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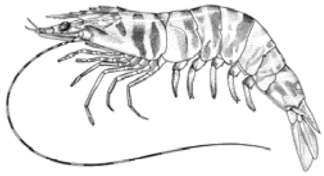
Stock Assessment of the Torres Strait

Tiger Prawn Fishery (*Penaeus esculentus*)



Tiger prawn

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Sustainable Fisheries

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General Disclaimer:
The Department of Primary Industries and Fisheries (DPI&F) seeks to maximise the economic potential of Queensland's primary industries on a sustainable basis.

This publication details the 2004 updated assessment of the tiger prawn stock in Torres Strait. This assessment addresses most of the recommendations of the 2003 Dr Die review. This document also provides a summary of the Industry Workshop held in July 2005. This publication and other assessment reports can be viewed and downloaded from the DPI&F stock assessment web site http://www2.dpi.qld.gov.au/far/14367.html .

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Non-technical summary

This report provides an update and refinement of the 2003 stock assessment of Torres Strait tiger prawns (O'Neill *et al.* 2005). It addressed specifically the recommendations from the 2003 independent stock assessment review (Table 1.1.1) and reinforced the scientific information provided to the Torres Strait Protected Zone Joint Authority (PZJA).

The Torres Strait Prawn Fishery is located to the east of the Warrior Reef complex within the Torres Strait Protected Zone (TSPZ), and in the defined 'outside but near' areas (Figure 1.2.1). It is the most valuable commercial fishery in the Torres Strait with an annual value to fishers of A$24 million. The prawn harvest consists mostly of the brown tiger prawn (*Penaeus esculentus* ≈ 650t) and the less valuable blue endeavour prawn (*Metapenaeus endeavouri* ≈ 1000t), with a minor catch of red spot king prawn (*Penaeus longistylus* ≈ 70t). The trawl fleet is mobile and at present consists of about 77 Australian vessels that operate both in the Torres Strait and on the Queensland East Coast. Seventeen of these vessels are licensed to operate in Australia's Northern Prawn Fishery. Although a total of 13,570 days of fishing access were allocated to Australian vessels in 1993 based on past fishing history, this effort cap has never been reached with maximum of about 12,000 days ever fished. Although it has been possible for up to eight Papua New Guinea (PNG) trawlers to seek endorsement to fish in the Australian area of the TSPZ and there are an additional three licences available for Torres Strait Islander participation in the fishery, none of these entitlements have been utilised.

The efficiency of this fishery increased considerably between 1980 and 2003. There have been increases in most of the general vessel characteristics, including average engine horsepower, gearbox ratios, trawl speed, fuel capacity and consumption, and adoption of propeller nozzles. The configuration of the nets towed had also experienced change characterised by a strong move to use of quad gear. Similarly, the use of flat otter boards had declined over the past 20 years particularly being replaced with louvre/kilfoil or bison type boards. Global positioning systems, computer mapping softwares, and bycatch reduction and turtle excluder devices are now fully adopted (100% of vessels). These changes and adoptions have resulted in fishing power for tiger prawns increasing at an average rate of 1.39% each year.

Average catch rates of tiger prawns, standardised for annual increases in fishing power, declined from 1980 to 1994. They stabilised between 1995 and 1999, and increased marginally each year from 2000 to 2003. The tiger prawn stock assessment, based on these catch rates, used two modelling approaches - a monthly delay difference model and an annual surplus production model. The monthly delay difference model predicted that biomass declined between 1980 and 1989, but varied around the population size that supported maximum sustainable yield (B_{MSY}) between 1990 and 2003. The delay difference model indicated the 2003 biomass was above B_{MSY}. Estimates of maximum sustainable yield (MSY) and fishing effort (E_{MSY}) were 606 and 676 tonnes, and 8245 and 9197 boat nights in 2003, for the Ricker and Beverton-Holt spawner-recruitment relationships respectively. The surplus production model predicted a declining "one-way-trip" of exploitable biomass for Torres Strait tiger prawns, and the 2003 biomass was at about B_{MSY}. Calculations of maximum sustainable yield were comparable to the delay difference model. The fishery independent index of tiger prawn recruitment from February/March between 1999 and 2002 showed high agreement to the standandardised fishery catch rates and the delay difference model.

In July 2005 a workshop was run to allow fishers, scientists and managers to collaborate on the development of alternative management strategies that were likely to result in the sustainable harvest of Torres Strait tiger prawns while permitting some additional fishing directed towards endeavour prawns in southern Torres Strait waters (> 10°S). The main proposal discussed and developed at the workshop was the strategy of using two trigger points to control the allowable effort in the fishery while leaving the allocated fishing days unchanged. The first trigger point would activate a spatial closure aimed at reducing the impact of any further fishing on the tiger prawn spawning stock and the second would close the whole fishery to limit the total annual tiger prawn catch to a sustainable level.

Simulations of various fishing strategies showed that from 2003, when the tiger prawn biomass was above B_{MSY} (the biomass which supports maximum sustainable yield), fishing at 80% E_{MSY} would be effective at maintaining tiger prawns above B_{MSY}, but not exceedingly, resulting in lower risks of over fishing, maintaining harvests and improving catch rates. Fishing for tiger prawns at E_{MSY} and allowing extra effort for endeavour prawns had higher risk of tiger prawn biomasses falling less than B_{MSY}, higher variation between annual harvests and lower catch rates.

The overall key objective in undertaking this study was to reinforce the scientific advice provided to the Torres Strait Protected Zone Joint Authority (PZJA). This project successfully achieved this by updating the tiger prawn stock assessment to 2003. In total 16 out of 21 of Dr Die's high, medium and low priority recommendations were incorporated into the assessment (Table 7.1.1). Of the five recommendations not completed, three were being addressed by the Torres Strait CRC task 1.5, the collection of landings data for the years prior to 1980 was not feasible as we were unable to locate any operators from that period who had retained their catch records and the recommendation to use a target reference point of either 75% or 80% E_{MSY} was a management recommendation yet to be employed. After incorporating the recommendations the results from the updated assessment were the same as from O'Neill *et al.* (2005) in terms of biomass ratios between 1980 and 2001 and estimates of MSY.

KEYWORDS: Fishing power, effort creep, standardised catch rates, prawns, otter trawling, regression analysis, stock assessment, reference points, management strategy evaluation.

1 Introduction

1.1 Background and need

In October 2003 the results of the Torres Strait component of the Fisheries Research and Development Corporation project (FRDC 1999/120) 'Reference point management and the role of catch-per-unit effort in prawn and scallop fisheries' was presented to industry, managers and other stakeholders in the Torres Strait prawn fishery (O'Neill *et al.* 2005). This project was successfully completed between 1999 and 2003 by researchers within the Department of Primary Industries and Fisheries (DPI&F), Queensland. This research investigated ways of standardising catch rates provided from logbook catch records, developed stock assessment models for the eastern king, saucer scallop and Torres Strait tiger prawn trawl sectors, and examined a range of model-based and data-based reference points. This three-year project represents the most significant contribution to the assessment of Queensland's and Torres Strait's trawl stocks. The reasons are as follows:

1. The Report included, for the first time in the assessment of these stocks, the application of internationally recognised fisheries stock assessment reference points, including Maximum Sustainable Yield (MSY), measures of the effort associated with MSY (E_{MSY}), and fractions thereof, including $2/3E_{MSY}$ and $3/4E_{MSY}$. The work contrasts these with the reference points currently prescribed in the Queensland Trawl Fishery Management Plan; referring to the "70% of average catch rates". The work reported on the accuracy and robustness of both the model-based and database reference points.
2. For the first time in the Queensland and Torres Strait trawl fishery, annual changes in fishing power were quantified and published in *Fisheries Research 65;(O'Neill et al. 2003)*. While fishing effort is recorded in logbooks, it had never before been adjusted to take account of increases in fishing power due to such technologies as vessel size, GPS, try gear etc. The increases in fishing power were measured and applied to standardise fishing effort and catch rates for each trawl sector.
3. For the first time in the trawl fisheries management, stock-recruitment relationships were considered in stock assessments and management evaluations.
4. Never before have management alternatives in the Queensland and Torres Strait trawl sectors been modelled to predict future outcomes on sustainability, industry catches and management activity. The management modelling scenarios presented in the report give managers and fishermen information about likely impacts of future management decisions.
5. Finally, the project had gone to considerable lengths to incorporate uncertainty in key population parameters and model outputs, certainly more than any other previous modelling of the trawl stocks. It has achieved this by extensive use of Monte Carlo and boot-strapping methods.

In October 2003 Dr David Die, an international recognised stock assessment expert from the Miami University (Florida, USA), independently reviewed the Torres Strait component of the above project ("Review of the Stock Assessment of the Torres Strait Prawn Fishery"; (Die 2003). He provided a number of recommendations aimed at improving the stock assessment and addressing the concerns of fishers about the model and the data used. In his review Dr. Die states…

"*The new assessment presented by O'Neill and Turnbull (2003) are a considerable improvement from the previous assessments. Major improvements were obtained by:*

- *Extending the estimation of relative abundance to a larger time period (1980-2002) and updating the effort creep analysis for the same period*
- *Using a seasonal delay-difference model that captures more of the information contained in the data and allows for the explicit incorporation of stock recruitment functions in the assessment.*
- *Conducting extensive estimation of the uncertainty in the assessment results through bootstrap analyses*
- *Developing a framework for quantitative evaluation of management strategies*

The scientific advice produced by such assessments is therefore of high quality and is sustained by the use of state of the art statistical analysis and simulation modelling.

As for any assessment there are improvements that can be made in the analyses and presentation of results. Although some of the improvements suggested may change the details of the advice on stock status it is unlikely that the general conclusions reached by the recent assessment will change."

The purpose for this report was to address Dr David Die's list of recommendations to strengthen the assessment by O'Neill *et al.* (2005). The assessment estimated a potential large reduction in the current allocations of fishing nights to operators. The fishery managers have expressed an urgent need to address the key recommendations made by Dr Die, so as to maximise the confidence in the results obtained from the assessments. All recommendations from the review were qualified with the priority that the reviewer placed on them. Table 1.1.1 lists the high, medium and low priority recommendations.

The most important priority recommendations from Dr Die relate to estimating fishing power and standardising catch rates. For this report we re-estimated average annual changes in fishing power (effort creep), compared alternate analyses to standardised catch rates, and applied the delay difference and surplus production models with these estimates of relative abundance. A further key high priority recommendation was that the working group should develop target objectives for the fishery and alternative management strategies to reach the targets and that these strategies should be evaluated by the Management Strategy Evaluation (MSE) method. This recommendation was addressed by means of an industry workshop aimed at developing a more strategic management of the fishery that would potentially allow more fishing effort to be applied to the endeavour prawn stock whilst ensuring that the tiger prawn stock was not overfished. This may reduce the impacts of the proposed effort reduction on industry whilst ensuring that the tiger prawn harvest was sustainable. The outcomes of the workshop were simulated using the delay difference model.

Collation and incorporation of catch and effort data administered by Papua New Guinea was a recommendation arising from the review. Although Dr Die rated this as a low priority, the Australian prawn operators have repeatedly requested that PNG data be added into the stock assessment. Whilst it is unlikely that the inclusion of this data will significantly change the results from the models, this recommendation still holds a very significant level of political weighting.

Table 1.1.1 The David Die stock assessment recommendations. High priority was given to those recommendations that, when followed, may significantly change the scientific advice provided and that can be followed up in a short space of time (weeks). Medium priority was given to those recommendations that can lead to significant change in the advice but that require months of work. Low priority was given to those that are unlikely to change the advice. * flags that the priority was not addressed due to time constraints.

Assessment Component and Priority	**Recommendation**
Catch Data	
1. Medium*	That unloading data are obtained, even if it is only samples for some vessels, and that a GLM model is run to determine the significance of correction factors for estimates of landings obtained from logbook data. Factors to be considered in the GLM model could be month, year, area (may not be possible if vessels fish in more than one area during a single unloading period), and possibly type package used to pack prawns. The dependent variable should be the logbook catch for a vessel and the independent the unloading catch for the same vessel in the same period of time. If enough size-grade data is present in logbooks size grade could be also used as a factor. If yearly factors are significant this may put into question the catch rate estimates from logbooks.
2. Low	Data from the PNG side of the fishery should be collated to estimate the annual catch harvested by PNG boats so that this catch can be included in the assessments made by the Torres Strait Prawn Working Group. Also cpue data should be collected so as to start developing indices of abundance from the PNG side of the fishery.
3. Low	That possible biases (time shifts and smoothing) in the procedure to allocate unloading data to particular time periods is investigated by using data for vessels/years when both unloading and logbook data is available.
4. Low*	Analyse commercial grading data from logbooks and unloading data to determine the size composition of the catches to initially estimate annual indices of the timing of recruitment. Use these data on recruitment timing in the delay difference model. If the grading data is of high quality and abundant, develop catch at size matrices to develop a fully size/age structured model.
Fishing Power and Standardised Catch Rates	
5. High	That the current database on chain size is used to calculate the expected reduction in fishing power resulting from chain size reductions that occurred in 2001.
6. High	That a 4% decrease in fishing power as a result of the decrease in net size that occurred in 2002 is adopted as the best available estimate for this effect and used in the stock assessment.
7. High	That the effort creep schedule is re-estimated for the last two years and that the delay difference models be run with the new estimates of relative abundance for 2001 and 2002.
8. High	Use a unit of fishing effort in the past (e.g. 1980 effort unit) as the reference for effort creep calculation and reporting. Include a table with the annual nominal effort and the effort corrected for effort creep (in appropriate reference-year units) in the all the reports of the assessment.
9. Medium	That a standardized catch per unit of effort be estimated for endeavour prawns to estimate relative abundance for this species. Use GLM method as for tiger prawns.
10. Medium	That a new GLM is carried out to estimate standardized catch per unit of effort by creating two new area strata as follows: a) Split northern strata in two by choosing grids that are inside the Warrior reef closure and outside of it, and b) split southern strata in two by choosing grids that are in the areas where the highest king prawn catches exist (closer to the reef), To examine if the resulting standardized catch per unit of effort is significantly different to the one obtained in the current assessment.
11. Medium	That the results from the GLM used to estimate effort creep factors are used to estimate an alternative standardised cpue series. This series should be compared to the one used in the current assessment (corrected for effort creep) and used as a sensitivity analysis.
12. Medium	That a new GLM is run by using only data from vessels that were providing data in the early part of the season. This series should be compared to the one used in the current assessment and used as a sensitivity analysis.
13. Medium	That the vessel characteristics database is updated every year.
14. Medium*	That old data on landings and catch rates are sought from industry for the period prior to 1980 and these data are used to develop priors for the stock biomass ratio in 1980.
Stock Models and Management Strategy Evaluation (MSE)	
15. High	Further testing of the production model implementation in MATLAB and EXCEL should be made and comparisons to other implementations of the production model implementations such as ASPIC, BIODYN (Punt and Hilborn 1996) or FISHLAB (Kell and Smith 2000) should be conducted to confirm that the production model results are repeatable.
16. High	That only production models with all data be considered to estimate reference points. Also, that the best fits to the data, those of the Fox model, be considered as offering optimistic views of the productivity of the stock.
17. High	Use delay difference model as base case for assessments. Use B_{MSY} and E_{MSY} as limits reference points. The prawn biomass should always be maintained above B_{MSY} and the standardised effort below E_{MSY}.
18. High	Use a target reference point of either 75% or 80% E_{MSY}.
19. High	Working group should develop alternative management strategies to reach target reference points. These strategies should be evaluated by the MSE method.
20. Medium	Management strategies to be tested need to be develop by working group MSE should then be repeated for those strategies
21. Medium	The status quo strategy should be estimated with the 2001 and 2002 data, not the 1999-2002.

1.2 Description of the trawl fishery

1.2.1 Main features of the 2003 fishery

Target catch composition	Tiger prawn (45%), endeavour prawn (48%) and king prawn (7%)
Total catch and effort	1,597 t from 9,000 days of effort; observed CPUE 177 kg/day
Current value	$23.5m, both export and domestic markets
Current fleet	77 Australian licensed vessels assigned 13,486 fishing days
Papua New Guinea licences	Potentially 8 licences equating up to 2,200 fishing days
Torres Strait Islander licences	Potentially 3 licences equating up to 825 fishing days
Location	Torres Strait Protected Zone and outside but near area
Fishing method	Vessels <20m; quad or double otter gear, net size 80m; mesh 48mm
Main by-product	Bugs and squid
Market	Export tiger prawns to Japan and endeavour prawns to Europe. Endeavour, king and smaller tiger prawns sold domestically.
Management	Input controls: limited entry, gear and vessel size restrictions, allocated days of fishing access, seasonal and area closures.
Stock assessment	Delay difference and surplus production models.

The Torres Strait Prawn Fishery (TSPF) is a multi-species prawn fishery which operates in the eastern section of the Torres Strait Protected Zone (TSPZ) Figure 1.2.1 and the defined ‘outside but near’ area. It is the most valuable commercial fishery in Torres Strait with an annual value to fishers of AUD$18-23 million. A mobile fleet of about 77 Australian vessels operates both in the TSPF and on the Queensland East Coast. Seventeen of these vessels are also licensed to operate in the Northern Prawn Fishery. The main prawn-trawling ground in Torres Strait is to the east of the Warrior Reef complex, centred on Yorke Islands that form one of the main anchorages for the prawn trawl fleet. Australian-licensed trawlers can remain in the Torres Strait fishing grounds for extended periods because they are supported by mother-ship and fuel-barge supply services.

The Torres Strait licenses are transferable and have an allocation of fishing days attached to them. Although a total of 13,570 days of fishing access were allocated to Australian vessels operating in the fishery in 1993, this effort cap has never been reached. Under the Torres Strait Protected Zone Treaty Papua New Guinea is also entitled to harvest approximately 25% of the catch from the Australian area of the TSPZ and similarly Australia is entitled to harvest to 25% of the catch of the PNG area of the TSPZ. To give effect to this entitlement, an agreed number of PNG trawlers can be endorsed to fish in the Australian waters of the TSPZ for the full season (275 days). The number of PNG vessels that can be endorsed is based on the current three year average catch of Australian waters of the TSPZ plus an adjustment for Australian operators opting not to cross-border fish in PNG waters of the TSPZ. Currently up to eight PNG trawlers could be endorsed under the cross border fishing arrangements which potentially represents an additional 2,200 days of fishing effort in Australian waters. Despite the cross border fishing arrangements only a few PNG vessels have sporadically fished in the TSPZ and their area of operation has been confined to PNG waters (north of the fisheries jurisdiction line). Although three additional licences were reserved for use by Torres Strait Islanders these licences were never activated. The islander licenses were for a full season and hence represented a potential 825 additional days of fishing effort that could have been activate in the Australian section of the fishery. Although the potential effort of the Australian section of the fishery has reduced since the early 1980’s the 2005 management arrangements still allowed a potential level of fishing effort that was substantially higher than both the historic annual effort and the level of fishing that is generally considered by researchers, managers and industry to be sustainable and economically viable.

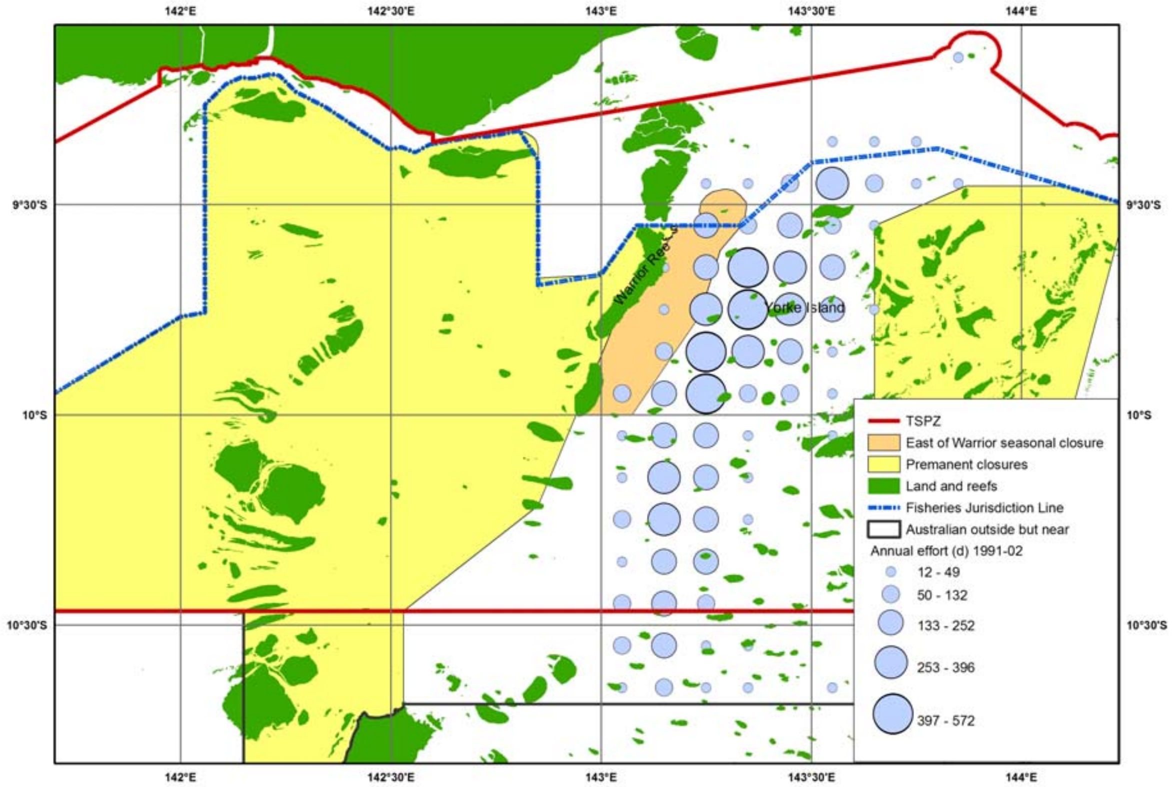

Figure 1.2.1 Location of the Torres Strait Prawn Fishery indicated by the annual fishing effort summarised by six-minute grids, the Torres Strait Protected Zone, the Fisheries Jurisdiction Lines, and the Australian outside but near area of the prawn fishery.

1.2.2 History and management

The prawn trawl fishery in Torres Strait began in the mid-1970s, extending northward from the prawn fishery along the Queensland east coast. When the Torres Strait prawn fishery began, all east coast and Northern Prawn Fishery prawn trawlers were entitled to fish in Torres Strait, effectively allowing access to all of about 1200 vessels. When the Torres Strait Treaty was ratified in 1985 approximately 500 vessels had obtained a licence to operate in the Torres Strait Prawn Fishery (TSPF).

Since 1985 the Australian and Queensland Governments under the Torres Strait Treaty have jointly managed the TSPF. In 1987 the Protected Zone Joint Authority (PZJA) introduced limited entry and licences were restricted to the 150 vessels that had any history of fishing in Torres Strait. In 1989 an industry supported freeze on licences was implemented and by June 1992 around 110 vessels were licensed in the fishery. Days of fishing access to Australian vessels, based on the maximum of previous fishing history plus 10%, was introduced at the start of 1993 and in 1994 arrangements to allow trading of licences and fishing access days were implemented. As at January 2004, there were 77 Australian licensed vessels assigned 13,486 fishing days, compared with 110 licensed vessels in June 1992 with a potential 30,250 fishing days (Kung *et al.* 2004).

Seasonal and area closures have played an important role in the management of the fishery. In 1980 the area to the west of the Warrior Reefs was closed at the request of industry, to protect juvenile prawn stocks. The first seasonal closure to trawling in the TSPF and the Queensland East Coast Otter Trawl fishery (ECOTF) extended from 1st January to 28th February 1985 and coincided with the time when small less valuable prawns recruited into the fishery. A similar closure was implemented for the 13th December 1985 to 28th February 1986. There was no closure in 1986-87 in the TSPF and ECOTF as northern-based operators were concerned that effort was being aggregated into the first months after the closure, causing a pulse fishing effect. The seasonal closure was reintroduced however for subsequent years. In 1989 a split seasonal closure was implemented; 23rd December to 15th April 1989 north of 10° 13' S and from the 23rd

December to 7th March south of that latitude. At industries request the spilt closure was replaced with a total seasonal closure from 15th December 1989 to 15th April 1990. Catches at the start of that season and the result of prawn tagging conducted by DPI&F during February and March indicated that the 1990 season opened too late, resulting in a decreased harvest. Based on research conducted by DPI&F during the late 1980's and consultation with Islanders, industry proposed the east of Warrior Reef Closure and a reduced seasonal closure from 1st December to 1st March. The combined effect of these closures allows most prawns migrating from west to east through the Warrior Reefs to reach export grade size before they are fished.

1.3 Past stock assessments

Early assessment of tiger prawns in the Torres Strait was based on estimation of the Maximum Constant Yield (MCY) produced by DPI&F in 1991 (Turnbull and Watson 1995). Research trawl data collected during the years 1986 to 1989 were used to calculate an MCY for each species. The MCY for the fishery was estimated to be 1370 t consisting of 585 t tiger prawns, 685 t endeavour prawns and 100 t king prawns. A summary of this assessment, 1992 Fishery Status Report for Torres Strait Prawns, is contained in Turnbull and Watson (1995). The second formal stock assessment was conducted in 1994 and is described in detail in Turnbull and Watson (1995). That assessment showed that a natural mortality of 0.2 per month (the value used in the 1991 assessment and widely reported in the literature) will produce an MCY for the fishery of 1,903 t, consisting of: 682t tiger prawns, 1035t endeavour prawns, and 186t king prawns. Estimates of the effort required to produce an annual fishing mortality equal to $F_{0.1}$ were 106,400 hours (88,700 - 133,300 h) for catchability estimates of 2.5 x 10^{-5} h^{-1} (2 x 10^{-5} - 3 x 10^{-5} h^{-1}). These equate to 9,900 (8,200 - 12,400) unstandardised days, as the average number of hours trawled per night in Torres Strait during the years 1998-2002 was 10.8. More recent estimates of average fishing effort required for catching maximum-sustainable-yield (MSY and E_{MSY}) of tiger prawns were calculated from more formal stock assessment methods (Table 1.3.1). The predictions compared overall suggest fishing effort, standardised to 2002 fishing power, should be below 10,000 nights. These results were produced from a range of model fits and further sensitivity results documented by O'Neill *et al.* (2005) suggest a similar tendency of sustainable fishing effort below 10,000 nights.

Table 1.3.1 Past stock assessment estimates of maximum harvest and fishing effort for tiger prawns. ^{nom} indicates unstandardised fishing effort; ^{2002} indicates fishing effort standardised to 2002 fishing power; ^{2} model assumed 1980 was at virgin stock size; $^{1.7}$ model assumed 1980 was at 85% of virgin stock size; ^{Beverton} represents Beverton-Holt spawner-recruitment relationship; ^{Ricker} represents Ricker's relationship. Note other model sensitivity results are presented in O'Neill *et al.* (2005).

Report Reference	Stock Assessment Method	Assessment Year	Management Quantity	Harvest (Tonnes)	Fishing Effort (Nights)
(Turnbull and Watson 1995)	Research Trawl Survey	1991	MCY	585	-
		1994	MCY and $E_{0.1}$	682	$9,900^{nom}$ (8,200 – 12,400)
	Schaefer Production Model	2000	MSY and E_{MSY}	665 (628 – 710)	$10,308^{nom}$ (9,131 – 13,256)
(O'Neill *et al.* 2005)	Fox Production Model	2002	MSY and E_{MSY}	643 t (607 - 689)	$11,353^{2002}$ (8,548 – 12,806)
(Die 2003)	Schaefer Production Model^{2}	2002	MSY and E_{MSY}	572 (374 – 630)	$9,235^{2002}$ (6,340 – 10,373)
	Schaefer Production Model$^{1.7}$	2002	MSY and E_{MSY}	532 (353 – 575)	$8,170^{2002}$ (5,091 – 8,975)
(O'Neill *et al.* 2005)	Delay Difference Model^{Beverton}	2002	MSY and E_{MSY}	698 (490 – 958)	$8,257^{2002}$ (5,797 – 11,333)
	Delay Difference Model^{Ricker}	2002	MSY and E_{MSY}	611 (426 – 808)	$7,228^{2002}$ (5,040 – 9,559)

1.4 Objectives

The overall key objective in undertaking this study was to reinforce the scientific advice provided to the Torres Strait Protected Zone Joint Authority (PZJA).

This was to be achieved by:

1. Addressing most of the high and medium priority recommendations from the independent review of the Torres Strait Tiger prawn stock assessment to minimise uncertainties in the scientific advice on sustainable fishing levels in the prawn fishery.
2. Developing via the Prawn Working Group (PWG)/ Industry Workshop, alternative management strategies to cap effort directed at tiger prawns at sustainable levels while investigating an increase or diversion of effort towards endeavour prawns.
3. Assessing the impact of the alternative management strategies developed in point two above using state of the art modelling techniques.
4. Collate the commercial harvest data from the Papua New Guinea (PNG) side of the fishery to factor into the stock assessment.

Due to circumstances beyond the control of the principal investigators the "Alternative Management Strategy Workshop" was delayed until July 2005. The outputs from this study provided a major contribution to the workshop.

2 Harvest statistics

2.1 Annual trends

Two data sources were used to compile the available time-series of prawn harvests from the Torres Strait. The first data source was the 1978 to 1988 monthly unloading catch-statistics recorded by the Northern Fisheries Unit (a Commonwealth Authority) and provides the prawn total harvests for those years. The second data source was the daily logbook catches recorded from 1980 to 2003. During the years 1980-1988 all Northern Prawn Fishery endorsed vessels were required to record daily catch and effort whilst in the NPF and Torres Strait Fisheries. In addition some non-NPF vessels voluntarily filled out the NPF logbook whilst fishing in Torres Strait. Since 1988 it has been compulsory for all Torres Strait endorsed vessels to provide daily logbook returns. This data was collected as part of the Australian Fisheries Management Authority (AFMA) logbook program and provides catch rates for the years 1980-2003 and prawn total harvests for the years 1989-2003. The data extraction processes are detailed in section 4.1 page 25. Figure 2.1.1 compares the unload catch-statistics collected during 1978-1988 with the daily logbook catch records collected during 1980-88.

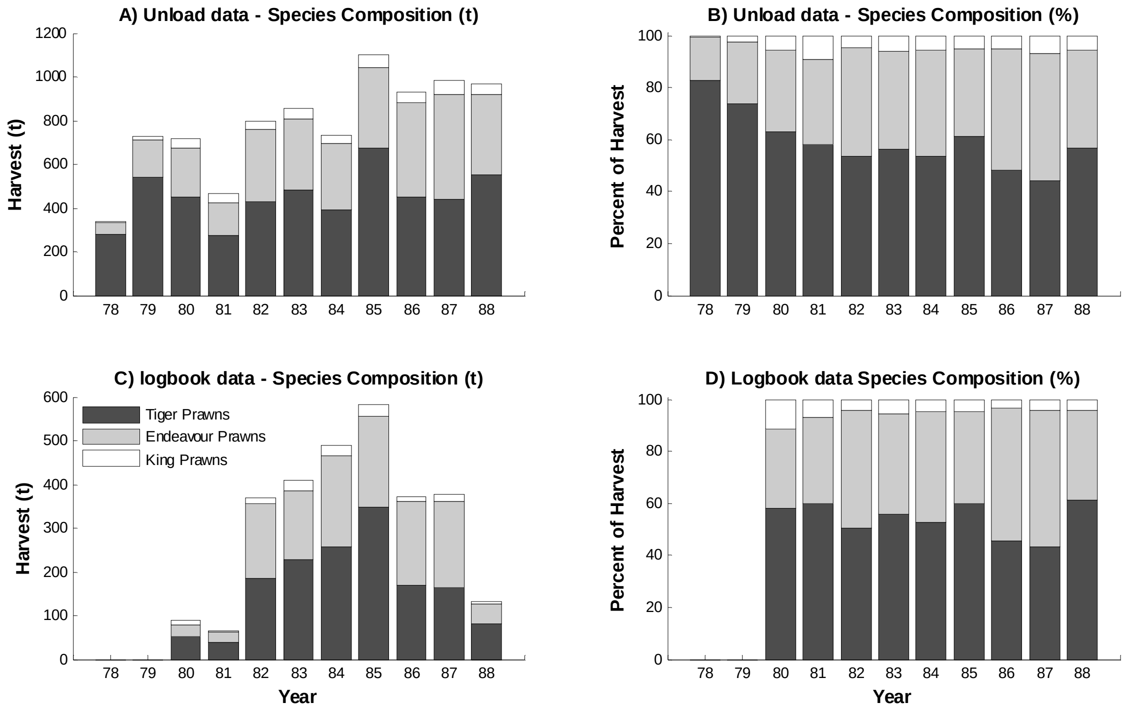

Figure 2.1.1 Unloading and logbook records of prawn harvest by species from 1978 to 1988.

The logbook data provides a subset of the total catch records with the highest coverage (40-50%) during the years 1982-1987. The years of low coverage were 1980-1981 and 1988. The trend in species composition of the logbook data matches fairly closely the trend in the species composition trend in the unload data. This indicated the logbook data was representative of the total catch with respect to species composition. The trends in catch and species composition for the years 1978-2003 (Figure 2.1.2) were constructed by combining the 1978-1988 unload data with the 1989-2003 logbook data.

Total catch has increased from around 400 tonne to an average of 1,800 tonne during the 1990's and recent years. The increase in catches that occurred in 1991-1992 was largely associated with the implementation of the East of Warrior Closure, which is designed to increases the average size of the prawns at first harvest by limiting fishing pressure along the eastern edge of the Warrior Reefs. Research surveys conducted by DPI&F during the late 1980's and early 1990's indicate high abundance of prawns below export size grade inside the closed area. An assessment conducted by (Turnbull and Watson 1991) indicates the closure has increased the yield of endeavour prawns and to a lesser extent tiger prawns by limiting growth overfishing. Most industry members support the East of Warrior closure and believe that it is beneficial to the fishery. Prior to 1991 the timing of the seasonal closure varied and was generally aligned with the seasonal closure in the Northern Prawn Fishery. In some years March and beginning of April, which tend to be the most productive months, were closed. Since the end of 1990 the seasonal closure has been fixed at 15th December to 1st March.

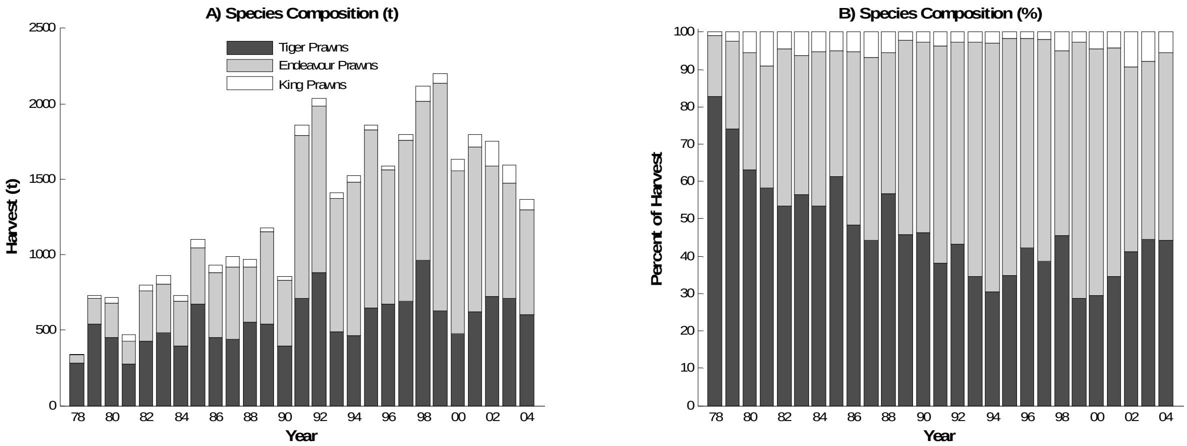

Figure 2.1.2 The Torres Strait prawn harvest by species recorded between 1978 and 2004.

Tiger prawn catch since 1991 has averaged about 660 tonne and ranged from a low of 479 tonne in 2000 to a high of 965 tonne in 1998. Catches over the last two years were higher than average. Since 1998 DPI&F has conducted annual trawl surveys at the start of the season along the northern Queensland east coast and in Torres Strait. The recruitment indices derived from the fishery independent surveys indicate that 1998 was a year of exceptionally high tiger prawn recruitment and that 2000 was a year of low recruitment.

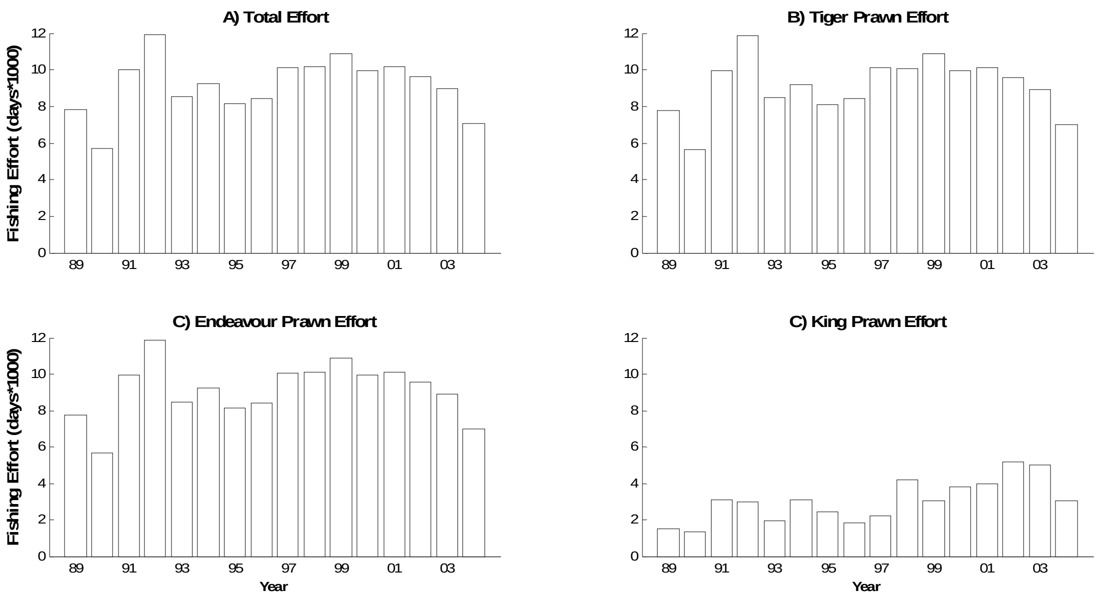

Figure 2.1.3 Total fishing effort reported catching each prawn species from 1989 to 2004.

Since the late 1970's the percentage of tiger prawn in the catch has decreased from about 80 percent to around 40 percent while endeavour prawn has increased to about 55 percent of the catch. The change in species composition appeared to be due to both an increase in the average biomass of endeavour prawns and expansion of fishing effort into the southern section of Torres Strait. The proportion of king prawns in the catch has varied between 2-10% of the catch with no general trend over time. King prawn catches in the last two years were higher than average.

The daily vessel catch and effort records since 1989 show that most trawls contain both tiger and endeavour prawns. There are only 718 (0.46%) daily vessel records with tiger prawn but no endeavour prawn and 852 (0.55%) records with endeavour prawn but no tiger prawn. This is further illustrated in Figure 2.1.3 which shows that the annual total fishing effort is virtually identical to the effort associated with tiger prawn catch and the effort associated with endeavour prawn catch. The effort associated with king prawn catch was much lower reflecting the lower abundance of this species. There is no recorded source of total fishing effort data for the years prior to 1989. During the 1990's both total fishing effort and effort linked to either tiger prawn or endeavour prawn catch has varied between 8,000 and nearly 12,000 days with the average of about 9,900 days.

2.2 Seasonal trends

There was marked seasonal decline in fishing effort and catches of each species (Figure 2.2.1) during the fishing season. The early months of the season (March to May) generally accounted for 40-50% of the annual fishing effort and about 60% of the harvest (Figure 2.2.2 and Figure 2.2.3). The observed trends in effort are partly driven by the seasonal closure and the mobility of the fleet. The seasonal closure produces increased effort during March-April as there is a general expectation by fishers that best catches should immediately follow the closure. In addition most of the vessels are endorsed to fish on the Queensland east coast and about 17 vessels are currently endorsed to fish in the Northern Prawn Fishery (NPF). Vessels move between these fisheries depending on where fishers can take the best catch. The NPF vessels tend to fish in Torres Strait during March and June-July when the NPF is closed to fishing.

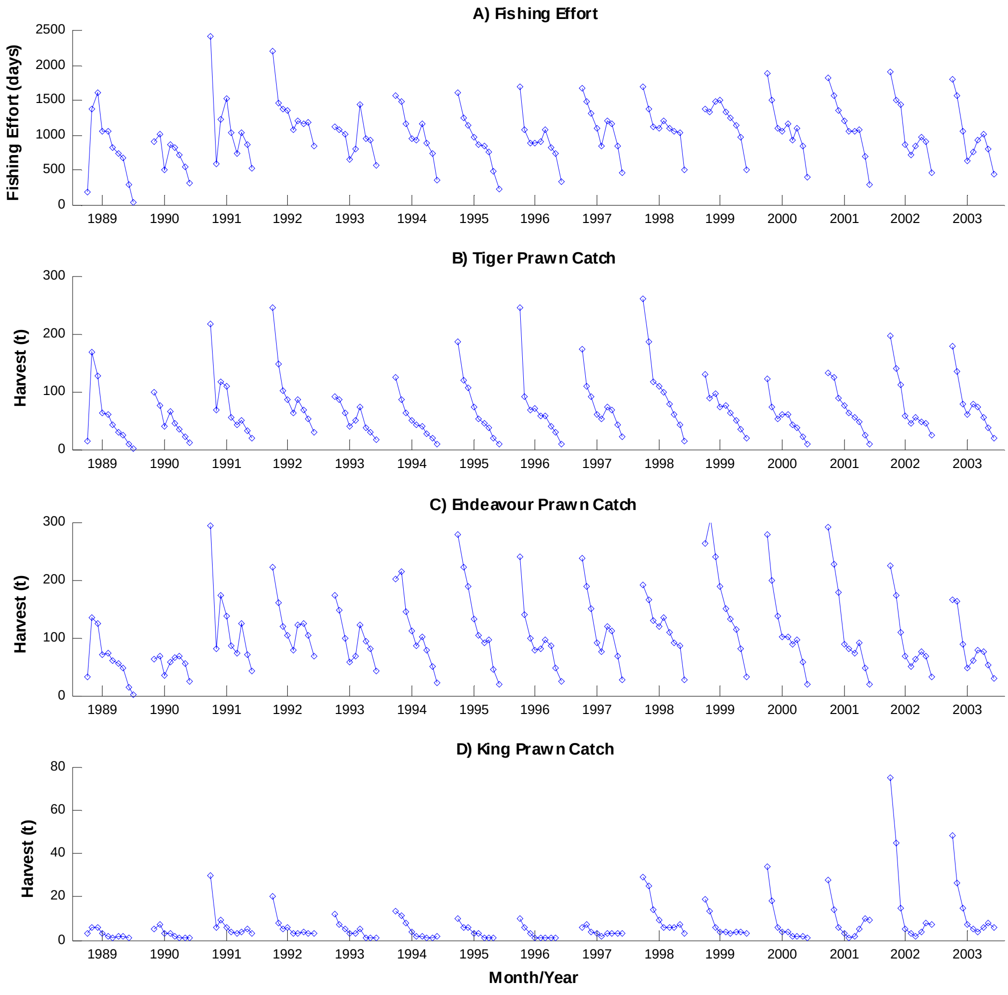

Figure 2.2.1 Monthly fishing effort and harvest by each prawn species.

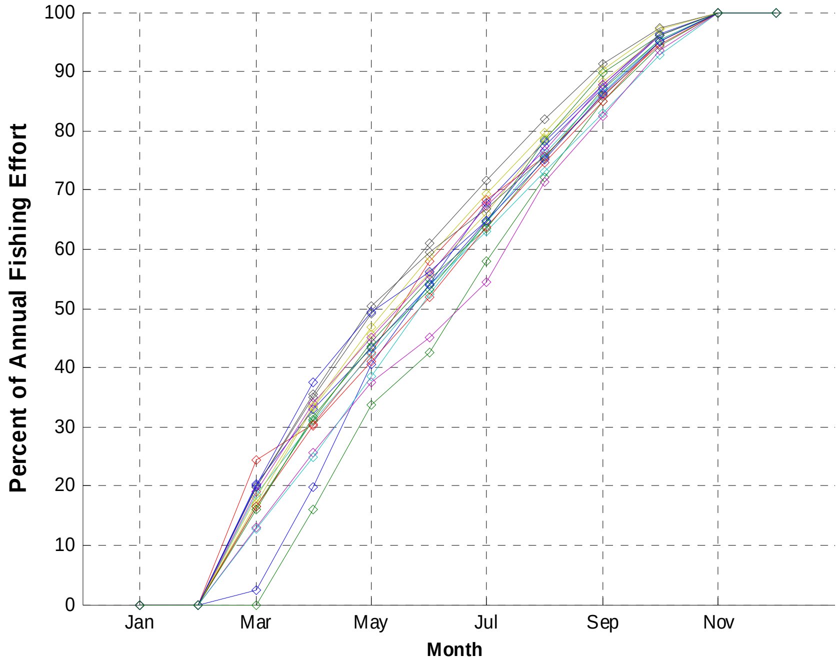

Figure 2.2.2 Monthly cumulative percentage of fishing effort. Each line represents a different year from 1989 to 2004. The early months of the season from March to May accounted for about 40-50% of annual fishing effort.

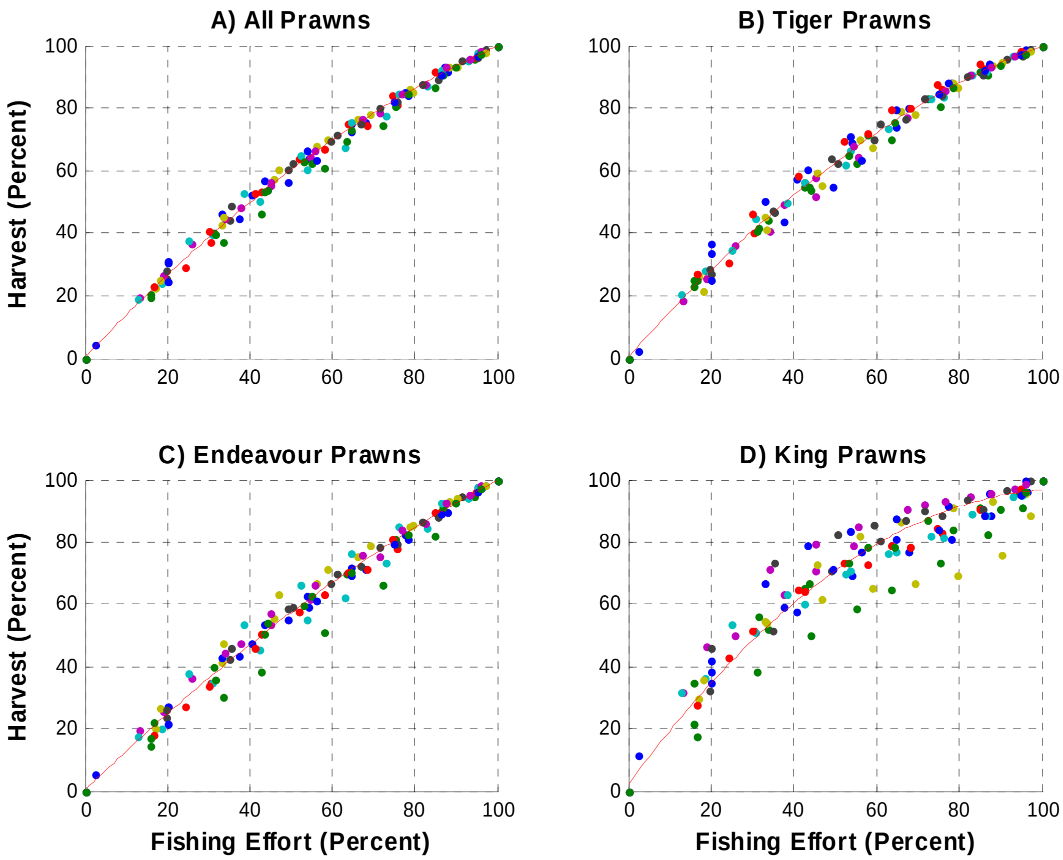

Figure 2.2.3 Cumulative relationship between monthly harvest (t) and fishing effort (days) for A) tiger, endeavour and king prawns combined, B) tiger prawns, C) endeavour prawns, and D) king prawns. About 50% of annual fishing effort results in about 60% of the harvest.

2.3 Spatial trends

Although the distributions of tiger and endeavour prawns catches strongly overlapped, the catch rates of tiger prawns tended to be higher in the northern section of the fishery (Figure 2.3.1). Conversely the catch rates of endeavour prawns tended to be higher in the southern section of the fishery (>10°). The areas of high endeavour prawn catch rates in the north were largely on the western side of the fishery, close to Warrior Reef. In contrast the high tiger prawn catch rates extended into the deeper waters on the eastern side of the fishery.

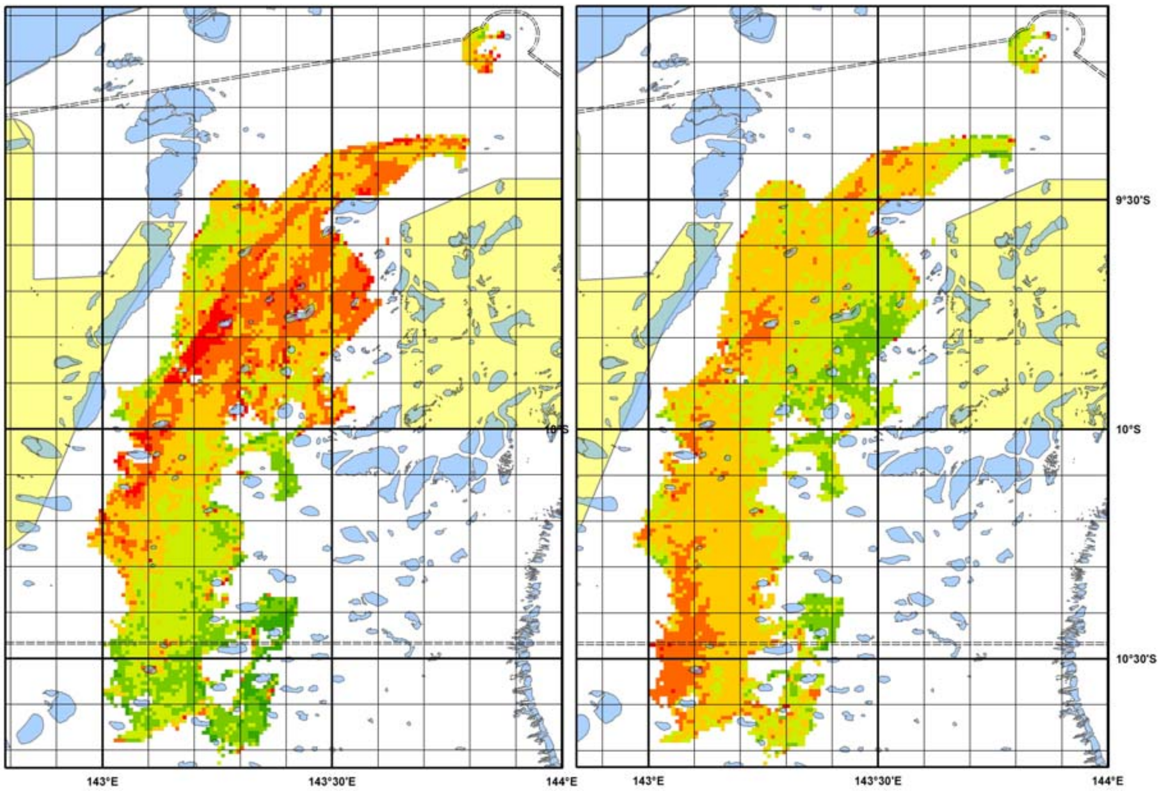

Figure 2.3.1 Catch rates for tiger (left) and endeavour prawns (right) based on daily logbook records matched with vessel satellite positioning data. The graduated colours from red indicate high, orange/yellow average and green low catch rates.

The catch rate maps presented in Figure 2.3.1 were based on daily logbook data for the years 2000-2003 matched with fine scale vessel location data from the Vessel Monitoring System (VMS). The maps were produced using software developed by the FRDC Project 2002/056 "Innovative Stock Assessment and Effort Mapping using VMS". The general rule of only presenting bulk data from five or more vessels was applied when producing the maps.

The spatial distribution of the catch from the logbook data for the years 1980-1988 (Figure 2.3.2) was compared with the logbook data for the years 1991-2002 (Figure 2.3.3) to check for possible shifts in the spatial distribution of the catch and effort. Prior to 1985 Australian vessels could legally fish in PNG waters and the only spatial closure was to the west of the Warrior Reefs.

Dr Dave Die's recommendation 10 (high) was to increase the spatial stratification of the daily vessel data to account for the implementation of the East of Warrior Closure in 1991 and to better reflect variations in the distribution of king prawns in the southern area. The previous north-south stratification only accounted for the shift in the species composition of tiger and endeavour prawns with latitude. The proportion of tiger prawns in the catch was generally higher in the northern grids and endeavour prawns are more predominant in the southern grids. This trend is evident in both the 1980-88 data and the 1991-2002 data.

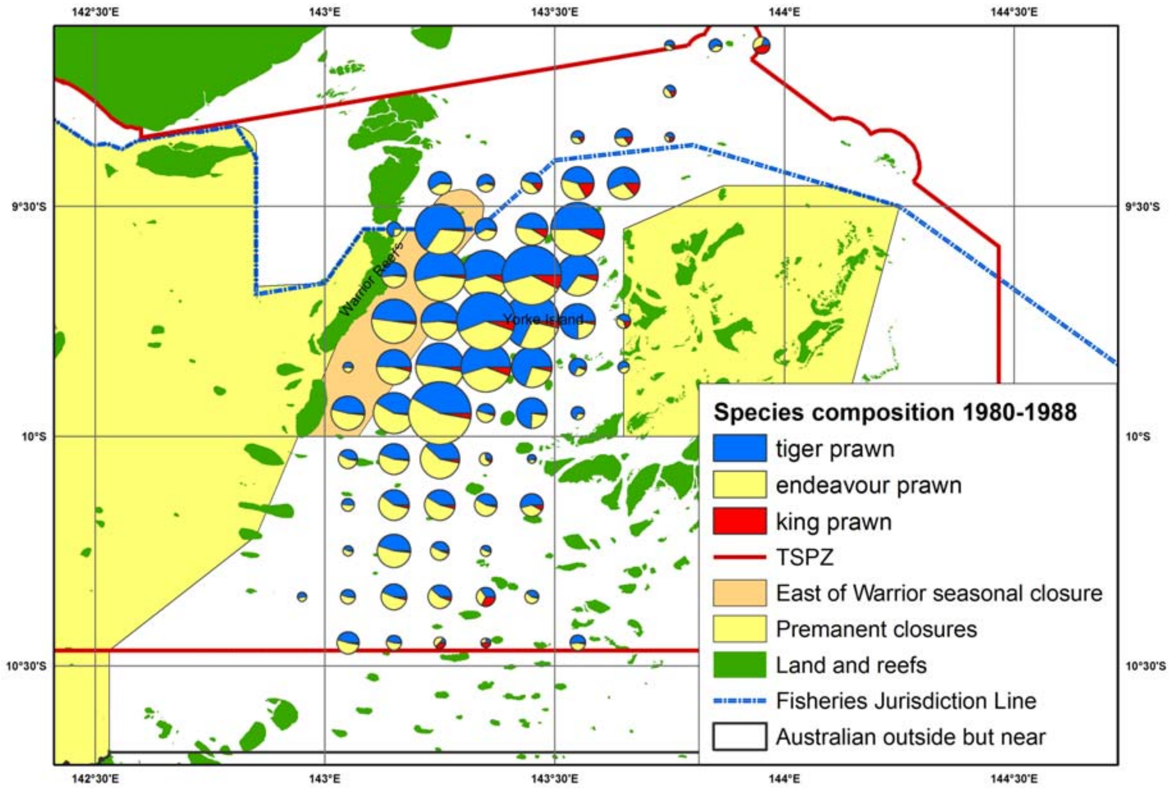

Figure 2.3.2 Spatial distribution of harvest from 1980 to 1988. The diameters of the pie plots indicate the average annual harvest of each six-minute logbook grid and the proportions indicate the average species composition. The smallest circle represents ~0.5t/yr and the largest ~23t/yr of prawn.

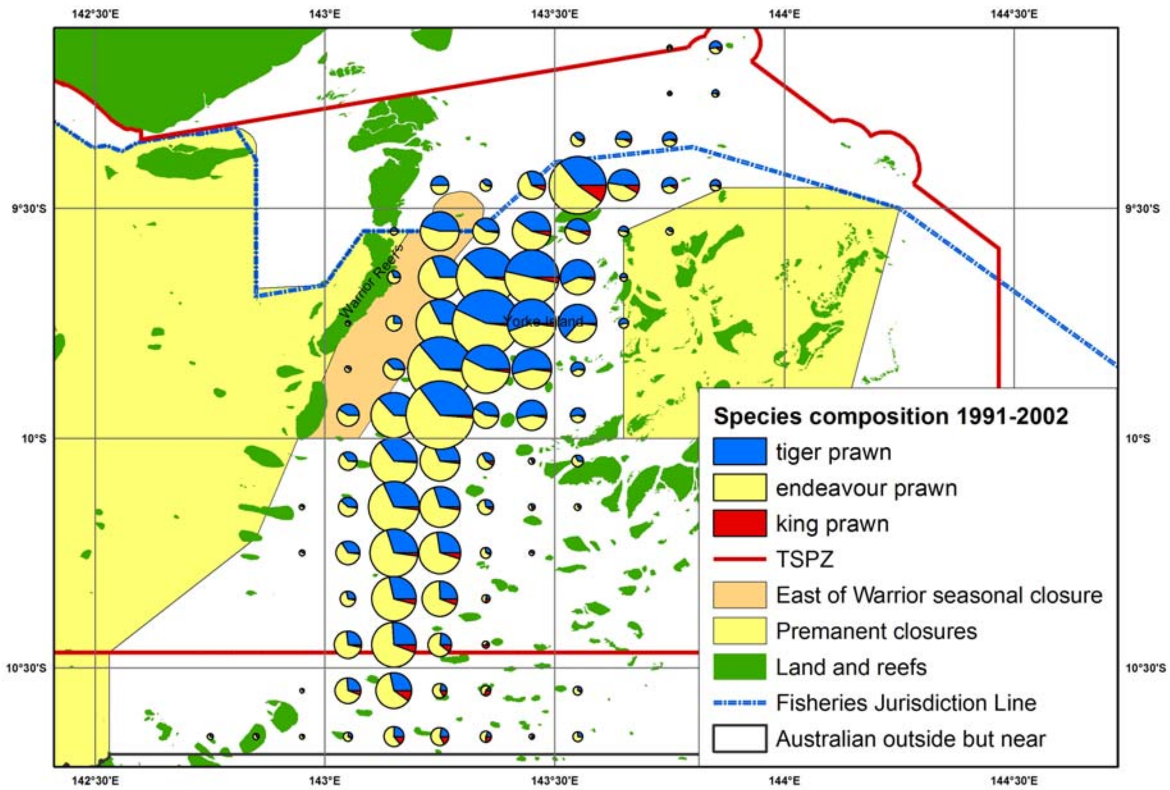

Figure 2.3.3 Spatial distribution of harvest from 1991 to 2002. The diameters of the pie plots indicate the average annual harvest of each six-minute logbook grid and the proportions indicate the average species composition. The smallest circle represents ~0.5t /yr and the largest ~105t/yr of prawn.

A comparison of Figure 2.3.2 and Figure 2.3.3 indicates that during 1980-1988 relatively more catch and fishing effort occurred in the northern stratum than during the 1991-2003. Similarly there was relatively more catch in the area to the east of Warrior Reefs. Since 1991 this area has only been open during August to November and is lightly trawled during those months. The revised four-way spatial stratification is illustrated in Figure 2.3.4. The six-minute grids that are entirely or partly inside the East of Warrior Closure were re-assigned as new strata coded as "EWC". Although David Die suggested splitting the south stratum into two areas based on the distribution of king prawn catches there is no clear trend in the species composition data on which to base the suggested split. Therefore the southern stratum was left the same as that used in the previous assessment. Australian trawlers can legally fish within the 3-mile territorial waters around Bramble and Anchor Cays that are located in the northern section of the PNG area of jurisdiction. As this area is only lightly fished and essentially represents fishing grounds in the extreme northern section of the TSPZ; these grids were coded as a separate stratum called "Bramble Cay"

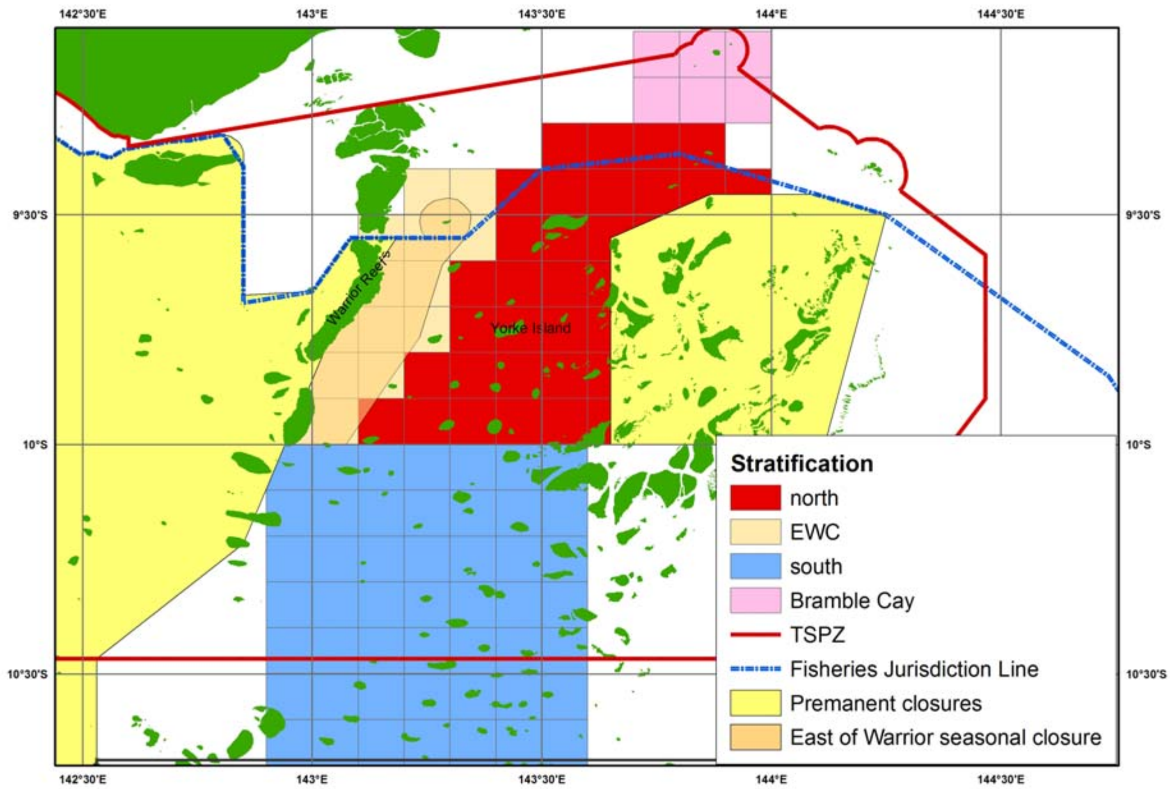

Figure 2.3.4 Four-way stratification of the fishery.

2.4 Papua New Guinea

Daily catch and effort records of Papua New Guinea (PNG) vessels operating in the Torres Strait Protected Zone were provided by the National Fisheries Agency (NFA) in Papua New Guinea. Initially NFA experienced problems with the spatial referencing of the data, which made it difficult to separate Gulf of Papua records from TSPZ records. Jane Bishop (CSIRO) who is involved in a collaborative project with Barre Kare (NFA) to analyse the Gulf of Papua trawl data, assisted with the extraction of the PNG Torres Strait trawl data. There were a small number of daily trawl records that contained banana and leader prawn catch. Based on advice from Barre Kare (NFA PNG) these records were filtered from the PNG TSPZ dataset. It was assumed that these records had been incorrectly spatially coded and were not from the Torres Strait prawn fishery. These species are however two of the main targets in the Gulf of Papua fishery and the PNG vessels that have fished in the TSPZ primarily fish the Gulf of Papua.

The only records of PNG vessels fishing in Torres Strait are from four vessels during August 1988 to April 1989 and five vessels during August 2001 to October 2003. The total recorded tiger prawn catch was about 36 tonnes and the total recorded fishing was 880 days. The annual tiger prawn catch, for the years that were fished, ranged from 0.4 tonnes (2001) to 11.8 tonne (1988). The catches taken by the three vessels that were recorded as fishing during August/September of 2003 were missing. The missing catch was estimated using the catch rates of the other vessels fishing those months and the recorded effort of the three vessels in question. The PNG tiger prawn catch was included in with the Australian tiger prawn catch in the updated stock assessment. Due to the relatively very low number of fishing records compared with Australian data the PNG daily catch rates were not included as indices in the stock assessment.

3 Trawl vessel gear and technology changes

3.1 Methods

Information on which devices and technologies were adopted by fishers, and when they were adopted, was obtained from a purposely-designed survey of past and present Torres Strait fishing vessel owner/operators. These vessel owner/operators were selected randomly from the entire trawl fleet of 97 vessels that had fished during 1989 and 2003.

Interviewees were asked to provide written records of vessel characteristics for the interview. Changes in the following characteristics and the date of each change were recorded for each vessel:

- Skippers (owner operated, relative of owner, or non-relative)
- Vessel length, engine power (HP), gear box ratio (reduction), average trawl speed (knots), fuel capacity (litres), fuel consumption per night (litres), propeller size and pitch (inches), and the presence or absence of a propeller nozzle.
- Navigation equipment: presence or absence of global positioning systems (GPS) and plotters, computer mapping software, sonar and colour sounder.
- The use, position, type and size of try-gear; try-gear is a small (1-3 fathom) net used for frequent 10-20 minute sampling of trawl grounds.
- The type and use of bycatch reduction devices (brd) and turtle exclusion devices (ted).
- Trawl net configurations –
    - Number of nets (double, triple, or quad nets).
    - Total net head rope length (fathoms) combined for all nets.
    - Net mesh size (mm).
    - Type of ground chain (fixed drop chain, drop chain with sliding rings, drop rope and chain combined, looped chain or other less common configurations) and chain size (mm).
    - Type of otter board types (Bison, Flat, Kilfoil, Louvre or other less common types) and size (total board area = board length x width).

3.1.1.1 Results

The questionnaire considered a number of different vessel characteristics thought to affect fishing power. The 66 interviews represented a response rate of 88% of the 75 operators who were contacted. Overall, the sample of vessels collectively accounted for about 60% of the sector's total prawn catch between 1989 and 2003. A breakdown of the number of owners or skippers who were operating and interviewed for each year is provided in Table 3.1.1; the breakdown is also provided as a percentage of total catch and fishing effort. It is also important to note the further back in time that the project sought information through the interviews the less information was available. The reason for this was because the early observations (those prior to 1980 for Torres Strait) were based on the recollections of a very small number of operators who were available for interview.

Since the early 1990's a high percentage of the fishing effort in all of the spatial strata, including the lightly fished Bramble Cay stratum, can be matched with the questionnaire data. Figure 3.1.1 shows both the percentage of fishing effort that can be linked with the vessel and gear survey data and the total number of fishing days recorded for each year in each stratum. Note that the recorded effort prior to 1989 is a subset (40-50%) of the estimated total fishing effort for the years 1982-1987. Although the Bramble Cay stratum had been lightly fished in comparison to the other strata the coverage in terms of the vessel and gear information was still high.

Table 3.1.1 Breakdown of the number of owners and skippers operating in each year that were interviewed as part of the questionnaire. The survey breakdown shows that 70% of the fishery was covered in the latter years.

Fishing Year	Number of Vessels	Percent of Prawn Harvest	Percent of Fishing Effort
1974	1		
1975	1		
1976	1		
1977	1		
1978	1		
1979	2		
1980	5		
1981	9		
1982	9	8	7
1983	15	11	8
1984	18	15	15
1985	21	19	21
1986	21	14	13
1987	25	14	16
1988	34	3	3
1989	39	25	24
1990	46	32	31
1991	51	36	35
1992	52	39	39
1993	56	38	38
1994	62	46	46
1995	69	54	55
1996	82	67	68
1997	86	71	72
1998	91	75	75
1999	94	79	78
2000	89	64	63
2001	44	65	67
2002	48	65	66
2003	49	68	69

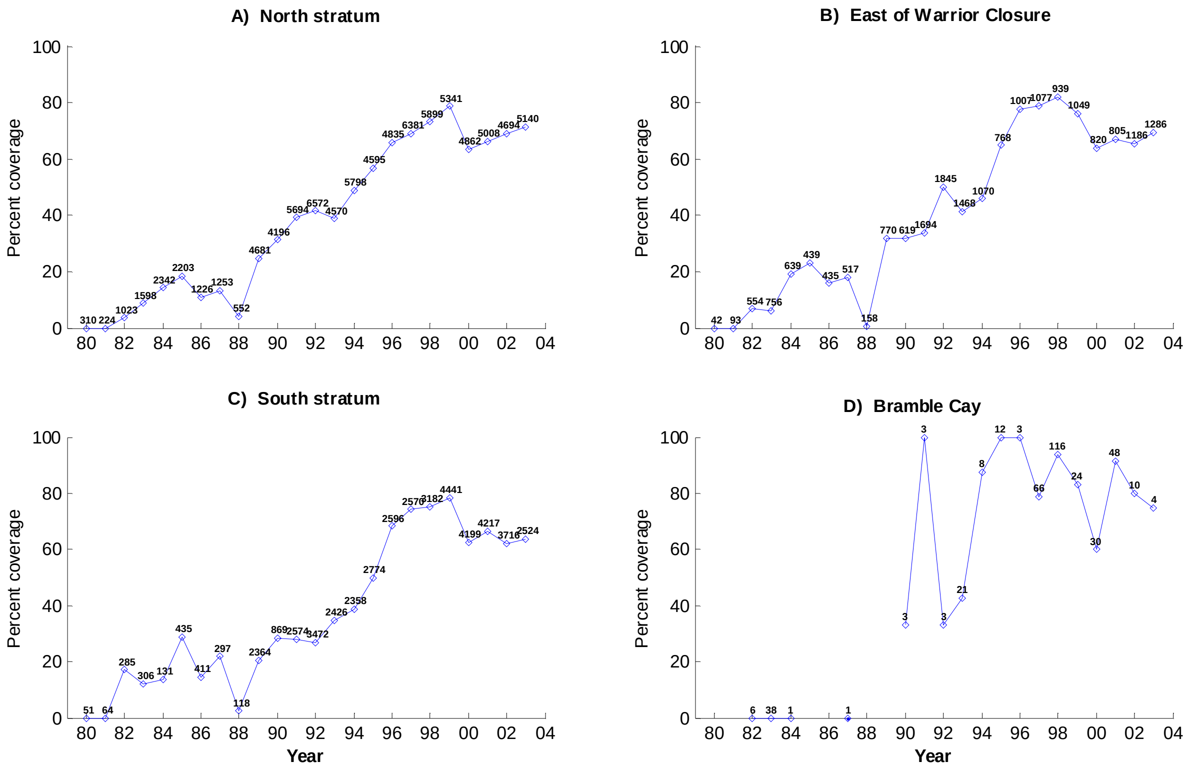

Figure 3.1.1 Percent coverage of the logbook fishing effort in each strata by the vessels that were recorded in the questionaires. The numbers indicate the total logbook days of all vessels recorded each year in each strata.

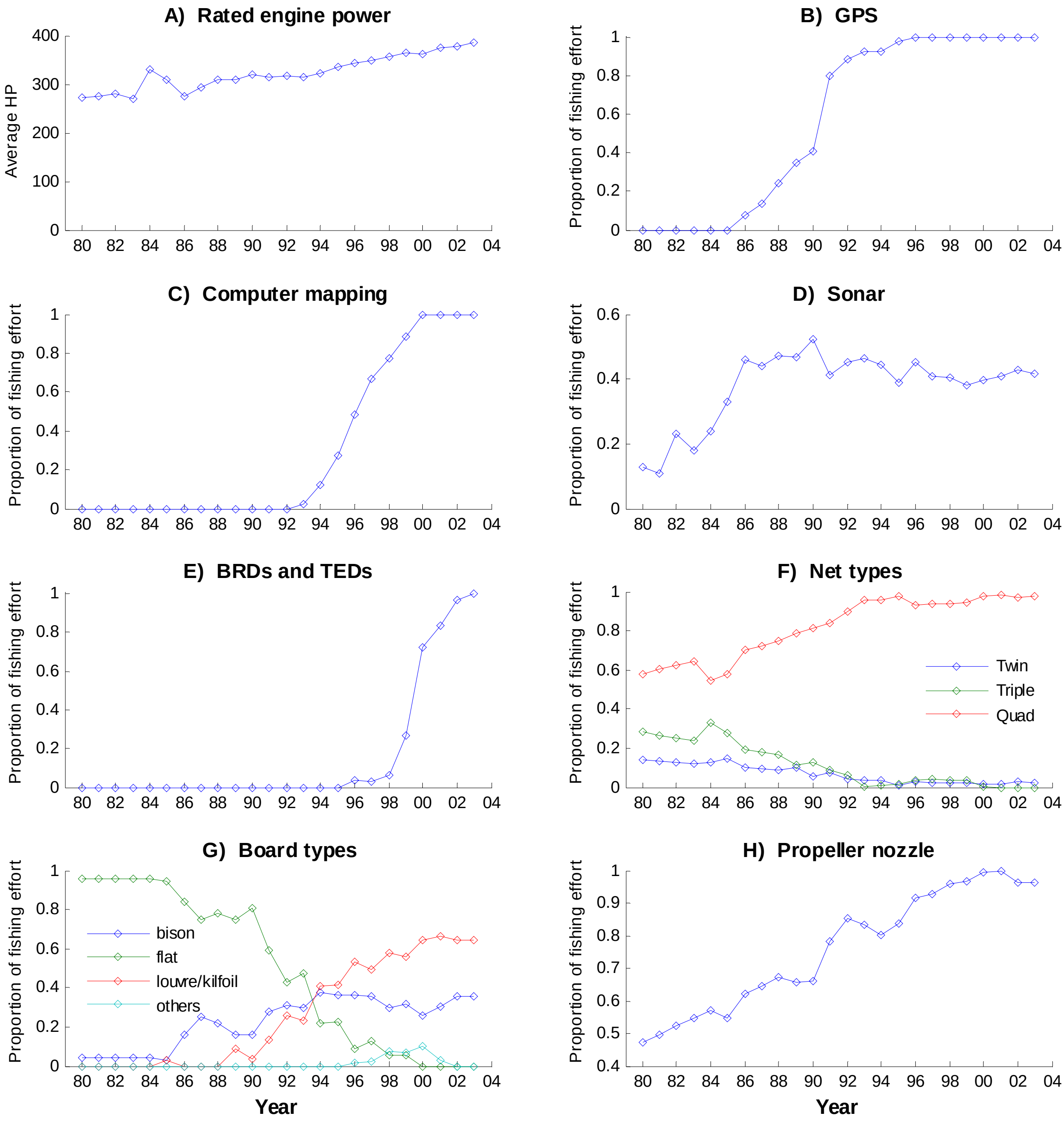

Figure 3.1.2 Average vessel and gear configurations that were used to estimate fishing power. Subplot A): The averages for rated engine power engine were weighted according to the number of days fished by each vessel in each fishing year. The other plots represent the percent of fishing effort (boat days) in each fishing year with that particular device.

The vessel and gear characteristics that were found to have a significant effect on fishing power while not being strongly correlated with each other were; engine horsepower, adoption of GPS, adoption of computer mapping software, use of sonar, use of a BRD and/or TED, the net configuration, the type of boards used and whether a propeller nozzle was fitted. Figure 3.1.2 shows the trends for each of these factors using an average weighted by the fishing effort. The average engine horsepower has steadily increased over the years from 275 to 384 hp whereas adoption of GPS by the fleet occurred fairly rapidly during the years 1986 to 1996. Similarly use of computer based navigation software occurred rapidly during 1991 to 1999. Use of sonar appears to have increased from a low level during the early 1980's then stabilised at 40-50 percent usage. The use of a BRD's and/or a TED's, which have a negative impact on fishing power, has increased rapidly from only a few percent in 1998 to 100 percent in 2003. This rapid uptake was partly driven by management changes that made it compulsory to use a TED by the beginning of the 2002 fishing season and a BRD at the start of 2004 fishing season. Net type had gradually changed over time with the use of quad gear increasing from around 60 percent to about 98 percent, while the use of twin gear and triple gear had decreased from about 14 and 28 percent respectively to only a few percent. The type of otter boards had also changed dramatically. The use of flat timber boards declined from nearly 100 percent in the early 1980's to zero usage by the late 1990's. The flat boards have been replaced with bison boards and louver/kilfoil boards that now account for 40 percent and 60 percent respectively of the fishing effort in recent years. Use of a propeller nozzle had steadily increased from about 50 percent to nearly 100 percent in recent years. Figure 3.1.3 shows additional trends for the vessels on average to higher gearbox ratios, higher fuel use per night, larger fuel capacity, and marginally faster trawl speeds. There was no significant change in the fleet's average hull units, vessel length, propeller pitch and diameters, net size, mesh size and chain size.

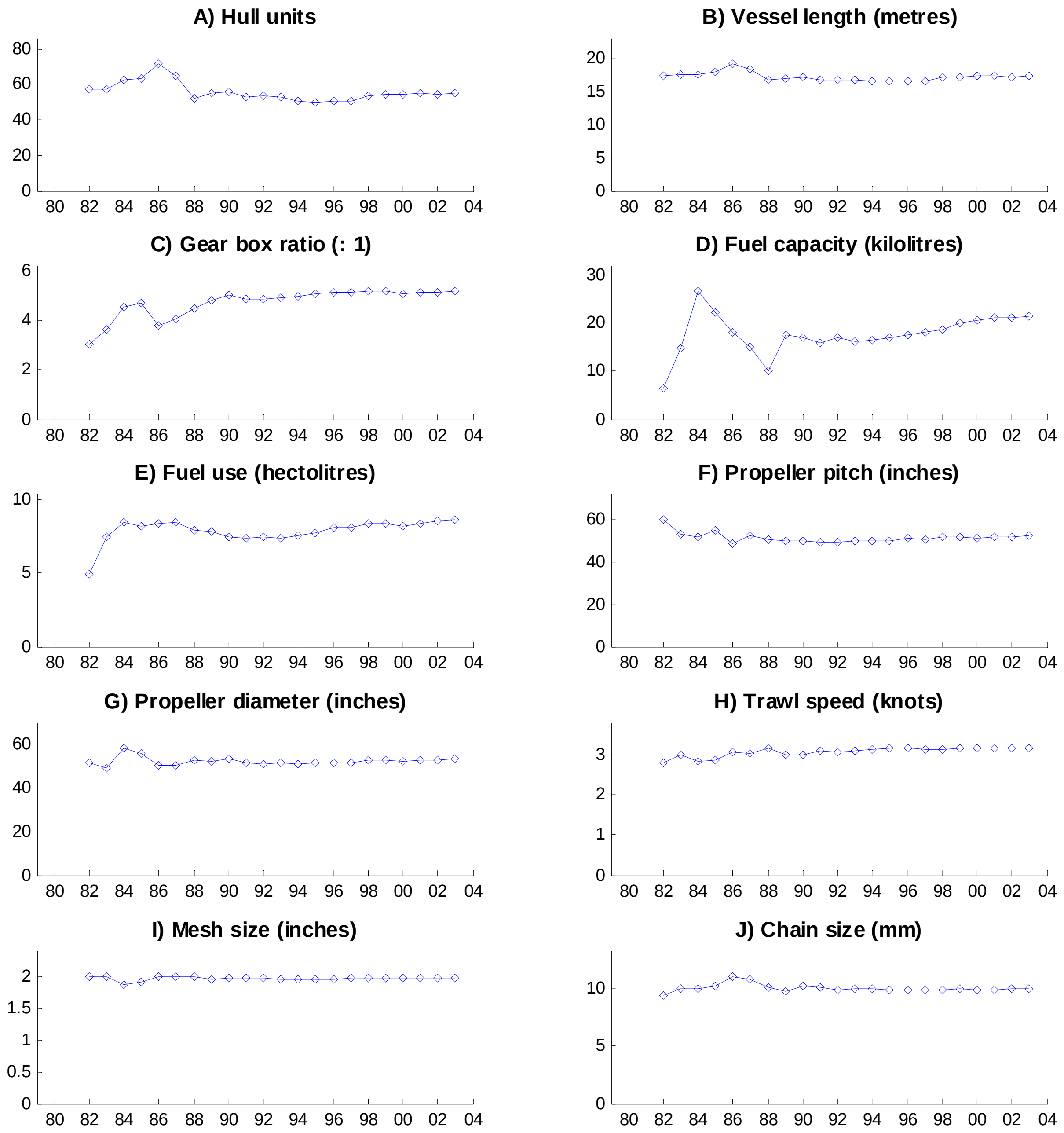

Figure 3.1.3 Average vessel and gear specifications for additional variables quantified in the survey. The averages were weighted according to the number of days fished by each vessel in each fishing year.

4 Fishing power and catch rates

4.1 Methods

Catch Data

The analyses were based on Torres Strait logbook prawn catch and effort data from 1980 to 2003. The data consisted of the daily prawn catch (tiger, endeavour and king separated) by each individual vessel. The spatial resolution of catches recorded from the Torres Strait was on 6 x 6 minute grids. No data exclusion rules were applied; the data exclusion rules of less than 20 kilograms of tiger prawns and vessels fishing less than five days in any month were not imposed as per O'Neill *et al.* (2005). The application or non-application of the data exclusion rules has no impact on the analyses (O'Neill *et al.* 2003; O'Neill *et al.* 2005).

All Torres Strait prawn catches from 1980 to 2003 were downloaded from the AFMA vessel operation and species catch tables. These data were then loaded into Microsoft Access and range checks performed to identify and correct outlying catch errors. A cross tab query was then used to combine the operation and catch data in a single table of daily vessel catches of each prawn species. In the AFMA database, tiger prawn catches were defined by the species code 27701900, endeavour prawns by 27701903, and king prawns by 27701928. There was a very small amount of tiger prawn catch recorded under the general prawn code, 27701000. This code however, represented less than 0.4% of all prawn catches taken in the Torres Strait and was not used. The small number of daily records with zero catches for tiger prawns (< 0.5% of records) and records with position locations outside of the designated area for the Torres Strait fishery (<0.06% of records) were excluded from the data. For tiger, endeavour and king prawns, a calendar year was viewed as suitable for a fishing-year.

Statistical analysis

The analysis used a general linear model (GLM) assuming normally distributed errors on the log scale. The response variable was based on individual vessel daily catches by species for a spatial area. In this report we comment on changes in fishing power affecting the catch. However, because fishing effort is implied in our analysis as an explanatory variable (daily = 1), the findings are pertinent to both catch and catch rates.

Since catches of adult eastern king prawns are known to vary markedly with lunar phase (Courtney *et al.* 1996), it was suspected that catches of prawns in the Torres Strait might also vary with lunar phase. Lunar phase was therefore considered in the analysis. Variation in catch rates was tested against a calculated luminance measure (ranging between 0 = New Moon and 1 = Full moon; Courtney *et al.* 2002). This luminance measure followed a sinusoidal pattern, and was replicated and advanced by 7 days (~ ¼ lunar period) in order to approximate the cosine of the luminance (Figure 4.1.1). Together these patterns were periodic and model a cyclic variation in catch rates corresponding to new moon, waxing moon, full moon and waning moon phases. The approach used only two degrees of freedom in the analysis compared to the four level factor used for lunar quarters as defined by O'Neill *et al.* (2005) and Courtney *et al.* (2002).

As recommended by David Die the stratification of the catch data for the Torres Strait was increased from two strata to five. The original split by latitude north and south of 10°S was proposed at the 2001 Torres Strait Fishery Assessment Group (TSFAG) Workshop in 2001 and used by O'Neill *et al.* (2005) and Die (2003). This split was on the basis of species composition of the catch, the average catch rates of tiger prawns and fishing effort; catches in the southern area have a higher proportion of endeavour prawns and a lower tiger prawn catch rate. A new stratum within the “north” was defined to cover the area of the East of Warrior closure that was first implemented in 1991 (Figure 2.3.4). There is a small amount of fishing that occurs in the Australian waters around Bramble Cay. As this area is isolated from the main part of the fishery

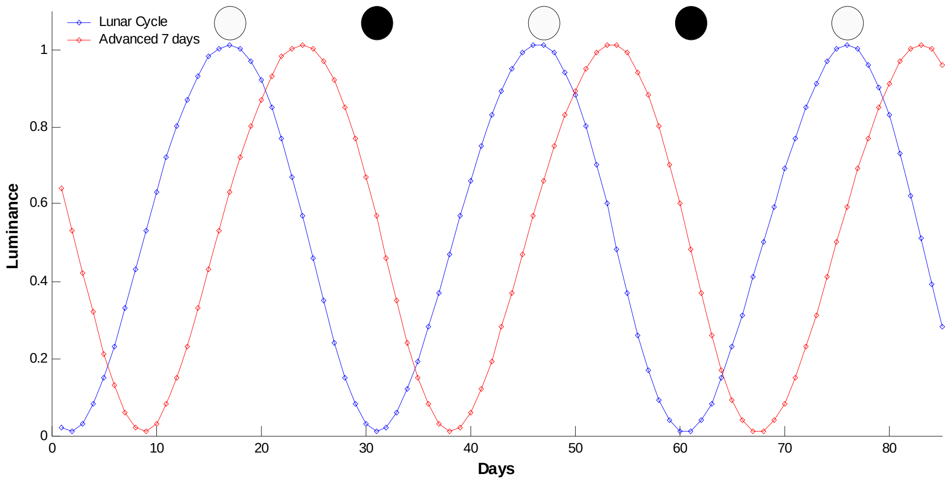

Figure 4.1.1 The lunar phase cycle (blue line) illustrated over 85 days. The red line illustrates the lunar cycle advanced by seven days. Together these lines were used to model prawn catches allowing for new moon, waxing moon, full moon and waning moon effects.

by PNG waters and would be more indicative of tiger prawn stocks in PNG waters this area was defined as a separate stratum. Prior to the implementation of the Torres Strait Treaty in 1985, Australian trawlers could legally fish north of the current fisheries jurisdiction line. Consequently there are a small number of records for grids that are now completely inside PNG waters. These records were grouped into a fifth (PNG) stratum. Given the lack of contrast to clearly separate the southern strata in two by choosing grids that are in the areas where the highest king prawn catches exist (Die 2003), we instead examined the significance of the king and endeavour prawns on tiger prawn catches as covariates in the analysis. In total these five area strata, plus the use of king and endeavour prawn catches as covariates, addressed Dr Die's 10th recommendation to include more spatial resolution in the analysis (Table 1.1.1; page 7). All catches south of 10.7 degrees of latitude were treated as part of the Queensland East Coast Trawl fishery.

The final tiger model considered fishing year, calendar month, five different spatial areas, lunar phase cycles, king and endeavour prawn catches, and the vessel's gear characteristics as explanatory variables. Catches were predicted according to the catch-biomass relationship defined by Hilborn and Walters (1992)

$$C_{vayml} = B_{ayml} E_{vayml} q_{vayml} \quad (1)$$

where C_{vayml} was the daily catch of the vth vessel in area a, during fishing year y, month m and lunar cycle l. B_{ayml} was the biomass or abundance term for prawns, E_{vayml} was the type of day fished (either a full night, part-night or daytime fishing) ≈ 1, and q_{vayml} was the measure of prawn catchability. The logarithm of the relationship (Equation 1) reduced to an additive form (Equation 2), rather than the original multiplicative form, and was defined in a GLM as

$$\log(C_{vayml}) = \beta_0 + \boldsymbol{\beta}_1 + \boldsymbol{\beta}_2 + \boldsymbol{\beta}_3 + \varepsilon \qquad (2)$$

where β_0 was a scaler intercept parameter to be estimated, $\boldsymbol{\beta}_1$, $\boldsymbol{\beta}_2$, and $\boldsymbol{\beta}_3$ were vector parameters to be estimated, and ε was the error term (NID(0,σ^2)). The term $\boldsymbol{\beta}_1$, which related to changes in $\log(B_{ayml})$, was expressed by the interaction effects of fishing areas, fishing years, months, and the additive effect of lunar cycle. The catchability of prawns, $\boldsymbol{\beta}_2 \approx \log(q_{vayml})$, was represented by a vector of capture system variables including different vessel characteristics, navigation equipment, bycatch reduction devices and trawl net configurations. This component of the model was the exclusive focus of interpretation to calculate fishing power changes. The result from the abundance vector ($\boldsymbol{\beta}_1$), specifically the interaction between year and month terms, was used to calculate standardised catch rates. The vector $\boldsymbol{\beta}_3$ was an adjustment factor for a full night, part night or daytime fishing, so that a fishing day was standard measure E =1.

The statistical software package was used to carry out the analysis and provide asymptotic standard errors for all estimates. Stepwise regression was used to select optimal model parameters ($p<0.05$). Model selection was compared using Akaike's Information Criteria (AIC) and deviance statistics. Any influential parameter correlations were assessed and removed if necessary. The analysis of residuals from each GLM fit supported the use of the normal residual distribution on the log scale. A Gamma model with log link was also fitted and produced similar coefficients and predictions to the log linear model described above.

In addition we also analysed catches of endeavour prawns and the economic catch (labelled as species combined) defined as tiger prawns + king prawns + ½ endeavour prawns as per Bishop *et al.* (2004). Similar models and fitting procedures were used as for tiger prawns.

Estimating relative fishing power

All statistically significant parameter estimates ($\boldsymbol{\beta}_2$) from the GLM were used to calculate yearly changes in the average relative fishing power (Table 4.2.1). The catchability coefficients ($\boldsymbol{\beta}_2$) were multiplied by their corresponding average logarithm value or their proportion use in total fishing effort in each fishing year. These predictions were scaled to express relative fishing power in each year as a proportional change relative to the base reference fishing year considered, which was 1989 for Torres Strait. The logarithm averages and proportions were calculated from the GLM data, so as to reflect the make up of fishing effort in each fishing year. Both of the combined continuous and categorical covariates across the different fishing years y expressed relative fishing power as a percentage of the fishing year 1989:

$$f_y = \exp\left(\mathbf{X}_y \boldsymbol{\beta}_2^{\mathbf{T}}\right),$$

where $\mathbf{X}_y$ was the matrix of average logarithm values for continuous covariates and proportions for categorical covariates in each fishing year y, $\boldsymbol{\beta}_2^{\mathbf{T}}$ was the transpose of the vector of catchability coefficients and exp is the exponential function. The yearly predictions were scaled by f_y / f_{1989}.

4.2 Analysis of prawn catches

Table 4.2.1 contains the regression parameter estimates for the various gears and technologies for tiger prawns, endeavour prawns, and species combined (tiger prawns + king prawns + ½ endeavour prawns). Note that two analyses were run for tiger prawns according to Dr Die's 12th recommendation (Table 1.1.1, page 7). The first analysis used only tiger prawn logbook data matched with vessel information. The second analysis again used only tiger prawn logbook data matched with vessel information, but only those vessels that recorded catches before and after 1989. A number of significant effects on catch could be measured in each analysis. Vessels with 50 HP more rated engine power were associated with between 2% and 5% larger catches. Vessels with sonar were associated with having between 7% and 14% larger catches. The effect of global positioning systems (GPS) differed between analyses. For tiger prawns, vessels with GPS were associated with between 9% and 28% larger catches. In contrast, vessels with GPS were associated with 13% lower endeavour prawn catches. GPS was not significant in the species combined analysis. Vessels with computer mapping software, such as C-plot, were associated with between 6% and 11% larger tiger prawn catches. However, computer-mapping software was not significantly associated with endeavour prawns. Vessels with a turtle excluder device (TED) and/or bycatch reduction device (BRD) were associated with having between 4% and 12% lower catches. Vessels with a propeller nozzle were associated with between 7% and 11% larger tiger prawn catches. However, a vessel with a propeller nozzle was not associated with higher tiger prawn catches in the second analysis which had less than half as much data. Most of these Torres Strait parameter estimates were similar to those estimated by Robins et al. (1998), GPS (4%), GPS and plotter (7%), by Bishop *et al.* (2000), GPS (5%) and propeller nozzle (7%) and by Bishop *et al.* (2004), GPS (7%) and NAV3 plot software (23%); they are also consistent with previous Torres Strait tiger prawn analyses O'Neill *et al.* (2003) and O'Neill *et al.* (2005). The descriptions above are relative and specific to each gear and technology. However, it should be noted that every vessel has multiple gears and technologies, and that the estimated individual effects are not simply additive. Overall vessel fishing-power is a multivariate function with a complex combination of gears and technologies.

Table 4.2.1 Summary of analysis, parameter estimates β_2 and standard errors in parenthesis from the general linear model (natural log transformed), for tiger prawns, endeavour prawns and species combined (tiger prawns + king prawns + ½ endeavour prawns). n.s. indicates the parameter was not significant and excluded from the analysis (p>0.05).

Summary of Analysis	Tiger Prawn	Tiger Prawn	Endeavour Prawn	Species Combined
Data	All vessels with gear data	Only vessels with gear data prior to 1989	All vessels with gear data	All vessels with gear data
Sums of Squares β_1	16140.4	6247.7	12797.4311	10287.7
Sums of Squares β_2	889.3	475.6	1432.2174	943.8
Residual SS	18789.3	6438.0	22815.2029	8361.4
Degrees of Freedom	316, 76792	306, 30435	305, 76837	313, 77078
R^2	47.5	51.1	38.4	57.3
Parameter Estimates β_2 (Log)				
Rated engine power (HP)	0.318 (0.011)	0.191 (0.023)	0.662 (0.012)	0.465 (0.007)
GPS	0.09 (0.01)	0.248 (0.015)	-0.144 (0.012)	n.s.
Computer mapping	0.101 (0.006)	0.056 (0.012)	n.s.	0.057 (0.004)
Sonar	0.128 (0.004)	0.127 (0.006)	0.068 (0.004)	0.098 (0.003)
BRD and/or TED (present)	-0.106 (0.008)	-0.133 (0.015)	-0.043 (0.008)	-0.073 (0.005)
Net - Twin	0	0	0	0
Net - Triple	0.011 (0.016)	0.368 (0.021)	0.219 (0.017)	0.049 (0.01)
Net - Quad	0.085 (0.011)	0.149 (0.013)	0.212 (0.012)	0.106 (0.007)
Boards - bison	0	0	0	0
Boards - flat	0.038 (0.007)	-0.121 (0.01)	-0.041 (0.007)	0.019 (0.004)
Boards - louvre/kilfoil	-0.009 (0.005)	-0.183 (0.007)	-0.117 (0.005)	-0.037 (0.003)
Boards - other less used types	-0.09 (0.012)	-0.176 (0.015)	0.041 (0.013)	0.04 (0.008)
Propeller nozzle	0.072 (0.007)	n.s.	0.104 (0.008)	0.094 (0.005)

For all analyses there was no evidence of highly correlated gear and technology (β_2) parameters (Table 4.2.2). The correlations were all small and similar between analyses. The only notable parameter correlation (ρ = 0.724) was between triple and quad net gear. The effect of removing this parameter correlation from the tiger prawn analysis was little in the sense that the inferences on remaining parameters were unchanged. In addition, removing this correlation resulted in little change from the overall average fishing power estimates (section 4.3). Because of the small influence of this correlation and the importance to account for the use of twin gear, we left the net factor in the analysis. In addition to the small parameter correlations, Figure 3.1.2 show that there was a good contrast of vessels with and without different gears and technologies through time. Having this contrast provided confidence that we have measured the effects of the different gears and technologies with reasonable precision. Parameter correlations were also examined between the annual tiger prawn index of abundance (fishing year term in the generalised linear model), and the gear and technology (β_2) parameters. Only the parameters for computer mapping software, and turtle excluder device (TED) and/or bycatch reduction device (BRD) showed weak correlation with the fishing year parameters (generally less than 0.3).

Table 4.2.3 shows the possible vessel and trawl net covariates for analysis. All of these variables are important for higher fishing power. However, given some of the positive correlations, it was not possible to accurately measure their individual effects when they were combined in the analysis. Engine rate power (HP) was used as a surrogate of overall vessel capacity as it was correlated with vessel length, hull units, fuel capacity and use; it also explained significant variation in catch (Table 4.2.1). Engine rate power (HP) was also marginally correlated with net size and chain size. Fuel capacity was correlated with gearbox ratio, propeller size and pitch. Given the consistent use (i.e. lack of contrast) of vessels using the same net and chain sizes through time, their effects could not be measured with any precision. In addition, given their consistent use, they contribute very little to overall fishing power change in the Torres Strait.

Table 4.2.2 The tiger prawn general linear model β_2 parameter correlations between the different vessel characteristics. Only one significant correlation was present between quad and triple net gear.

Parameters Estimates β_2	Engine HP	GPS	Comp. Map.	Sonar	BRD - TED	Net - Triple	Net - Quad	Boards - flat	Boards – lou./kil.	Boards - other	Propeller nozzle
Rated engine power (HP)	1										
GPS	-0.192	1									
Computer mapping	-0.222	0.032	1								
Sonar	-0.053	-0.085	0.067	1							
BRD and/or TED (present)	0.046	-0.015	0.036	0.05	1						
Net - Triple	0.062	0.098	0.013	0.004	0.002	1					
Net - Quad	0.041	0.043	-0.008	0.008	-0.02	0.724	1				
Boards - flat	0.029	-0.127	-0.062	0.056	0.003	-0.252	-0.225	1			
Boards - louvre/kilfoil	0.105	-0.056	-0.046	0.1	-0.05	-0.197	-0.213	0.386	1		
Boards - other less used types	0.05	-0.029	-0.079	0.137	0.019	-0.055	-0.074	0.138	0.278	1	
Propeller nozzle	0.107	-0.01	-0.013	-0.2	-0.026	0.148	0.075	0.082	0.036	-0.025	1

Table 4.2.3 Linear correlations between some of the different capture system covariates including different vessel characteristics and trawl net configurations.

Vessel and Gear Variables	Hull units	Vessel length	Engine HP	Gear box ratio	Fuel capacity	Fuel use	Propeller pitch	Propeller Size	Trawl speed	Net Size	Mesh Size	Chain Size
Vessel hull units	1											
Vessel length	0.866	1										
Engine HP	0.491	0.556	1									
Gear box ratio	0.395	0.33	0.283	1								
Fuel capacity	0.713	0.655	0.454	0.467	1							
Fuel use	0.52	0.654	0.724	0.149	0.51	1						
Propeller pitch	0.466	0.442	0.254	0.539	0.401	0.303	1					
Propeller Size	0.685	0.609	0.406	0.667	0.637	0.493	0.612	1				
Trawl speed	-0.038	-0.072	0.076	-0.136	-0.12	0.095	0.129	-0.015	1			
Net Size	0.432	0.302	0.436	0.431	0.318	0.247	0.289	0.457	0.12	1		
Mesh Size	0.11	0.21	0.149	-0.099	0.038	-0.05	-0.088	-0.068	-0.232	-0.067	1	
Chain Size	0.304	0.383	0.387	-0.03	0.095	0.545	0.108	0.198	0.054	0.209	-0.264	1

For the statistical analyses of tiger prawns, endeavour prawns, and species combined (tiger prawns + king prawns + ½ endeavour prawns) there was no evidence to suggest the models were inadequate or that the use of lognormal errors were inappropriate. The plots of standardised residuals in Figure 4.2.3 shows that the use of normal errors on the log scale was appropriate (subplot A) with no pattern in standardised residuals (subplot B). The linear normality plots (subplot C) show that there were a number of outliers with standardised residuals in excess of minus four. These standardised residuals were few in comparison to the number of catches analysed (see Table 4.2.1 for degrees of freedom). The influence of such data points had little effect upon the estimation of the parameters. For example, removing their effect resulted in little change in the parameters, suggesting the number of outliers were not influential because of the size of the data set. The distribution of observed catches on the log scale was relatively normal (subplot D).

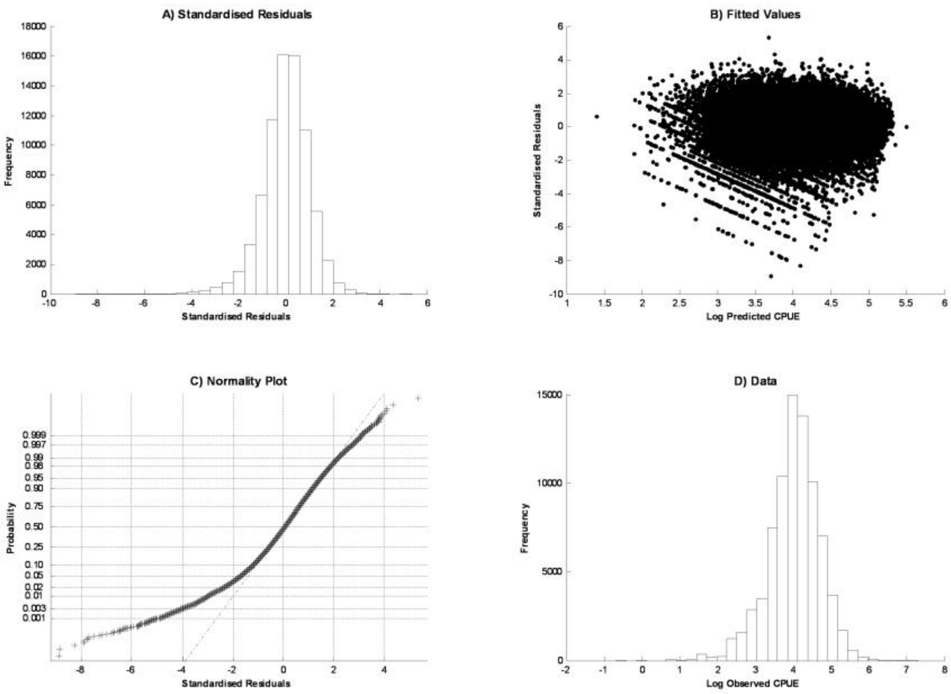

Figure 4.2.1 Standardised residuals for tiger prawns using all data matched with gear information. The use of normal errors on the log scale was appropriate with no pattern in standardised residuals.

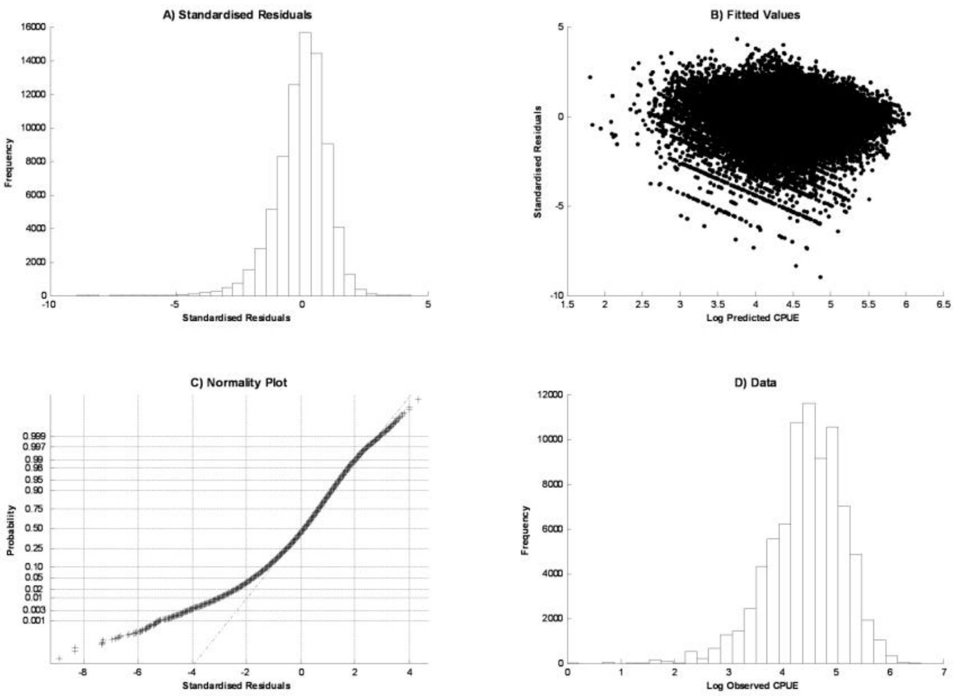

Figure 4.2.2 Standardised residuals for endeavour prawns using all data matched with gear information. The use of normal errors on the log scale was appropriate with no pattern in standardised residuals.

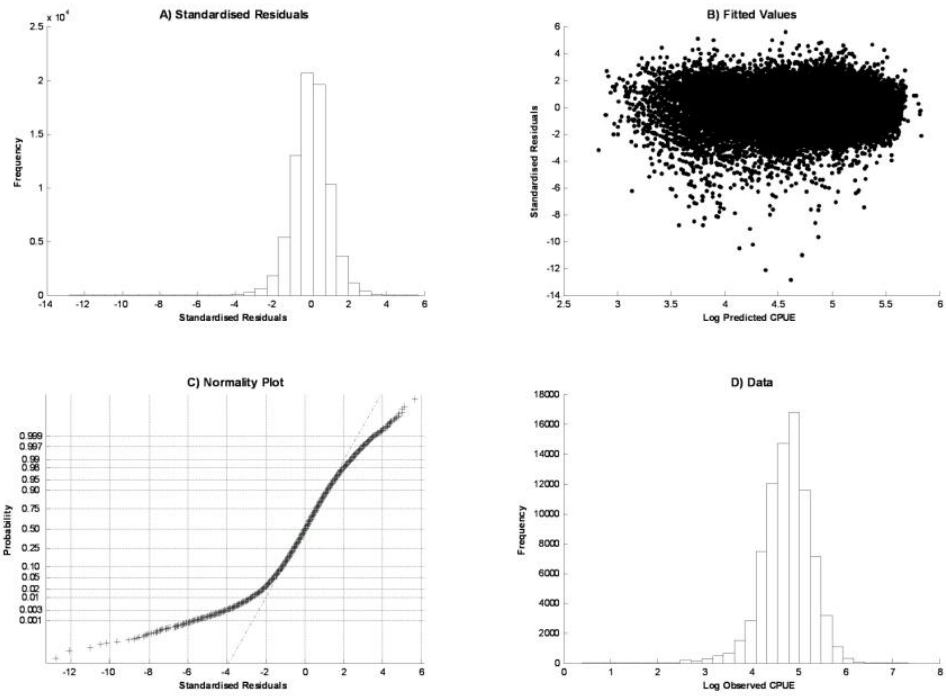

Figure 4.2.3 Standardised residuals for the species combined analysis using all data matched with gear information. The use of normal errors on the log scale was appropriate with no pattern in standardised residuals.

4.3 Estimates of fishing power

Estimated annual increases in average relative fishing power are presented in Figure 4.3.1 and Table 4.3.1. For the 24-fishing years from 1980 to 2003, tiger prawn fishing power increased by 25% assuming no negative net effect in 2002 and 2003. The percentage was 21% assuming a 4% negative effect as suggest by Dr David Die. Fishing power increased sharply between 1990 and 1998 (the peak in fishing power). This increase was driven by the adoption of global positioning systems (GPS), computer-mapping softwares such as C-plot, propeller nozzles, quad nets and increased engine rated power. Estimated fishing power increases were marginally lower for the species combined analysis (tiger prawns + king prawns + ½ endeavour prawns). This result shows that fishing power change for endeavour prawns was less compared to tiger prawns. Both the updated tiger prawn and species combined results were similar to the previous 2002 tiger prawn result (O'Neill et al. 2005). Figure 4.3.2 illustrates a comparison between observed fishing effort and effort when standardised to 1989 fishing power. The figure shows that a fleet with 1989 fishing power would have fished fewer days for the same catch prior to 1989, but would have needed to fish more days after 1989 for the same catch.

Table 4.3.1 Proportion change in average annual fishing power from 1980 to 2003 (95% confidence intervals shown in parentheses), for the Torres Strait trawl sector (using 1982 to 2003 GLM analysis). Note the proportion change represents the difference from the base reference year 1989, which was set at 1. The linear increase is the regression slope of the fishing power change from 1980 to 2003 (expressed as a %). These estimates are plotted in Figure 4.3.1

Fishing Year	Tiger Prawn	Tiger Prawn 4% Net Effect	Species Combined
1980	0.872 (0.859 : 0.883)	0.872 (0.859 : 0.883)	0.877 (0.871 : 0.883)
1981	0.877 (0.864 : 0.888)	0.877 (0.864 : 0.888)	0.885 (0.879 : 0.89)
1982	0.897 (0.885 : 0.908)	0.897 (0.885 : 0.908)	0.905 (0.9 : 0.91)
1983	0.884 (0.872 : 0.894)	0.884 (0.872 : 0.894)	0.889 (0.883 : 0.894)
1984	0.944 (0.929 : 0.958)	0.944 (0.929 : 0.958)	0.974 (0.969 : 0.98)
1985	0.935 (0.921 : 0.948)	0.935 (0.921 : 0.948)	0.954 (0.95 : 0.959)
1986	0.932 (0.922 : 0.941)	0.932 (0.922 : 0.941)	0.934 (0.93 : 0.938)
1987	0.955 (0.948 : 0.962)	0.955 (0.948 : 0.962)	0.967 (0.964 : 0.97)
1988	0.989 (0.985 : 0.992)	0.989 (0.985 : 0.992)	0.998 (0.995 : 0.999)
1989	1	1	1
1990	1.029 (1.026 : 1.032)	1.029 (1.026 : 1.032)	1.024 (1.023 : 1.025)
1991	1.046 (1.031 : 1.063)	1.046 (1.031 : 1.063)	1.017 (1.015 : 1.021)
1992	1.064 (1.044 : 1.089)	1.064 (1.044 : 1.089)	1.032 (1.028 : 1.038)
1993	1.075 (1.054 : 1.101)	1.075 (1.054 : 1.101)	1.038 (1.033 : 1.043)
1994	1.076 (1.051 : 1.107)	1.076 (1.051 : 1.107)	1.042 (1.036 : 1.049)
1995	1.11 (1.08 : 1.143)	1.11 (1.08 : 1.143)	1.071 (1.063 : 1.078)
1996	1.142 (1.106 : 1.178)	1.142 (1.106 : 1.178)	1.098 (1.086 : 1.108)
1997	1.166 (1.126 : 1.202)	1.166 (1.126 : 1.202)	1.118 (1.103 : 1.13)
1998	1.178 (1.134 : 1.216)	1.178 (1.134 : 1.216)	1.136 (1.119 : 1.15)
1999	1.172 (1.124 : 1.215)	1.172 (1.124 : 1.215)	1.137 (1.119 : 1.153)
2000	1.126 (1.07 : 1.179)	1.126 (1.07 : 1.179)	1.106 (1.082 : 1.128)
2001	1.136 (1.079 : 1.192)	1.136 (1.079 : 1.192)	1.116 (1.091 : 1.141)
2002	1.126 (1.069 : 1.185)	1.086 (1.029 : 1.145)	1.108 (1.082 : 1.135)
2003	1.126 (1.069 : 1.186)	1.086 (1.029 : 1.146)	1.112 (1.086 : 1.139)
Linear increase %	1.39 (1.15 : 1.63)	1.31 (1.07 : 1.55)	1.07 (0.98 : 1.17)

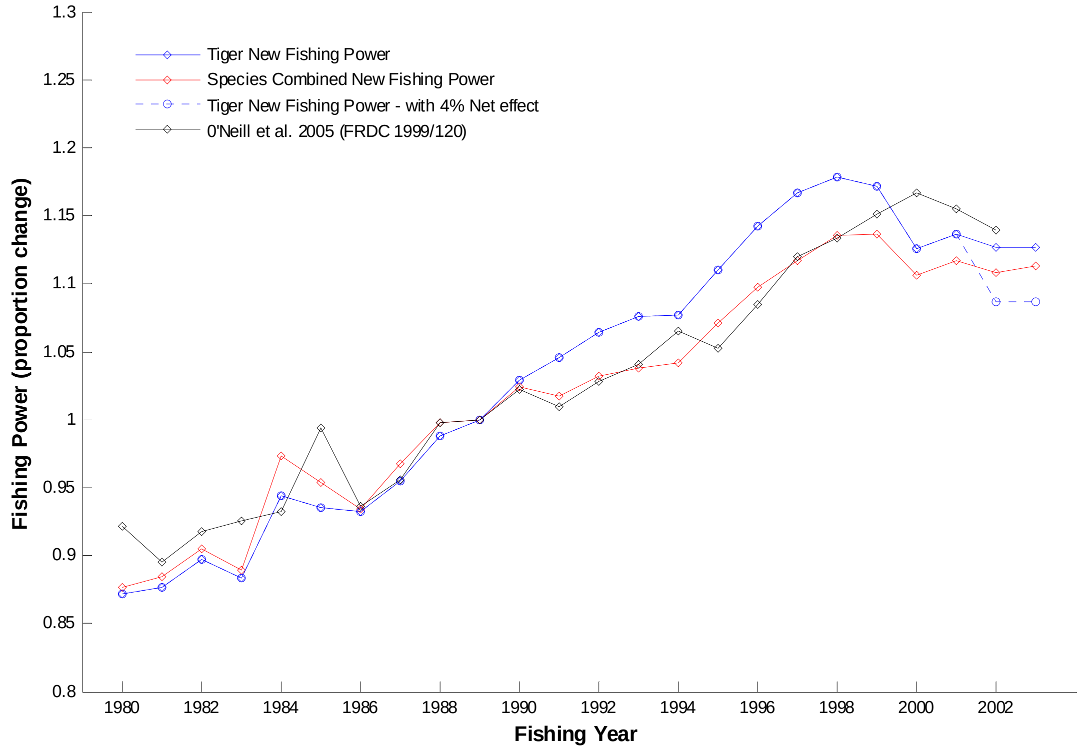

Figure 4.3.1 Comparison of updated annual fishing power increases for tiger prawns, species combined (tiger prawns + king prawns + ½ endeavour prawns) and from the previous tiger prawn analysis (O'Neill *et al.* 2005). Note the proportion change represents the difference from the base reference year 1989, which was set at 1.

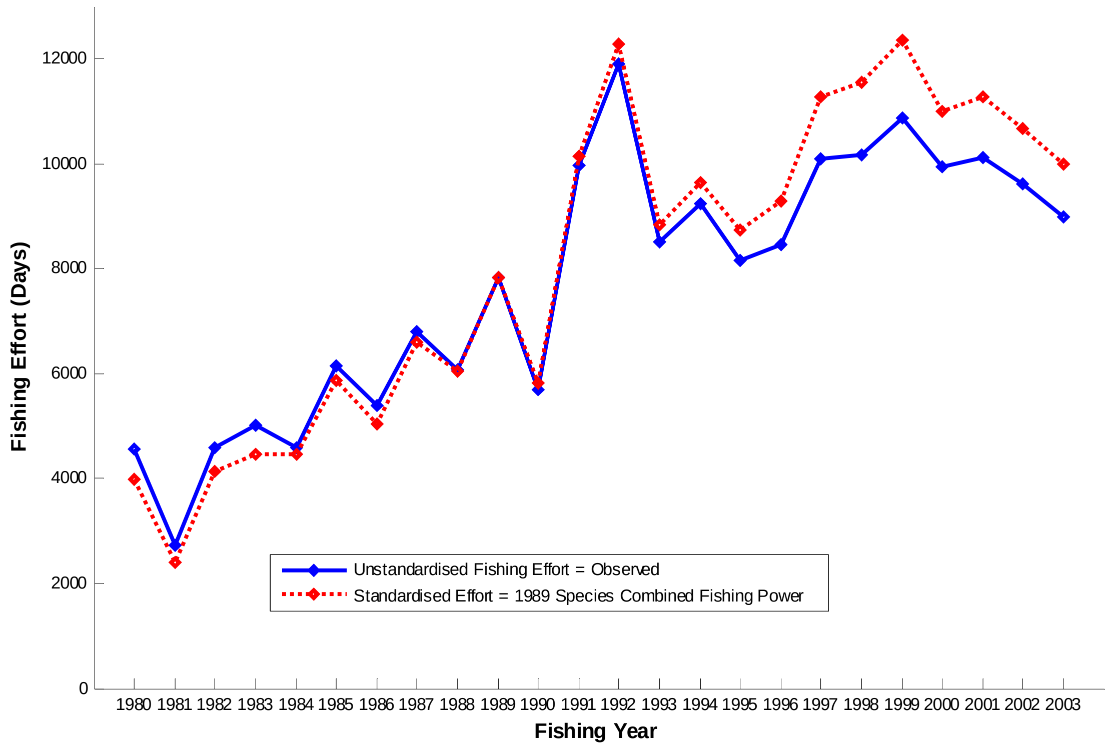

Figure 4.3.2 Illustration of the effect of standardising fishing effort. The blue line is the observed days of fishing and the red dotted line is the days of fishing standardised to a vessel with 1989 average fishing power.

4.4 Standardised catch rates

The section presents monthly-standardised-catch-rates for tiger and endeavour prawns. The simplified term catch-rates is used from here on to refer to monthly-standardised-catch-rates. Three time series of tiger prawn catch rates were calculated (Figure 4.4.1) and compared according to Dr David Die's recommendations 9, 11 and 12 (Table 1.1.1, page 7). These were:

1. Predict catch rates from the GLM analysis column 2, Table 4.2.1, page 28. This refers to the first analysis described using only tiger prawn logbook data matched with vessel information.
2. Predict catch rates from the GLM analysis column 3, Table 4.2.1, page 28. This refers to the second analysis described again using only tiger prawn logbook data matched with vessel information, but only those vessels that recorded catches before and after 1989.
3. Predict catch rates from a GLM using all logbook data offset for annual increases in fishing power (includes the 4% net effect; from column 3, Table 4.3.1, page 32). This approach utilises all data even were there was missing vessel information. It is the same approach as from O'Neill *et al.* (2005). The model specification was without the capture system variables $\boldsymbol{\beta}_2$ and their effect was replaced by using annual increases in fishing power as an offset.

The predicted catch rates from the 1st and 3rd analyses were very similar, especially for the compulsory logbook reporting from 1989 to 2003. They only diverge marginally prior to 1989, when the data thinned in the 1st analysis. The predicted catch rates from the 2nd analysis tended to be higher compared to the 1st and 3rd analyses. Figure 4.4.2 compares predicted catch rates from the three analyses against the unstandardised catch rates (ignoring fishing power change). The standardised catch rates were predicted for constant 2003 fishing power through time, with the 4% negative net effect and for a full nights fishing. All trends in catch rates show a decline from 1980 to 1994. Catch rates between 1995 and 1999 stabilised, and increased marginally each year after 2000. The effect of standardising to 2003 fishing power shows higher catch rates especially in the 1980's. The analyses also showed that there is a strong seasonal decline (year and month interaction) in catch rates from March to November. Ignoring this pattern and generalising catch rates annually significantly reduced contrast in the data. Also, catch rates were predicted to be marginally higher on the making moon (Figure 4.4.3). The predicted catch rates from the third analysis were used in the tiger prawn delay difference model.

Figure 4.4.4 compares catch rates for two analyses similar to (1) and (3) above. The results show seasonal declines in catch rates and an overall increase from 1980 to 1999. Catch rates from 2001 to 2003 have consistently declined. Higher catch rates are shown for standardising to 2003 fishing power and for a full nights fishing.

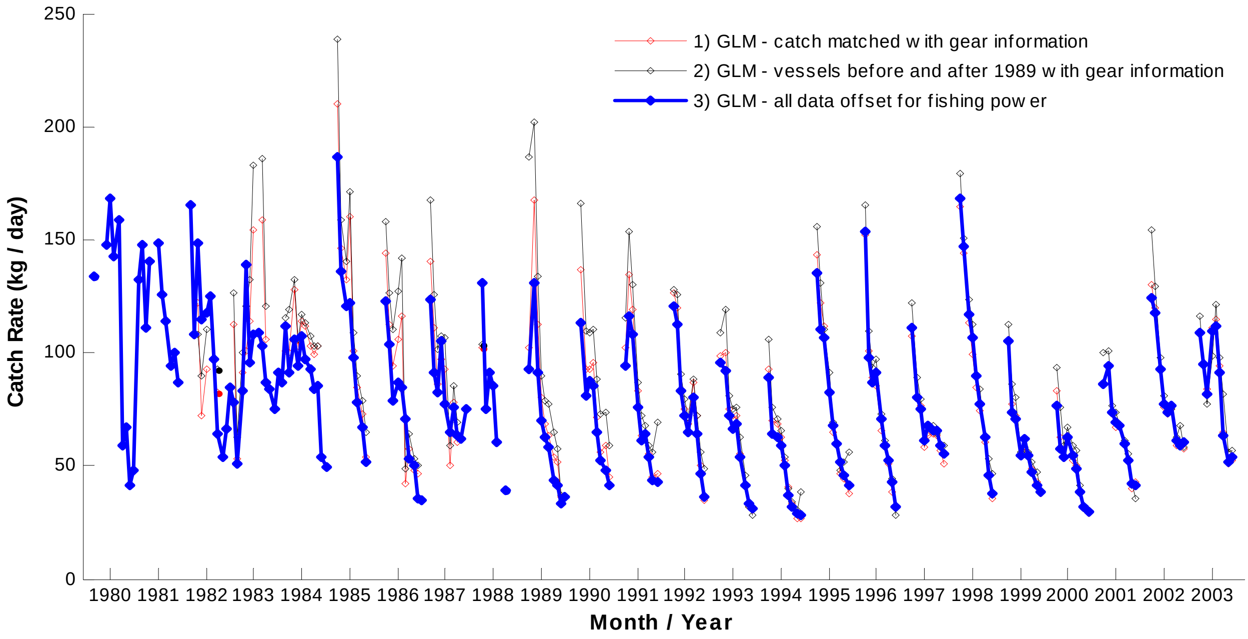

Figure 4.4.1 Comparison of tiger prawn catch rates. The 1st and 3rd analyses calculated very similar catch rates. The 2nd analysis calculated higher catch-rates.

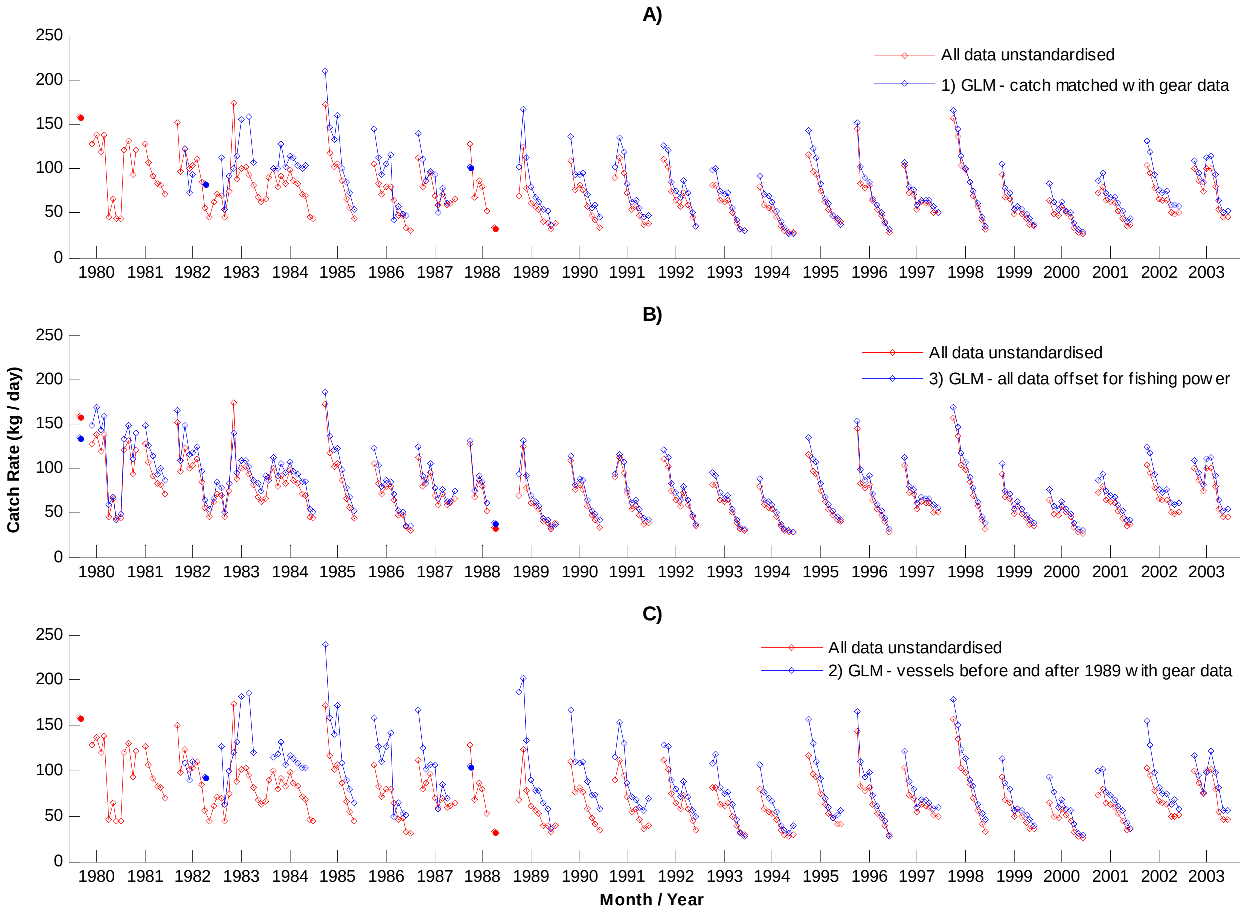

Figure 4.4.2 Comparison of the three tiger prawn analyses against the raw unstandardised catch rates. Note the seasonal declines in catch rates and the overall gradual decline from 1980 to 1994; catch rates stabilised thereafter and increased in 2002 and 2003. The gaps in catch rates are due to the three-month seasonal closure (December to February).

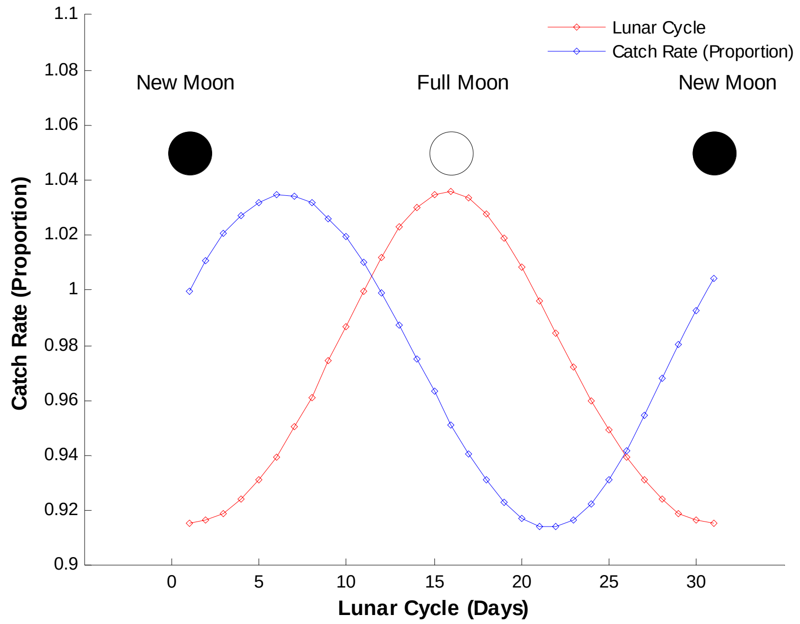

Figure 4.4.3 The estimated average proportional change in catch rates with lunar phase. The predictions show that higher catch rates associate with the making moon phase.

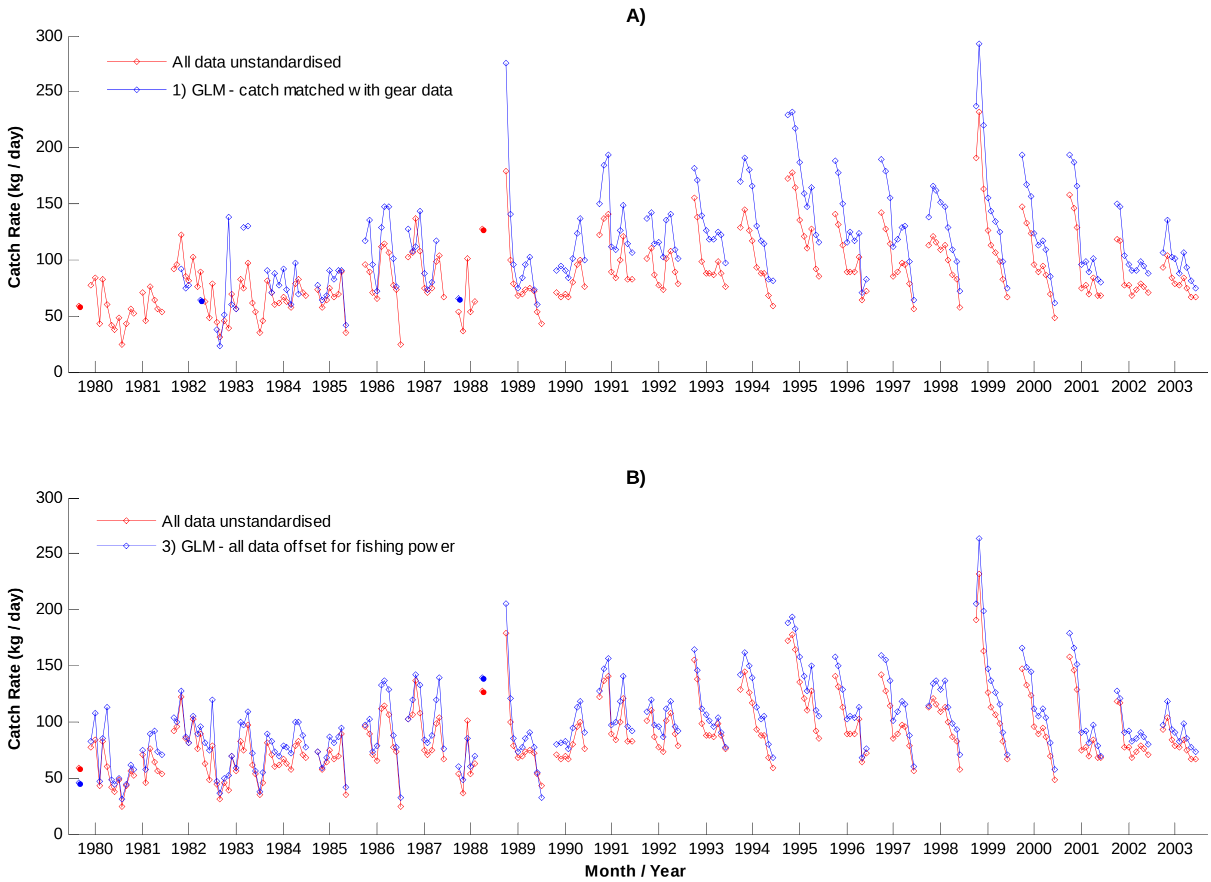

Figure 4.4.4 Comparison of two endeavour prawn analyses against the raw unstandardised catch rates. Note the seasonal declines in catch rates and the overall increase from 1980 to 1999; catch rates thereafter have declined. The gaps in catch rates are due to the three-month seasonal closure (December to February).

5 Tiger prawn stock assessment - 2004

5.1 Monthly delay difference

The Deriso-Schnute delay difference model was used to assess the Torres Strait tiger prawns (Deriso 1980; Schnute 1985; Quinn and Deriso 1999; Dichmont *et al.* 2001). The model simplified the mathematics of population age-structures so that population biomass followed a single delay difference equation, and prawn growth was approximated by the Brody growth curve. The model analysed the available time-series of standardised monthly-catch-rates to estimate harvest rates and therefore calculate monthly exploitable population biomass and numbers of prawns. This model captured the monthly dynamics of the prawn population, the seasonality of the fishery, and estimated spawning and recruitment trends. It contained biologically meaningful parameters for prawn growth, natural mortality, and recruitment and allowed realistic variations in these parameters. The model also allowed for some of these parameters to be estimated directly from standardised catch rate (relative abundance) data.

Table 5.1.1 The equations defining the delay-difference modelling for Torres Strait tiger prawns.

Equation	Population Dynamics: Monthly Delay Difference	Notation
(1)	Exploitable Biomass: B_t (kgs) $B_t = (1+\rho)e^{-Z_{t-1}}B_{t-1} - \rho e^{-Z_{t-1}}e^{-Z_{t-2}}B_{t-2}$ $-\rho e^{-Z_{t-1}} w_{r-1} p_t N_{r,y} + w_r p_t N_{r,y}$	t: sequential monthly time step 1,2,…,12 months, where the first month is January and the twelfth month is December. e: exponential function ρ: prawn growth parameter.
(2)	Exploitable Numbers N_t $N_t = N_{t-1}e^{-Z_{t-1}} + p_t N_{r,y}$	Z_{t-1}: Total Mortality in month t-1. Z_{t-2}: Total Mortality in month t-2.
(3)	Average weight of prawns older than recruitment age three months. $w_t = (1+\rho)w_{t-1} - \rho w_{t-2}$	w_r: average weight (kgs) of a tiger prawn at recruitment age (5 months) to the fishery. w_{r-1}: average weight of a tiger prawn one month before it enters the fishery.
(4)	Recruitment pattern: monthly proportion of annual recruits p_t: $p_t = \frac{1}{2\pi I_0(\kappa)} e^{\kappa\cos(t-\mu)}$ according to a von Mises directional distribution (Mardia and Jupp 2000) The resulting recruitment pattern was normalised to 1: $p_t = p_t / \sum p_t$:	$N_{r,y}$: estimated number of newly recruited prawns in fishing year y. I_0 denotes the modified Bessel function of the first kind and order 0, μ was the estimated mode of the distribution, and κ is known as the concentration parameter. p_t: sums to one in each fishing year.
(5)	Monthly Total Mortality Z_t $Z_t = M + F_t$ where $F_t = -\log_e\left(1 - \frac{C_t}{B_t}\right)$ (Haddon 2001).	M: 0.2 monthly instantaneous rate of natural mortality for both prawns. F_t: instantaneous fishing mortality. C_t: observed monthly catch kgs.
(6)	Predicted Monthly Catch C_t kgs $\hat{C}_t = \frac{F_t}{Z_t} B_t \left(1 - e^{-Z_t}\right)$	B_t was replaced with N_t to calculated catch in numbers of prawns.
(7)	Predicted monthly catch rate: $\hat{cpue}_t = qB_t$	q: catchability coefficient.
(8)	Approximate annual female prawns spawning S_y $S_y = 0.5 \sum_{t=Jan}^{Dec} \boldsymbol{\beta}_t \frac{1-e^{-Z_t}}{Z_t} N_t$	$\boldsymbol{\beta}_t$: vector of monthly spawning patterns (sum of proportions normalised to one)

The dynamics of the delay difference model followed equations (1) and (2) which described the biomass (B) and numbers (N) of prawns alive at the start of month t (Table 5.1.1). In these equations, monthly recruitment was calculated by the product of the within fishing year recruitment pattern (equation 4) and the total number of prawns recruiting in the fishing year (N_r) (Dichmont *et al.* 1999). The growth of prawns older than the recruitment age of three months (r) was approximated by the Brody curve (equation 3). The value of ρ was estimated by fitting the growth equation to the sexes-combined von Bertalanffy average growth curve (Die *et al.* 1999, and Glaister *et al.* 1987; see data section). Once the time series of prawn biomass and number of prawns were calculated, monthly total catch and catch rates were predicted using equations (6) and (7). The spawning index of female prawns in each fishing year was approximated using the within year spawning pattern and half the effective number of prawns alive each fishing-year (equation 8) (Dichmont *et al.* 2001).

In total 27 parameters were estimated in the analysis. The analysis used standardised catch rates from January 1980 to December 2003 as calculated from the general linear model using all data offset to 2003 fishing power. Initial biomasses in the first two months were calculated based on the relationship $B = cpue / q$ (Hilborn and Walters 1992). The 'fminsearch' MATLAB simplex and 'fminunc' MATLAB nonlinear Quasi-Newton search routines were used and compared to carry out the estimation by maximum likelihood (MATLAB 2002). The following algorithm was used:

1. Set initial values for the recruitment-pattern parameters μ and κ to approximately match the within fishing year average catch rate trend, and set the annual number of prawn recruits to the previous 2003 stock assessments. This step required some work to initialise starting parameter values. Altering the scale of the starting recruitment estimates and monitoring the log-likelihood narrowed down the initial starting values.
2. Calculate monthly biomass and prawn numbers using equations (1 & 2).
3. Predict the monthly catch rate using equation (7).
4. Compute the negative normal log-likelihood of the data using:

$$-\log \ell = \frac{n}{2}\left(\log(2\pi) + 2\log\left(sqrt\left(\frac{1}{n}\sum_t \left(\log\left(cpue_t \right) - \log\left(\hat{cpue}_t \right) \right)^2 \right) \right) + 1 \right),$$

where n was number of observed catch rates, π is 3.14159, log is the natural logarithm function, *sqrt* is the square root function and *cpue* was the monthly standardised catch rate and $\hat{cpue}$ was the predicted catch rate.

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

$$\lambda_1 = \begin{cases} 0 & if\left(C_t \le B_t\right) \\ \sum\left(C_t - B\right)^2 & otherwise \end{cases}.$$

The second penalty function λ_2 prevented extremely low exploitation rates:

$$\lambda_2 = \begin{cases} 0 & if\ \dfrac{CN_y}{R_y} \ge h \\ 1000\left(h - \dfrac{CN_y}{R_y} \right)^2 & otherwise \end{cases} \quad \text{(Hall and Watson 2000)},$$

where h was the minimum annual harvest fraction, CN_y were the accumulated number of prawns caught across the fishing years (Table 5.1.1), and the value 1000 was used to ensure adequate weighting in the optimisation. Three values of 0.2, 0.1, and 0.01 for h were tested as informative priors.

5. Minimise the negative log-likelihood by changing the parameter estimates using the simplex or Quasi-Newton iteration method.

Once convergence was achieved, alternative initial parameter estimates were tested to ensure accurate maximum likelihood. The penalty functions examined resulted in no effect on parameter estimates.

The main assumptions of the delay difference analyses were:

- Standardised catch rate is proportional to abundance.
- Constant natural mortality and prawn catchability.
- Average prawn growth.
- Age at first recruitment to the fishery was 5 months for tiger prawns. All post-recruitment size classes were equally vulnerable to fishing.
- Accurate reporting of the commercial catches.

5.2 Annual surplus production

The simplest time dynamic fisheries population models are those that consider only a single indicator of population size, usually biomass. These models ignore age or size structure and do not explicitly consider natural mortality, growth and recruitment. They are called biomass dynamic (or surplus production) models and take several variations on the traditional logistic models of ecology. The most commonly used of these is the Schaefer form of the surplus production model. Only three main parameters are to be estimated which makes it simple and convenient to apply. These are the intrinsic population growth rate (r), the population carrying capacity (K; virgin stock size) and catchability coefficient (*q*). This model is well described by Punt (1993), Prager (1994) and Haddon (2001), and relies on the annual standardised catch per unit effort index being proportional to the trend in stock abundance. Another similar form of the production model, the Fox model, was also applied. The asymmetry of the Fox production model (results were equivalent to the Pella production model) provided an optimistic comparison of Torres Strait tiger prawns compared to the Schaefer model. The surplus production analyses used annual standardised catch rates from 1980 to 2003 as calculated from the general linear model using all data offset to 2003 fishing power. Dr David Die's recommendation 15 (Table 1.1.1, page 7) to further test the model's (Haddon 2001) implementation in Matlab against others such as ASPIC (Prager 1994) was addressed.

Population biomass was calculated according to the simple function:

$$B_{t+1} = B_t + f(B_t) - C_t ,$$

where $f(B_t) = rB_t\left(1-\frac{B_t}{K}\right)$ was the Schaefer form and $f(B_t) = \log_e(K) rB_t\left(1-\frac{\log_e(B_t)}{\log_e(K)}\right)$ was the Fox form of surplus production, B_{t+1} was the exploitable biomass at the start of fishing year $t+1$, r was the intrinsic rate of population growth, K was the average unexploited equilibrium biomass (carrying capacity) and C_t was the observed catch during fishing year t. Initial biomass in the first fishing year was calculated based on the relationship $B = cpue / q$ (Hilborn and Walters 1992).

Standardised catch per unit effort data was used as an index to estimate biomass through $\hat{cpue}_t = qB_t$.

To apply the production models both observed and predicted catch rates were natural log transformed. In Matlab, parameter estimates were found by minimising the negative log-likelihood:

$$-\log \ell = \frac{n}{2}\left(\log_e(2\pi) + 2\log_e(\hat{\sigma}) + 1\right) + LLpen ,$$

where n was the number of fishing years in the catch rate time-series, $\hat{\sigma} = \sqrt{\sum_t \frac{\left(\log_e(cpue_t) - \log_e(\hat{cpue}_t) \right)^2}{n}}$ and, *LLpen* was a penalising term to minimise the probability that the starting biomass B_1 was greater than carrying capacity K. The simplex minimising method in MATLAB (fminsearch) was used in the estimation procedure.

5.3 Statistical uncertainty in models

In the previous two sections, the methods for fitting stock assessment models to estimate biological parameters were outlined. This section describes the statistics used for measuring the goodness of fit of each model, measuring the precision of the parameters estimated, and calculating the confidence intervals.

Having modelled the Torres Strait tiger prawns, the parameters estimated were assessed against their relative precision to ensure the model was appropriate for the data. Parameter estimates were the values that maximised the log-likelihood (i.e. fit) of the model for the data observed. If the parameter estimates described the data well, their level of precision will be high. The resulting log-likelihood will be greater compared with a less appropriate model's log-likelihood considered against the number of parameters in each model. The objective was for the fitted model to have an appropriate combination of parameters and a reliable level of accuracy in order to make predictions of management quantities, and inferences on reference points. The discrepancy between the predicted catch rates and the observed was measured and a decision was made on whether the discrepancy was acceptable or not. This discrepancy was the measure of statistical uncertainty. Other types of uncertainty regarding the appropriateness of the model's framework (model uncertainty), the fixing of certain biological parameters (conditioning uncertainty) and the behaviour of the models performing only to the average situation (process uncertainty) are dealt with later in the simulation framework.

A range of statistics plots was used to measure the goodness of fit (statistical uncertainty) between the observed standardised catch rates and those predicted by the model. These were:

- Time series plot of the observed and predicted catch rates.
- Plot of standardised residuals against predicted values. The standardised residuals were calculated by

$$r_t = \frac{y_t - \mathrm{E}(y_t)}{\sqrt{Var(y_t)}},$$

where $\mathrm{E}(y_t)$ were the predicted catch rates, y_t the observed catch rates and $\mathrm{Var}(y_t)$ was the variance of the stock assessment model fit $\hat{\sigma}^2 = \sum_t \frac{\left(\log_e(cpue_t) - \log_e(\hat{cpue}_t) \right)^2}{n}$.

- Histogram and normality plot of standardised residuals.

Parameter standard errors for the delay difference model were taken from the square root of the diagonal elements in the asymptotic covariance matrix. The asymptotic covariance matrix of the parameter estimates was given by the inverse of the Hessian matrix of second derivatives with respect to variation in model parameters evaluated at the maximum likelihood estimate. The 'fminunc' Matlab routine estimated the Hessian. In order to summarise the precision of the parameter estimates a series of simple t-tests were presented. The t-tests were used to examine the significance of each parameter. The hypothesis tested was

$$H_0: \quad \beta_i = 0 \qquad H_1: \quad \beta_i \neq 0$$

where β_t was an estimated parameter. The t-statistic used was $t = \frac{\beta_i}{SE_{\beta_i}}$, compared against the critical t-value for the probability level $\alpha = 0.05$ and the model residual degrees of freedom.

Confidence intervals on all outputs from the delay difference models were generated by a Monte Carlo routine of running the models for 1000 variations in the parameters estimated. Table 5.3.1 outlines these steps:

Table 5.3.1 Algorithm used to generate 90% confidence intervals for the delay difference model outputs.

1.	Use the estimated model parameters and their covariance matrix to construct a multivariate normal distribution.
2.	Draw a random sample parameter-vector from the multivariate normal distribution calculated in step 1.
3.	Use the random sample of parameters to obtain a sample historical trajectory for the stock (ie run model with parameters).
4.	Repeat the process from step two to three 1000 times to obtain a large number of trajectories and outputs, each of which reflects the correlations among estimated parameters.
5.	Calculate 5% and 95% percentiles to generate 90% confidence intervals.

In addition, to demonstrate the delay difference model's sensitivity to the assumed known monthly natural mortality (M=0.2), we compared outputs by changing this parameter to other plausible values of 20% higher and lower (M=0.24 and M=0.16). We refer to the 2003 Torres Strait tiger prawn assessment for other sensitivity relationships examining higher and lower rates of prawn growth and fishing power (O'Neill *et al.* 2005) .

Bootstrap methods were used for the surplus production models to obtain distributions for parameter estimates and bias corrected confidence intervals on all outputs (Haddon 2001). The methods used a series of steps to resample the residuals from the optimal model fits. A total of 1000 independent catch rate time-series were generated by the bootstrap sampling. Each independent catch-rate series were constructed by

$$cpue^* = c\hat{p}ue\left(\frac{cpue}{c\hat{p}ue}\right),$$

where $cpue^*$ were the new bootstrapped catch rates, $c\hat{p}ue$ were the optimised models predicted catch rates, and *cpue* were the observed standardised catch rates. The surplus production model was fitted to all 1000 catch-rate time series. Bias corrected 90% confidence intervals were calculated on all model outputs by adjusting the appropriate lower and upper percentiles by

$$P_{lower} = \Phi(2z - 1.645)$$
$$P_{upper} = \Phi(2z + 1.645)$$

where z is the inverse cumulative normal distribution of the proportion of bootstraps less than the optimal estimate $z = \Phi^{-1}(p_{lessthan})$.

5.4 Spawner-recruitment relationships

WHAT ARE THEY?

One of the most important pieces of information required for modelling the status of fisheries is the relationship between spawning and recruitment. This relationship defines how much the spawning stock can be reduced before recruitment is not sufficient enough to replace those being caught. This is known as recruitment overfishing. Annual recruitment is naturally highly variable and very difficult to quantify. To conduct a management strategy evaluation, a spawner-recruitment relationship is generally required to project the population and fishery forward in time to examine different management scenarios.

A number of models have been used to describe spawner-recruitment relationships (Ricker 1954; Schaefer 1954; Beverton and Holt 1957; Ricker 1975; Deriso 1980; Schnute 1985). In this assessment we compared the commonly used Beverton-Holt and Ricker models (Table 5.4.2). The Beverton-Holt model was devised to incorporate density-dependent survival rates reflecting competition for critical resources. What this means simply is that an unfished population over time will reach a limit maximum (i.e. carrying capacity). The model balances between density-independent and density-dependent juvenile mortality, and implies that the larger the spawning stock the faster the juveniles will die (Haddon 2001). The Ricker model allows for the addition of other mechanisms to generate density-dependence upon the total population size. These include, for example, the possibility of cannibalism of juveniles by adults (e.g. Barramundi or Tailor), density-dependent transmission of disease, density dependent growth combined with size dependent predation (Haddon 2001).

A number of prawn fisheries throughout the world have shown that the level of recruitment is related to the size of the parental population (the spawners). (Ye 2000) conducted a meta-analysis of 13 penaeid prawn fisheries to test the hypothesis that recruitment is a random process. His analysis rejected this hypothesis, and showed that recruitment was related to spawner abundance and concluded that prawn populations should be managed to maintain sufficient spawning stock abundance to yield high recruitment. This paper also illustrated clear relationships between spawners and recruitment for brown (*Penaeus esculentus*) and grooved (*P. semisulcatus*) tiger prawns from western and northern Australia. The 2000 assessment of the Northern Prawn Fishery (NPF) detailed these spawner recruitment relationships and described their steepness according to the expected recruitment at 20% of the virgin spawner stock size (Table 5.4.1) (Dichmont *et al.* 2001). The higher the steepness, the smaller the spawner stock size required to reach the recruitment asymptote (Figure 5.4.1). Stocks with high steepness tend to have higher resilience to fishing than stocks with low steepness. All of the prawn stocks analysed by Ye (2000) typically had steepness less than 0.5. In the NPF steepness was low and ranged 0.26 to 0.34 for the brown tiger prawn, which is the species of focus in this Torres Strait assessment.

Table 5.4.1 Comparison of steepness measures, with 90% confidence intervals, from the Beveton-Holt and Ricker curves for Australia's Northern Prawn Fishery (Dichmont *et al.* 2001).

Model	Brown Tiger Prawn	Grooved Tiger Prawn
Beverton Holt	0.284 (0.261-0.339)	0.311 (0.281-0.364)
Ricker	0.279 (0.257-0.321)	0.304 (0.279-0.339)

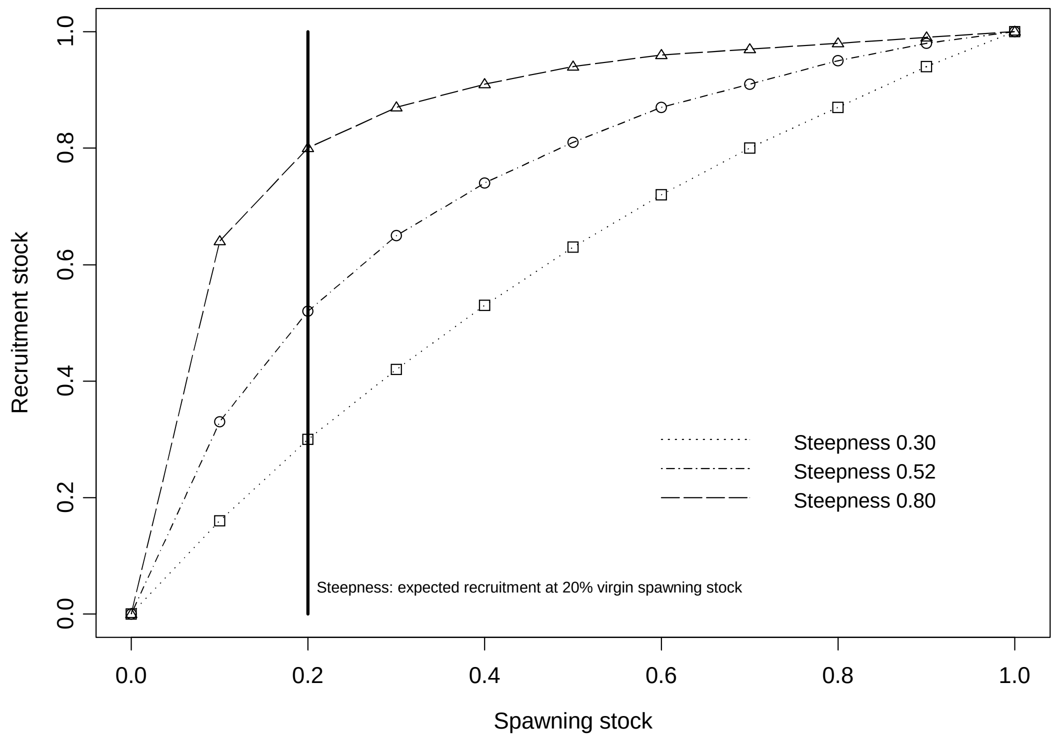

Figure 5.4.1 Illustrative Beverton-holt spawner-recruitment curves with different steepness. Virgin spawning and recruitment stock sizes are equal to 1, with the figure scaled proportionally. Solid line defines steepness as the expected recruitment at 20% of virgin spawning stock. Stocks with high steepness tend to have high resilience to fishing, but can dramatically collapse if fished too heavy; stocks with low steepness have lower resilience to fishing and can exhibit a gradual fish down effect over time.

HOW DID WE MEASURE SPAWNING AND RECRUITMENT?

The spawner-recruitment relationships (Table 5.4.2) were fitted directly to the estimated annual spawning and recruitment levels from the Torres Strait tiger prawn delay difference model. This was possible because the entire time series of total catches and catch rates stretched 24 years and the data provided some of the contrast necessary to detect a reduced spawning stock. The Matlab 'fminunc' search routine was used to carry out parameter estimation by minimising the negative log-likelihood:

$$-\log \ell = \frac{n}{2}\left(\log(2\pi) + 2\log\left(sqrt\left(\frac{1}{n}\sum_{y}\left(\log(N_{r,y}) - \log(\hat{N}_{r,y})\right)^2 \right)\right) + 1 \right)$$

where n was number of fishing years, y identified a fishing year, π is 3.14159, log is the natural logarithm function, *sqrt* is the square root function, $N_{r,y}$ was the number of prawn recruits estimated by the delay difference model, $\hat{N}_{r,y}$ was the predicted number of recruits according to the spawner-recruitment equation. The parameter covariance matrix was given by the inverse of the Hessian matrix.

Table 5.4.2 Spawner-recruitment (*S/R*) and steepness equations.

Relationship	Equation	Notation
Beverton-Holt *S/R*	$\hat{N}_{r,y+1} = \frac{S_y}{\alpha + \beta S_y} e^{\eta}$	y: fishing years S_y: Female Spawning Index α,β: spawner-recruitment parameters to be estimated
Ricker *S/R*	$\hat{N}_{r,y+1} = \alpha S_y e^{-\beta S_y} e^{\eta}$	e^{η} : log normal error
Steepness of *S/R*	$\frac{\hat{R}_{0.2S_0}}{\hat{R}_0}$	$\hat{R}_{0.2S_0}$: mean recruitment at 20% virgin spawning stock. $\hat{R}_0$: virgin recruitment.

In addition to fitting the spawner-recruitment relationships, the resulting residuals were examined for autocorrelations and patterns to determine if the model fit was inadequate. If significant autocorrelation is present, recruitment successes may be correlated. That is, high recruitment years may be followed by another high year, and low recruitment years followed by another low year. The cause of autocorrelations may be due to environmental effects on the stock recruitment relationship. Autocorrelations were examined using the autoregressive integrated moving-average (ARIMA) time-series modelling package in (GENSTAT 2003). This measured the amount of correlation between residuals for different time lags ranging from one to twenty years. The results showed no significant autocorrelations to suggest obvious environmental effects or any necessity to consider alternative fitting procedures (Dichmont *et al.* 2001). Scatter plots of residuals against predicted recruitments were used to show that no patterns existed and that the model fits were adequate.

5.5 Equilibrium reference points

THE DELAY DIFFERENCE MODEL

The calculation of equilibrium management reference points was based on optimising the dynamics of the model through fishing effort. The model dynamics were started at a random biomass. After this the recruitment dynamics were calculated according to the spawner recruitment relationship. The model was run over twenty years, with recruitment calculated to ensure that the yield was maximised at different levels of fishing effort. The product from the 20 years of fishing was the equilibrium catch measured in kilograms or numbers of prawns. The dynamics of the models were optimised for various reference points including catch and standardised fishing-effort at Maximum Sustainable Yield (MSY and E_{MSY}). This simplified technique calculated the same values as the yield-per-recruit approach (O'Neill *et al.* 2005).

The calculations of equilibrium reference points differ for the Schaefer and Fox models (Hilborn and Walters 1992; Haddon 2001). Maximum sustainable yield and the fishing effort required to catch MSY, E_{MSY}, were calculated by

$$MSY = \frac{rK}{4} \text{ and } E_{MSY} = \frac{r}{2q} \text{ for the Schaefer model, and}$$

$$MSY = \frac{rK}{e^1} \text{ and } E_{MSY} = \frac{r}{q} \text{ for the Fox model,}$$

The parameters r, K, and q are defined for the surplus production model in section 5.2, page 39.

5.6 Biological data

Table 5.6.1 contains a summary of the biological inputs used to calculate average prawn growth, weight, size at first recruitment to the fishery and one month prior, natural mortality and the relative monthly spawning pattern for the brown tiger prawn (*Penaeus esculentus*) in the Torres Strait. These biological parameters are deterministic. The model sensitivity to natural mortality is reported as part of the stock assessment.

Table 5.6.1 The tiger prawn biological parameters used as inputs into the delay difference model.

Parameters	Estimates	Data sources
Von Bertalanffy prawn growth		
L_∞ k (male)	34.7 CL mm; 0.2417 month^{-1}	(Watson and Turnbull 1993)
L_∞ k (female)	43.6 CL mm; 0.2167 month^{-1}	
Brody prawn growth		
ρ (sexes combined)	0.90865166	As above
Carapace length to weight		
$w_{grams} = aCL^b$		
a_{male} , b_{male}	0.0024, 2.72	(Watson 1990)
a_{female} , b_{female}	0.0026, 2.67	
Carapace length at recruitment		
Male	24 mm	(Watson 1990), and
Female	28 mm	(Watson and Turnbull 1993)
Natural Mortality (M)	0.2	(Watson 1990 and Garcia 1985)
Monthly Spawning Pattern (Proportion, β)		
January	0.1055	Estimated by O'Neill *et al.* (2005)
February	0.1022	Using 1986-91 data from
March	0.0823	Watson and Turnbull (1993)
April	0.0746	
May	0.0764	
June	0.0543	
July	0.0760	
August	0.0880	
September	0.0789	
October	0.0965	
November	0.0808	
December	0.0847	

There were several growth estimates based on animals tagged to the east and west of Warrior Reef and also two tagging experiments, 1987 and 1988 (Watson and Turnbull 1993). The growth parameters for male and female prawns tagged and recaptured east of the Warrior Reef in 1987 were used as they are based on a larger sample size than for 1988. In addition, examination of the 95% confidence intervals for the growth parameters of female prawns tagged and recaptured east of the Warrior Reef in 1987 were in between the west 1987 and 1988 estimates. Similarly the east 1987 male growth rate estimate overlaps the west 1987 and 1988 estimates. For these reasons we considered them to be the most representative estimates to use.

The measure of relative spawning was calculated by analysing an index of population fecundity (PFI), which is the relative number of eggs produced or potentially produced by the population each month (Keating *et al.* 1990). The PFI used to estimate the monthly spawning pattern was based on the number of female brown tiger prawns with mature ovaries per square metre of seabed swept by the trawl nets, their length distribution and the fecundity to carapace length relationship. In addition the probability of insemination of ripe females was incorporated into the PFI calculations (Keating *et al.* 1990). This index was estimated from monthly trawl survey data collected in Torres Strait during 1986-1991. The mean PFI by year, month and region was used in a general linear model to estimate the monthly pattern with region (West of Warrior Reef, East of Warrior Reef, Fishery) as a factor in the model. Generally the relative amount of spawning was greatest in January and February (Figure 5.6.1). This result was used with the population estimates in the model to calculate spawning stock sizes.

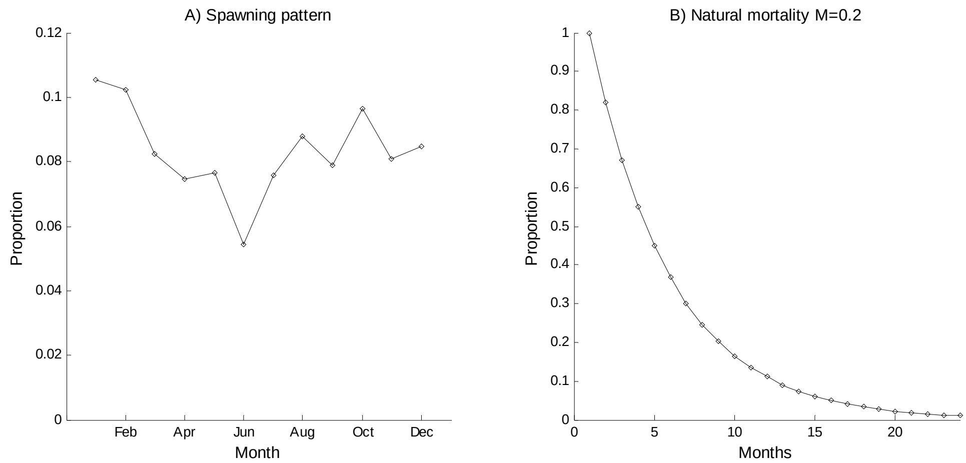

Figure 5.6.1 A) Histological staging of female tiger prawns in the Torres Strait showed no clear peaks in relative spawning, but was highest in January and February. B) Tagging data suggests that in the order of 18% of recruited tiger prawns die every month to natural causes.

5.7 Results

Stock assessment

The stock assessment used two modelling approaches - a monthly delay difference model and an annual surplus production model (Figure 5.7.1 and Figure 5.7.2 respectively). The delay difference model compared biomass trends for three monthly rates of natural mortality (M) using the annual estimates of increase in fishing power (including the recommended 4% drop in fishing power due to smaller net restrictions as suggested by Dr Die; Table 4.3.1, page 32). Figure 5.7.1A resulted from assuming M=0.20 month-1, which based on the literature, is likely to be the most accurate estimate of natural mortality. Figure 5.7.1B compared a 20% lower rate of natural mortality (M=0.16 month-1) and a 20% higher rate of natural mortality (M=0.24). The purpose of comparing different outputs was to highlight the dependences of natural mortality. The base-case results should always be used to compare dependences (Figure 5.7.1A).

The monthly delay difference model predicted that biomass, expressed as a ratio to virgin exploitable stock biomass size, declined between 1980 and 1989, but varied around BMSY between 1990 and 2003 (Figure 5.7.1). Under all scenarios of natural mortality the delay difference model indicated the 2003 biomass was above BMSY. The Ricker stock-recruitment curve and the delay difference model were used together to estimate the equilibrium virgin stock size (B0) and the population size that supports maximum sustainable yield (BMSY).

Both the Ricker and Beverton-Holt forms of the spawning-recruitment relationship were reported because their optimal curve fits varied at low spawning stock sizes (Figure 5.7.3). The measure of steepness, defined as the average productivity of recruitment at 20% of virgin spawning stock size, was statistically significant for the Ricker curve (Figure 5.7.3 and Table 5.7.1). However, the shape of the Beverton-Holt curve was uncertain with large confidence intervals on steepness (Figure 5.7.3 and Table 5.7.1). Estimates of maximum sustainable yield (MSY) and fishing effort (E_{MSY}) were 606 and 676 tonnes, and 8245 and 9197 boat nights in 2003, for the Ricker and Beverton-Holt spawner-recruitment relationships respectively (Table 5.7.1). Additional sensitivity analysis on the delay difference model showed that the calculations of MSY and E_{MSY}

were not dramatically sensitive to different assumptions of natural mortality (Table 5.7.1). However, E_{MSY} was sensitive to different annual increases in fishing power and the form of spawner-recruitment relationship, with lower estimates associated with higher fishing power (Table 5.7.1).

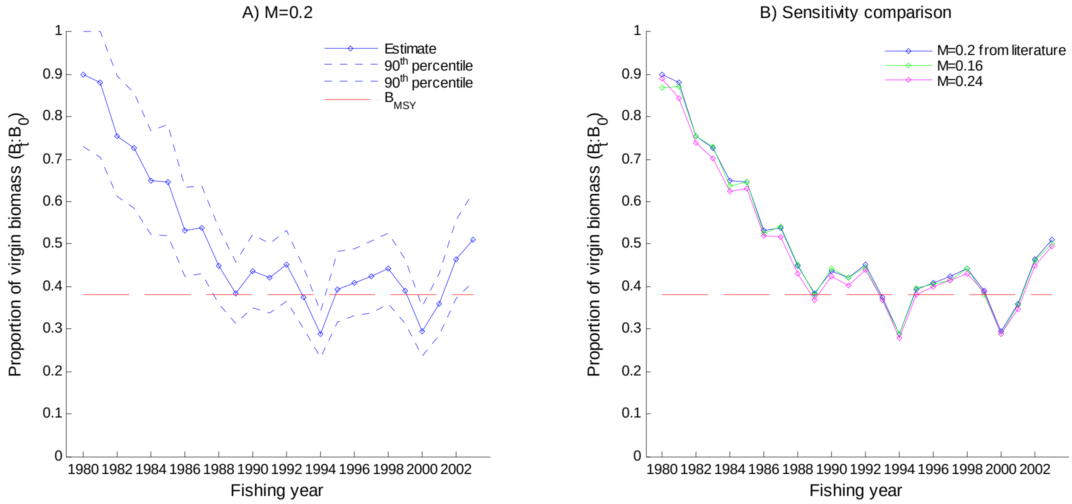

Figure 5.7.1 The monthly delay difference model predicted declining exploitable biomasses for Torres Strait tiger prawns between 1980 and 1994. Since 1995, biomasses varied around the reference point for maximum sustainable yield (B_{MSY} the red dashed line; calculated from the Ricker curve). Subplot A) resulted from assuming natural mortality M=0.2 month-1, and subplot B) compared three variations in M. The dotted lines represent the 90th percentiles.

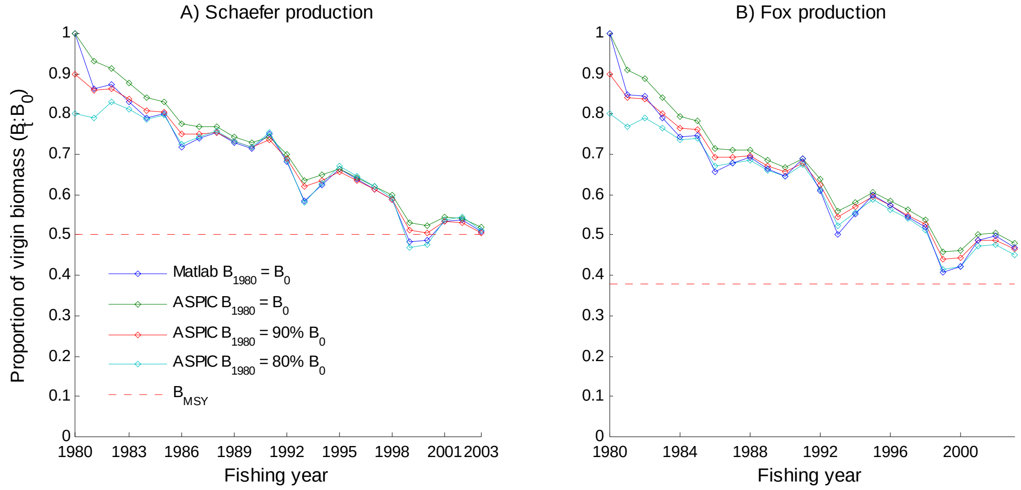

Figure 5.7.2 The annual surplus production analyses all predicted a similiar "one-way-trip" of declining exploitable biomasses for Torres Strait tiger prawns. Subplot A) compares results from the Schaefer form of production, and subplot B), compares the Fox form. All starting biomasses in 1980 were constrained to either virgin stock size (B_0), 90% B_0, or 80% B_0.

Results from the surplus-production models are provided in Figure 5.7.2 and Table 5.7.2. All analyses were "constrained" to start the 1980 biomass at either equilibrium virgin stock size (B_0), 90%B_0, or 80%B_0. This was done as the "unconstrained" estimate converged to an unrealistic ratio of the 1980 biomass equal to 2.5 times virgin biomass. A penalising term in the log-likelihood was used to minimise the probability that the starting biomass in 1980 was greater than the estimated virgin stock size. This result suggested it was reasonable to fix the starting biomass in 1980 to virgin. All models predicted a declining "one-way-trip" of exploitable biomass for Torres Strait tiger prawns, and the 2003 biomass was at about B_{MSY} (Figure 5.7.2). Calculations of MSY were comparable across model runs (Table 5.7.2). However, the levels of fishing effort that should give rise to the MSY were much higher for the Fox models compared to the delay difference and Schaefer estimates.

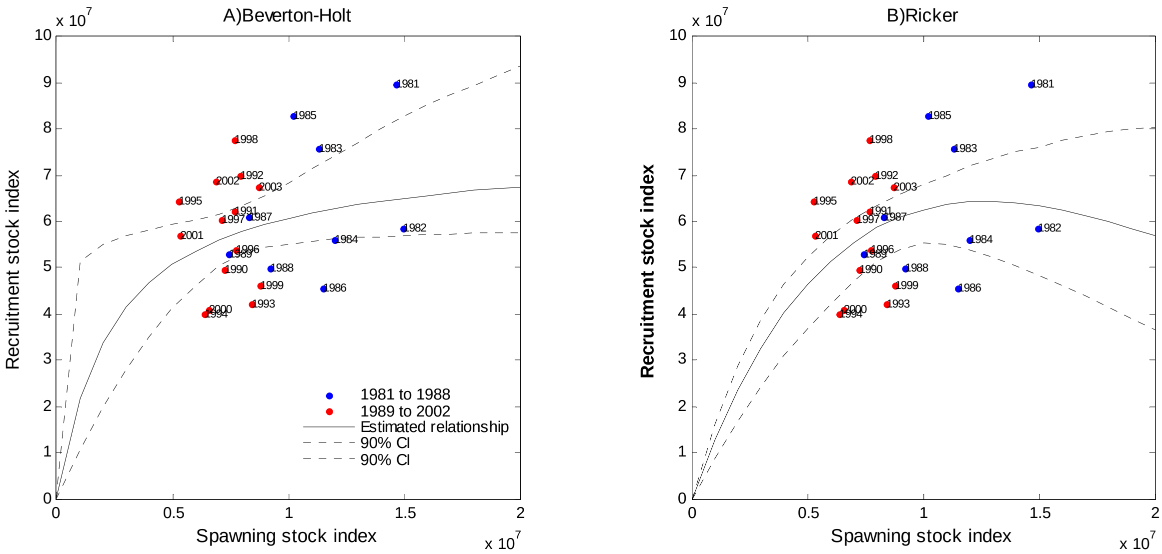

Figure 5.7.3 The spawner-recruitment relationships assuming A) the Beverton-Holt form, or B) the Ricker form. One-year autocorrelations between residuals were non-significant at –0.209.

Table 5.7.1 The spawner-recruitment and delay-difference equilibrium-management parameters. For the spawner-recruitment parameters, the numbers within the parenthesis refer to the standard error and T statistic. For the measures of steepness and equilibrium-management 90% confidence intervals are shown. Additional equilibrium estimates of management are provided based on varying natural mortality (M). E_{MSY} (2003 nights) corresponds to 2003 fishing power (including the reduced 4% net effect). E_{MSY} (1998 nights) is a comparison relating to peak fishing power.

Parameters	Ricker	Beverton-Holt
Spawner-Recruitment		
alpha α	13.760779 (2.239487; 6.14)	0.03296 (0.024827; 1.33)
beta β	7.872085E-08 (1.784896E-08; 4.41)	1.315823E-08 (3.048894E-09; 4.32)
Steepness	0.46 (0.36:0.55)	0.58 (0.40:0.90)
Management; M=0.2		
MSY (tonnes)	606 (436:722)	676 (523:899)
E_{MSY} (2003 nights)	8245 (5932 : 9823)	9197 (7116 : 12231)
E_{MSY} (1998 nights)	8026 (5775 : 9563)	8954 (6927 : 11907)
Sensitivity M=0.16		
SY (tonnes)	620	726
E_{MSY} (2003 nights)	8435	9878
Sensitivity M=0.24		
MSY (tonnes)	592	653
E_{MSY} (2003 nights)	8054	8884

Table 5.7.2 Equilibrium management parameters estimated from the surplus production models. ASPIC 80% and Matlab 95% bootstrap bias corrected confidence intervals are shown in parenthesis. The Matlab Schaefer model is shown in Table 5.7.3.

Production Model	Constraint B_{1980}/K	MSY (t)	E_{MSY} (2003 days)
ASPIC (ver. 5)			
Schaefer	1	601 (349:659)	9600 (7348:11250)
Schaefer	0.9	607 (291:653)	9420 (6260:10800)
Schaefer	0.8	643 (478:688)	9830 (7920:11500)
Fox	1	668 (537:753)	13400 (11500:18100)
Fox	0.9	661 (495:734)	12800 (10900 16000)
Fox	0.8	659 (505:728)	12400 (9950:15400)
Matlab			
Fox	1	681 (584:748)	13243 (11018:15984)

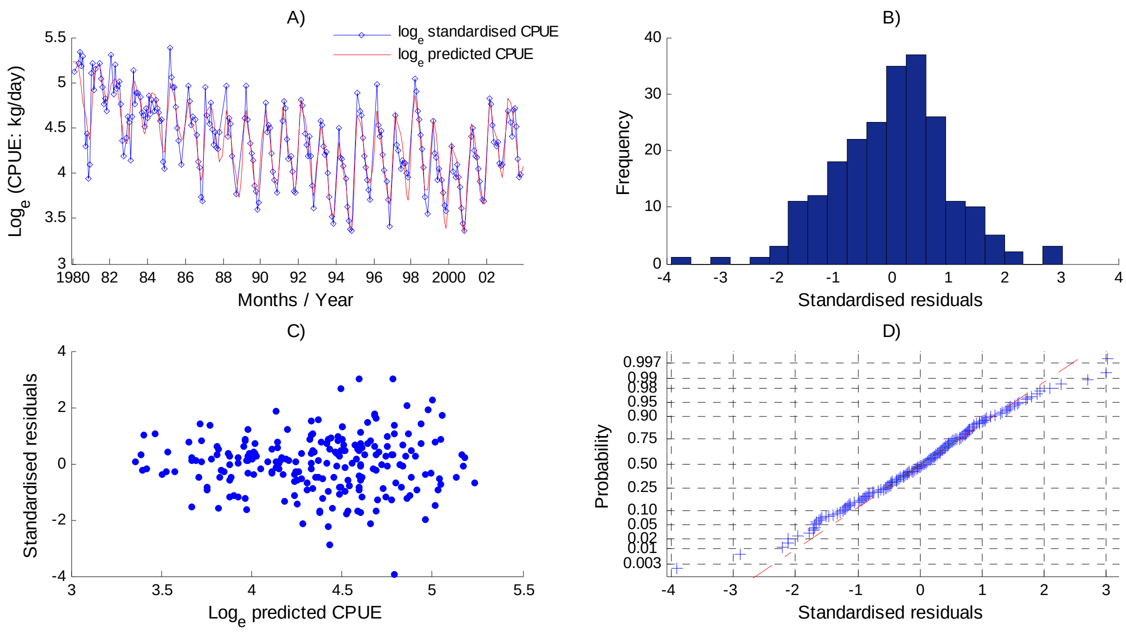

Figure 5.7.4 The delay difference model A) modelled the trend in standardised catch-rates quite well, B) standardised residuals was normal distributed, C) using log-normal errors was appropriate with no pattern in standardised residuals, and D) had a linear normality plot.

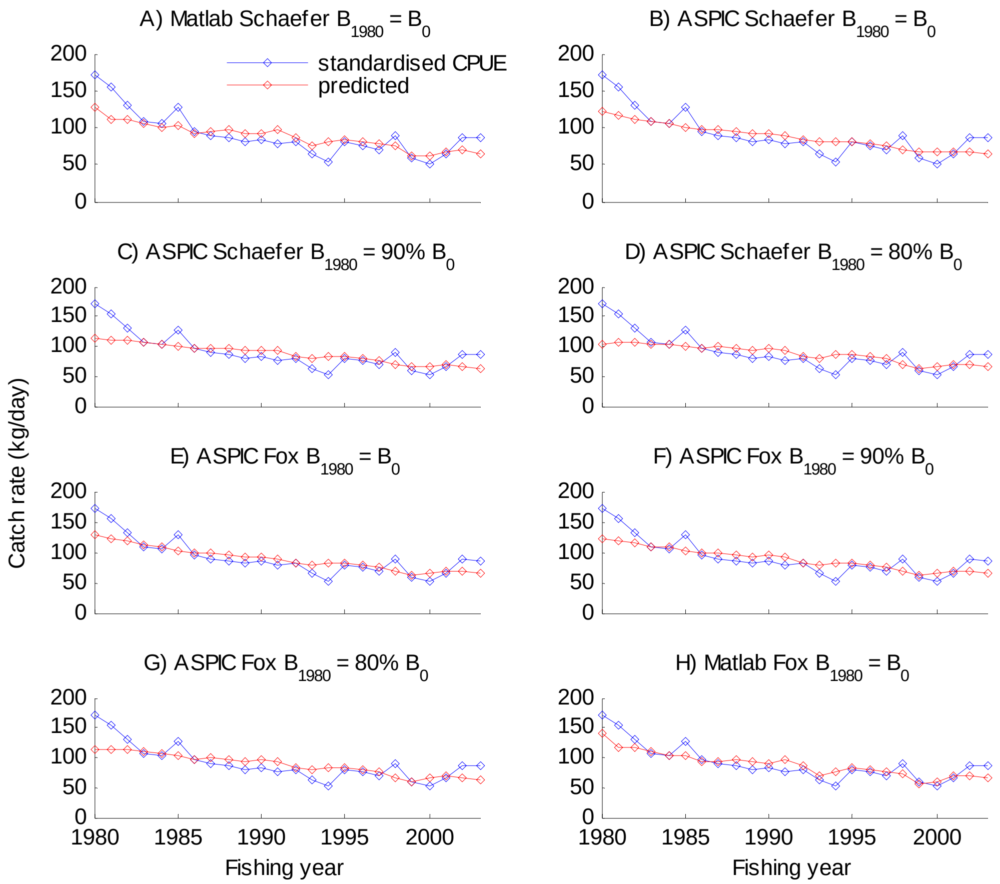

Figure 5.7.5 The constrained surplus production model fits. Subplot H) shows the best fit; with the Matlab Fox model predicting (red line) the trend in standardised catch-rates (blue line) reasonably well. All the other model fits were marginally sub-optimal, especially the fit to 1980 and 1981 catch rates, but were not statistically different to H).

For the delay difference stock assessment there was no evidence to suggest the model was inadequate for the data or that the use of lognormal errors was inappropriate. Figure 5.7.4 shows that the model predicted the standardised catch rates quite well, although it marginally under estimated about eight (out of 24) of the monthly peak catch rates present in the time series. The standardised residuals for these large catch rates were all less than four, indicating they were not extreme. The largest residual of –3.91 was from February 1983. This standardised catch-rate was unusually low at 62 kg/day, but the model calculated this at 120 kg/day, as catch-rates were typically largest in February and March. The influence of such data points had little effect on the log-likelihood or upon the estimation of the parameters. For example, removing this large residual resulted in little change in the parameter estimates, suggesting the model captured these observations reasonably well and that it accurately modelled the year-to-year and month-to-month patterns of tiger prawn catch rates. The surplus production models generally fit smoothly through the "one-way-trip" decline in annual catch rates (Figure 5.7.5). The next section of results describes more about the surplus production fits and the "one-way-trip" issue.

TESTING THE PRODUCTION MODEL

Recommendation 15 in Table 1.1.1, page 7, outlines Dr David Die's suggestion to further test the production model implementation in MATLAB. He stated that comparisons should be made with other tested implementations of the production model such as ASPIC (Prager 2004), BIODYN (Punt and Hilborn 1997) or FISHLAB (Kell and Smith 2000) . This recommendation arose to confirm that the Haddon (2001) methodology programmed in Matlab was repeatable; parameter estimates from Matlab and ASPIC in the 2003 review produced different results.

To test the production model implementation we first analysed the 1980 to 2003 annual harvests and catch-rates in Matlab and ASPIC. The ASPIC software was run conditioning the fit on yield (Prager 1994, 2004). The parameter estimates from both models were quite different with Matlab estimating higher catchability (q), lower virgin population size (K), and a faster rate of replacement (r) (Table 5.7.3 A). ASPIC converged to a less optimum solution with higher sums of squares. However, both model fits calculated similar management quantities (Table 5.7.3 A), and trends in biomass (Figure 5.7.6). The reason for the lack of repeatability to estimate the production model parameters was due to the situation known as a "one-way-trip" (Figure 5.7.7 A); as highlighted by Dr Die (Die 2003). The situation consists of a fishery with continuously increasing fishing effort and declining catch rates. This type of annual time-series is common in many fisheries and is the most difficult to interpret (Hilborn and Walters 1992). The annual time-series of data (Figure 5.7.7A) does not have good contrast, and any single line of the data can be fit by a number of different parameter combinations (even though fishing effort has stabilised in recent years) whereas the monthly data (Figure 5.7.7B) shows more contrast upon which the delay difference model is based. Therefore, fitting a production model to annual data through different software packages will most likely give a range of different parameter estimates.

Table 5.7.3 Matlab verse ASPIC (fit conditioned on yield): comparison of parameter estimates (q, r, and K) and management quantities (MSY and E_{MSY}) for A) using 1980 to 2003 catch rates and B) using ASPIC to simulate 10 more years of future catch rates at 3000 nights of fishing and analysing this test data (1980 – 2013) in Matlab. The estimates are from the Schaefer production model (described in section 5.2, page 39) assuming the starting biomass in 1980 = K; SS = log sums of squares.

Schaefer Model	Model Fit (SS)	q	r	K	MSY	E_{MSY}
A) 1980 – 2003 Data						
ASPIC (ver. 5; Fortran simplex optimisation)	0.8307	0.023	0.448	5363 t	601 t	9600
Matlab (simplex and Quasi Newton optimisation)	0.8118	0.038	0.768	3319 t	637 t	9987
B) 1980 – 2003 Data, plus 10 years of future data generated from ASPIC						
Matlab (simplex optimisation)		0.025	0.479	5052 t	604 t	9615

To test the validity of the Matlab version we simulated 10 years of extra annual harvests and catch rates at 3000 days of fishing to remove the effect of the "one-way-trip". This extra (test) data was generated using ASPIC's parameter estimates (q, r, and K; Table 5.7.3 A). This new simulated data provided strong contrast between low and high fishing effort and catch rates (Figure 5.7.8). Fitting the Matlab model to the test data produced nearly identical parameters estimates and management quantities to ASPIC (Table 5.7.3B). The very slight difference present was due to Haddon's methodology treating each fishing year as a discrete time step, whereas

Prager's method includes exponential terms that treat time as continuous and therefore all calculations move more smoothly with time. The test data and analysis highlights the point that if the fishing industry fished at lower levels than current for about five years, the resulting data would remove significant uncertainty in the assessment and provide long term confidence in setting sustainable limits of fishing. However, the economics of fishing less than 5000 days would make this experiment unpalatable and unviable.

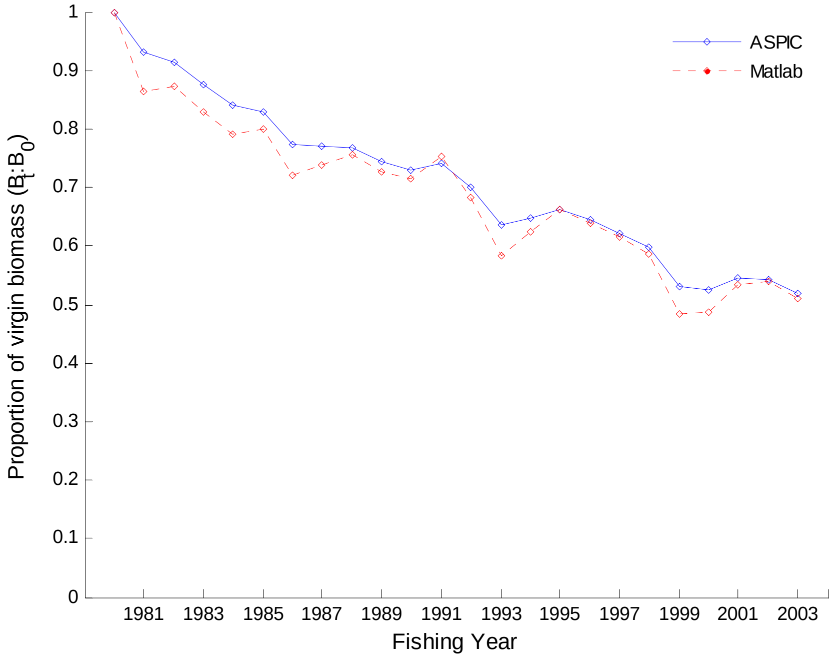

Figure 5.7.6 Matlab verse ASPIC: comparison of biomass ratios using 1980 to 2003 catch-rates. The estimates are from the Schaefer production model (section 5.2, page 39) assuming the starting biomass in 1980 = K.

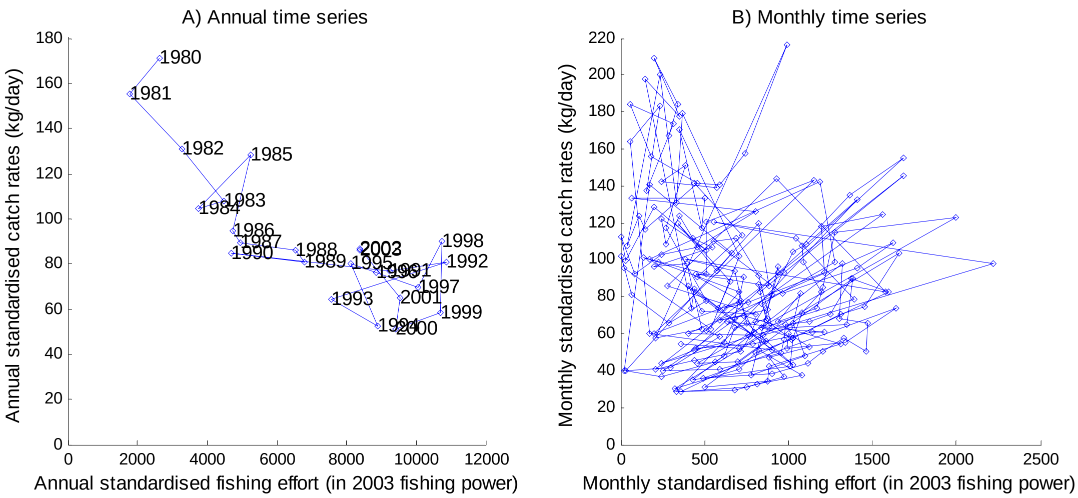

Figure 5.7.7 A) The annual time series of tiger prawn catch rates declines for increasing fishing effort. This type of time series is called a one-way trip (Hilborn and Walters 1992). B) The monthly time series has strong contrast with catch rates and effort varied over their range.

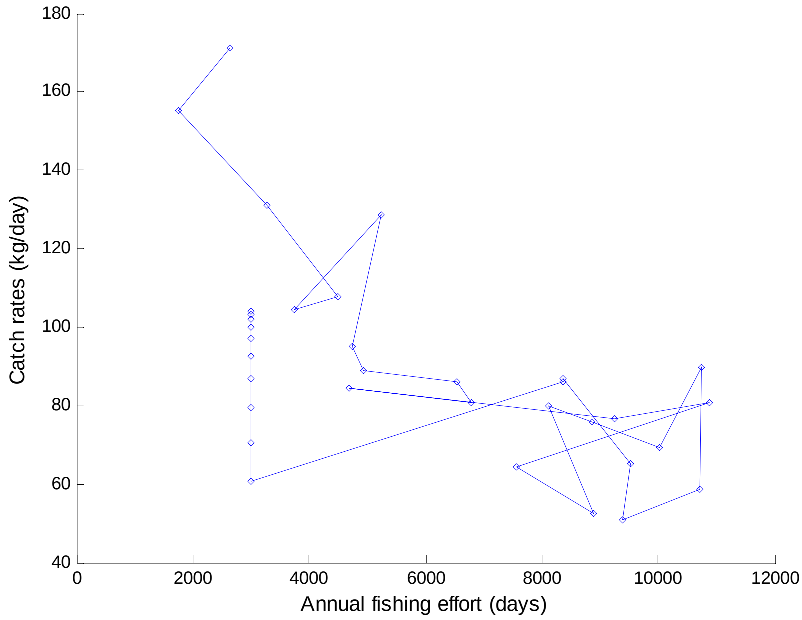

Figure 5.7.8 The annual time series of tiger prawn catch rates and fishing effort, with 10 extra years of simulated (test) data at 3000 days of fishing. This simulated data provided contrast and removed the one-way-trip effect.

5.8 Fishery independent survey

5.8.1 Data and analysis

Fishery-independent recruitment surveys of Torres Strait prawns were conducted between 1998 and 2002 during late February to early March (Turnbull *et al.* 2005). All surveys used the Department of Primary Industries and Fisheries 18-metre research trawler the "Gwendoline May". The surveys were designed to provide standardised catch-rates of commercial prawns by using where possible, the same vessel, trawl nets, time of the season, lunar phase and site locations for each survey. The survey aimed to minimise the variation in catch-rates due to vessel/sampling effects and produce a relative annual index of changes in the recruitment of tiger prawns. As the catch-rates were recorded just prior to the opening of the Torres Strait prawn trawl season, they provide independent information on recruitment levels to the fishery at the start of the season. The timing of the survey each year was as close as possible to the new moon. The survey sites were fixed and chosen to represent both the area open to fishing and the closure areas around Warrior Reef that harbour juvenile prawns. A quad gear configuration consisting of 4 by 4 fathom nets was used to trawl one nautical mile at each sample site.

The location (Figure 5.8.1) and stratification (Table 5.8.1) of the Torres Strait survey sites is based on the known biology of the commercial prawn stock in Torres Strait (Blyth *et al.* 1990, Turnbull and Watson 1991) and the current spatial/temporal closure arrangements for the fishery. The monthly research trawl surveys and prawn tagging conducted by the Department of Primary Industries and Fisheries (DPI&F) during 1985–1991 indicated that brown tiger prawns move off the seagrass nurseries on Warrior Reef into the shallow silty waters to the west of the reef at a very small size, then grow and migrate from the closed area west of Warrior Reef, eastward into the fishery (Turnbull 1991; Turnbull and Watson 1991; Watson and Turnbull 1993).

The brown tiger prawn catches were analysed through a standard general linear model (McCullagh and Nelder 1989). The response variable was based on single net's catch (kilograms) of brown tiger prawns. The main focus of the analysis was to estimate the change in average catch-rates between years for a recruitment index. The sampling sites were considered as nested factors within three areas of the Torres Strait (1) the fishery east of the east-warrior reef closure, (2) east of warrior reef closure and (3) west of the warrior reefs (Figure 5.8.1). The corresponding statistical weights (proportions) used were 0.6, 0.16 and 0.24 respectively. These weights were to account for the spatial size of each area and were calculated by totalling the number of 6x6 minute spatial logbook grids related to each area. The number of grids relating to each area respectively was 45, 12, and 18. The final model specification was:

$$catch = \mu + year + area + area.site + \varepsilon$$

where μ was a scaler parameter for the overall mean, and ε was the normal error term. The statistical software package (GENSTAT 2003) was used to carry out the analysis and provide asymptotic standard errors for all estimates. The analysis of residuals supported the use of normally distributed errors.

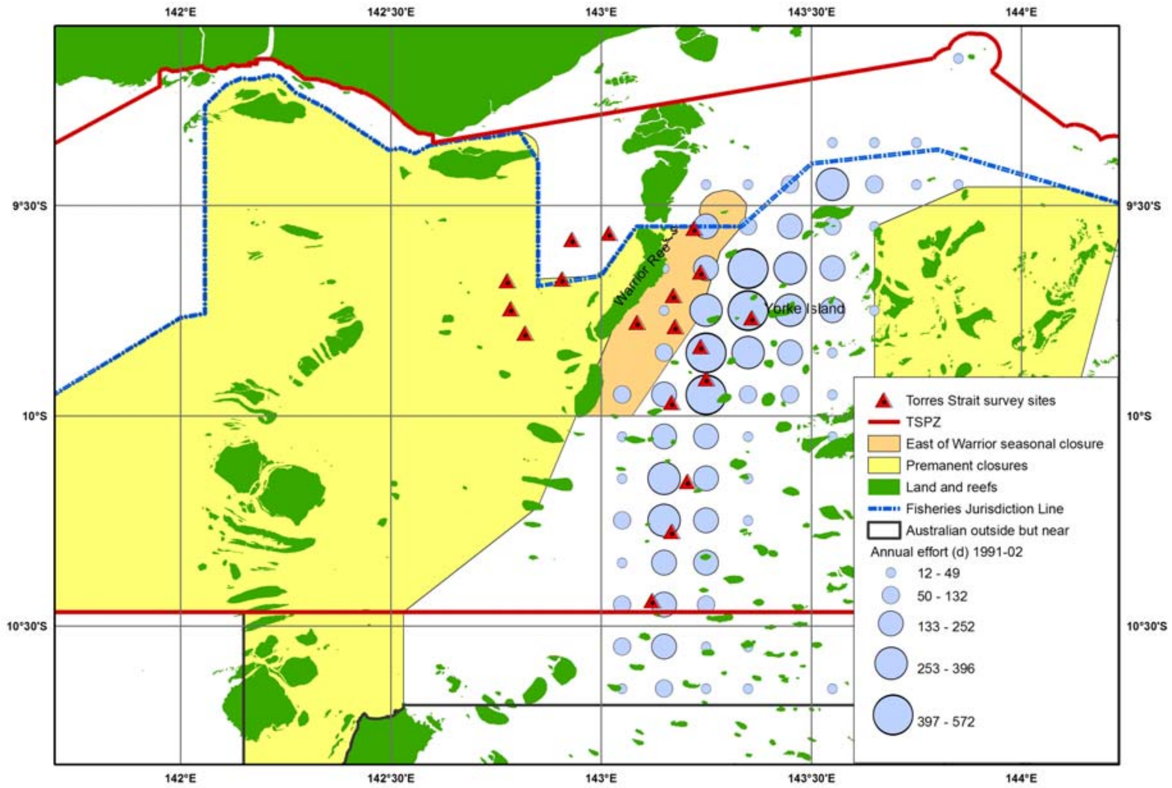

Figure 5.8.1 Torres Strait surveys sites. Note that two sites are within Torres Strait waters that are under Papua New Guinea jurisdiction. The average annual fishing effort by six-minute grid for the years 1991–2002 indicates the main area in which Australian trawlers operate.

Table 5.8.1 Stratification of the Torres Strait survey sites.

Strata name	Number of sites	Description of strata
Fishery	7	Area open to fishing from 1 March to 30 November.
East of Warrior Closure	5	Area open to fishing from the 1 August to 30 November.
West	6	Permanently closed area west of Warrior Reef.

5.8.2 Recruitment index

The weight of all brown tiger prawns retained in each site and net (sample) was used as the response variable to calculate an independent index of recruitment. As the survey was conducted at the end of a three-month seasonal closure and approximately six months after the spring spawning period, most of the prawns can be consider as recruits to the fishery. This index was compared with fishery-based standardised catch-rates from March in each year (section 4.4) and from the delay difference stock model estimated recruitment (section 5.7) (Figure 5.8.2).

All three methods estimated similar recruitment indices from 1999 to 2002. The fishery independent survey indicated much higher recruitment in 1998. A simpler model treating the sampling sites as a blocking term, dropping the three large sub-areas of the Torres Strait, produced nearly identical predictions for the different years as the nested model described above.

The effects of the bycatch reduction and turtle excluder device, and net positions on the survey results were non-significant (*P*>0.05; Table 5.8.2).

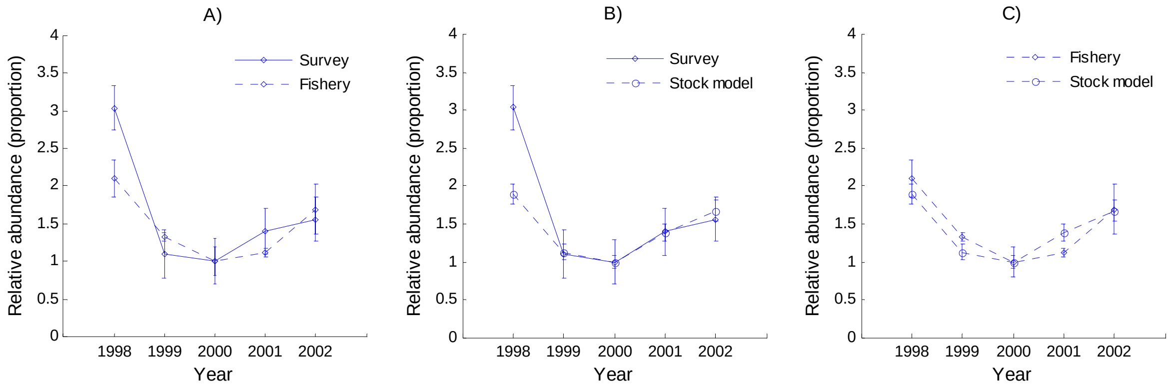

Figure 5.8.2 Comparison of recruitment indices from A) the fishery-independent survey and March standardised catch rates from the fishery, B) the fishery-independent survey and the delay difference stock model, and C) March standardised catch rates from the fishery and the delay difference stock model. All three methods estimated similar recruitment indices from 1999 to 2002. The fishery independent survey indicated much higher recruitment in 1998. Error bars represent 95% confidence intervals.

Table 5.8.2 F-tests showing no significant effects of the bycatch reduction and turtle excluder devices, and net positions on the survey results (P > 0.05).

Treatment	Degrees of Freedom	F-ratio	*P*-value
Bycatch reduction device	1,249	0.26	0.613
Net position	1,315	0.3	0.828

5.9 Discussion

5.9.1 Trawl vessel gear and technology changes

Section 3 quantified the rates of adoption of influential technical changes affecting fishing power in the Torres Strait trawl fishery over the past 24 years (1980-2003). Similar studies were undertaken by Brunenmeister (1981) for the United States shrimp stocks in the Gulf and Mexico, Chifamba (1995) for the Lake Kariba sardine fishery in Zimbabwe, Bishop and Sterling (1999) and Dichmont *et al.* (2003) for Australia's Northern Prawn Fishery (NPF), and O'Neill *et al.* (2005) for Queensland's east coast and Torres Strait's trawl fisheries.

Brunenmeister (1981) examined change in five vessel characteristics; gross tonnage, vessel length, horsepower, net number and average net size. Chifamba (1995) examined vessel mobility, engine type and horsepower, echo sounder, radio usage, winch type, net diameter and depth, the type number and wattage of underwater lights, and interestingly the insurance value of the vessel. Bishop and Sterling (1999) and Dichmont *et al.* (2003) sought information from fishers on vessel and trawl gear specifications, BRD and TED usage, searching capabilities, including deployment of spotter planes, fleet cooperation factors, navigational equipment and factors affecting the swept area of the trawl gear. The most recent of these reports documents that 70% of the fleet are vessels greater than 20 metres in length (mean = 22 metres), average engine power in the order of 400-470 HP, average trawl speed 3.2 knots, average propeller diameter of 64 inches, and that all vessels typically use double gear with bison otter boards. These vessels adopted global positioning systems between 1989 and 1992, and computer mapping software and satellite phones in 1997. The survey by O'Neill *et al.* (2005) and O'Neill *et al.* (2003) found that the Torres Strait trawl fleet was more technically advanced than vessels working in Queensland east coast waters, but less than those operating in the Australian Northern Prawn Fishery. For example, Torres Strait vessels have consistently been larger, with greater fuel consumption, more powerful engines, gearboxes and propellers, and greater average steaming and trawl speeds than Queensland east coast vessels. Another similar comparison can be drawn with Australia's Northern Prawn vessels being larger and more powerful than Torres Strait or Queensland east coast vessels. O'Neill *et al.* (2005) suggested that some technologies were introduced into the Queensland fishery "via the top end", possibly from multiple endorsed (Queensland/Torres Strait/NPF) vessels, and progressively adopted over time in the southern scallop and eastern king prawn trawl sectors.

While the Torres Strait gear and technology database was updated to the end of the 2003 calendar year and the most influential technologies appear to have been considered in the present study, its important to acknowledge that some influences may not yet be identified and that new technologies will continue to be invented and adopted into the future. We strongly support Dr David Die's recommendation 13 (Table 1.1.1, page 7) and the recommendations from O'Neill *et al.* (2005) to continue collecting data on changing vessels characteristics each year. The need for this is to estimate average annual increases in fishing power and to standardise catch rates. This should be achieved using a similar questionnaire approach as used herein, or using "gear sheets" that are completed by fishers with logbook returns (similar to that in the Queensland trawl logbooks), or possibly a combination of the two.

In summary, the results from the gear and technology data confirm that changes in vessel characteristics, fishing gear, navigation and communication have taken place over the last 24 years and that several technologies (e.g. new propeller designs) may still be adopted by the Torres Strait trawl fleet. The adoption of global positioning systems, computer mapping softwares, quad net gear, propeller nozzles, turtle excluder and bycatch reduction devices are nearly at about 100%. Average engine rated horsepower is nearing the management limit of 400 HP. Therefore, these items are unlikely to contribute significantly to higher fishing power in the future. However, new technologies are always likely to emerge and be adopted in future, and therefore the fleet's fishing power will change.

5.10 Fishing power and standardised catch rates

IMPLICATIONS

Fishing power in the Torres Strait tiger prawn sector had significant rates of increase between 1980 and 1999 (Figure 4.3.1). This was not surprising given the increases in average engine size, the number of vessels using global positioning systems and computer mapping softwares. However, since 1999 the trawl fleet's fishing power declined due to the adoption of turtle excluders, bycatch reduction devices and restrictions for smaller net size in 2002 and 2003 (assumed 4% effect; see recommendation 6, Table 1.1.1, page 7). The effects of standardising average catch rates according to changes in average annual fishing power were quite significant (Figure 4.4.2). The resulting catch rates standardised to 2003 fishing power were higher compared to the observed nominal catch rates, and this effect on the stock assessment is quite important. For example, Wang and Die (1996) reported that equilibrium yield estimates for the brown tiger prawn (*P. esculentus*) in the Northern Prawn Fishery were very sensitive to the rate of increase in fishing power. If the rate of annual increase in fishing power in this *P. esculentus* fishery was 2%, maximum sustainable yield would be 2200 tonnes. In comparison, if the annual increase in fishing power were 5%, maximum sustainable yield would be about 1800 tonnes. O'Neill *et al.* (2005) showed that estimates of higher fishing power and therefore higher average catch rates resulted in lower estimates of fishing effort required to harvest maximum sustainable yield (E_{MSY}). It is important to note that our estimates of increases in fishing power were different between years, and their influence on estimates of reference points such as fishing effort at maximum sustainable yield (E_{MSY}) should be examined closely. Especially the selection of the past unit of fishing effort to use in the stock assessment (e.g. fishing power from the most recent year, or the maximum year, etc?; note recommendation 8, Table 1.1.1, page 7)

STATISTICAL COMMENT: CORRELATED ERRORS

In this report general linear models were used to analyse tiger and endeavour prawn catches. The data were essentially observational as each vessel's catch was a result of many factors affecting the swept area of the trawl gear, different fishing strategies, the searching ability to locate high catching areas and other influences from a range of unknown factors. These data differ from experimental data where the effects of particular fishing gears and technologies on fishing power may be quantified by systematically comparing catches with different devices. The method here of using vessel and gear technology data to measure changes in average relative fishing power has been used by Hilborn and Walters (1992), Robins *et al.* (1998) and Bishop *et al.* (2000). One criticism of this approach is that catches from the same vessels fishing in different areas and times are likely to be correlated. This can lead to correlations in the model error structure that may lead to incorrect inferences (due to biased parameter estimates or over- or under- estimated standard errors). Whether any of these will occur, or in which direction, can be difficult to predict in advance, because they depend on the patterns of correlations that occur in the data. In light of this, (Bishop *et al.* 2000) investigated the use of generalised estimating equations (GEE) to allow for the effects of these correlations on parameter and variance estimation in data from a similar prawn trawl fishery, but the gains in accuracy over the general linear model were marginal. The maximum level of bias they reported was twice the "model-based" standard error. All our parameter estimates would still be significant if this bias was applied. However, Bishop *et al.* (2004) recently employed daily data, compared to monthly (Bishop *et al.* 2000), in models that showed little correlation. They compared a range of modelling approaches (linear, mixed, generalised estimating equations - GEE, and general linear models – GLM). In their analyses, the modelling of correlation error structures did not alter conclusions from simpler statistical models. The temporal unit used in this report was daily and as such correlations are less than those of Bishop *et al.* (2000) and supportive of the conclusions by Bishop *et al.* (2004) .

STATISTICAL COMMENT: CONFOUNDING

A recent report by the CSIRO assessed new approaches to fishing power analysis and its application in the Northern Prawn Fishery (NPF) (Dichmont *et al.* 2003). Their data and work highlighted the important problem of confounding. 'Confounding' is the term used to describe when a statistical analysis, for instance using a generalised linear model, cannot accurately separate the effects of different parameters. This is not a failing of the analysis technique, but a failing of the data. Essentially in the NPF, the fishery dependent (observational) catch and effort data lacked information to separate with certainty the annual change in prawn abundance from the annual change in fishing power. Their data was confounded mostly due to vessel's simultaneously upgrading gears and technologies during the long seasonal closures and a systematic pattern of fishing areas within the fishery. In the ideal world confounding is avoided through carefully designed experiments. An example of this would be to ensure that all vessels fished randomly across the fishery using a random combination of all gear types. However, vessels in the NPF fish in a systematic pattern and are working to maximise economic return.

For the Torres Strait, we were cautious given the possible issue of confounding between changing prawn abundance and fishing power. It must be acknowledged that the Torres Strait analysis was based entirely on logbook data. This was the same as for the NPF, however we believe the issue of confounding in the Torres Strait data was less evident. This provided some confidence in our analyses and the catch rate index used in the stock assessment. To demonstrate the quality of data we emphasize the important characteristics of the Torres Strait. The Torres Strait trawl fishery comprises of about 77 active vessels with about as many owners. Vessel upgrades since 1980 have been completed in many different months but mostly during January within the seasonal closure. The range of months when vessels upgraded was probably a result of the Australian owned vessels also fishing in the Queensland east coast trawl fishery. However, since the introduction of the north Queensland trawl closure between 15th December and 1st March, most vessel upgrades in the future will probably be made at this time of year. As well, the Torres Strait is a small spatial area compared the Queensland east coast or the NPF and vessels generally fish in all areas of the fishery. These characteristics provide good contrast together with a mixture of vessels through time having or not having a global positioning system, computer mapping software, propeller nozzle, sonar, bycatch reduction device and a turtle excluder device. In addition a range of net configurations, otter boards and engine sizes were used. To put these useful characteristics in context with the NPF, their vessels have a small number of owners, upgrades are typically all within the seasonal closures, the fishery covers a large spatial area and fishing is systematic in high catching locations targeting at least four different prawn species. These characteristics make estimating fishing power and changes in prawn abundance more difficult compared to the Torres Strait. In summary we have shown strong similarity between our estimated catch rates from the fishery and those from fishery independent surveys, but future analyses should strive to further this work and investigate the need to include fishery independent data in the analyses.

5.10.1 Stock assessment

The stock assessment presented updates the 2002 results for Torres Strait tiger prawns (O'Neill *et al.* 2005). The assessment was based on monthly time steps and captured the seasonal patterns in fishing effort and catches. The model brought together the biological relationships on tiger prawn growth, natural mortality and spawning. It also included estimates of annual increases in fishing power, historical catch rates prior to the compulsory logbook system implemented in 1989, and spawner-recruitment relationships. In addition, the outcome from the monthly model was compared alongside the more simplistic annual surplus production models. It should be noted that the assessment was based on a time series of 24 years and a degree of uncertainty in relation to the estimated spawner-recruitment relationships remain. These spawner-recruitment relationships are key inputs to determine the status of this fishery. They require regular updated analysis and should be discussed in detail by researchers, managers and industry. It was highlighted in the review of the 2001 assessment of tiger prawns in the Northern Prawn Fishery, that with 30 years of catch and effort data, the fishery was still only considered to have limited/moderate data (Deriso 2001).

The results for tiger prawns are needed by management and industry to determine a level of fishing access that is sustainable and options for reduction of latent effort in the Torres Strait. Initially the Torres Strait had a very high level of latent effort that was reduced through reductions in the number of licenses and allocation of fishing days to individual licenses. The allocation of days was based on the highest effort recorded by individual vessels plus 10%, which explains why the current cap (13,570 days of fishing for Australian vessels) has never been reached. Effort in recent years has averaged about 9,000 days and the highest ever recorded was 11,907 days in 1991. The previous assessment by Turnbull and Watson (1995), suggested that the maximum sustainable effort (E_{MSY}) was about 10,600 days using an assumed natural mortality rate of 0.2 per month. The authors (Turnbull and Watson 1995) also noted that due to the mobility of the fleet, fishing effort in Torres Strait was largely controlled by catch rates within Torres Strait and adjacent fisheries. They also noted that if in the future, fishing effort was ‘locked into the fishery’ then the current cap may need to be reviewed. Recent changes to management in Queensland have now restricted the ability of vessels to move freely between fisheries. Hence the need to determine a limit reference point for fishing effort that has a high probability of ensuring sustainable catch levels and accounts for the potential fishing effort of all sectors (Australian, Islander and PNG).

The results from the monthly delay difference model suggest that from 1980 to 1994 tiger prawns stocks were fished down to the level estimated to produce the Maximum Sustainable Yield (B_{MSY}). Since 1994 the delay difference model suggested that stock size appears to have oscillated around B_{MSY}. Recruitment was predicted to be above average in 2002 and 2003, with the biomass in 2003 above B_{MSY}; recruitment from the model was shown to be highly correlated with the fishery-independent recruitment index. The surplus production models show an oscillation about B_{MSY} in 2003, but there was evidence of a continued decline in the time series suggesting a “one way trip” effect when using annual catch rates in the assessment (Hilborn and Walters 1992).

The advantage of the delay difference model was that it utilised the large seasonal changes in catch and effort that provide good contrast to the time-series data. The yearly data used in the surplus production models lacked contrast. The problem with this type of data is that there is little information about management parameters such as optimum exploitation rate or MSY (Hilborn and Walters 1992). As a result the monthly delay difference model appeared to best reflect the dynamics of the data. As an example, the delay difference model indicated increased tiger prawn biomasses in 1992 and 1998 and lows in 1994 and 2000 that corresponded with highs and lows of commercial catch and catch rates. The model biomass estimates also match with recruitment indices from fishery independent surveys conducted during 1998-2002 (Turnbull *et al*. 2005). The indices show the low recruitment in 2000. In contrast the biomass estimates of the surplus production models do not match as closely with the annual pattern of catch and effort.

All of the results indicate that the stock was harvested at MSY (~ 600-680t) and that any increase in fishing effort could reduce stock productivity. The MSY estimates were close to the Maximum Constant Yield for tiger prawn (682 t) estimated by Turnbull and Watson (1995) and MSY (~650t) by O'Neill *et al.* (2005). Estimates of E_{MSY} were variable across the models, ranging from about 8,000 to 13,500 nights. The estimates of E_{MSY} were more variable as they are dependent on the estimate of catchability (q) for each optimal fit and assumption about the changes in fishing power over the time-series. The management quantities estimated from the delay difference modelling were also highly dependent on the spawner-recruitment relationships, which were highly uncertain. To date the Torres Strait managers and industry have focused on using E_{MSY} as a starting point for discussions on reductions in fishing effort. A lower risk approach may be to consider other alternatives such as $3/4E_{MSY}$ (see recommendation 18; Table 1.1.1; page 7).

In this project stock assessment models as described by Dichmont *et al.* (1999), Dichmont *et al.* (2001) and Haddon (2001) were used to analyse the population of Torres Strait tiger prawns. The monthly delay-difference model used a lognormal likelihood to estimate parameters on tiger prawn catchability and recruitment, whereas the annual surplus production model estimated prawn catchability, annual population intrinsic growth rate and virgin stock size. Both models assumed standardised catch rates were a reliable index of population abundance. The monthly model was more applicable as it accurately reflected the important within year pattern of fishing effort. The monthly model allowed for estimation of within year recruitment patterns of the prawns and overall the analyses facilitated critical assessment of the trawl sector, thereby making more effective use of the catch and effort data and past biological work on the species. Further enhancements to the assessment could be made through a new monthly length-based model that utilises both fishery independent and dependent data. Difficulties will remain using surplus production models on the prawn stock, because the model cannot accurately estimate the population intrinsic growth rate (r) with little contrast in annual catch rates. The parameter r had high correlation with estimated virgin stock size, clouding the status of the tiger prawn stock. Ideally strong contrasts between catch rates and fishing effort, and a long time-series is required to estimate surplus production parameters with confidence (Hilborn and Walters 1992).

6 Alternative management strategy workshop

6.1 Introduction

The concept of convening an "Alternative Management Strategy Workshop" for the fishery arose from the David Die review. Recommendations 18 (high priority, Table 1.1.1) which suggests that the "Working Group should develop alternative management strategies to reach target reference points and that these strategies should be evaluated by the management strategy evaluation method". Implicit in this recommendation was the need to define clear reference points for the fishery that are agreed upon by the Prawn Working Group and to develop management strategies that could allow a diversion of effort to target endeavour prawns whilst ensuring that catch of tiger prawns is sustainable. Although the management agencies initially proposed that the workshop occur in mid 2004 as a component of the presentation of the updated stock assessment results, industry representatives were not prepared to participate in a workshop at that point in time.

In March 2005 industry representatives agreed to the concept of the workshop so an organising committee was formed consisting of representatives from the Management Agencies, industry and research. The workshop was held in late July 2005 and was immediately followed by a Prawn Working Group meeting to consider the recommendations from the workshop.

6.2 Workshop objectives

The intent of the workshop was to allow fishers, scientists and managers to collaborate on the development and testing (by simulation) of several alternative management strategies. There was a suggestion that the fishery could be managed more strategically to ensure that the tiger prawns stock was not overfished while simultaneously allowing more fishing effort to be applied to the endeavour prawn stock. This research study had a significant input into the workshop by providing a summary of the available biological information on the Torres Strait tiger prawn stock, the fishery catch and effort data and modifying the delay difference model to allow simulation of temporal and spatial closure options.

The main objectives of the workshop were to:

1. Develop and evaluate possible management strategies that are likely to result in a sustainable harvest of the Torres Strait tiger prawn stock while permitting some additional fishing effort directed towards the endeavour prawn stock.
2. Allow industry and other stake holders to become more familiar with the process of computer scenario modelling and develop an appreciation of the possible outcomes of different management scenarios.
3. Allow industry to have an input into and a feeling of ownership of the management arrangements in the fishery.

Objective 2 was achieved by providing workshop participants access to an Excel version of the delay difference model. This version was specifically designed to:

(a) Serve as an educational tool that would enable workshop participants to become more familiar with the assessment process and the response of the delay difference tiger prawn model to various levels of fishing effort and closure options.

(b) Provide a tool for testing a variety of alternative management scenarios proposed by the workshop participants.

6.3 Overview of the workshop

The workshop was well attended by industry and Torres Strait Islander representatives. Robert Ferguson attended as the representative for the Department of Environment and Heritage. Mark Plunkett, a Barrister with experience in fisheries and conflict negotiation, was contracted as the independent Chair to facilitate the workshop proceedings. The workshop agenda allowed considerable time for discussion of management issues and options both in small groups and as the combined group. The small groups were encouraged to use the Excel model that had been loaded onto a number of computers spread around the conference room.

The workshop commenced with a key presentation on status of the fishery and known biology of tiger prawns in Torres Strait to set the scene for the workshop. This presentation provided the background required by participants to discuss management options. The main sections of the presentation were;

1) The commercial catch and effort data (see section 2)
   a) Historical trends in catch and effort, both spatial and temporal.
   b) Significant management changes that have occurred in the fishery - closures, limited entry.
2) A summary of biological research (Blyth *et al.* 1990; Turnbull and Watson 1991; Watson and Turnbull 1993)
   a) The results of monthly trawl surveys and tagging programs conducted by DPI&F Torres Strait Prawn Project during 1986-1991.
   b) Current knowledge of the tiger prawn life-cycle – recruitment, growth, migration and spawning, based on all of the research conducted in Torres Strait.
3) Stock assessment
   a) The assessment process and the results of the July 2004 assessment (see section 5).
   b) Forward simulation model – an introduction to the Excel version of the simulation model.

During the course of the workshop there were a number of presentations from other invited speakers. Samara Miller (Industry), Barry Evans (Industry) and Cameron Dixon (SARDI), jointly gave a presentation titled "*South Australia's Spencer Gulf: Are there any lessons to be learnt from this fishery?*". This was an overview of the Real Time Management (RTM) used in the Spencer Gulf prawn fishery. The Gulf has been divided into a large number of fishing blocks and regions. During fishing operations a "committee at sea (of fishers)" provide information to the Primary Industries and Resources South Australia (PIRSA) on an ongoing basis, which is used to amend in "real time" a sustainable harvest strategy for the fishery. The strategy is based on opening and closing of individual "blocks". The "committee at sea" base their advice on reports of undersized product and "spot" surveys conducted by fishers in areas closed to fishing. This presentation was effective in stimulating discussion of ideas for the management of the Torres Strait fishery, in particular the concept of an extension of the East of Warrior closure to reduce growth overfishing during the early months of the season.

Dana Hanna (Australian Bureau of Agricultural and Resource Economics) presented the result of an economic study of the Torres Strait Prawn Fishery and discussed the advantages of Individual Transferable Quotas (ITQs) as a management option. Industry clearly noted that they did not consider ITQs as an appropriate management option for the TSPF.

Philip Polon (NFA, PNG) was invited to discuss the Torres Strait Prawn Fishery from the Papua New Guinea perspective. His presentation highlighted the logical and economic constraints that have limited participation by PNG vessels in the TSPF.

The two remaining presentations were mainly information items. Roland Pitcher (CSIRO) presented preliminary results from the TS CRC Seabed Mapping project (*T 2.1 Mapping and Characterisation of Key Biotic and Physical Attributes of the Torres Strait Ecoystem*). The aim of this project is to contribute to ecosystem-based management of the fishery by providing the data needed for ecological modelling of the Torres Strait. The initial maps indicate that much of the trawl area has a sand substrate that is devoid of flora and fauna. Francis Pantus (CSIRO) then gave a presentation on the Ecological Modelling that is currently under development for Torres Strait (*T 3.3 Integrated Ecosystem Modelling for Evaluating Multiple-use Management Strategies*). One of the objectives of the Task is to evaluate the primary effects of trawling and the performance of different options for managing the fishery to achieve environmental objectives.

The workshop was effective in bringing together industry, management and other interested groups to brain-storm the current issues related to the management of the fishery and various management options for the fishery.

6.4 Background data

Plots of recent (1998-2004) monthly catch and effort data split between North and South of 10 degrees latitude were provided as a reality check for the model simulations (Figure 2.1.1 and Figure 6.4.2). The slight differences in the distribution of tiger and endeavour prawn stocks between the northern and southern sections of the fishery are the basis of a key assumption in the simulation model.

Examination of the figures indicates that;

- Effort is generally focused in the northern section during the early months of the season, particularly in years of higher tiger prawn recruitment (1998, 2003 and 2004).
- A larger proportion of the tiger prawn catch is taken from the northern section and catch rates of tiger prawns tend to be lower in the southern section.
- Although the catch rates of endeavour prawns are similar between the two areas they are higher in the south at the start of the season during years of good recruitment (1999).

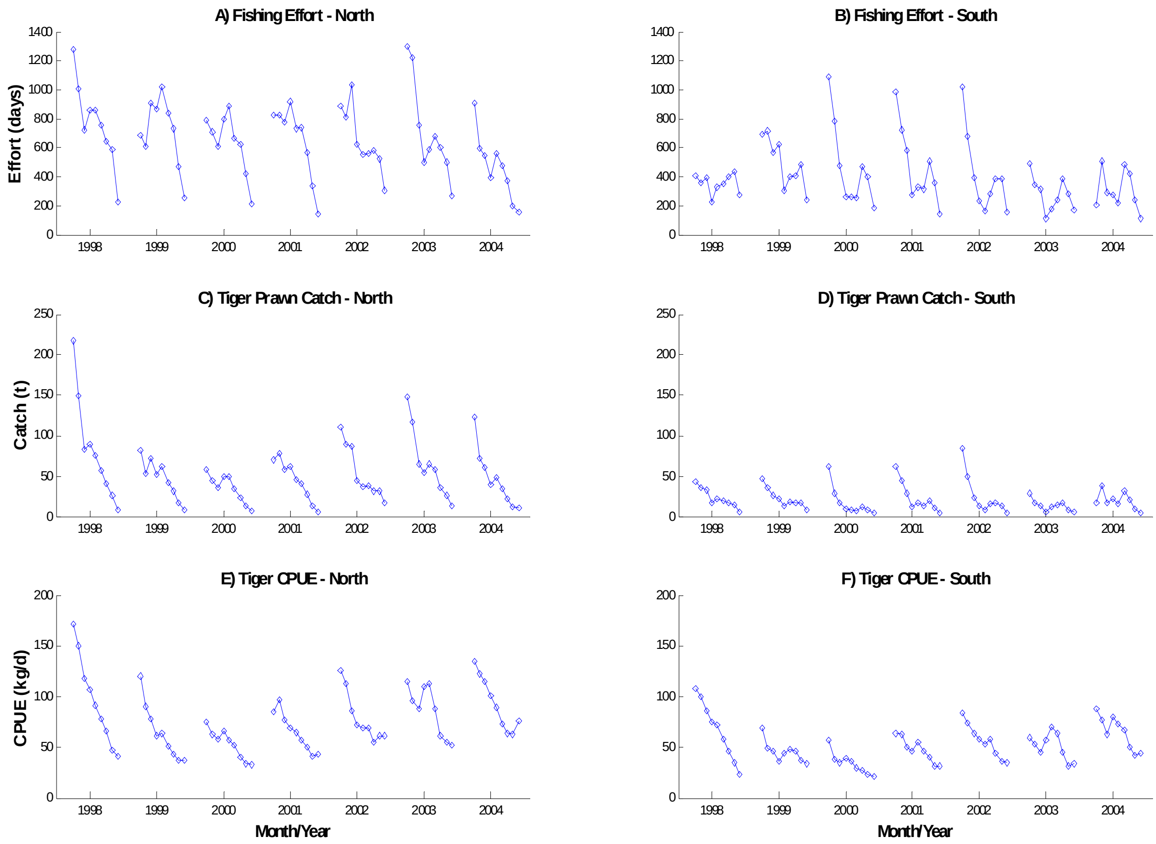

Figure 6.4.1 Monthly fishing effort, tiger prawn catch and catch rates north and south of 10 degrees latitude for the years 1998-2004.

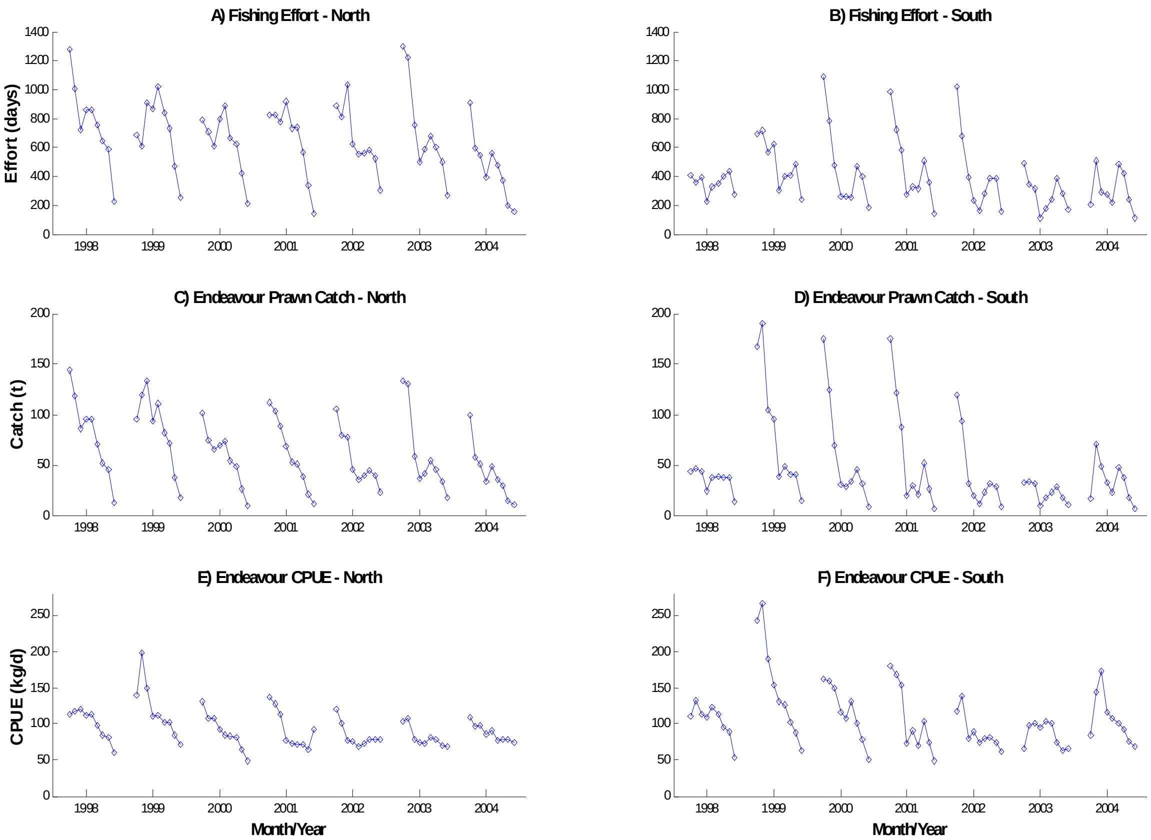

Figure 6.4.2 Monthly fishing effort, endeavour prawn catch and catch rates north and south of 10 degrees latitude for the years 1998-2004.

6.5 Workshop outputs

6.5.1 Summary of discussion and proposals

The following points were raised by workshop participants during the discussion components of the workshop, but were not final positions of any participants.

1) Total allocated days - legal cap
   a) There was a strong feeling by industry representatives of the need to preserve the asset value of the total allocated days by maintaining the current allocated fishing days at their current level (i.e. no reduction in days allocated).
   b) There was a clear understanding by all participants that all days allocated in the fishery would not be used (i.e. fishing habits and patterns would not change from current activities).

2) Allocated fishing days - fishing cap
   a) The use of trigger points, such as daily catch rates or total effort days (9,197 days) were discussed to control effort in the tiger prawn fishery.
   b) The need to consider the effect on endeavour prawns of any controls on tiger prawn fishing was raised, with a 2nd trigger point (12,000 days) discussed as a way of limiting effort.
   c) It was noted that the trigger cap proposals were based on no change to fishing patterns in the fishery.
   d) Discussions on target reference points and limit reference points as fishing caps were discussed, with the need to move towards target reference points noted to maintain long term sustainability.
   e) The need to review the reference points determined in 12 months following the restructure of the fleet (after vessel reductions due to the buy back arrangement

announced by the Acting Prime Minister on 27 July 2005.), and an update of the model to include data from the restructured fleet was discussed.

3) Use of moon closures in the fishery (see results section 4.4, Figure 4.4.3)
   a) The remoteness of the fishery was raised as a concern, with the cost to transfer crews during closure back to the mainland noted as prohibitive, and a concern with crews spending time on Islands was also raised as a concern by operators.
   b) The potential economic benefit for the region of moon closures was raised.

4) The potential benefits of a mid-season closure were raised. It was suggested that a closure in the prawn fishery sometime during June/July/August may;
   a) Reduce pressure on the tiger spawning stock and
   b) Reduce the potential trawl impacts on migrating tropical rock lobsters (TRL). Hence such a closure may benefit both the prawn and TRL fisheries.

5) Effects of changes in effort or fishing patterns on other fisheries and on the lifestyles of islanders needs to be considered as part of the process.

6) It was suggested that effort discussions should be focused on biomass available and not in terms of days.

7) Staged reductions
   a) Jim Prescott presented to the workshop two examples of staged effort reductions that included elements of the proposed buyback and uncompensated reductions. He noted that this was something that he had worked on and brought to the workshop without having discussed it with the management agencies and presented to stimulate discussion and did so without prejudice.
   b) Industry did not accept this proposal and noted that they did not want any form of a staged reduction.
   c) A number of participants raised concerns with the effect on the value of entitlements if a staged reduction approach was adopted.
   d) It was noted that a staged reduction process may assist stocks to better adjust as opposed to one large reduction.

8) Seasonal “shifting” closures (opening areas as season progressed) were proposed as a means of promoting larger prawn sizes (increasing value of catch) and also helping to preserve the biomass of the stock. This concept was drawn from the presentation by the South Australian participants.

9) Accessing additional fishing grounds (west of warrior) to share biomass across areas was also suggested to assist in sustainability of the stocks.

10) The potential to use other government programs (eg Prawn Industry Partnerships) to assist industry to adjust was raised.

11) Many noted the need to find or develop a model to assess the effects on stocks of endeavour prawns to changes in effort, fishing patterns and seasons as an important issue that must be addressed.

12) The use of the delay difference (Beverton Holt) model with updated figures to set effort levels for tigers for coming seasons was discussed as an important part of the process.

13) Industry representatives asked for the supply of preseason survey information to the industry to allow for adjustment of fishing patterns in response to stock levels and distribution if required.

The following is a copy of the written proposal submitted by industry to the workshop and subsequent Prawn Working Group meeting.

Key Industry Proposal - Key Industry Interests/Concerns

1. to ensure a sustainable fishing effort control is in place for the tiger prawn stock;
2. to ensure a sustainable fishing effort control is in place for the endeavour prawn stock; and
3. to maintain Industries assets (i.e. licences and allocated fishing days entitlements – whether these are held by Australian industry or PNG).

Industry proposes the following arrangement to deliver what we believe is a good outcome for both the sustainability issues and the asset retention issues.

Historically industry thought the fishing cap or caps had to be the same as the "legal" allocated fishing days cap. Given the major problems caused by this assumption, industry tried to find better ways to achieve both the sustainability and asset retention outcomes.

In summary industry propose that;

1. the existing total fishery effort cap of 13,454* allocated fishing days remain in place as the legal allocation cap and also the endeavour prawn fishing cap;

*this number will reduce as licences are amalgamated or sold out through the buy back arrangement announced by the Acting Prime Minister on 27 July 2005.

2. Within this overall fishing cap, have a "sub-cap" or control point for maximum sustainable fishing effort for tiger prawns.
   - Fish as normal, taking a mix of tiger and/or endeavour prawns until total fishing effort reaches 9,200 Allocated fishing Days (AFDs) measured by VMS
   - If/when 9,200 AFDs actual fishing effort is reached, then licensees are notified and identified areas of the fishery are closed to stop targeting of tiger prawns on the key tiger prawn grounds. This still allows fishing to continue in areas remaining open for endeavour prawns. Note that some small number of tiger prawns will still be taken but David Die felt that this would not be enough to cause any significant impact on tiger stock sustainability.

6.5.2 New proposed closures

Following the workshop a small committee of industry members and researchers collaborated to define the location of the spatial/ temporal closures options proposed during the workshop. The location of the closure lines were based on an examination of logbook data for the whole fleet summarised by month and six-minute logbook grid, personal fisher records and local fisher knowledge.

Three new spatial/ temporal closures (Figure 6.5.1.) were proposed:

1. Tiger spawner closure
   This area is the deeper trawl ground on the eastern side of the fishery and would be closed when effort reaches the tiger prawn trigger point. Industry believes that this area contains the main tiger prawn spawning grounds. The results of monthly research surveys conducted by DPI&F during the late 1980's indicate that tiger prawns in this area have a high fecundity (Blyth *et al.* 1990).

2. Full moon closure (see results section 4.4, Figure 4.4.3)
   This area (which is a subset of the area encompassed by the "tiger spawner closure") would be closed for a period of about 10 days over the full moon during the latter months of the season (possibly August to November). This closure would be implemented independently of the effort applied in the fishery. The aim of the closure is to reduce targeting of large spawning tiger prawns over the full moon. Industry representatives noted that in recent years there has been a shift of fishing effort over the full moon periods from the shallower area on the eastern side of Warrior Reef to the deeper water

east of Yorke Island. This shift in effort is a result of a decline in catch rates in the shallower areas whereas catch rates are maintained in the deeper water. This is possibly a result of the moonlight having less impact on prawn behaviour due to the increase in water depth.

3. An extension of the East of Warrior Closure (EWC)
   This area is an extension of the east of Warrior Reef spatial/ seasonal closure and would be closed for the first month or two of the season (March and April?). Although this closure is mainly aimed at preventing growth-overfishing by reducing targeting of the smaller prawn grades (> 30 count per pound) it could also allow more tiger prawns to spawn prior to being harvested. Data from monthly DPI&F research surveys conducted during 1986-1991 indicate the average size of female tiger prawns inside the proposed closure would be less than 31 mm carapace length (CL). Research on the reproductive condition of Torres Strait tiger prawns (Keating *et al.* 1990) and the Gulf of Carpentaria (Crocos 1987) indicate female brown tiger prawns of less than 32 mm CL have a much lower fecundity due to reduced maturity and insemination rates.

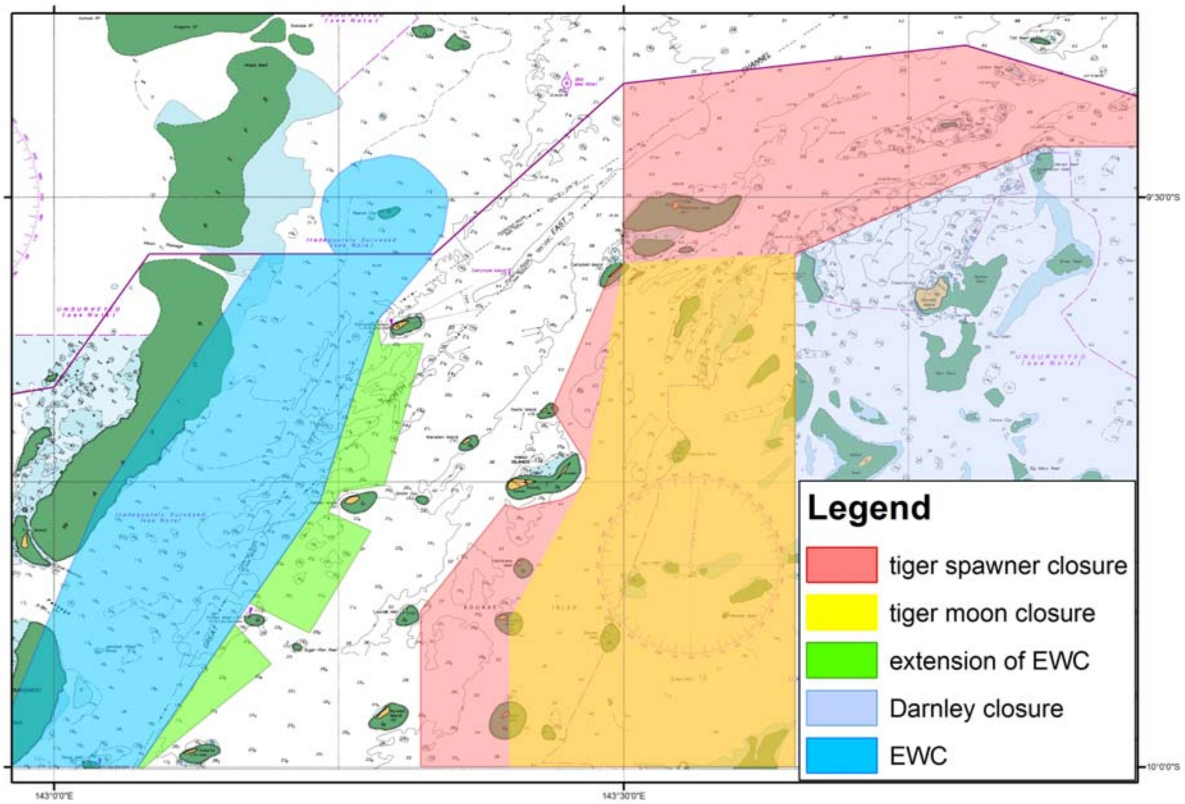

Figure 6.5.1 The new proposed closures. The existing East of Warrior and Darnley Closures are also shown.

6.6 Delay difference simulations

The performances of different management strategies were tested through a series of example simulations (Table 6.6.1). The simulations were run for two forms of spawner-recruitment relationships, different levels of fishing effort corresponding to $E_{MSY,}$ 80% E_{MSY}, effort between E_{MSY} and 80% $E_{MSY,}$ and in excess of E_{MSY}, and for different assumptions on the proportion of the overall tiger prawn stock in southern Torres Strait waters. The management strategies defined and tested at the workshop were:

1. When the year's cumulative fishing effort totalled the tiger prawn effort limit, additional fishing effort up to the total fishery effort limit was allowed only in southern Torres Strait waters.
2. When the year's cumulative fishing effort totalled the tiger prawn effort limit, the fishery was closed for the year.

For the management strategies, fishing mortality F_t in the forward projection component (2006 – 2015) of the delay difference model was modified by:

$$F_t = \begin{cases} q_{fishery} fp_t E_t & \text{for} \quad E_{cum} \le E_{tc} \\ q_{fishery} fp_t q_{adj} E_t A_t, & \text{for} \quad E_{cum} > E_{tot} \end{cases};$$

where $q_{fishery}$ was the average catchability of tiger prawns for the fishery in 2003 (labelled q in Table 2.4.1), fp_t was the proportional change in annual fishing power relative to 2003, E_t was the number of vessel days fished in month t, q_{adj} was the proportional adjustment in tiger prawn catchability for fishing only in southern Torres Strait waters, A_t *was* the proportional selectivity adjustment to fishing mortality F_t when fishing was restricted to southern Torres Strait waters, E_{cum} was the cumulative annual effort fished by month t, E_{tc} was the annual limit on tiger prawn fishing effort and E_{tot} was the annual limit on all trawl effort.

The algorithm we used for the simulations was similar to the forward projection methodology used by (Richards *et al.* 1998); further details are in (O'Neill *et al.* 2005). The simulation steps are outlined in Table 6.6.2. Details of the uncertainties allowed for are shown in Figure 6.6.1. On this figure the bolded lines with diamond markers indicate the base case averages for annual fishing power change, monthly pattern of fishing effort and monthly spawning pattern for tiger prawns. Normal random variations are illustrated for natural mortality (μ=0.2, σ=0.025), prawn growth (μ=0.908651667, σ=0.090865166) and the reduction (q_{adj}) in tiger prawn catchability (μ=0.82037, σ=0.02673512) for fishing only in the southern Torres Strait (> 10°S); where μ was the mean and σ was the standard deviation. Log-normal random variation is shown for the error ($e^{N(0,0.2178)}$) on predicted annual recruitments from the spawner-recruitment relationship. The uncertainties on model estimated parameters were generated using their covariance matrix to construct a multivariate normal distribution (Figure 6.6.2).

To evaluate potential management strategies the monthly delay difference model was used to operate the future possible or hypothetical dynamics of the tiger prawn population up to 2015. The model captured the temporal dynamics of the stock and allowed for stochastic variations (uncertainty) in all parameters. The other component of the simulations was the application of a fishing strategy (fishing effort). The expected outcomes from the simulations and probabilities indicating risks of overfishing relative to maximum sustainable yield are presented in the results section. The results assessed the consequences of a range of options which were discussed at the workshop. The results do not define a final management strategy or decision, but rather provide information on which to base management choices. At the workshop no target reference points were agreed on and outcomes from simulations were considered against only against the limit reference point of B_{MSY}. Note that different management options to these herein were examined by O'Neill *et al.* (2005).

Table 6.6.1 Ten different fishing efforts and southern area sizes were simulated through the delay difference model.

Model run	Spawner recruitment	Tiger prawn effort cap (E_{tc})	Fishery effort cap (E_{tot})	Southern sector (proportion on fishery A_t)
1	Beverton-Holt	9197	9197	0.4377
2	Beverton-Holt	7358	7358	0.4377
3	Beverton-Holt	9197	12000	0.4377
4	Beverton-Holt	8000	11000	0.4377
5	Beverton-Holt	7358	10000	0.4377
6	Beverton-Holt	7358	10000	0.34
7	Beverton-Holt	7358	10000	0.54
8	Ricker	8245	8245	0.4377
9	Ricker	6596	6596	0.4377
10	Ricker	8245	12000	0.4377
12	Ricker	6596	10000	0.4377

Table 6.6.2 Simulation algorithm in Matlab.

1. Optimise the base stock assessment model to the observed catch rate data for the stock.
2. Use the estimated model parameters and their covariance matrix to construct a multivariate normal distribution.
3. Draw a random sample parameter vector from the multivariate normal distribution.
4. Draw a random sample of values from the assumed known parameters.
5. Use the random sample of parameters to drive the delay difference model and to obtain a sample historical trajectory for the stock.
6. Choose a model run to test and starting level of fishing effort.
7. Run the operating model forward 10 years. Recruitment is simulated under a spawner-recruitment relationship.
8. The process from steps 3 to 7 were repeated a large number of times, to obtain a large number of trajectories, each of which reflected the correlations among model parameters estimated (1000 times).

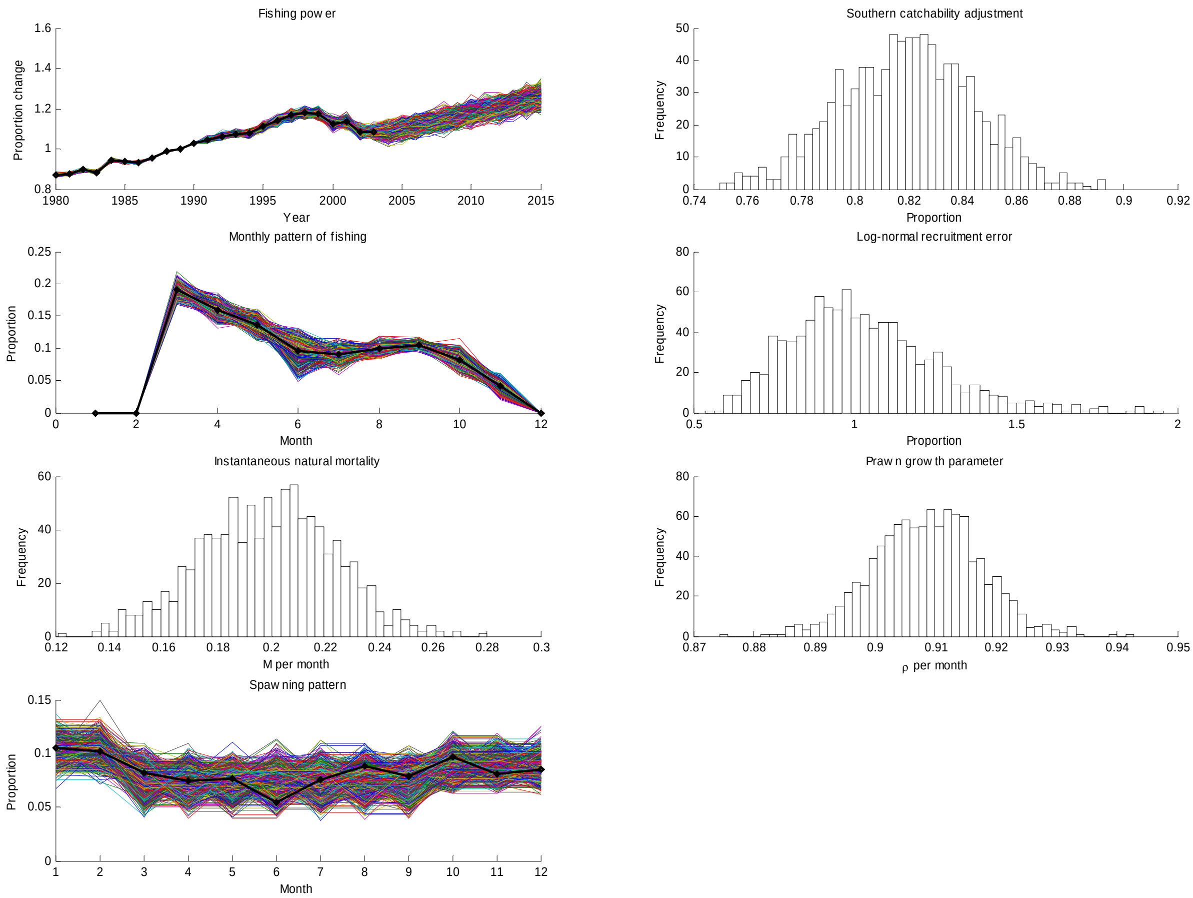

Figure 6.6.1 Plots of the uncertainties allowed for in the delay difference model.

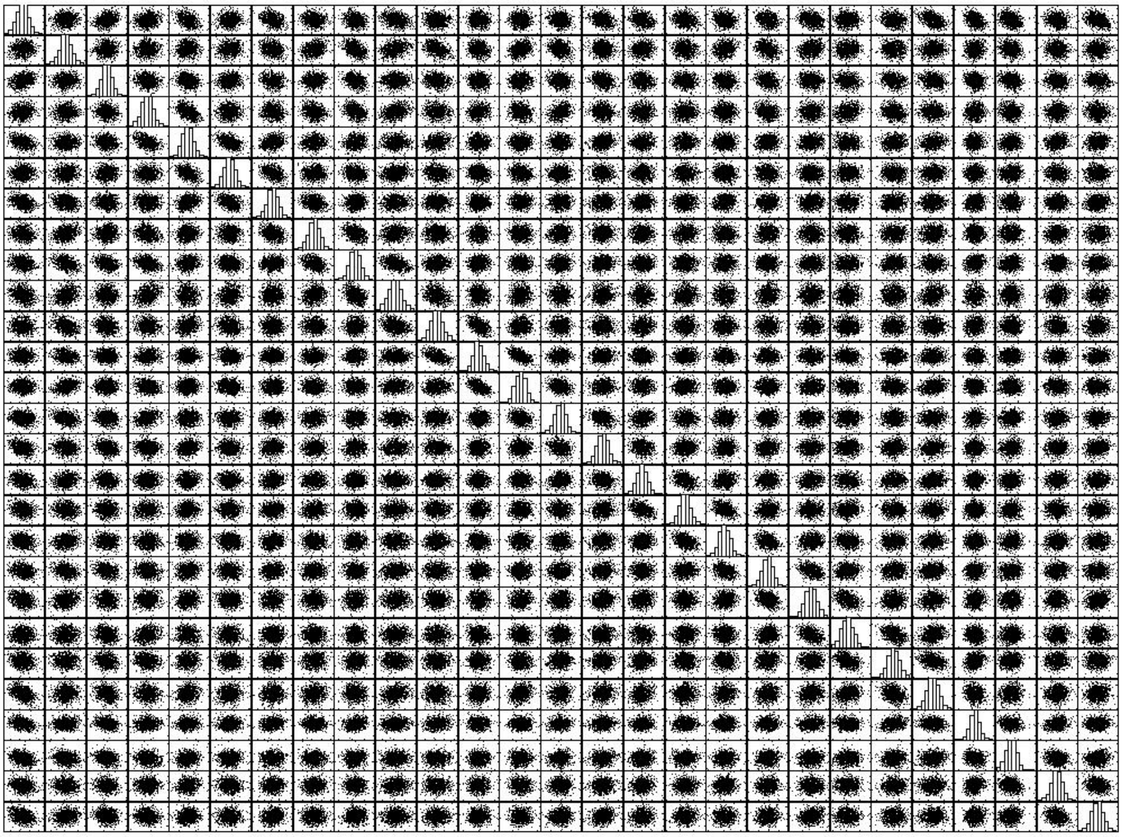

Figure 6.6.2 Matrix plot of 1000 random values of each model-estimated parameter as generated from the multivariate normal distribution with maximum likelihood estimates and covariance matrix. The row and column plots of parameters are ordered q,μ,κ, $N_{r,1980}$ … $N_{r,2003}$.

6.7 Results

The results presented in this section focus on the performance of different fishing strategies through the monthly delay-difference model using the Beverton-Holt and Ricker spawner-recruitment relationships (Table 6.6.1). The ten year forecasts from these simulations are summarised in

Table 6.7.1 and the yearly forecasts in Figure 6.7.1 to Figure 6.7.11 The results were presented to allow the reader to evaluate the trade offs in performance. The results do not define a final management strategy or the future status of tiger prawns, but rather they provide expected outcomes that may be used to help select appropriate fishing strategies.

For the simulations run, higher biomass ratios would be attained by the 80% E_{MSY} fishing strategy assuming either the Beverton-Holt or Ricker spawner recruitment relationships (model runs 2 and 9; Figure 6.7.2 and Figure 6.7.9**)**. After ten years, the median biomass ratios levelled just above B_{MSY} with a probability of about 60% confidence. The other fishing strategies resulted in lower biomass trajectories that fell below B_{MSY} with greater than 50% probability. The probability of future biomasses falling below B_{MSY} were much greater by setting limits for the tiger prawn fishing at E_{MSY} and for the fishery at 12000 days (model runs 3 and 10; Figure 6.7.3 and Figure 6.7.10**).**

The simulations indicated that for the fishing strategies examined the expected annual harvests of tiger prawns would be similar at about 680 t under the Beverton-Holt or 610 t under the Ricker spawner-recruitment relationship (

Table 6.7.1). The 80% E_{MSY} fishing strategy resulted in less variation between annual harvests and higher catch rates (Figure 6.7.2 and Figure 6.7.9).

The comparisons of outcomes from each fishing strategy were similar assuming either spawner-recruitment relationship or different fishery areas in southern Torres Strait waters.

Table 6.7.1 Median performance measures from the 10 year forward projection (2015) of each model run and fishing strategy.

Model run	Biomass ratio (B_{2015}:B_{MSY})	Risk P(B_{2015}<B_{MSY})	Harvest (tonnes)	Harvest standard deviation	Annual catch rate (kg / vessel day)
1	0.92	0.69	684	177	43
2	1.09	0.41	661	156	51
3	0.76	0.87	692	191	36
4	0.82	0.79	685	179	38
5	0.89	0.71	679	171	42
6	0.89	0.69	677	169	42
7	0.89	0.72	680	173	41
8	0.90	0.72	617	163	56
9	1.07	0.42	592	141	66
10	0.73	0.92	616	182	45
11	0.87	0.81	612	165	54

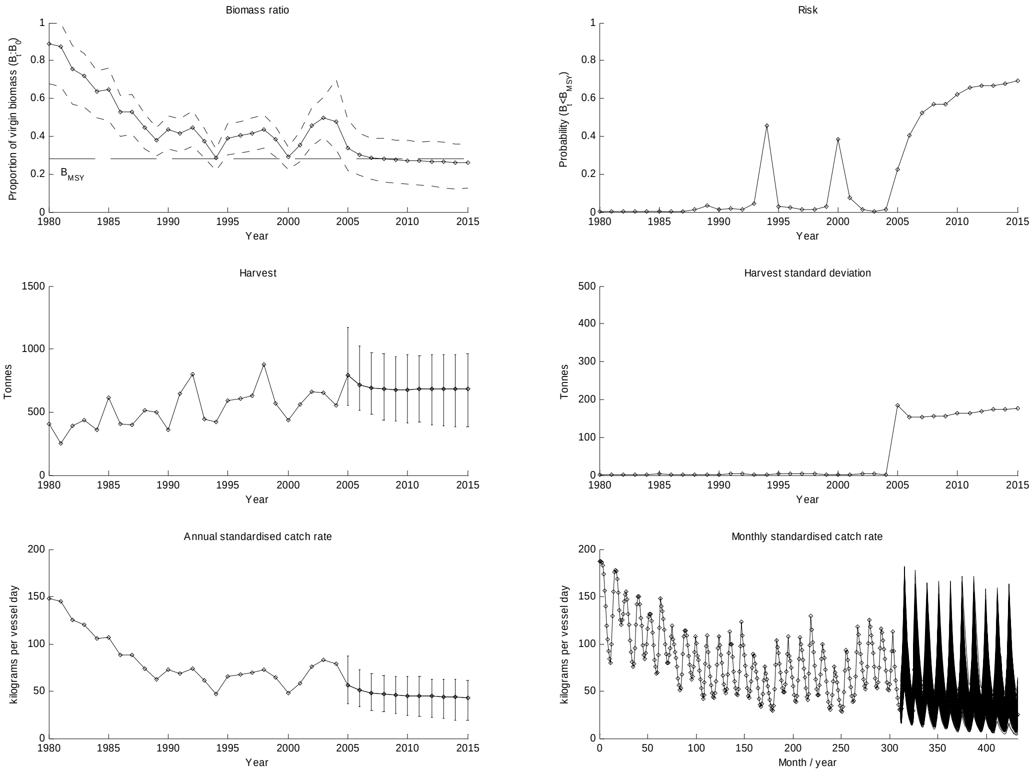

Figure 6.7.1 The expected biomass and harvest outcomes for Torres Strait tiger prawns from fishing to E_{MSY} in all areas; assuming the Beverton-Holt spawner recruitment relationship (model run 1).

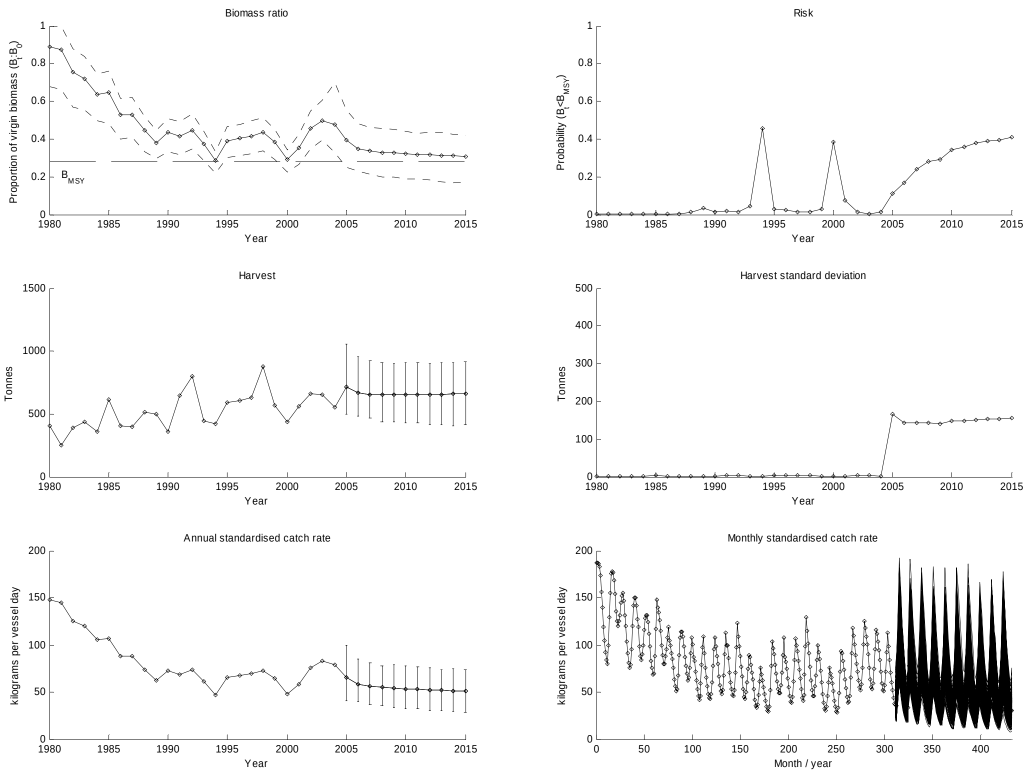

Figure 6.7.2 The expected biomass and harvest outcomes for Torres Strait tiger prawns from fishing to 80% E_{MSY} in all areas; assuming the Beverton-Holt spawner recruitment relationship (model run 2).

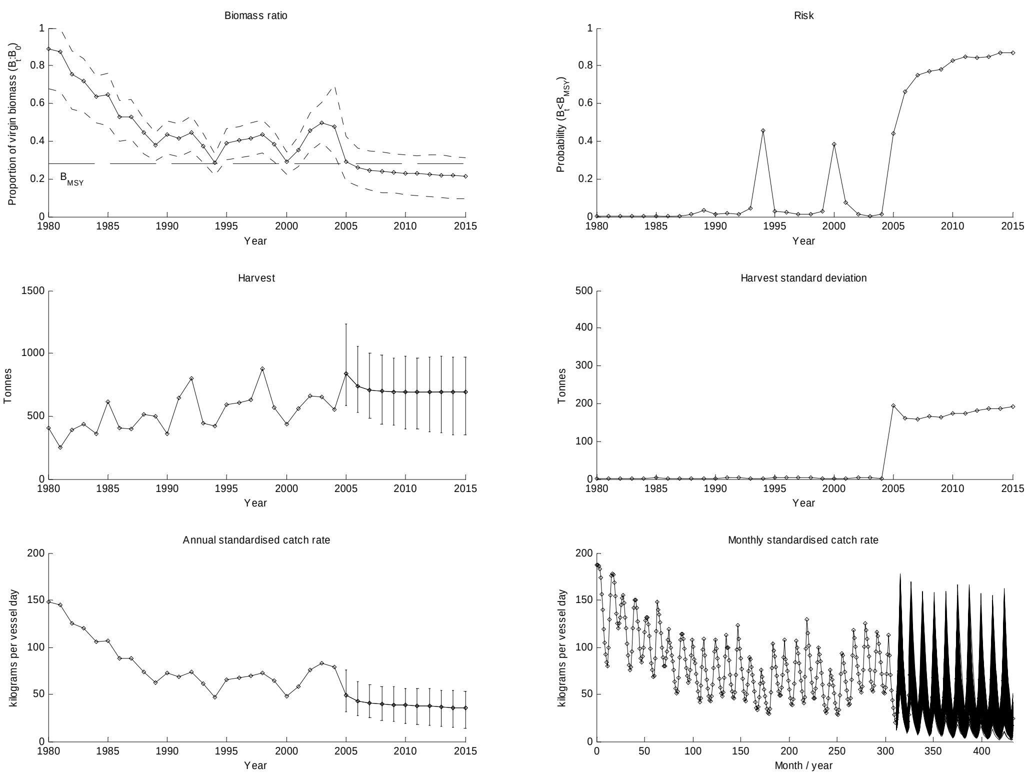

Figure 6.7.3 The expected biomass and harvest outcomes for Torres Strait tiger prawns from fishing to E_{MSY} in all areas, plus additional days in southern waters to total 12000 days; assuming the Beverton-Holt spawner recruitment relationship and a southern fishery area of 0.4377 (model run 3).

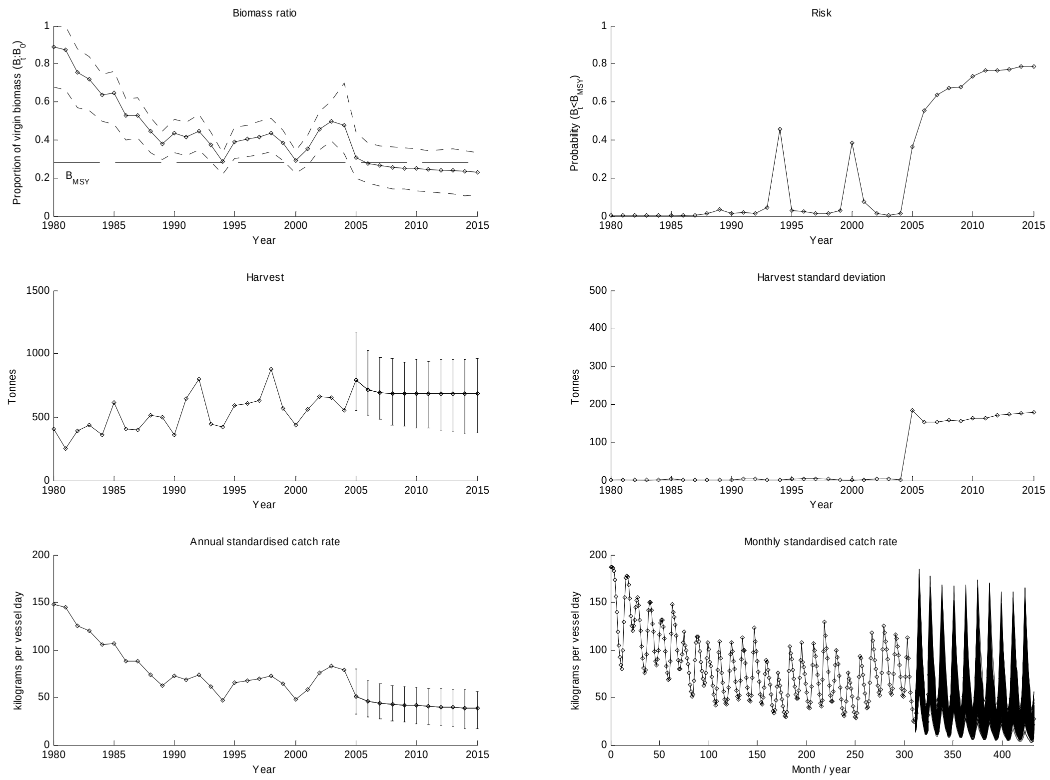

Figure 6.7.4 The expected biomass and harvest outcomes for Torres Strait tiger prawns from fishing to 8000 days in all areas, plus additional days in southern waters to total 11000 days; assuming the Beverton-Holt spawner recruitment relationship and a southern fishery area of 0.4377 (model run 4)

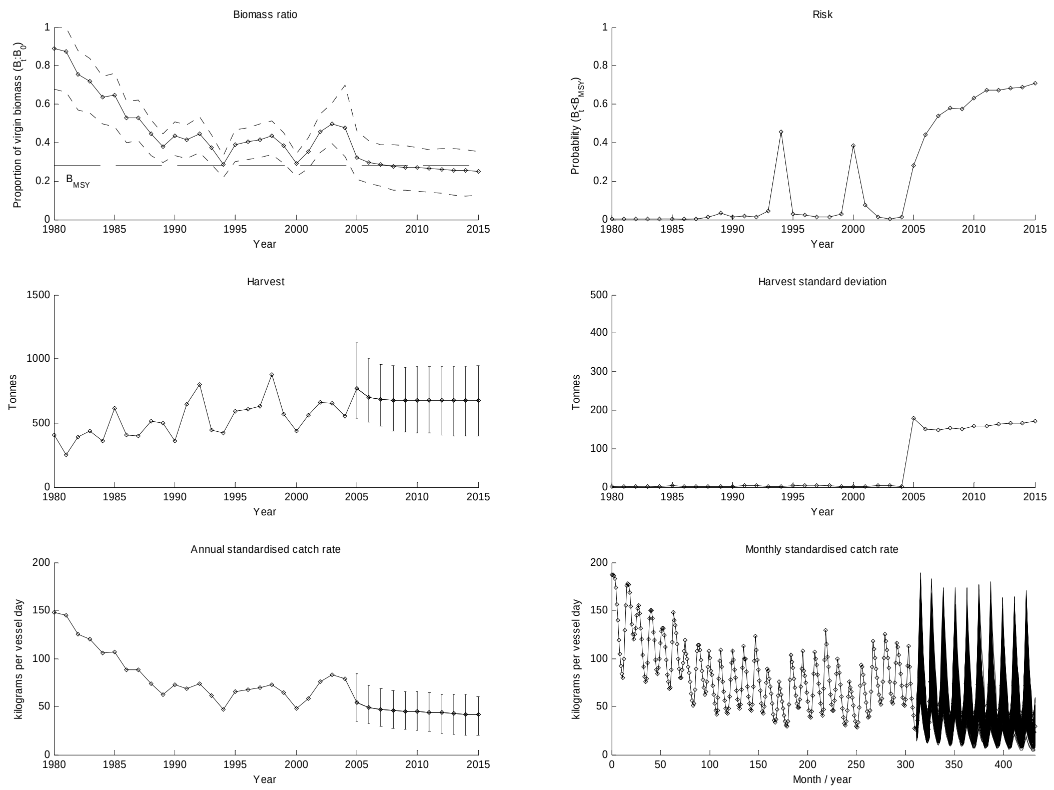

Figure 6.7.5 The expected biomass and harvest outcomes for Torres Strait tiger prawns from fishing to 80% E_{MSY} in all areas, plus additional days in southern waters to total 10000 days; assuming the Beverton-Holt spawner recruitment relationship and a southern fishery area of 0.4377 (model run 5).

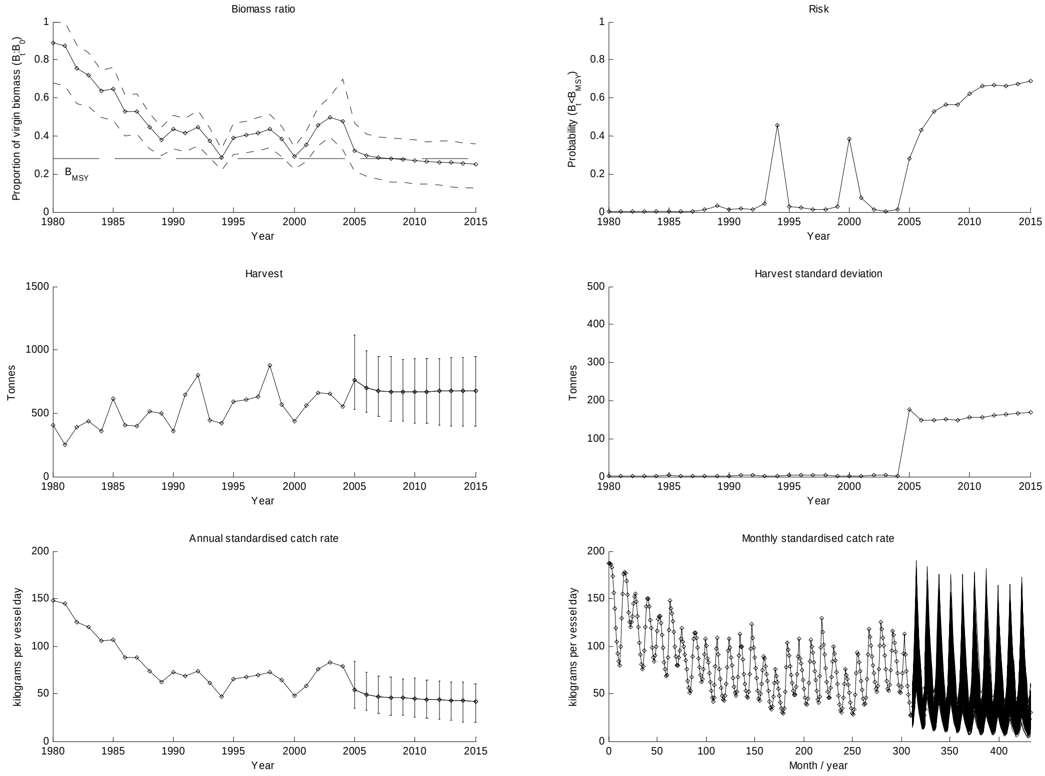

Figure 6.7.6 The expected biomass and harvest outcomes for Torres Strait tiger prawns from fishing to 80% E_{MSY} in all areas, plus additional days in southern waters to total 10000 days; assuming the Beverton-Holt spawner recruitment relationship and a southern fishery area of 0.34 (model run 6).

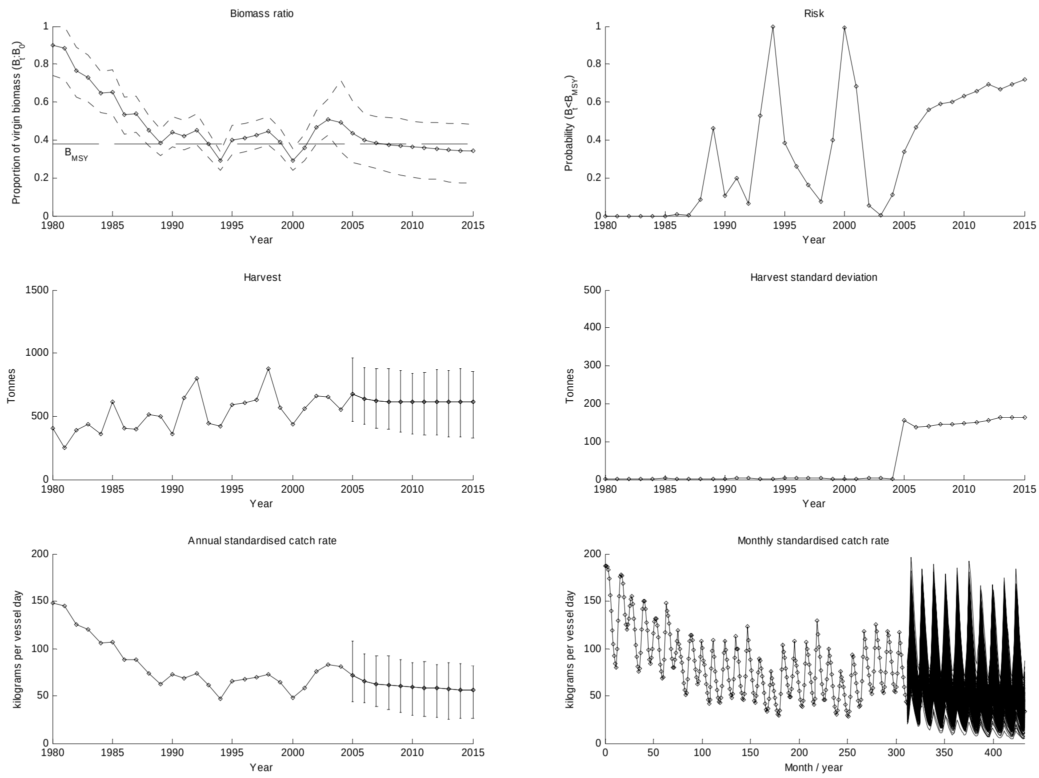

Figure 6.7.7 The expected biomass and harvest outcomes for Torres Strait tiger prawns from fishing to 80% E_{MSY} in all areas, plus additional days in southern waters to total 10000 days; assuming the Beverton-Holt spawner recruitment relationship and a southern fishery area of 0.54 (model run 7).

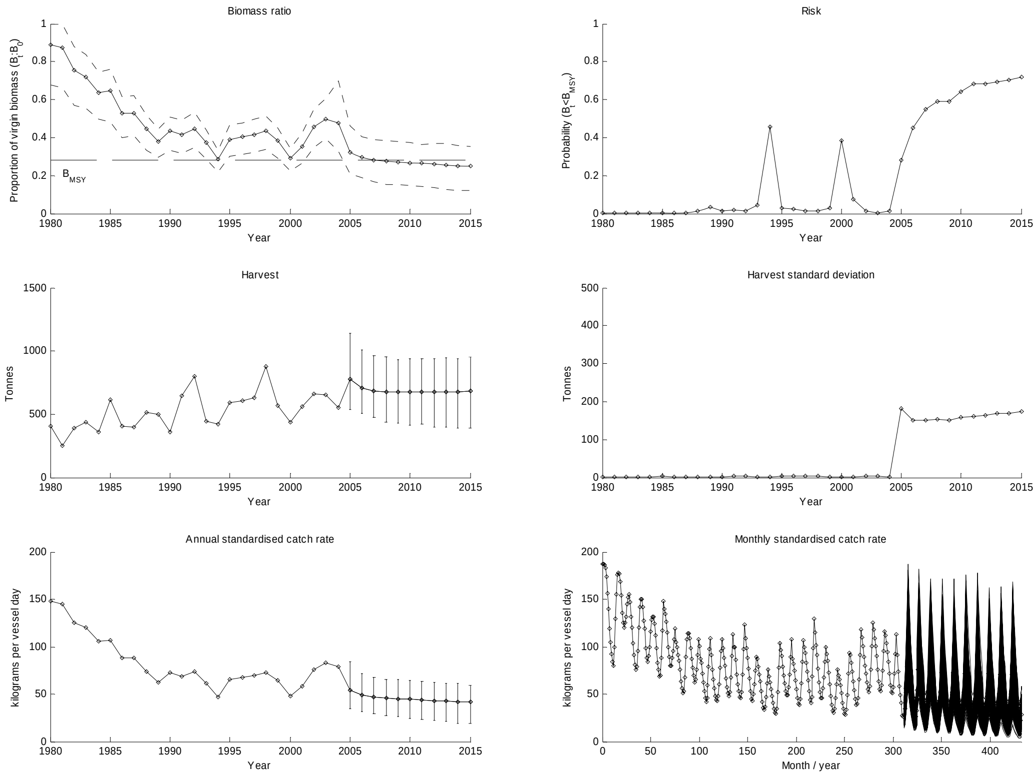

Figure 6.7.8 The expected biomass and harvest outcomes for Torres Strait tiger prawns from fishing to E_{MSY} in all areas; assuming the Ricker spawner recruitment relationship (model run 8).

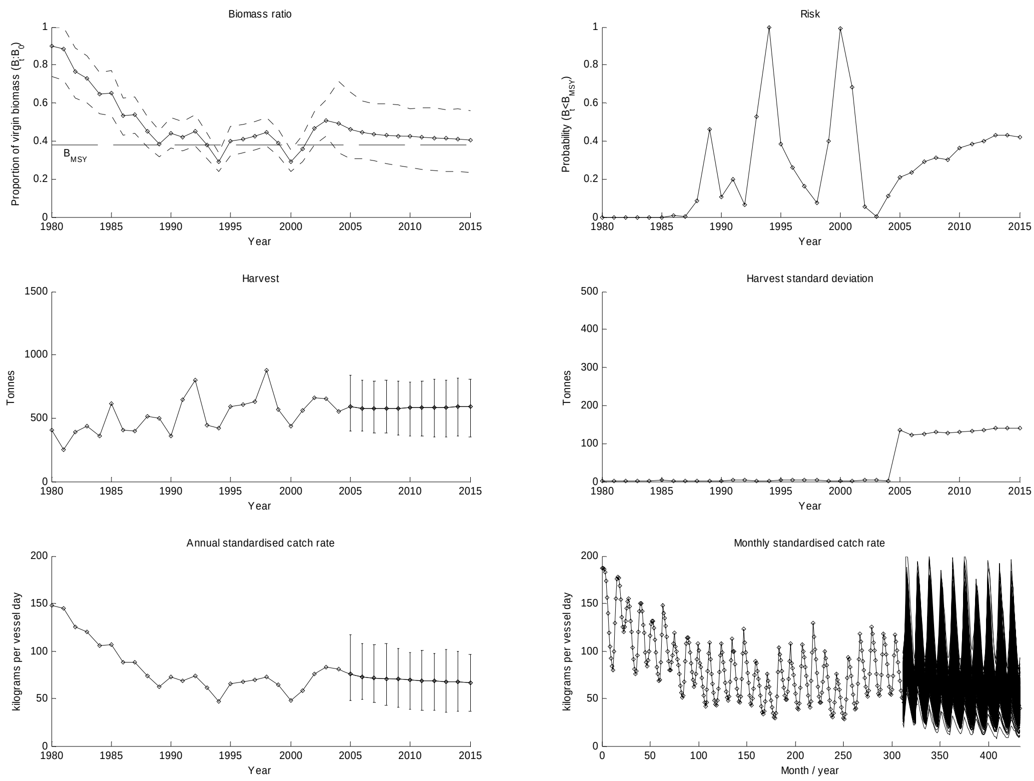

Figure 6.7.9 The expected biomass and harvest outcomes for Torres Strait tiger prawns from fishing to 80% E_{MSY} in all areas; assuming the Ricker spawner recruitment relationship (model run 9).

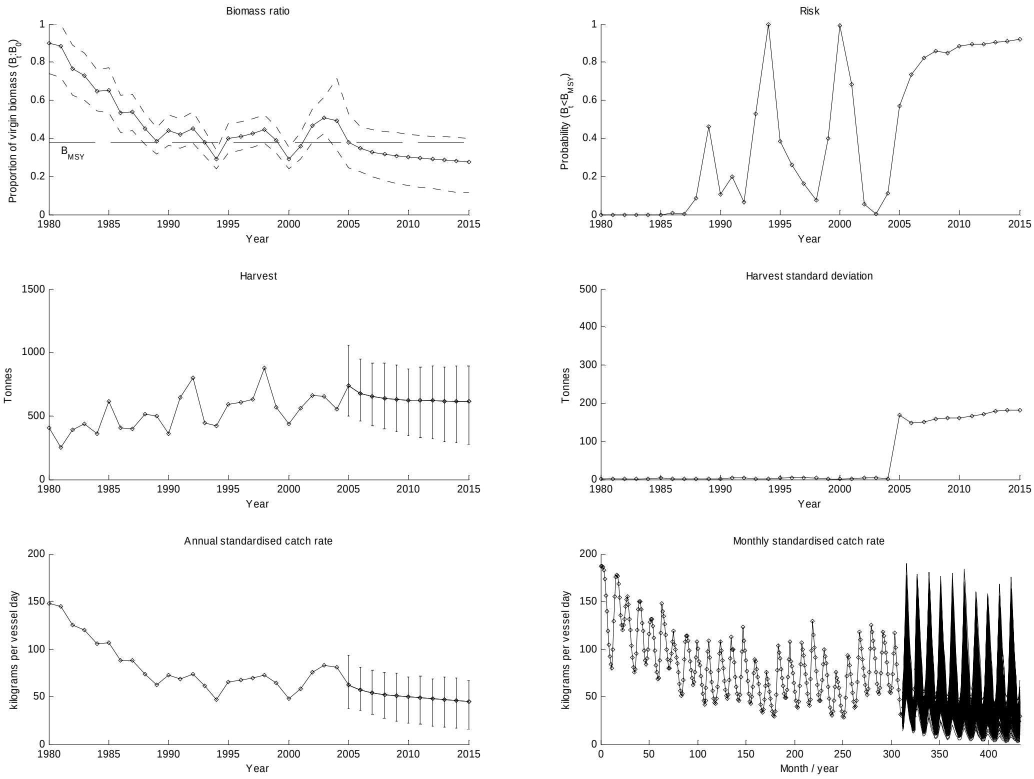

Figure 6.7.10 The expected biomass and harvest outcomes for Torres Strait tiger prawns from fishing to 80% E_{MSY} in all areas, plus additional days in southern waters to total 12000 days; assuming the Ricker spawner recruitment relationship and a southern fishery area of 0.4377 (model run 10).

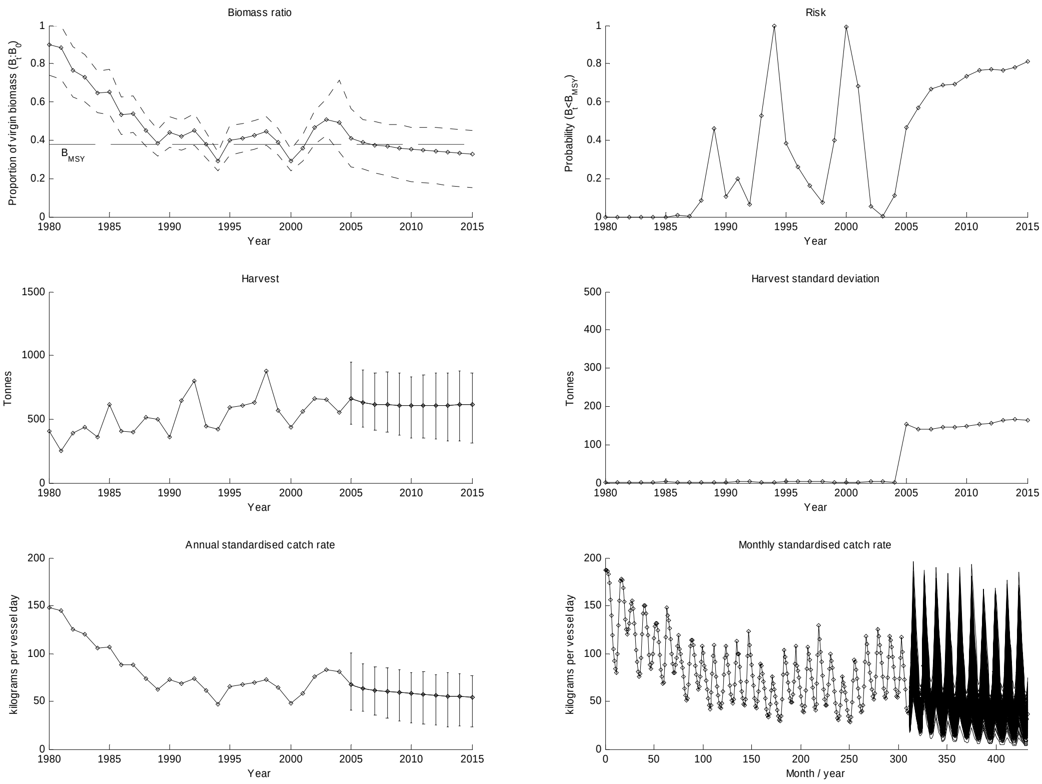

Figure 6.7.11 The expected biomass and harvest outcomes for Torres Strait tiger prawns from fishing to 80% E_{MSY} in all areas, plus additional days in southern waters to total 10000 days; assuming the Ricker spawner recruitment relationship and a southern fishery area of 0.4377 (model run 11).

6.8 Discussion

6.8.1 Alternative management workshop

The workshop was successful and achieved all of the stated objectives. With respect to objective 1, industry and managers at the workshop agreed on proposing that there should be a limit on total trawl fishing effort in the Torres Strait and within this total limit, a sub-limit be introduced to control fishing on tiger prawns. This management framework (strategy) was incorporated into the delay difference model. The Excel version of the model (objective 2) was well received and utilised by workshop participants to test ideas. The Excel model was also used to illustrate during the final discussion session, the predicted trends in future biomass, catch and catch rates for the industry proposal compared with high and low levels of total fishing effort. In terms of objective 3, the workshop provided an ideal opportunity for a wide range of industry members to discuss and propose management options.

The announcement during the workshop by the Acting Prime Minister and Minister for Trade, the Hon Mark Vaile MP, that the Australian Government proposed the purchase entitlements to formally account for Papua New Guinea using their treaty entitlements in the fishery, had a significant impact on the industry participants. This proposed buy-back was factored into the workshop discussions.

The main proposal developed at the workshop was the strategy of using trigger points to control the allowable effort in the fishery. Industry supported this concept as an additional, mechanism for limiting effort at levels that are considered sustainable. They argued that this mechanism would be easy to implement and have less impact on licence holders than adjusting the allocated days. Two trigger points were suggested. The first would activate a spatial closure aimed at reducing the impact of any further fishing on the tiger prawn spawning stock. The second would close the whole fishery to limit the total annual catch of tiger prawns to a sustainable level. Industry noted that the trigger points they proposed for the 2006 season were limit reference points and that in the current economic climate of high fuel prices it was unlikely that this effort limit would be reached. Industry recommended an updated stock assessment and review of the trigger points during the later part of 2006 to adjust the trigger points. The assessment update would account for changes that may occur in the fleet structure as a result of to the proposed buy-back announced during the workshop. In addition Industry indicated they would consider moving towards target reference levels once the new system had been in operation for a few years.

It should be noted that on 9th November 2005, independent of the alternative management workshop, the Torres Strait Protected Zone Joint Authority (PZJA) announced that trawl licences will be granted for the 2006 season with pro-rata reductions to an overall cap of 9197 days (E_{MSY}; Beverton-Holt spawner recruitment relationship).

6.8.2 Simulations and reference points

The comparison of different fishing strategies from this report and those from O'Neill *et al.* (2005) has provided DPI&F, AFMA and their management committees a basis to consider sustainable levels of fishing for tiger prawns in Torres Strait waters. The results quantified the benefits of various fishing strategies. However, the strategies were not selected to optimise management for the Torres Strait tiger prawn fishery; as the objectives are yet to be defined. This research was timely and provided updated information for further discussion of potential reference points, management strategies and objectives.

The simulations suggested that from 2003, where the tiger prawn biomass was above B_{MSY}, fishing at 80% E_{MSY} would expect to result in future biomasses above B_{MSY}. It should be noted that stock assessment is prone to uncertainties (especially in the spawner-recruitment relation) and for this reason fishing at or greater than E_{MSY} had higher risks of lower biomasses and performed poorly in relation to expected harvest outcomes for industry. Compared to 80% E_{MSY}, similar expected outcomes for tiger prawn biomasses and harvests were calculated for ¾ and 2/3 E_{MSY} (O'Neill *et al.* 2005). These fishing strategies (80%, ¾, or 2/3 of E_{MSY}) appear effective at maintaining the Torres Strait tiger prawn stock above B_{MSY}, but not exceedingly, resulting in lower risks of under or over fishing, maintaining harvests and improving catch rates. These fishing strategies would also result in less frequent management interventions (O'Neill *et al.* 2005).

Stock assessment recommendation 18 from Dr Die is yet to be resolved. Management have defined the use of B_{MSY} or E_{MSY} as limit reference points. However, no target objectives for the fishery have been defined. These should be developed by the Prawn Working Group. Setting a target reference point can be easy in the management process, but identifying the mechanisms to achieve the target is more difficult. Table 6.8.1 lists two hypothetical starting points to consider for defining target reference points. These reference points are model-based, however data-based reference points could also be considered and further examples of target fishing strategies should be compared from other fisheries (e.g. South and Western Australia). In addition the example thought process or questions that could be followed to define a target reference point might be:

- What is the current exploitable stock size?
- What target levels of exploitable stock size do management want?
- What is the timeframe to achieve the target level?
- What mechanisms can be used to achieve target?

Section 6.5 summarises outputs from the workshop that may help define mechanisms for achieving target reference points.

Table 6.8.1 Two hypothetical examples of defining model-based reference points. *P*=probability.

Limit reference point	Target reference point	Review period	Strategy to achieve target
B_{MSY}	1.2 B_{MSY}	Annual stock assessment	¾ E_{MSY}
$P(B_t>B_{MSY})=0.5$	$P(B_t>B_{MSY})=0.7$	Annual stock assessment	2/3 E_{MSY}

7 Summary

7.1 Summary of the objectives that were achieved

Objective 1. Addressing most of the high and medium priority recommendations from the independent review of the Torres Strait Tiger prawn stock assessment to minimise uncertainties in the scientific advice on sustainable fishing levels in the prawn fishery.

The overall key objective in undertaking this study was to reinforce the scientific advice provided to the Torres Strait Protected Zone Joint Authority (PZJA). This project successfully achieved this by updating the tiger prawn stock assessment to 2003. In total 16 out of 21 of Dr Die's high, medium and low priority recommendations were incorporated into the assessment (Table 7.1.1). Of the five recommendations not completed, three were being addressed by the Torres Strait CRC task 1.5, the collection of landings data for the years prior to 1980 was not feasible as we were unable to locate any operators from that period who had retained their catch records and the recommendation to use a target reference point of either 75% or 80% EMSY was a management recommendation yet to be employed. After incorporating the recommendations the results from the updated assessment were similar to (O'Neill *et al.* 2005) in terms of biomass ratios between 1980 and 2001 and estimates of MSY.

Table 7.1.1 Summary on the accomplishment of review recommendations

Recommendation number, priority and abbreviation from the independent review (detailed in Table 1.1.1)	Recommendations addressed?	Report section where completed or otherwise
1. Medium – correction factors for logbook landings.	No	Addressed by CRC Task 1.5.
2. Low – harvest taken by Papua New Guinea vessels.	Yes	2.1
3. Low – allocating unloading data to time periods.	No	Addressed by CRC Task 1.5.
4. Low – commercial size grading data.	No	Addressed by CRC Task 1.5.
5. High – chain size reductions since 2001.	Yes	2.2 and 2.3
6. High – net size reductions since 2002.	Yes	2.2 and 2.3
7. High – update fishing power estimates.	Yes	2.3
8. High – select a unit of fishing effort.	Yes	2.4
9. Medium – standardise endeavour prawn catch rates.	Yes	2.3
10. Medium – area strata for catch rate standardisations.	Yes	2.3
11. Medium – use GLM for calculating catch rates.	Yes	2.3
12. Medium – data only from vessels prior to 1988.	Yes	2.3
13. Medium – vessel characteristics database.	Yes	2.2
14. Medium – collect harvest data prior to 1980.	No	No operators retained catch records.
15. High – test production model.	Yes	2.4
16. High – all data used in production models.	Yes	2.4
17. High – use delay difference model.	Yes	2.4
18. High – set target reference points.	No	Management recommendation not set.
19. High – working group to develop fishing strategies.	Yes	3
20. Medium – MSE to assess strategies.	Yes	3
21. Medium – status quo from last two years.	Yes	2.3 and 2.4

Objective 2. Developing via the Prawn Working Group (PWG)/ Industry Workshop, alternative management strategies to cap effort directed at tiger prawns at sustainable levels while investigating an increase or diversion of effort towards endeavour prawns.

In March 2005 industry representatives agreed to the concept of the workshop and so an organising committee was formed consisting of representatives from the management agencies, industry and research. The workshop was held in late July 2005 and intended to allow fishers, scientists and managers to collaborate on the development and testing (by modelling) of several alternative management strategies. Participants at the workshop utilised an Excel version of the delay difference stock model and focused on developing a fishing strategy that was likely to result in the sustainable harvest of Torres Strait tiger prawns while permitting some additional fishing towards endeavour prawns in southern Torres Strait waters (>10°S). This research project participated significantly at the workshop by providing a summary of the available biological information on the Torres Strait tiger prawn stock, the fishery catch and effort statistics, the status of the tiger prawn fishery and modifying the delay difference assessment model to allow simulation of management options. The outcomes from assessing this fishing strategy through simulation are described below under objective 3.

Objective 3. Assessing the impact of the alternative management strategies developed in point two above using state of the art Management Strategy Evaluation (MSE) modelling techniques.

The performances of different management/fishing strategies were tested through a series of 1000 simulations of the delay difference stock model through the computer software Matlab. The simulations showed that from 2003, when the tiger prawn biomass was above B_{MSY} (the biomass which supports maximum sustainable yield), fishing at 80% E_{MSY} would be effective at maintaining tiger prawns above B_{MSY}, but not exceedingly, resulting in lower risks of over fishing, maintaining harvests and improving catch rates. Fishing for tiger prawns at E_{MSY} and allowing extra effort for endeavour prawns had higher risk of tiger prawn biomasses falling less than B_{MSY}, higher variation between annual harvests and lower catch rates.

Objective 4. Collate the commercial harvest data from the Papua New Guinea (PNG) side of the fishery to factor into the stock assessment.

Daily catch and effort records of Papua New Guinea vessels operating in the Torres Strait Protected Zone were provided by the National Fisheries Agency in Papua New Guinea. The total recorded tiger prawn catch was about 36 tonnes and the total recorded fishing was 880 days. The annual tiger prawn catch ranged from 0.4 tonnes (2001) to 11.8 tonne (1988). This catch was included with the tiger prawn harvest taken by Australian vessels in the assessment.

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9 Appendix – Reviewers Comments

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February 28, 2006

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Dear Mr. O'Neill;

I am writing to provide a review of the revised stock assessment entitled "Stock Assessment of the Torres Strait Tiger Prawn Fishery". I have reviewed Dr. David Die's comments on the previous version of the assessment and evaluated the changes in the document in response to his comments.

I found this assessment to be quite comprehensive and enjoyed the authors approach to describing uncertainty throughout the document. The assessment is very clear about the assumptions made, and sensitivity analyses were incorporated throughout. I believe the revised document effectively addressed Dr. Die's recommendations. The authors re-analyzed portions of the data listed as high priority (e.g., fishing power, standardized CPUE, both the surplus production and delay-difference models) in response to his comments. The result was an improved assessment. Below I highlight the areas that have been improved in this revision, and note a few places where assessments in the future could benefit.

- The description of how outliers in the predicted standardized CPUE data would influence the likelihood estimates was very useful, and the model shows a good fit (Figure 5.7.4).

- The lack of contrast in the annual catch-rate and effort plots (Figure 5.7.7) is very typical of fisheries data, and I agree it limits the inferences that can be made using annual trends. The decision to go with the monthly catch rates in the delay-difference model is warranted.

- The use of ten years of simulated data to compare the Matlab surplus production model results to the more commonly used ASPIC software analysis (recommended by Dr. Die) was a useful exercise and confirmed that the Matlab version originally used will provide similar parameter estimates (page 58).

- In future assessments, I recommend a different organization in the text. The text of this assessment seemed scattered, with methods following results repeatedly as the assessment moved from the CPUE standardization to the modeling sections. I would prefer a distinct methods section followed by results. The organization made it somewhat difficult to find portions, because methods were spread throughout the document.

- The authors define confounding on page 65 as a problem with the data rather than the analysis. Although this is true once confounding has occurred, confounding itself is the result of an inadequate experimental design to separate effects. In this case, the assessment was unable to fully separate prawn abundance from changes in fishing power, but the problem appears to be relatively minor for the Torres Strait fishery given the large number of vessels and owners, which provided contrast in the data. To address this problem in future assessments, fishery independent data could be collected at varying fishing powers (e.g., HP or net configurations) to assess the differences in catch rates. My point here is that fishing power can be separated from abundance changes and it may be important to do so, but it cannot be done from fishery dependent data where all vessels are increasing in fishing power at roughly the same rate each year. Future fishery independent sampling efforts could consider a range of gear designs to provide contrast in the fishing power data each year. The authors made this point on page 66, and I agree that fishery independent data could provide contrast and will likely be important in the future.

- The correlation between the delay-difference model predictions and the fishery independent recruitment index is a very strong point in this assessment (p. 67) and lends credence to their conclusions of a declining and recently increasing stock size.

- The Alternative Management Workshop is a great idea and one advocated by Dr. Carl Walters for years. Having the stock assessment scientists and fishers discuss the management of the tiger prawn stock is what we need for effective fisheries management. It appears that the workshop was successful, although difficult decisions appear to still remain (Dr. Die's recommendation #18 of further effort restrictions and 75-80% E_{MSY}). This is not unexpected but the workshop appears to have started a dialogue that will benefit future assessments and management.

In summary, I believe this assessment did a very thorough job of data analysis and estimating uncertainty in the model predictions. The work here is state-of-the-art and this is among the most comprehensive stock assessments I have seen. I wish the authors and fishers good luck with the tiger prawn fishery.

Cordially,

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