catch and effort and the area under the normalised rank order curves are consistent with the findings of Zhou *et al.* (2007, 2008) and suggest the mechanism giving rise to the between year negative power function they detected. Following the generalised fishery dynamic described by Winters and Wheeler (1985), our results are consistent with the notion that a contraction of fishing over time towards a stable and predictable centre of the fishing area has enabled fishers to progressively refocus their searching power on the contracting core of the fishing ground. We suggest that as the stock contracted towards the predictable centre of the hotspot, the searching time required to locate schooling banana prawns has diminished, and over the years this allowed the fishers to increase the efficiency of their fishing (i.e. catchability) as the stock declined.

In 2006, catches of banana prawns in other regions of the Northern Prawn Fishery were low early in the season, and the NPF focussed considerably more fishing pressure in Albatross Bay than in the previous 5 years. A catch of some 398 t resulted from the increased fishing activity (355 boat days) in 2006 (Ye, CSIRO Marine and Atmospheric Research, pers. comm.). Clearly, the 2006 catch was much larger than the catches of 2000 to 2005 (3 to 141 t), although still lower than the long-term average catch for the region (643 t per annum from 1970 to 1999). The magnitude of that catch suggests a moderate level of biomass re-building over the previous few years of very low nominal fishing effort and this is supported by the analyses of Zhou *et al.* (2008). However, the decline in the catch to 230 t in 2007 (202 boat days) suggests that the slight rebuilding may already have been reversed.

Conclusions

Since 1970, the Albatross Bay banana prawn fishery has been contracting steadily towards the stable geographic centre of the fishing grounds. Our analyses suggest that the decline of banana prawn catches in Albatross Bay from 1999 until 2005 was an extension of a trend that began in the early 1970s and note that the banana prawn stock of Albatross Bay meets all the criteria specified by Penn *et al.* (1989) for a penaeid stock likely to be vulnerable to recruitment-overfishing (see also Garcia 1996; Yee 2000). Although other factors may also help explain the decline of Albatross Bay catches since 2000, the spatial trend in catches suggests an obvious mechanism by which catchability and fishing pressure have escalated as the stock declined and raise the possibility that some level of recruitment overfishing contributed to the recent decline. Similar, though less pronounced, spatial contractions were also displayed in other banana prawn stocks in the Northern Prawn Fishery (Fig. 6). These findings and those of Zhou *et al.* (2007, 2008), who found evidence for an increase in catchability as stock size declines in three banana prawn stocks of the NPF, raises the possibility that similar if less advanced overfishing is occurring in other stocks of banana prawns in northern Australia.

We believe this to be the first observation of a *Penaeus* prawn fishing ground contracting as biomass declines, adding further support to the contention of Winters and Wheeler (1985) that the contraction of an area occupied by a stock as biomass declines is a generalised phenomena observed widely across fisheries resources and not a dynamic confined to only certain finfish and molluscs.

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