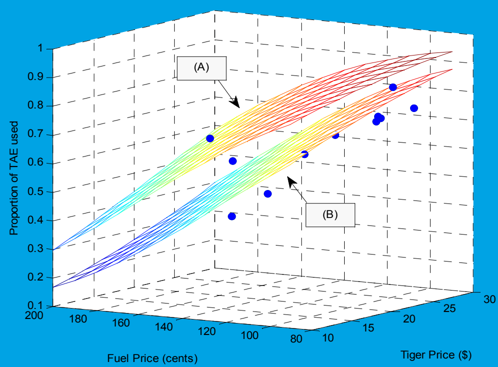
Queensland **Primary Industries and Fisheries**

Torres Strait Prawn Spatial Management Research Project 2007-09

Final Report for DAFF Consultancy DAFF83/06

June 2009



Clive T. Turnbull, Mai Tanimoto, Michael F. O'Neill, Alex Campbell and Carissa L. Fairweather

Australian Government
Department of Agriculture, Fisheries and Forestry

National Fisheries Authority
Papua New Guinea

Queensland Government

This document may be cited as:
Turnbull, C.T., Tanimoto, M., O'Neill, M.F., Campbell, A. and Fairweather, C.L. (2009) Torres Strait Spatial Management Research Project 2007-09. Final Report for DAFF Consultancy DAFF83/06. Department of Employment, Economic Development and Innovation, Brisbane, Australia

Acknowledgements
The research presented in this report was funded by the Department of Agriculture, Fisheries and Forestry (DAFF), and Queensland Primary Industries and Fisheries. The National Fisheries Authority of Papua New Guinea (NFA) funded the 2007 trawl surveys of the PNG area of the Torres Strait Protected Zone. The authors thank the Australian Fisheries Management Authority for the provision of Torres Strait Prawn Fishery logbook data.

The authors thank James Woodhams (BRS) and Veronica Rodriguez (BRS) who peer reviewed the document and TSPMAC members for their comments.

The publication provides an assessment of a proposed tiger prawn spawner closure and the 'risk' associated with a range of levels of fishing effort in Torres Strait Prawn Fishery (TSPF). The assessment is based on trawl surveys of the fishery conducted during 2007-08 and simulation modelling. The detailed results of the both the trawl surveys and the simulation model are presented. The report also details the results of an endeavour prawn stock assessment for the TSPF. These results will inform the development of a harvest strategy for the TSPF.

This publication can be viewed and downloaded from the Torres Strait Protected Zone Joint Authority website:
http://www.pzja.gov.au/resources/publications/scientific.htm

On 26 March 2009, the Department of Primary Industries and Fisheries was amalgamated with other government departments to form the Department of Employment, Economic Development and Innovation.

Contents

1 Non-technical summary

1.1 Background and Need

The need for this study largely arose out the 9th November 2005 announcement by the Protected Zone Joint Authority (PZJA) to grant trawl licences for the 2006 season with a pro-rata reduction in days of allocated fishing effort to an overall cap of 9197 days. As a result of this change all operators in the Torres Strait Prawn Fishery (TSPF) lost one third of their days of fishing access. This change in the management arrangements was at odds with the outcomes of the July 2005 'Alternative Management Workshop' and industry heavily lobbied the Federal Government over the decision by the PZJA. The main proposal developed at the workshop was the strategy of using trigger points to control the allowable effort in the fishery rather than reducing the allocated fishing days linked to each licence. The proposal was also aimed at ensuring a sustainable harvest of the tiger prawn stock whilst allowing some additional effort directed at the endeavour prawn stock. Although there was a reliable stock assessment that had been externally reviewed for the tiger prawn stock there was no equivalent stock assessment for the endeavour prawn stock. The only available estimate of sustainable endeavour prawn harvest was an estimate of Maximum Constant Yield (MCY) based largely on QDPI trawl survey data collected during 1986-91. Industry strongly argued the need for a current endeavour prawn stock assessment of the same style as the tiger prawn assessment.

In the 2006-07 federal budget, the Australian Government announced $1 million of special research funding to conduct research into the TSPF that would assess and further develop the spatial management arrangements proposed at the July 2005 Alternative Management Workshop. QPIF successfully tendered for this research funding which was combined with additional funding from the National Fisheries Agency of Papua New Guinea to conduct trawl surveys of the PNG area of the TSPZ during 2007.

The level of active effort in the TSPF has always been considerably lower than the 13540 allocated fishing days assigned to the licences in the fishery in 1993. During this decade the size of the *active* fleet has dropped from 74 to 37 vessels and the observed fishing effort from an average of 10264 days during 1997-2001 to less than 4000 vessel nights in 2008. This decrease in the effort resulted in the annual harvest dropping from the average of 1,900 t per annum during the 1997-2001 to 907t in 2008. The largest decrease has been in the endeavour prawn harvest due to fishers targeting the more valuable tiger prawns. The decrease in fishing effort is due to the combined effect of the reduced allocation to Australian vessels, a down turn in the economics of prawn trawling (e.g. declining prawn market price and increasing fuel costs) and a decrease in the infrastructure (supply barges and air services) that support this remote fishery.

This report provides an assessment of a proposed tiger prawn spawner closure and the 'risk' associated with a range of levels of fishing effort in the Torres Strait Prawn Fishery (TSPF). The assessment is based on trawl surveys of the fishery conducted during 2007-08 and simulation modelling (Component 1 of the contact). The report also details the results of an endeavour prawn stock assessment for the TSPF (Component 2 of the contract). These results will inform the development of a harvest strategy for the TSPF.

A draft version of this report was made available to the members of the Torres Strait Prawn Management Advisory Committee (TSPMAC) for review and comment. James Woodhams (BRS) and Veronica Rodriguez (BRS) undertook and external independent scientific review of the report. The comments of the reviewers and TSPMAC members were addressed and incorporated into the final version of this report.

1.2 Research surveys

Fishery independent research trawl surveys were conducted during May, July, September and November of 2007 and 2008 by the QPIF research trawler, "Gwendoline May". Sampling sites were randomly spread through the main Australian trawl grounds and Papua New Guinea waters of the Torres Strait Protected Zone between Warrior Reef and Bramble Cay. Additional sites were located within relevant areas of the West and East of Warrior Reef closures to provide information on recruitment to the fishery. In addition the sites within the closed areas provided a measure of the proportion of spawning that was protected from fishing.

A half nautical mile trawl was conducted at each site using a quad gear configuration of four 4-fathom commercial mesh tiger prawn nets. The species, gender, carapace length and spawning condition of all commercial prawns from each net were recorded. The point data from the surveys was plotted and interpolated using Geographic Information Software (ArcGIS Version 9) to generate models of prawn distribution (raster plots) in terms of species abundance (stock size), size (prawn grades) and fecundity (egg production).

In Torres Strait the commercial catch categories are essentially single species as the tiger prawns are mainly brown tiger (*Penaeus esculentus*), endeavour prawns are mainly blue endeavour (*Metapenaeus endeavouri*) and king prawns are mainly redspot king prawns (*Melicertus longistylus*). The grooved tiger prawn (*Penaeus semisulcatus*) occurred occasionally throughout the area and the Japanese tiger or Kuruma prawn (*Marsupenaeus japonicus*) occurred in the sites near Bramble Cay and along the northern eastern edge of the TSPZ. A length-weight relationship was estimated for the Japanese tiger prawn using a sample of 224 animals collected during the surveys. The red endeavour prawn (*Metapenaeus ensis*) and the western king prawn (*Melicertus latisulcatus*) were only a small percentage of the catch (<1%).

The survey results indicate that the prawn stock of the PNG region is a continuation of the prawn stock in the Australian region as the overall catch composition and catch rates across the fishery are quite similar based on both weight and number of prawns. The regions with the highest catch rate and proportion of tiger prawns were the Central and Deep regions around Yorke Island. At a finer spatial scale there is variability between relatively close sites that reflect the patchy nature of the trawl grounds and is probably the result of variations in sediment type and depth. The deeper sites in the north-east and south-east areas of the fishery produced the highest catches of king prawns. Tiger and endeavour prawns clearly occur together as all of the sites produced at least a few of each species but at a finer spatial level there are areas where tiger prawns are more prevalent and others where endeavour prawns are more prevalent.

A relative measure of spawning or egg production, Population Fecundity Index (PFI), was calculated from the standardised catch rate of ripe female prawns of each species at each site and the relationship between female size (carapace length) and egg production. The plots show that the highest levels of spawning (egg production) for tiger prawn occurs in the deep water that runs from Bramble Cay south-west to Stephens Island and then to the south-east of Yorke Island. The relative proportion of tiger prawn spawning occurring in the deep region (proposed spawner closure) ranged from 15 to 35 percent with the highest being May and the lowest November. This is higher than the 12 percent estimated by the spatial simulation model indicating the model may have under estimated the size of the tiger prawn spawning stock in the deep area and hence the benefit of closing the area at high levels of effort. It is worth noting that 12 to 25 percent of the tiger prawn egg production occurs in the PNG region and that this area up until now has been only lightly fished and not at all in recent years. While this area is not fished it servers as a pseudo closure that protects about 15 percent of the tiger prawn egg production.

In contrast to tiger prawns the highest levels of endeavour spawning occurred in slightly shallower areas to the west of the tiger prawn spawning areas. As for tiger prawns there was a change in the intensity and spatial distribution of spawning during the season. The highest levels of egg production occurred during the September surveys of both years. During May of both years the highest levels of spawning occurred in the area to the south-west of Yorke Island. In July the highest levels tended to be north of Stephens Island and mainly within the PNG area. By September spawning had shifted to near

Dalrymple Island on the western side of the fishery and during November spawning was generally at a lower level.

The survey trawl catch rates for each site are a relative index of the stock abundance and were interpolated in ArcGIS to produce raster plots that show the relative spatial distribution of the tiger and endeavour prawn stocks throughout the fishery. These raster plots were overlaid with the model regions and the Spatial Analyst zonal statistics function used to estimate the distribution of the stocks across the model regions, relative to the stock of the Australian area. The average catch of the Australian region of the fishery during 2003-08 (1240t) was multiplied by the proportion of stock in the PNG region (0.18) to estimate the potential catches for the PNG region assuming vessels of the same fishing power and levels of fishing effort as for the Australian regions. The estimate potential catch of the PNG region is about 227t comprised of 103t tiger prawns, 114t of endeavour prawns and 10t of king prawns. This validates the use of 200 tonnes for the nominal catch of the PNG area in the calculations for the cross-border catch sharing arrangements.

Size distribution plots show that the smallest tiger and endeavour prawns occur in the shallow closure areas on the western side of the fishery and the largest are found in deep waters of the eastern and southern areas. Although there are slight variations this trend is consistent through out the fishing season. These plots can be used to assess whether the proposed extension to the East of Warrior closure would be of any benefit. The pooled data indicates that the southern half of the proposed closure would limit the harvesting of 15/20 female and 21/30 male tiger prawns. The seasonal plots indicate that the whole of the proposed closure has small tiger prawns during May but during the later months of the season the small prawns are restricted to the southern half. Relative size distribution plots of the tiger prawns by survey month (2007 and 2008 data pooled) indicate that the size distribution of tiger prawns in the proposed extension of the East of Warrior closure is similar to that of the East of Warrior closure. Although the size distribution of the Central and Deep regions are shifted to the right indicating a generally large size there are some small tiger prawns (<= 25 mm CL or 30+ grade) in all of the regions.

1.3 Spatial simulation modelling

A spatially explicit population simulation model (TSPFsim) was developed in order to assess the effectiveness of the management arrangements proposed at the July 2005 Alternative Management Workshop and to determine the “risk” associated with a range of fishing efforts. The model utilised the results of the 2007 trawl surveys and prawn tagging studies conducted in Torres Strait during 1986-90. The performance of the management scenarios was evaluated in terms of the probability that the biomass falls below the level that can support Maximum Sustainable Yield (MSY) (B_{MSY}), the limit reference point of $0.5B_{MSY}$ (B_{LIM}), and the ratio of biomass in the last year of simulation (B_{2017}) relative to target reference point (B_{TARG}) which is defined as 1.2 B_{MSY}. Although B_{TARG} is often considered to be a proxy for the biomass required for Maximum Economic Yield (MEY), in the current economic climate for TSPF, B_{MEY} is probably much higher than B_{TARG} and therefore an inappropriate reference point for managing this fishery.

For tiger prawns, the risk of biomass falling below B_{LIM} was negligible except for effort at 12000 nights. When 12000 nights was fully fished every year of the virtual future projection (2008 - 2017), it was highly likely that the tiger and endeavour prawn biomass in 2017 would be below B_{MSY} and 11% of simulations indicated tiger prawn biomass would fall below B_{LIM}. For endeavour prawns, there was no risk of biomass falling below B_{LIM} for all levels of effort tested. The B_{2017} was relatively close to B_{TARG} at 9200 - 10200 nights.

The simulation model results suggested that the proposed tiger spawner closure would have a minimal benefit for the fishery in terms of reducing the risk of overfishing the tiger prawn stock and maximising the productivity of the fishery. Possible reasons for this were: 1) within the model the proportion of spawners protected by this closure was relatively small; 2) the additional effort re-allocated into other regions after the closure was introduced countered the number of spawners protected in closed region; and 3) the effort trigger points were only activated in the latter part of the fishing season when the fishing pressure was relatively low.

The simulation results also showed that the effort trigger points were unlikely to be activated unless 100% usage of total allocated effort was assumed (no implementation error; fishers use up all their nights). Fishers do not currently fully utilize all their allocated nights due to the current general market conditions of low prawn prices and high fuel costs. Unless this situation changes it is unlikely that the triggers will be activated. Even if the TAE was increased to 12000 nights, it is unlikely that fishers would make full use of their allocated nights under the current economic conditions, the likelihood of overfishing is low and the proposed spawner closure would not be activated. These results will inform the long-term harvest strategy for the TSPF by providing stakeholders with estimates of the risk of the stock biomass falling below a sustainable level for a range of fishing effort.

One of the biggest challenges in the model development was to simulate the movement of prawns between regions using a movement transition matrix that was based largely on tiger prawn tagging data. Although the overall movement of the Torres Strait prawns was generally well captured by the model there were some discrepancies between the model and survey estimates of spawning.

The distribution of tiger and endeavour prawn stocks overlaps spatially making it difficult to control *targeting* of effort for each species through the use of spatial management arrangements. The performance measures indicated that endeavour prawns are more resilient to fishing pressure than tiger prawns. As the endeavour prawn price is almost half the value of tiger prawns and fuel cost is high, there is no incentive for the industry to target endeavour prawns. Therefore the risk of overfishing endeavour prawns is low and that the TSPF is biologically sustainable for both species as long as the more susceptible tiger prawns are harvested sustainably.

1.4 Endeavour prawn stock assessment

The fitting of a stock assessment model to the data for endeavour prawns in Torres Strait has been challenging due to the nature of the harvest data available for this species. As the distribution of tiger and endeavour prawns completely overlap there are few daily vessels records that report only one of the species. Although the AFMA logbooks have a target species field many TSPF fishers do not fill out this field and the reliability of the information where it has been filled out is dubious as fishers target the mix of species which provide the highest return rather than a particular species. At industry meetings fishers have stated that they “target dollars not a species”. Endeavour prawns are of less value than tiger prawns so they tend to be the secondary target species making the CPUE data for endeavour prawns less reliable than the tiger prawn CPUE data. The CPUE data for the years prior to 1989 came from a variable a subset of the total fishing effort, making the catch rates for those years even less reliable as an index of abundance.

Another difficulty with the data is that the endeavour prawn harvest during the years 1991-2001 was significantly higher than prior to 1991. Possible reasons for this trend are; the East of Warrior Closure, increased targeting of endeavour prawns during the 1990’s and possible discarding of endeavour prawn catch during the early 1980’s.

As the CPUE data does not appear to be a consistent index of abundance over the whole time series different catchability coefficients were calculated for the two data periods: pre 1989 and the compulsory logbook period (post 1988). The catchability coefficient for the post 1988 period was estimated as higher than for the voluntary period.

Catch rate standardisation analysis indicates that the increase in fishing power for endeavour prawns was less than for tiger prawns and that the 10% decrease in net size during 2002-03 resulted in a 3% reduction in fishing power. This is slightly less than the 4 % negative net size effect suggested by Dr David Die which was based on fishing power studies conducted by CSIRO in the Northern Prawn Fishery. A few navigation systems (GPS, computer mapping and sonar) were found to have a negative effect on endeavour prawn catch rates. A possible explanation is that the adoption of these navigation systems enabled fishers to target with greater efficiency the more valuable tiger prawns in preference to the less valuable endeavour prawns.

The endeavour prawn assessment model was initially developed by modifying the existing tiger assessment model to suit the biology of endeavour prawns. Although the estimates of Maximum Sustainable Yield (MSY) from the delay difference model were similar to the average endeavour prawn catch during the 1990's, there was a large level of uncertainty around the MSY estimates and the spawner-recruitment relationship parameters.

An alternative assessment model was developed using an age and length based model that can better utilise the biological information available for the species. The model follows the dynamics of each sex, size and age cohort separately and enables us to capture the substantial size related variation in reproduction that occurs in these species. A Bayesian estimation technique (Monte Carlo Markov Chain (MCMC) algorithm) was used for the model optimisation.

The results from a stochastic version of the model which considered variations in the spawner-recruitment (S-R) relationship and a deterministic version with no variations in the S-R relationship are both presented in the report. Each model was fitted with the steepness of the S-R curve fixed at 0.5 and 0.7 to test the sensitivity of the model outputs to the S-R relationship. The stochastic model was more conservative than the deterministic model. Within each model, higher MSY estimates were obtained with higher steepness.

While the delay-difference model had two separate fitting processes (model fitting followed by fitting of the spawner-recruitment relationship based on the model output), the age-size structured model did this in one hit. The delay-difference fitted the CPUE data well, but the spawner-recruitment relationships fitted to the estimated spawning stocks was poor and highly uncertain. This resulted in large error/uncertainties in the management parameters. The age-size structured model may seem to have a poorer fit to the CPUE data, but it is clear that it has a better fit to the spawner-recruitment relationship. Unfortunately the stochastic age-size model had a problem with model convergence and there were difficulties in interpreting the results. Whilst the deterministic age-size structure model does not fit as well as the others models and it is ideal to incorporate stochasticity in the spawner-recruitment relationships it is the preferred model for this assessment.

Although none of the endeavour prawn stock assessment models fit well to the data we recommend the deterministic age-size model, and in particular the deterministic run with steepness fixed at 0.5, as the preferred and most plausible endeavour prawn stock assessment. The MSY estimated from this model was 1105t (90% CI 1060:1184) and is plausible given the historical catch and effort trends observed during the 1990s and is similar to the 1035t Maximum Constant Yield estimated by Turnbull and Watson in 1994 for endeavour prawn in Torres Strait. The overall conclusion of the endeavour prawn stock assessment is that the fishing has not impacted the endeavour prawn stock, which confirms Dr David Die's hypothesis in the 2003 review. The sustainability of the Torres Strait Prawn Fishery would be maintained as long as the tiger prawn stock was managed appropriately.

Keywords: stock assessment, spatial simulation model, fishery independent, spatial management, endeavour prawn, tiger prawn, Torres Strait, Management Strategy Evaluation

2 Background

2.1 Need

The need for this study largely arose out the 9th November 2005 announcement by the Protected Zone Joint Authority (PZJA) to grant trawl licences for the 2006 season with a pro-rata reduction in days of allocated fishing effort to an overall cap of 9197 days. As a result of this change all operators in the TSPF lost one third of their days of fishing access. This change in the management arrangements was at odds with the outcomes of the July 2005 'Alternative Management Workshop' and industry heavily lobbied the Federal Government over the decision by the PZJA. The main proposal developed at the workshop was the strategy of using trigger points to control the allowable effort in the fishery rather than reducing the allocated fishing days linked to each licence. The proposal was also aimed at ensuring a sustainable harvest of the tiger prawn stock whilst allowing some additional effort directed at the endeavour prawn stock. Although there was a reliable stock assessment that had been externally reviewed (Die 2003) for the tiger prawn stock there was no equivalent stock assessment for the endeavour prawn stock. The only available estimate of sustainable endeavour prawn harvest was an estimate of Maximum Constant Yield (MCY) based largely on QDPI trawl survey data collected during 1986-91 (Turnbull and Watson 1995). Industry strongly argued the need for a current endeavour prawn stock assessment of the same style as the tiger prawn assessment.

In the 2006-07 federal budget, the Australian Government announced $1 million of special research funding to conduct research into the TSPF that would assess and further develop the spatial management arrangements proposed at the July 2005 Alternative Management Workshop. DAFF was assigned responsibility for administration of the funding and the tendering of research agencies to conduct the research. DAFF divided the contract into two components that reflect parts (a) and (b) of the Services Required (section 2.2);

- Component 1: collection of trawl survey data and the use of the data to assess the alternative workshop proposal and
- Component 2: produce a stock assessment for the Torres Strait Endeavour Prawn Fishery (*Metapenaeus endeavouri*).

In late January the tender submitted by QPIF to conduct the research was chosen as the successful tender. It was explicitly stated in the QPIF submission that components 1 and 2 would be combined into one integrated project. A final contract between DAFF and QPIF was developed and signed in late March 2007. A detailed project plan was developed by QPIF and submitted to the Research Steering Committee for discussion and approval on the 11th April 2007.

During the 2006 Bilateral meeting with Papua New Guinea (PNG) the National Fisheries Agency (NFA) made a commitment of $50,000 for QPIF to conduct trawl surveys of the PNG area of the TSPZ. The Research Steering Committee agreed that the option of extending the DAFF surveys into the PNG jurisdiction should be pursued using this PNG funding, and to increase overall efficiency. This was strongly supported by the industry members who were keen to enhance the data provided by the surveys and to ensure more complete coverage of the straddling prawn stocks. Authorisation for the Gwendoline May to operate within the PNG area during the 2007 season had already been approved as part of the LTMP surveys and because QPIF had flagged the potential extension of the DAFF surveys using the NFA funding. QPIF liaised with NFA on the development of a contract to fund the extension of the DAFF 2007 surveys into the PNG jurisdiction of the TSPZ.

At the June 2007 TSPMAC meeting it was proposed that the $29,000 of uncommitted DAFF funding for TSPF research could be best utilised to continue surveying the PNG area of the TSPZ during 2008. A proposal was developed by QPIF and accepted by DAFF. An amendment was made to the existing contract to include the additional funding and the extension of the 2008 surveys into the PNG jurisdiction of the TSPZ.

2.2 Services Required

The services required of the research consultant are specified in the research contract under "Schedule 1 – Consultancy Services". The following is an extract of the relevant section of Schedule 1. Chapters 3 and 4 addresses part (a) of the services required and Chapter 5 addresses part (b).

1.1 Outline of Services Required

(a) The Consultant is required to design and conduct a series of trawl surveys for the Torres Strait Prawn Fishery during the 2007 and 2008 fishing seasons, to produce spatial and temporal scientific data for commercially exploited prawn species, and to use this data (and other existing data) to assess and/or refine the alternative management workshop proposals to evaluate the potential for additional fishing effort in the Torres Strait Prawn Fishery.

(b) The Consultant is also required to produce a stock assessment for the Torres Strait Endeavour Prawn Fishery (*Metapenaeus endeavouri*).

1.2 Objectives of the Services Required

The consultant is required to manage and conduct the Services Required to ensure fulfilment of the overarching research program objectives as follows:

(a) Assess and refine the proposals from the Alternative Management Workshop to develop alternative management strategies in the Torres Strait Prawn Fishery that:

(i) Ensure the long term viability of the fishery with regards to the ongoing sustainable harvest of commercial prawn stocks;

(ii) Ensure long term viability of the fishery by optimising economic performance through a range of measures; and

(iii) Provide improved access to the fishery for commercial licence holders (if appropriate).

(b) Where funds and resources are available, address the recommendations from the current DEH strategic assessment.

(c) Ensure that the results of the research undertaken under this Agreement can be incorporated into the fishery management plan for the TSPF.

2.3 Dissemination of results to stakeholders

2.3.1 Publications

- Research article in the 2008 and 2009 editions of the Torres Prawn Handbook.

- The Management Strategy Evaluation section of this project was submitted as a paper and presented at the 18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation held in Cairns, Australia from the 13–17th July 2009. The draft paper was reviewed the reviewers comments addressed and will be published in the Congress Proceedings.

2.3.2 Meetings

The current project results were presented to;

- The October 2007 Australia / PNG Bilateral Fisheries Talks in Port Moresby, Papua New Guinea. The results from the May and July surveys were disseminated via an agenda paper for the meeting and PowerPoint presentation.

- The December 2007 TSFMAC meeting. The results from the trawl surveys conducted during 2007 were disseminated via an agenda paper and a PowerPoint presentation.

- The February 2008 Harvest Strategy Port meetings with Industry and Managers. Results from the trawl surveys conducted during 2007 and preliminary results from an endeavour prawn stock assessment were disseminated via PowerPoint presentations.

- The April 2008 Project Steering Committee meeting reviewed the detailed interim report, which also served as a quarterly report. The information was also presented via PowerPoint presentations.

- The July 2008 TSPMAC meeting. Results from the trawl surveys conducted during 2007 and an update on the endeavour prawn stock assessment were disseminated via an agenda paper that also served as the quarterly report for second quarter of 2008.

- The November 2008 Australia / PNG Bilateral Fisheries Talks in Cairns were provided with an update on the results of the trawl surveys for 2007 and 2008, the endeavour prawn stock assessment and the development of an age and length base spatial simulation model for the TSPF tiger and endeavour prawn stocks via an agenda paper and PowerPoint presentation.

- An overview of the draft final report was presented to the June 2009 TSPMAC meeting via an agenda paper and a PowerPoint presentation. Printed copies of the draft final report were distributed to the representatives of the management agencies. A copy of the non-technical summary was distributed to all TSPMAC members. A CD with an electronic copy of the full report was offered to each TSPMAC member and most members accepted a copy. Comments from James Woodhams (BRS), Veronica Rodriguez (BRS) and TSPMAC members were addressed and incorporated into the final version of the report.

2.4 The Torres Strait Prawn Fishery

2.4.1 Description of the fishery

The Torres Strait Prawn Fishery (TSPF) operates in the international waters of the Torres Strait Protected Zone (TSPZ) between Australia and Papua New Guinea (PNG). The main species harvested are the brown tiger prawn (*Penaeus esculentus*) and the less valuable blue endeavour prawn (*Metapenaeus endeavouri*). In addition there is a minor catch of redspot king prawn (*Melicertus longistylus*).

Fishing effort by Australian vessels occurs to the east and south-east of the Warrior Reef complex. Figure 2.1 shows the distribution of fishing effort during the 2008 season. This distribution is typical of earlier years but at a lower level. The distribution of the catch by species for the 2007 and 2008 seasons is shown in Figure 2.2.

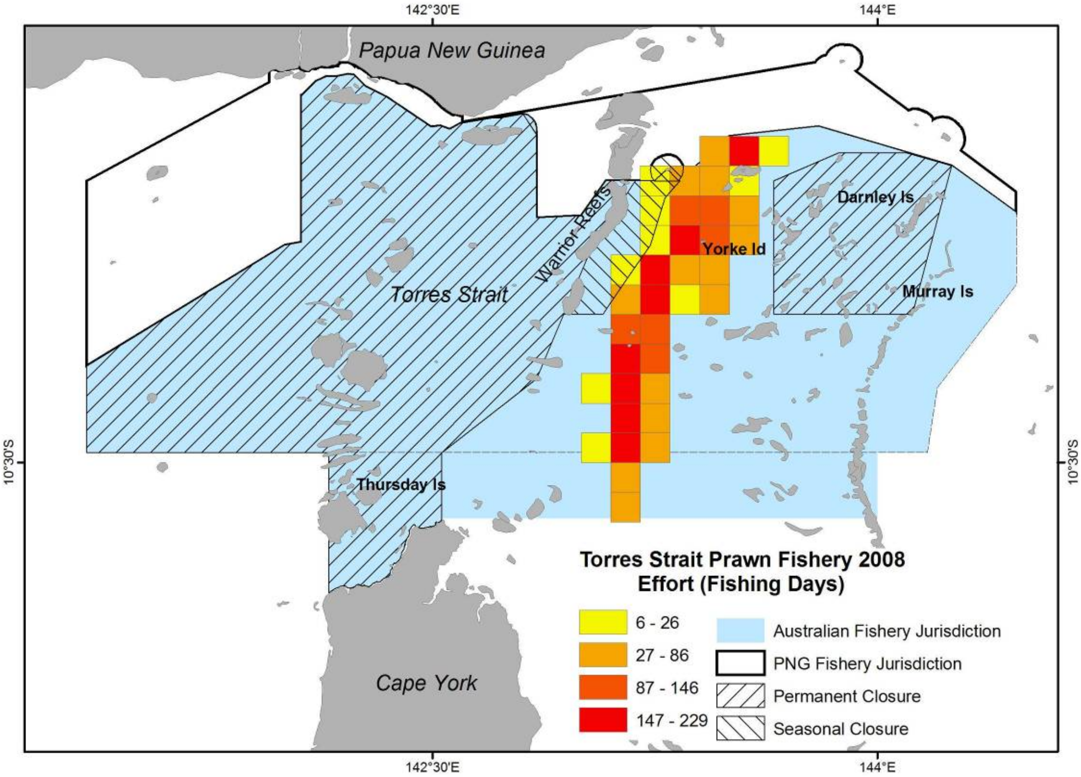


Figure 2.1 The spatial distribution of fishing effort in the TSPF during 2008.

2.4.2 Management of the fishery

The management of the TSPF falls under the jurisdiction of the Torres Strait Protected Zone Joint Authority (PZJA), which is comprised of the Commonwealth Fisheries Minister (Chair), the Queensland Fisheries Minister and the Chair of the Torres Strait Regional Authority. The fishery is managed under the Commonwealth Fisheries Act and the Torres Strait Protected Zone (TSPZ) Treaty between Australia and Papua New Guinea (PNG). The waters of the TSPZ are divided into areas of Australian and PNG jurisdiction and Bilateral Fisheries Meetings are held each year with PNG to discuss the management, enforcement and catch sharing arrangements for Torres Strait fisheries. The Torres Strait Treaty provides for "cross-border" fishing between the Australian and PNG jurisdictions of the TSPZ with PNG fishers being entitled to access 25 percent of the catch of the Australian jurisdiction and visa-versa. There has been limited fishing by PNG vessels in the TSPF and this has been restricted to the PNG area of the fishery. To date Australian fishers have opted to give up their entitlement to 25 percent of the catch of the PNG area and this has been factored into the estimation of the number of PNG vessels that participate in cross-border fishing. Fishing effort has been used as a proxy for catch in the "cross border" management arrangements as it is much easier to monitor and the Australian management arrangements for the TSPF are effort based.

The prawn fishery is primarily controlled by total allowable effort. In addition there is limited entry, fishing gear restrictions, a vessel size limit and spatial and seasonal closures. Linked to each licence are the number of allocated fishing days (nights) that each vessel can fish in the TSPF during the fishing season; 1st March to 30th November. At the start of the 2005 a total of 13454 fishing access days were allocated across the fleet (Kung et al. 2005). This is slightly lower than the 13570 allocated days that existed in the late 1990's due to the penalty on licence transfers to larger vessels (based on vessel length).

On the 9th November 2005, the PZJA announced that trawl licences would be granted for the 2006 season with a pro-rata reduction to an overall cap of 9200 days. In February 2006 the Commonwealth Government also funded a buy-back of licences and allocated fishing days, to give effect to catch sharing arrangements with PNG. As a result of the reduction in allocated fishing days and the buy-back the number of Australian licences in the fishery was reduced to 61 and the fishing days allocated to Australian operators now stands at 6,867 days (Taylor et al. 2006).

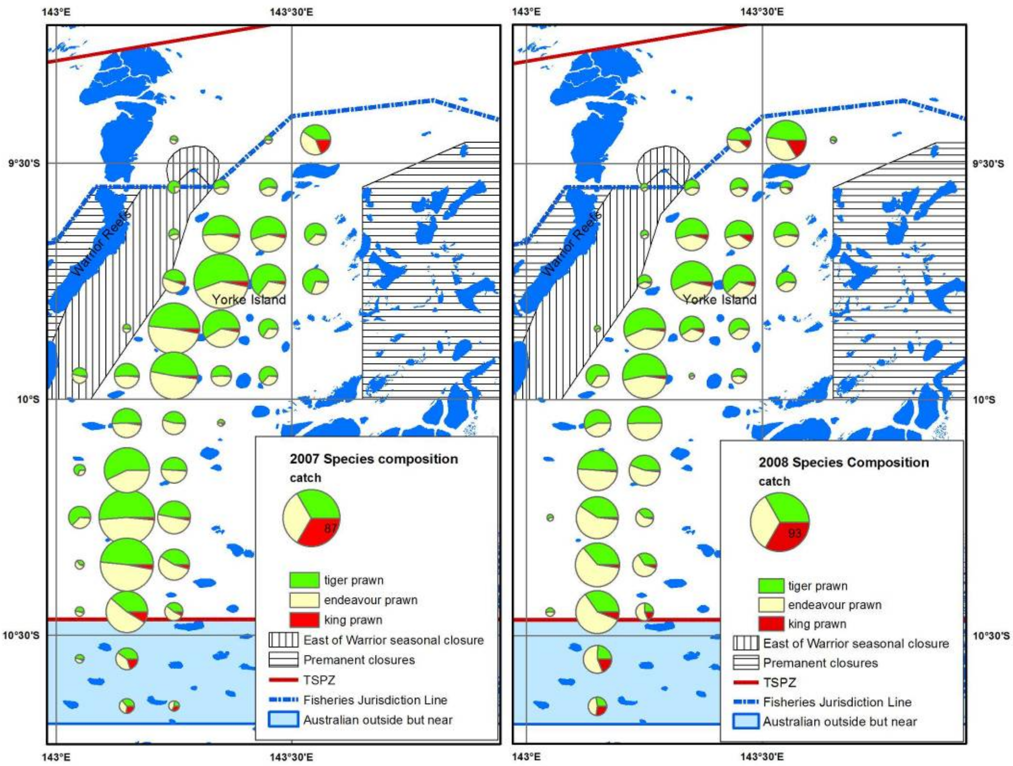


Figure 2.2 Spatial distribution of catches by species groups for the 2007 (Left) and 2008 (Right) seasons. The diameters of the pie charts indicate the total prawn catch for each grid. The largest pie on the 2007 map (3rd plot north of the outside but near area) represents 84 tonnes whereas the largest pie on the 2008 map (plot above the 10 degree line) represents 57 tonnes.

2.4.3 The 2005 Alternative Management Workshop

The concept of convening an "Alternative Management Strategy Workshop" for the TSPF arose from the 2003 David Die review of the tiger prawns stock assessment (Die 2003). Recommendation 18 suggested 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 the catch of tiger prawns is sustainable (O'Neill and Turnbull 2006).

A workshop was held in July 2005 to allow fishers, scientists and managers to examine alternative management strategies for the fishery, especially evaluating strategies that would sustain tiger prawns while permitting some additional fishing that was more directed towards endeavour prawns. The main proposal developed at the July 2005 Alternative Management Strategy Workshop was the use of trigger points to control the allowable effort in the fishery. The first (lower) trigger point would close the deep area to the east of Yorke Island that industry believes is the main tiger prawn spawning ground. Fishing for endeavour and tiger prawns could continue in the other areas of the fishery until the second (upper) trigger point was reached at which time the entire fishery would be closed. Industry proposed that the trigger points be set at 9,200 and 12,000 days for the 2006 season with a review in the latter part of 2006 based on the results of an update of the stock assessment. The updated assessment and review would determine whether the trigger points required adjustment to ensure sustainable tiger prawn harvest levels and to take into account changes in the fleet due to the purchase of days for cross-border fishing arrangements. Industry noted that it was unlikely that the lower trigger point would be reached during the 2006 season due to the current high fuel cost and low prawn prices.

At the workshop there was discussion about the appropriate trigger levels required to ensure that the total tiger prawn harvest (tiger catch up to the higher trigger point) was sustainable. The preliminary simulation model set up for the workshop indicated that the concept is feasible if appropriate trigger levels are selected. Varying the trigger points indicate that as the first (spawner) trigger is lowered the upper (total effort) trigger could be raised, to some extent, while still restricting the total tiger prawn harvest to a sustainable level. The main factors that impact on the level at which the trigger points can be set, to ensure a sustainable tiger harvest, while allowing some addition effort directed towards endeavour prawns are:

- The proportion of recruitment originating from the tiger prawn stock in the spawning closure area.
- The extent to which the tiger prawns harvested after the first trigger point would have contributed to recruitment and
- The level of targeting of endeavour prawn versus tiger prawn. In years of high endeavour prawn prices the tiger prawn harvest after the first trigger point may be lower than for the same amount of effort in a year of low endeavour prices due to changes in fishing behaviour (targeting tigers instead of endeavours after the first trigger point).

The aim of the trawl surveys that were a major component of the DAFF consultancy (chapter 3) was to quantify these three factors for use in a spatial simulation model (chapter 4).

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 2.3) 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 first (lower) trigger point. Industry believes that this area contains the main tiger prawn spawning grounds. The results of monthly research surveys conducted by QPIF during the late 1980's indicate that tiger prawns in this area have a high fecundity (produce lots of eggs).

2. Tiger moon closure

   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/April). Although this closure is mainly aimed at preventing growth overfishing by reducing the 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 QDPI 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 and the Gulf of Carpentaria indicate female brown tiger prawns of less than 32 mm CL have a much lower fecundity (produce a much lower number of fertile eggs) as they are only just starting to become mature and inseminated.

The results of the DAFF consultancy detailed in chapters 3 and 4 provide an assessment of the ‘tiger spawner closure’ and ‘extension of the East of Warrior closure’ proposals.

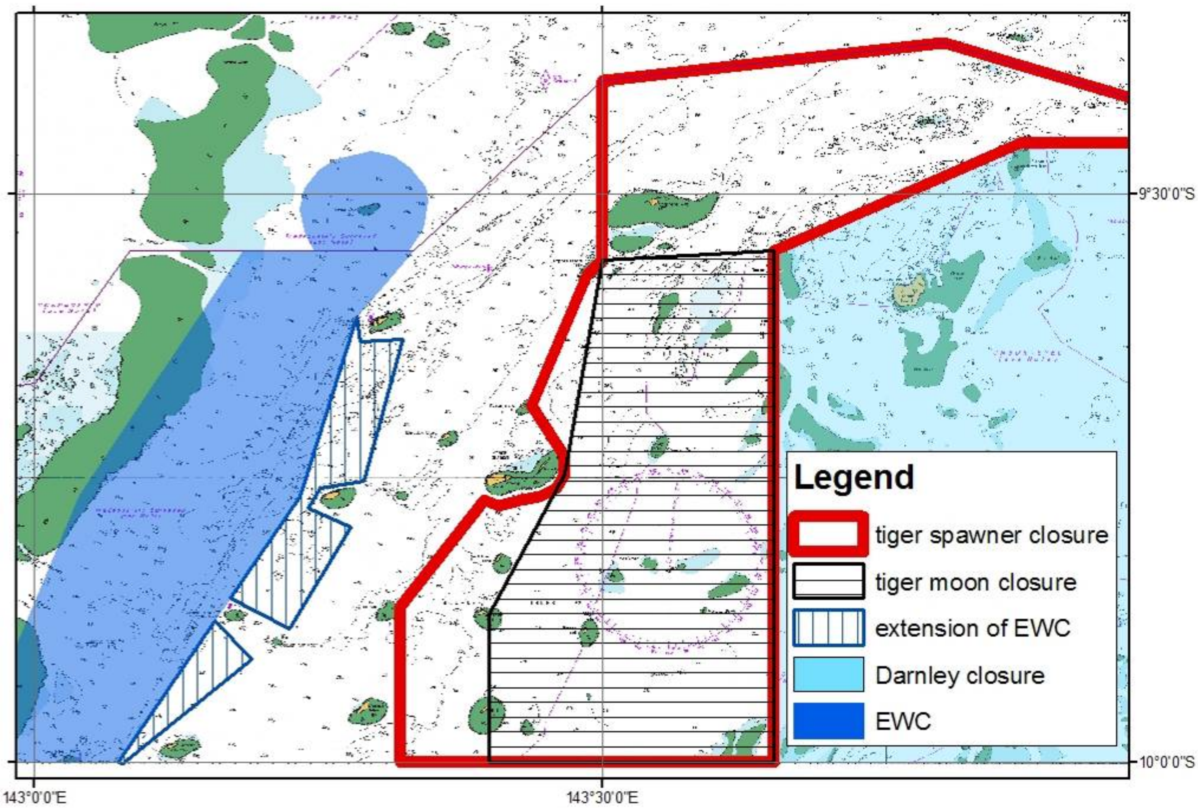


Figure 2.3 Location of the closures proposed at the Alternative Management Workshop and the existing East of Warrior and Darnley Closures.

2.4.4 Recent trends in fishing effort and catches

The level of active effort in the TSPF has always been considerably lower than the 13540 allocated fishing days assigned to the licences in the fishery in 1993. During this decade the size of the *active* fleet has dropped from 74 to 37 vessels and the observed fishing effort from an average of 10264 days during 1997-2001 to less than 4000 vessel nights in 2008 (Figure 2.4). This decrease in the effort resulted in the annual harvest dropping from the average of 1,900 t per annum during the 1997-2001 to 907t in 2008 (Figure 2.4). The largest decrease has been in the endeavour prawns harvest due to fishers targeting the more valuable tiger prawns. The decrease in fishing effort is due to the combined effect of the reduced allocation to Australian vessels, a down turn in the economics of prawn trawling (e.g. declining prawn market price and increasing fuel costs) and a decrease in the infrastructure (supply barges and air services) that support this remote fishery.

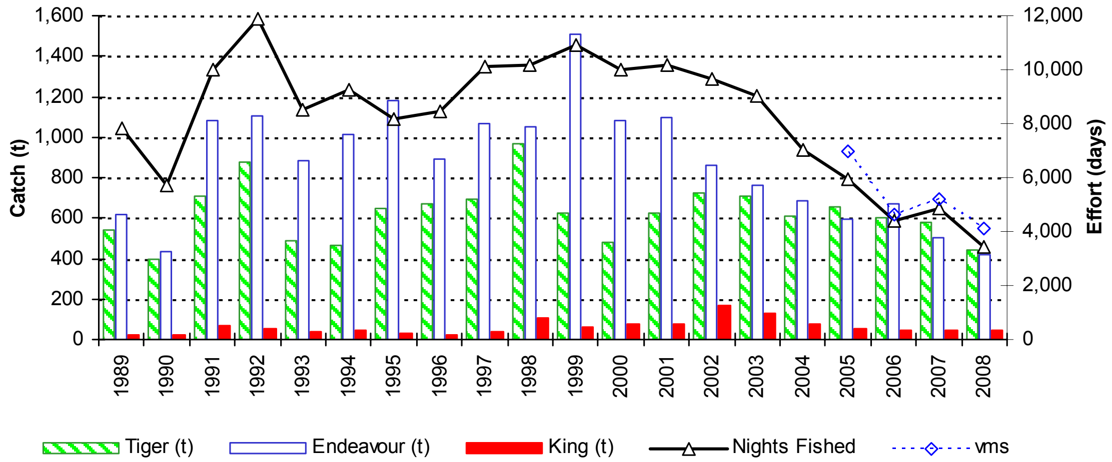


Figure 2.4 Historical catch and effort of the TSPF. Prawn catches by species groups (columns) scaled to the left Y axis and fishing effort in days (line) scaled to the right Y axis. The effort is based on logbook records from AFMA. The dotted line indicates the estimate of fishing effort based on the Queensland Primary Industries and Fisheries Vessel Monitoring System (VMS). The VMS occasionally flags vessels that are just steaming as fishing.

3 Trawl Surveys

Clive Turnbull, Carissa Fairweather and Mai Tanimoto

3.1 Introduction

A major component of the DAFF consultancy (DAFF83/06) was "to design and conduct a series of trawl surveys for the Torres Strait Prawn Fishery during the 2007 and 2008 fishing seasons, to produce spatial and temporal scientific data for commercially exploited prawn species, and to use this data (and other existing data) to assess and/or refine the alternative management workshop proposals to evaluate the potential for additional fishing effort in the Torres Strait Prawn Fishery" (Section 2.2 Services Required). This chapter reports the results of the trawl surveys conducted by the QPIF research trawler, "Gwendoline May", during May, July, September and November of 2007 and 2008.

The main objective of the trawl surveys was to provide the spatial and temporal (seasonal) information on the distribution of tiger and endeavour prawn stocks required to set up and test a spatial simulation model (Chapter 4) that could be used to assess and refine the tiger spawner closure proposed at the Alternative Management Workshop. The distribution of the stocks in terms of species, gender, size and spawning condition at different times of the fishing season were the data required to achieve this objective. The data from the surveys were also used to estimate the size of the harvestable prawn stock of the Papua New Guinea jurisdiction of the Torres Strait Protected Zone and to assess whether the proposed extension to the East of Warrior Reef closure would be effective in reducing the harvest of smaller and less valuable prawns (i.e. reducing growth overfishing).

3.2 Methods

3.2.1 Survey design

Allocation of trawl sites

The survey objectives were achieved by utilising the rule-of-thumb suggested by (Van der Meer 1997) for monitoring programs focusing on the abundance of marine benthic species: revisit many randomly selected stations, and make little effort per station. The strategy of revisiting the same sites (stations) removes the variation in catch rates that would result from re-randomising the sites for each survey. This is an important consideration as the trawl grounds of Torres Strait are quite variable in depth and sediment type over relatively short distances (a few nautical miles). This makes it very difficult to stratify the survey and commercial fisher data by depth or sediment type and increases the sample variance when sites are re-randomised between surveys. The shortest trawl distance that would provide a representative sample of each site (0.5 nautical miles) was chosen as the standard trawl length. This allowed the maximum number of sites to be trawled within the available survey charter time. This is the strategy recommended by (Van der Meer 1997) for monitoring programmes where the primary objective is detection of change. In the case of these surveys the changes we were seeking to detect were the spatial variation in the species composition, size and fecundity (egg production) at different times of the fishing season.

Trawl surveys were conducted by the "Gwendoline May" during May, July, September and November of 2007 and 2008 using the QPIF Long Term Monitoring Program (LTMP) nets and protocols. These protocols were favourably reviewed by Yimin Ye (CSIRO) in 2006. Dr Ye in his review of the QPIF LTMP trawl survey protocols made the following observations on sample design that are also relevant to the design of the DAFF surveys.

Van de Meer (1997) compared three survey designs that are frequently used to monitor year-to-year changes of benthic animals:

- *Design 1. Sampling stations are selected randomly each year*

- *Design 2. Sampling stations are selected randomly in the first year and then revisited in later years*
- *Design 3. Sampling stations are selected non-randomly in the first year and then revisited in following years.*

He found that Design 1 yields the largest variance and the lowest power, and thus the largest detectable effect size and the largest sample size are required to achieve a certain power; Design 2 generally results in a smaller variance of the estimators of year-to-year changes in abundance than Design 1, and therefore, a smaller sample size is needed to achieve a certain power; Design 3 produces the largest power, but a biased estimate of the mean for the whole area and an underestimated variance. Among the three designs, Design 2 performs better than Design 1 in terms of statistical power and better than Design 3 in terms of unbiasedness (for practical examples see Van der Meer (1997)).

The site allocation used for this study was a stratified design 2. The survey sites were randomly spread throughout the follow strata during the first survey then re-sampled during subsequent surveys;

1. The area fished by Australian trawlers.
2. The section of the permanently closure area around Yam Island.
3. The PNG waters north of the Fisheries Jurisdictions Line but within the TSPZ between Warrior Reef and Bramble Cay. This area has been only lightly fished. Prior to 1985 a small number of Australian trawlers legally fished this area and until recently a few Australian vessels legally fished the Australian Territorial waters around Bramble Cay.

The area fished by Australian trawlers was defined using commercial logbook data collected by the Australian Fisheries Management Authority (AFMA), Vessel Monitoring System (VMS) data collected by QPIF and Global Positioning System (GPS) plotter tracks obtained from commercial fishers. The EWC is a spatial / temporal closure designed to optimise the size at first harvest of the prawn stocks. The EWC is only open to fishing from the 1st August to the 30 November. The earlier research conducted by QDPI during 1986-91 indicates that EWC and the permanent closure area to the west of the Warrior Reefs harbour juvenile prawn and that some tiger prawns remain in the western area and spawn; especially in the area around Yam Island.

Potential sites were randomly allocated throughout the above strata using HawthTools in ArcGIS (Beyer 2004). Random positions that fell within dangerous trawl ground were replaced with nearby locations within areas that are regularly fished and safe to trawling. Some of the randomly allocated points were close to current QPIF LTMP trawl sites and the sites used by QDPI during 1986-1991. In these cases the position of the existing sites were utilised. These existing sites had also been randomly allocated throughout the main fishing area and adjacent closure areas. The overlap with early sites enables a degree of comparison of the current survey results with the historical survey data. The final site allocation (Figure 3.1) was checked against the closure proposals from the Alternative Management Workshop to ensure there were sufficient sites within the area of the proposed closures to provide the data needed to assess and refine the workshop proposals. A total of 115 sites were trawled during the first survey in May 2007. One of these sites in deep water near the Darnley Island closure was not repeated as it was too deep and dangerous to trawl in anything other that calm weather. Similarly in July 2008 two sites in the north-west of the PNG area were replaced with two replacement sites as the original sites were too dangerous to sample in the rough weather that prevailed during 2008.

The sites were classified into seven regions: West which encompasses the sites in the permanently closed area around Yam Island plus the six model regions used in the spatial modelling (chapter 4). The model regions are; the East of Warrior Closure (EWC), the proposed extension of the EWC (ExEwc), the proposed tiger spawner closure (Deep), the area between the ExEWC and Deep (Centre), the area of the fishery south of the 10 degree line (South) and Papua New Guinea waters between Warrior Reef and Bramble Cay (PNG). Figure 3.1 shows the trawl survey sites overlaid on these regions and the average depth of each site.

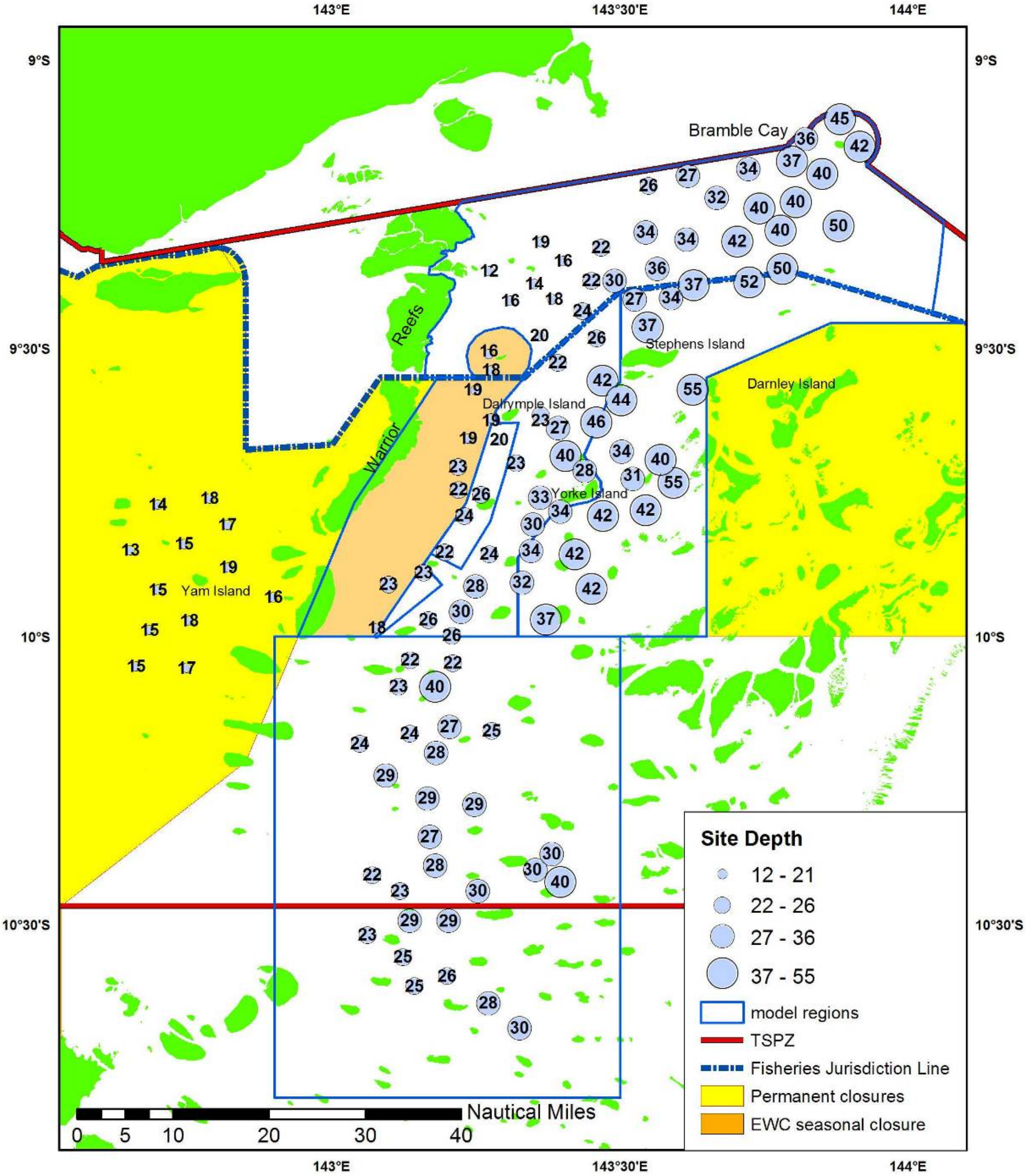


Figure 3.1 Location and depth (m) of the survey sites. The permanent closure areas to the West of Warrior Reef and around Darnley Island on eastern side of the fishery are shaded yellow. The East of Warrior Reef (EWC) spatial/ temporal closure is shaded orange. The model regions are overlaid to show the distribution of sites within the spatial simulation model regions.

Survey timing

The timing of the surveys is based on the following strategy to maximise the scientific value of the surveys.

- The May survey would in particular, provide information relevant to the proposed extension to the east of Warrior closure.

- July is at the start of the main tiger spawning season and just prior to the opening (1st August) of the east of Warrior closure and at the beginning of the time period during which the proposed "tiger spawner" closure could be triggered.
- September is in the middle of the spawning period and time period during which the "tiger spawner closure" could be triggered.
- November is the end of the fishing season hence provides data on the stock remaining at the end of the fishing season.

The surveys dates were centred on the first quarter of the moon. This period of the lunar phase tends to produce the highest commercial catch rates in the TSPF (O'Neill and Turnbull 2006) and tide generated currents are weakest. Due to rough weather some of the surveys were delayed / extended (Table 3.1).

Table 3.1 Trawl survey details.

Survey Number	*Survey Start Date*	*Survey End Date*	*Moon First Quarter*	*Comments*
1	19-May-07	28-May-07	23 May 07	
2	16-July-07	27-July-07	22 July 07	
3	14-Sept-07	23-Sept-07	19 Sept 07	
4	12-Nov-07	19-Nov-07	17 Nov 07	Due to cyclone Guba 25 sites in the PNG region and the deep water area around Yorke Island were missed.
5	11-Feb-08	12-Feb-08	14 Feb 08	Used the February 2008 LTMP survey to sample the deep water sites around Yorke Island that were missed in November.
6	06-May-08	17-May-08	12 May 08	
7	04-July-08	13-July-08	10 July 08	Due to extended rough weather missed the Bramble Cay sites.
8	03-Sept-08	14-Sept-08	07 Sept 08	
9	02-Nov-08	11-Nov-08	06 Nov 08	

Trawl nets

A quad gear configuration of four 4-fathom trawl nets was used to conduct the surveys. These are the same nets used by QPIF Long Term Fisheries Monitoring Program for the Queensland east coast and Torres Strait tiger/ endeavour prawn fisheries. The nets are a standard commercial tiger prawn net design used by the fishing industry but of slightly smaller headline length. Most vessels that operate in the TSPF use either four 5-fathom nets or four 4.5 fathom nets.

3.2.2 Survey data

The species, gender, carapace length and ovary condition of all commercial prawns retained in the 4 x 4-fathom trawl survey nets were recorded. The protocols for sample and data processing were the same as that used for the LTMP prawn trawl surveys. Back deck field sheets are used to record the details of each shot and the weights of commercial prawn retained in each net. This provided a real-time check on the operation of each net. Samples from nets that are considered not to have fished properly for some reason are flagged as non-quantitative. The weights of bycatch in the two inner nets and any interactions with Threatened, Endangered or protected species are also recorded.

A procedure for entering the data from the surveys into the Fisheries Resource Management (FRM) database was established. The FRM is a secure database operated by the Assessment and Monitoring section of QPIF. The FRM database is located on a server that is regularly backed up in the Primary Industries Building (PIB) in Brisbane. This has ensured secure storage of the data in a format that is compatible with other LTMP trawl data. Project staff can access this database through the QPIF intranet to download and analyse the data.

The site and sample information from the surveys was entered from the field sheets by the data entry personnel in PIB and then checked by project staff at the Northern Fisheries Centre (NFC) in Cairns. The individual prawn (catch) records were transcribed from digital voice recordings using Dragon Naturally Speaking Professional Version 9 (DNS) and then manually checked. Protocols were established to ensure the highest level of accuracy and efficiency in the checking of the transcribed prawn catch records. There were a large number of individual prawn (catch) records for each survey; 16,000 to 25,000 records per survey.

3.2.3 Data analysis

The standardised catch rate for each site, as weight of prawns, was used as a relative index of prawn abundance or stock size. A Population Fecundity Index (PFI) based on the estimated number of eggs produced by the ripe females at each site was used to plot the spatial distribution of egg production for the tiger and endeavour prawn stocks. Spatial interpolation analyses were conducted on the point survey data using the "TopoToRaster" function in Spatial Analyst Toobox of ArcGIS (ESRI) Geographic Information System software. This resulted in raster plots that are a model of the distributions based on the point data from the trawl surveys. The "Zonal statistics" function in Spatial Analyst was used to estimate the relative distribution of the tiger and endeavour prawn stocks and egg production across the spatial model regions.

3.3 Results

3.3.1 Catch composition

In Torres Strait the commercial catch categories are essentially single species (Table 3.2) as the tiger prawns are mainly brown tiger (*Penaeus esculentus*), endeavour prawns are mainly blue endeavour (*Metapenaeus endeavouri*) and king prawns are mainly redspot king prawns (*Melicertus longistylus*). The grooved tiger prawn (*Penaeus semisulcatus*) occurred occasionally throughout the area and the Japanese tiger or Kuruma prawn (*Marsupenaeus japonicus*) occurred in the sites near Bramble Cay and along the northern eastern edge of the TSPZ (Figure 3.27 and Figure.3.28). The red endeavour prawn (*Metapenaeus ensis*) and the western king prawn (*Melicertus latisulcatus*) were only a small percentage of the catch (<1%).

Table 3.2 Overall species composition as numbers of individuals, weight of individuals, and as a percentage of the total, based on pooled data for all surveys.

Species Name	***Species Category***	***Scientific name***	***Number***	***Weight (kg)***	***Percentage Composition***	
					Number	*Weight*
Brown Tiger	tiger	*Penaeus esculentus*	44403	1343.62	35.10	48.26
Grooved Tiger	tiger	*Penaeus semisulcatus*	291	11.41	0.23	0.41
Kuruma	tiger	*Marsupenaeus japonicus*	361	11.25	0.29	0.40
Blue Endeavour	endeavour	*Metapenaeus endeavouri*	71297	1208.73	56.36	43.41
Red Endeavour	endeavour	*Metapenaeus ensis*	22	0.35	0.02	0.01
Redspot King	king	*Melicertus longistylus*	9938	203.20	7.86	7.30
Western King	king	*Melicertus latisulcatus*	200	5.69	0.16	0.20
Total			**126512**	**2784.25**		

The survey catch compositions and catch rates indicate that the prawn stock of the PNG region is a continuation of the prawn stock in the Australian region. The overall catch composition and catch rates across the regions of the fishery are quite similar based on both weight and number of prawns (Figure

3.2). The regions with the highest catch rate and proportion of tiger prawns were the Central and Deep regions around Yorke Island. The individual site catch compositions based on pooled from all of the surveys are shown in Figure 3.3 as pie graphs of the weight of each catch category (tiger, endeavour, king). The size of each pie graph size is scaled by the average standardised catch rate for each site (kg/site/survey). These plots also illustrate the similarity between the Australian and PNG regions in terms of catch composition and catch rates and the variability between sites at a finer spatial scale.

The pie graphs in Figure 3.4 and Figure 3.5 indicate the species composition for each site and survey. Note that for the individual survey plots a standard pie graph size has been chosen that best displays the variation in catch composition. The number of prawns caught in the trawls sites around Yam Island (closed western area) was low making the species composition for these sites quite variable between surveys. This explains why sites that were predominately endeavour prawn in September 2008 switched to predominantly tiger prawn in November 2008. The lighter shaded graphs for the November 2007 plot (Figure 3.4) indicate the deeper water sites that were missed due to cyclone 'Guba' and were sampled in February during the LTMP survey. As there is a seasonal closure from the 30th November to the 1st March the prawn stocks were not subjected to any fishing pressure between the two surveys. Although allowances need to be made for growth, natural mortality and migration during December / January, the February data provides an indication of what may have been present at those sites during November.

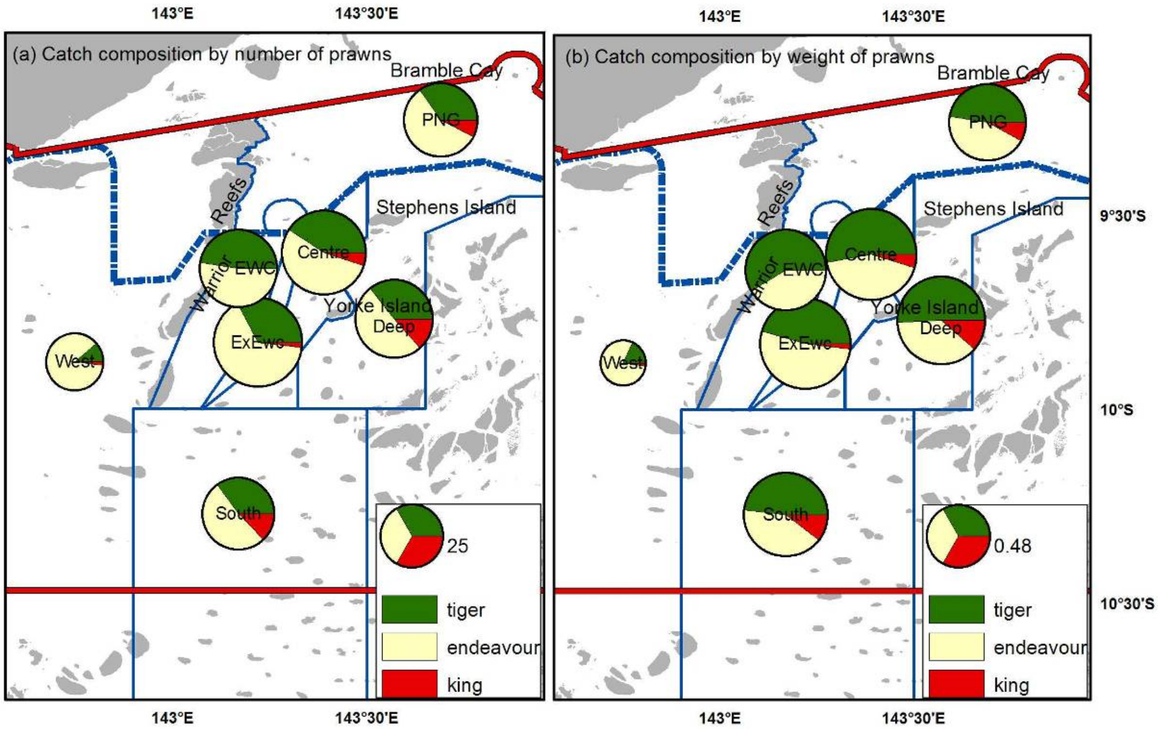


Figure 3.2 Catch composition by region using the pooled survey data. The left plot (a) is based on numbers of prawns and the right plot (b) on weights of prawn. The sizes of the plots are scaled by the standardised survey catch rates; plot (a) number per net and plot (b) kg per net.

Although the pooled data indicates similar catch composition and catch rate across the fishery there are sites that are relatively close together that can be quite different in species composition and / or catch rates. This reflects the patchy nature of the trawl grounds at a relatively small scale (5-10 nautical miles). Catch rates as weights of prawns were lowest in the closed area around Yam Island. The catch from these sites consisted largely of small endeavour prawns and small tiger prawns. The exception to this trend was November 2008 when seven of the sites produced mainly tiger prawns. The deeper sites in the north-east and south-east areas of the fishery produced the highest catches of king prawns. Tiger and endeavour prawns clearly occur together as all of the sites produced at least a few of each species. At a finer spatial level there are areas where tiger prawns are more prevalent and others where endeavour prawns are more prevalent. The variation probably reflects variations in sediment type and depth.

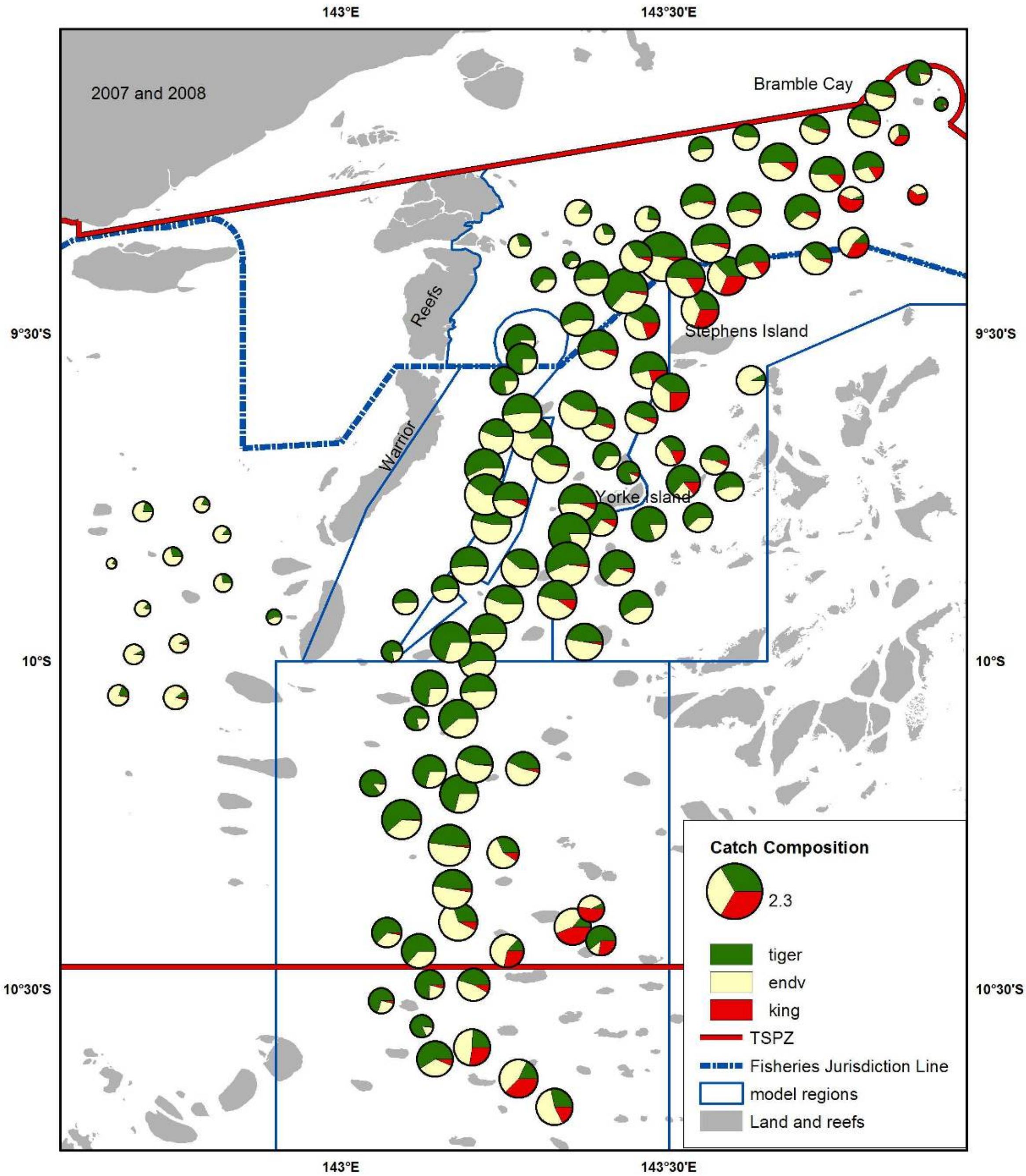


Figure 3.3 Catch composition base on weight of prawn in each catch category. The sizes of the pie charts indicate the prawn catch rate (CPUE). This plot is based on the data from all surveys grouped by site.

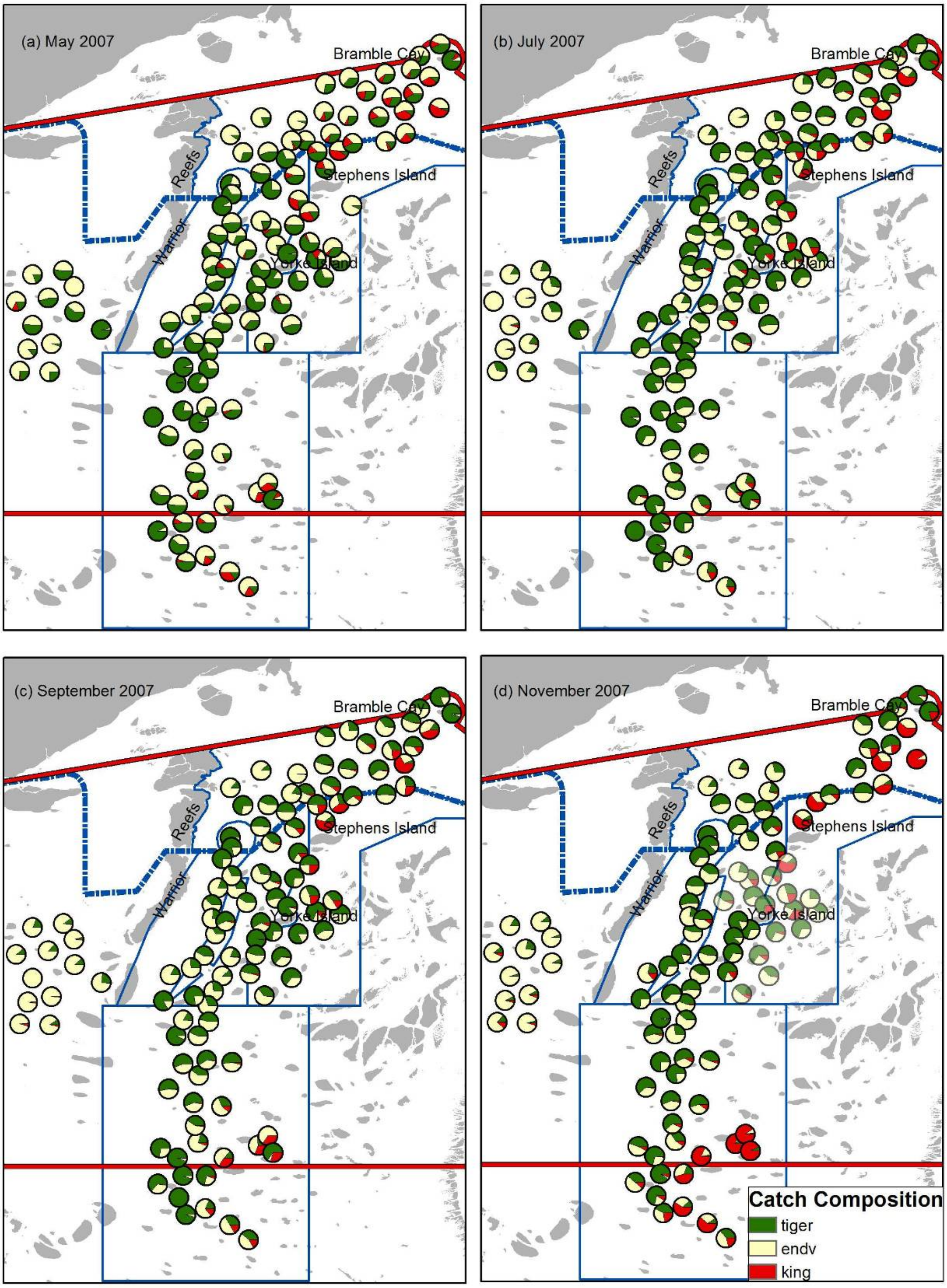


Figure 3.4 Catch composition by weight for the 2007 surveys. The lighter shaded graphs for the November 2007 survey indicate the deep water sites that were missed due to a cyclone and that were sampled during the February 2008 LTMP survey.

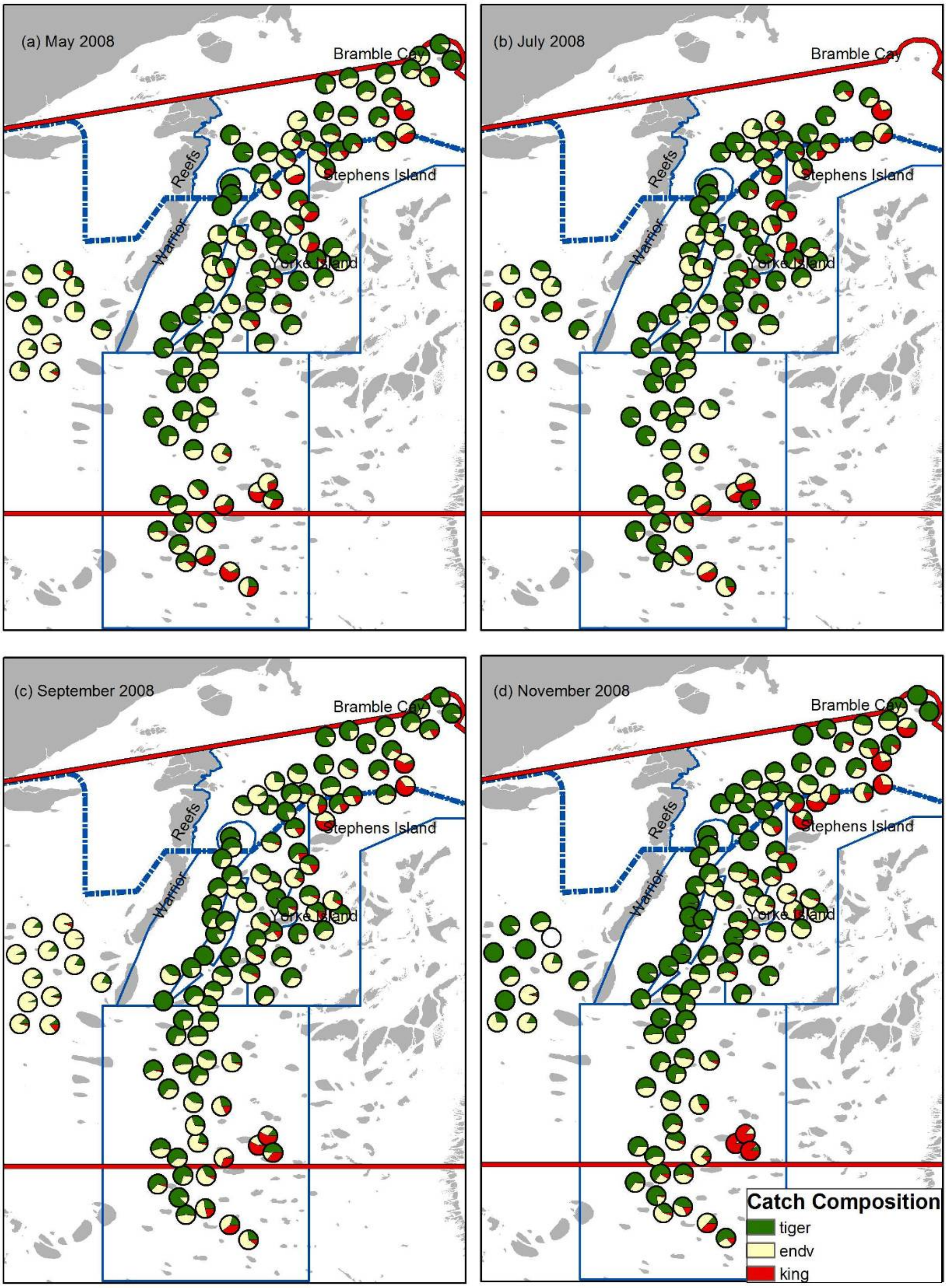


Figure 3.5 Catch composition by weight for the 2008 surveys.

This page deliberately left blank.

3.3.2 Distribution of spawning

A relative measure of spawning or egg production, Population Fecundity Index (PFI), was calculated from the standardised catch rate of ripe female prawns of each species at each site and the relationship between female size (carapace length) and egg production (Dall et al. 1990). This index was then scaled from 0-100 to standardise the plotting and interpolation of the point data in ArcGIS.

The highest levels of tiger prawn spawning (Figure 3.6) occurred in the deep sites (Figure 3.1) that form a band from Bramble Cay south-west to Stephens Island and then to the south-east of Yorke Island. There are also several deep sites in the southern region of the fishery that had high levels of spawning. The spatial distribution of tiger prawn spawning changes slightly during the season the highest levels of egg production occurring in the deep water to the south-east of Yorke Island during May and September whereas during July the highest levels were from Bramble Cay to south of Stephens Island. In November spawning was generally at a lower level and tended to occur in slightly shallower areas of the fishery. The same spatial / temporal pattern occurred during both years (Figure 3.8 and Figure 3.9).

The relative proportion of tiger prawn spawning occurring in the deep region (proposed spawner closure) ranged from 15 to 35 percent with the highest being May and the lowest November (Table 3.3). The table also shows that 12 to 25 percent of the tiger prawn egg production occurs in the PNG region.

Table 3.3 Percentage of tiger prawn egg production in each of the model regions.

Region	*All surveys*	*May-07*	*Jul-07*	*Sep-07*	*Nov-07*	*May-08*	*Jul-08*	*Sep-08*	*Nov-08*
South	43.9	39.0	52.5	44.9	43.7	37.1	33.7	38.8	47.7
EWC	5.6	1.3	3.3	5.4	6.4	2.4	2.9	8.1	10.3
ExEwc	1.7	0.4	1.1	1.5	2.6	1.5	1.1	1.6	2.8
Centre	11.7	10.5	10.4	9.5	14.7	11.6	9.5	12.8	12.0
Deep	22.4	35.2	17.3	25.1	20.9	33.4	28.0	23.6	14.8
PNG	14.8	13.5	15.4	13.6	11.7	14.1	24.8	15.1	12.4

In contrast to tiger prawns the highest levels of endeavour spawning occurred in slightly shallower areas to the west of the tiger prawn spawning areas (Figure 3.7). As for tiger prawns there was a change in the intensity and spatial distribution of spawning during the season. The highest levels of egg production occurred during the September surveys of both years. During May of both years the highest levels of spawning occurred in the area to the south-west of Yorke Island. In July the highest levels tended to be north of Stephens Island and mainly within the PNG area. By September spawning had shifted to near Dalrymple Island on the western side of the fishery and during November spawning was generally at a lower level.

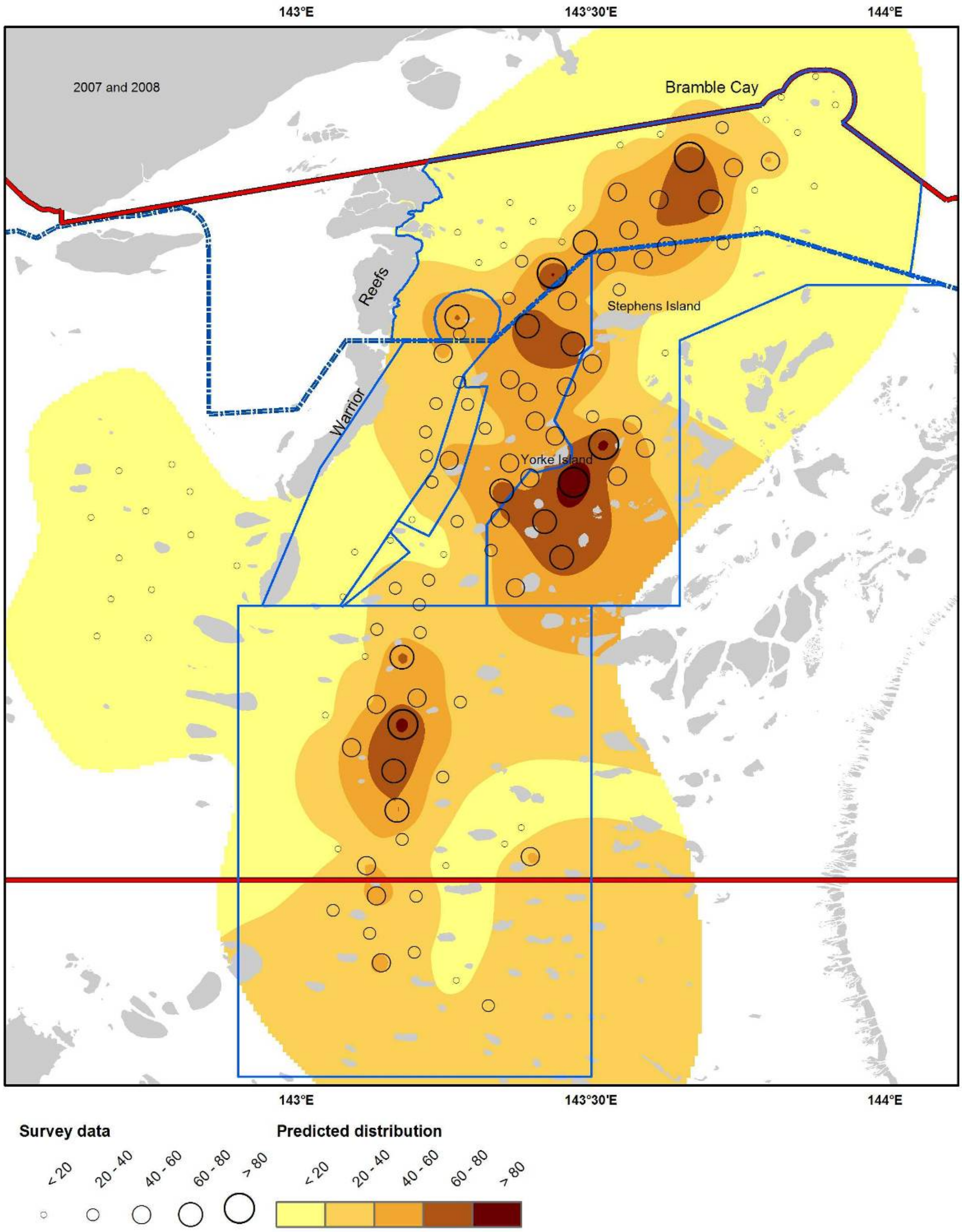


Figure 3.6 Spatial distribution of tiger prawn spawning over all surveys. Population Fecundity Index PFI on a relative scale of 0 to 100. The site with highest egg production (PFI) is scaled to 100.

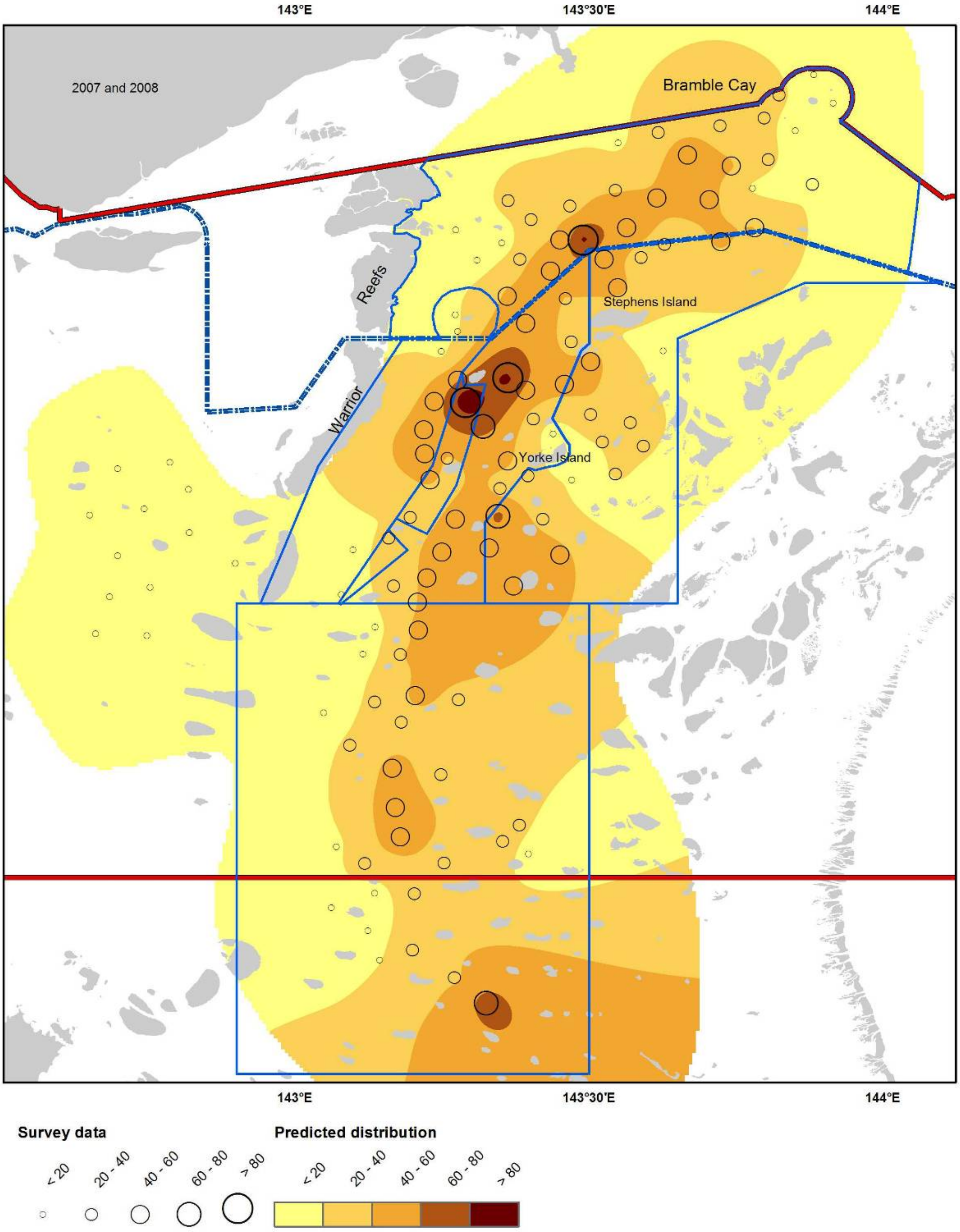


Figure 3.7 Spatial distribution of endeavour prawn spawning over all surveys. Population Fecundity Index PFI on a relative scale of 0 to 100. The site with highest egg production (PFI) is scaled to 100.

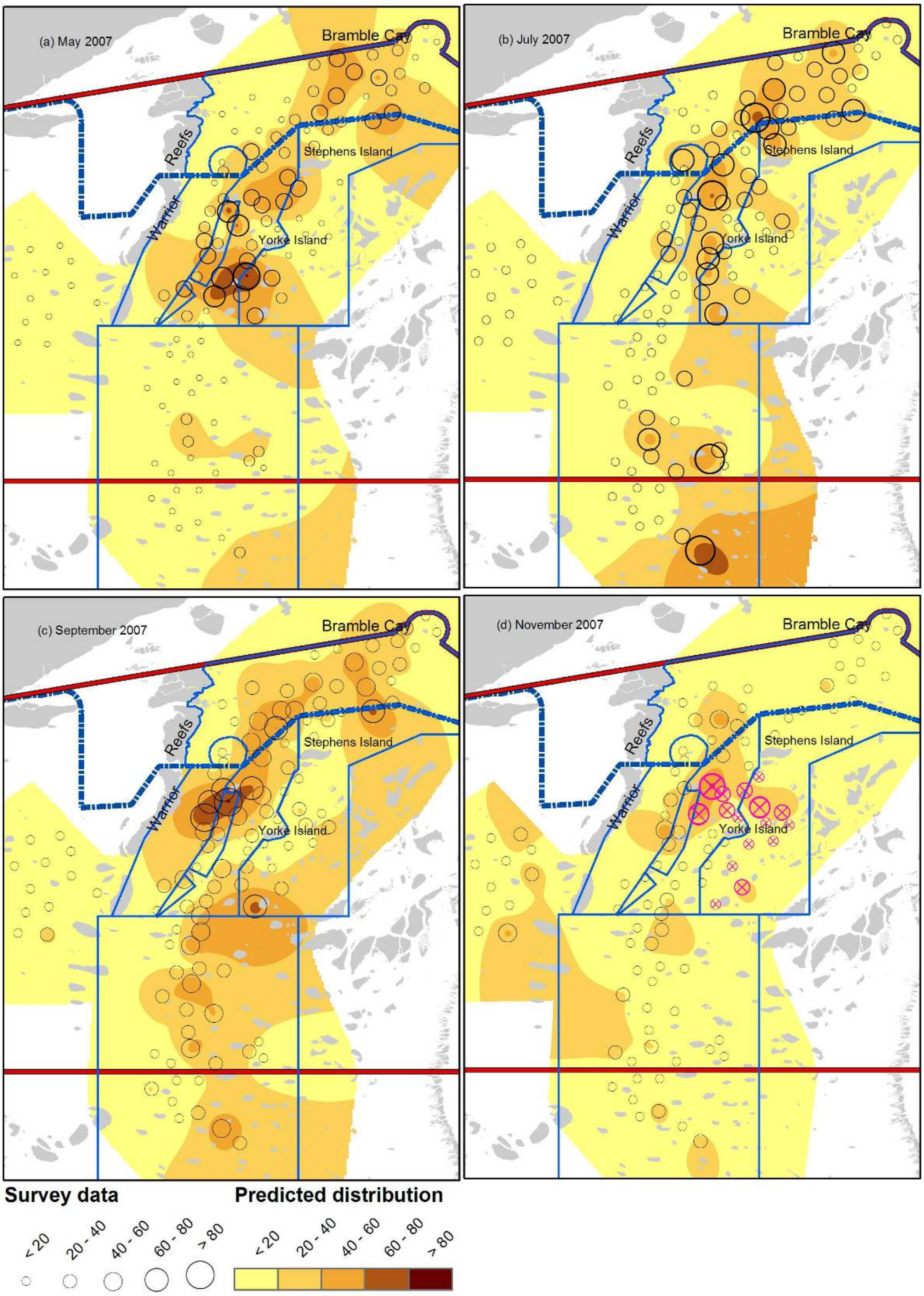


Figure 3.8 Spatial / temporal distribution of tiger prawn spawning from the 2007 surveys. Population Fecundity Index PFI on a relative scale of 0 to 100. The survey and site with highest egg production (PFI) is scaled to 100.

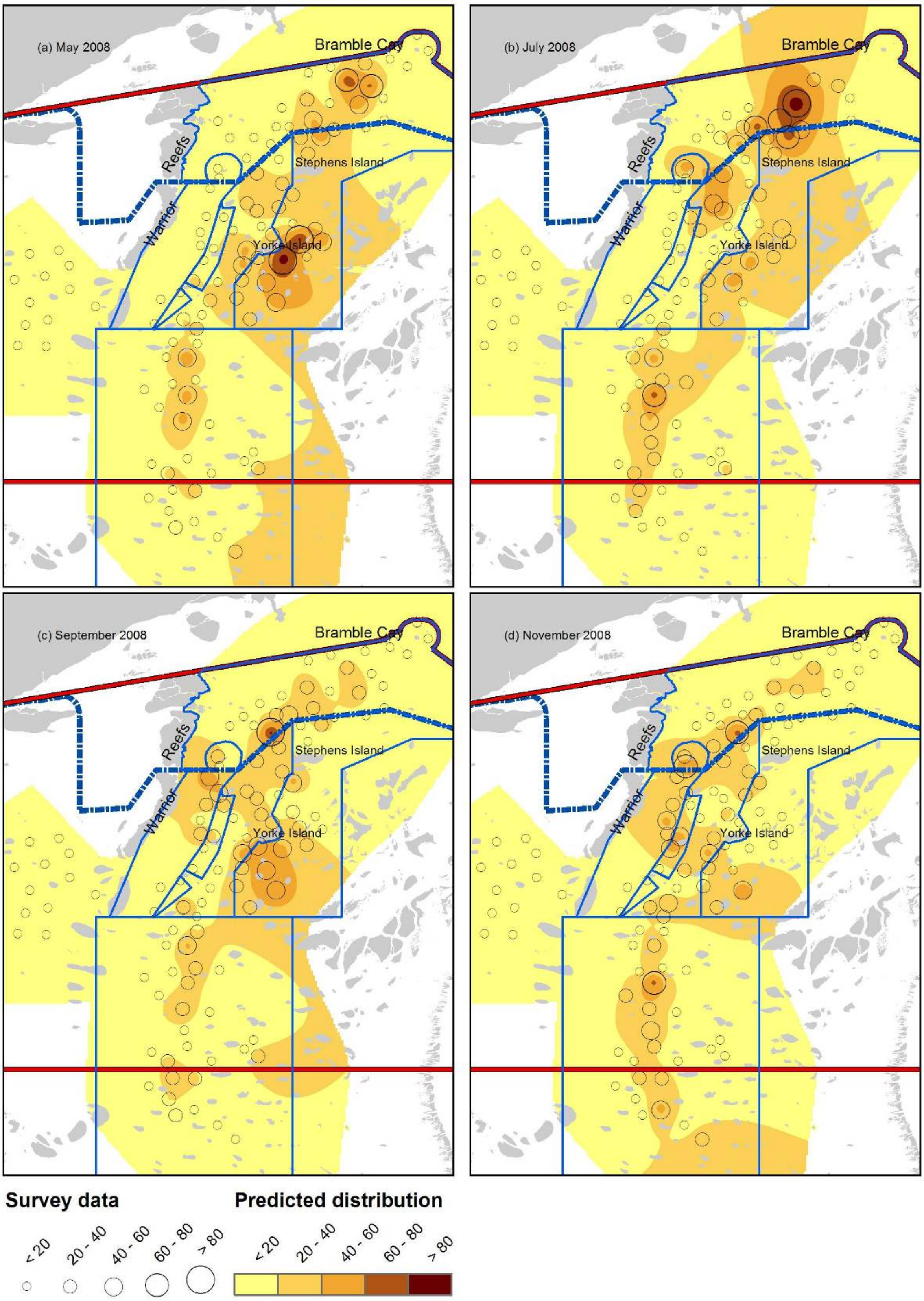


Figure 3.9 Spatial / temporal distribution of tiger prawn spawning from the 2008 surveys. Population Fecundity Index PFI on a relative scale of 0 to 100. The survey and site with highest egg production (PFI) is scaled to 100.

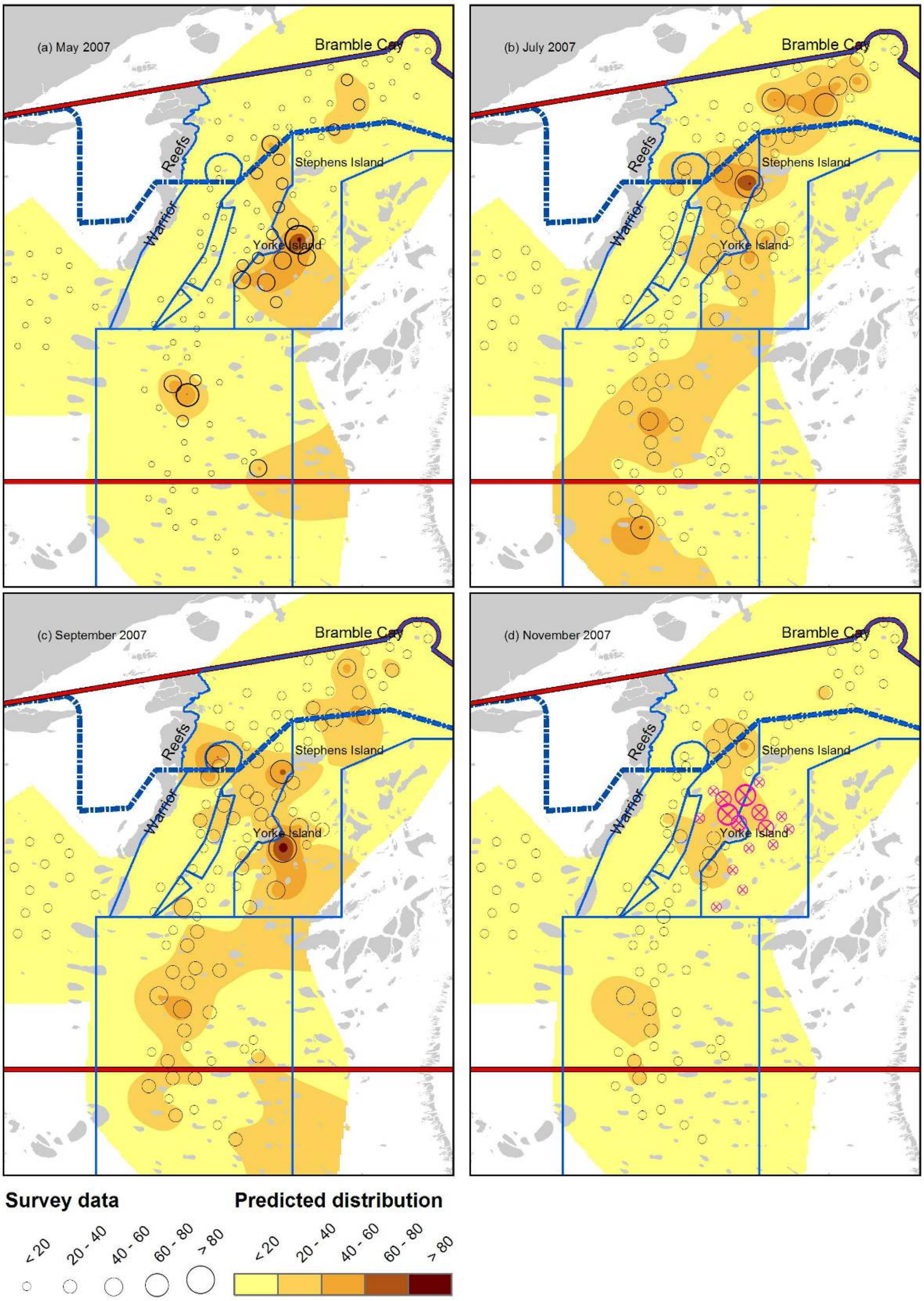


Figure 3.10 Spatial / temporal distribution of endeavour prawn spawning from the 2007 surveys. Population Fecundity Index PFI on a relative scale of 0 to 100. The survey and site with highest egg production (PFI) is scaled to 100.

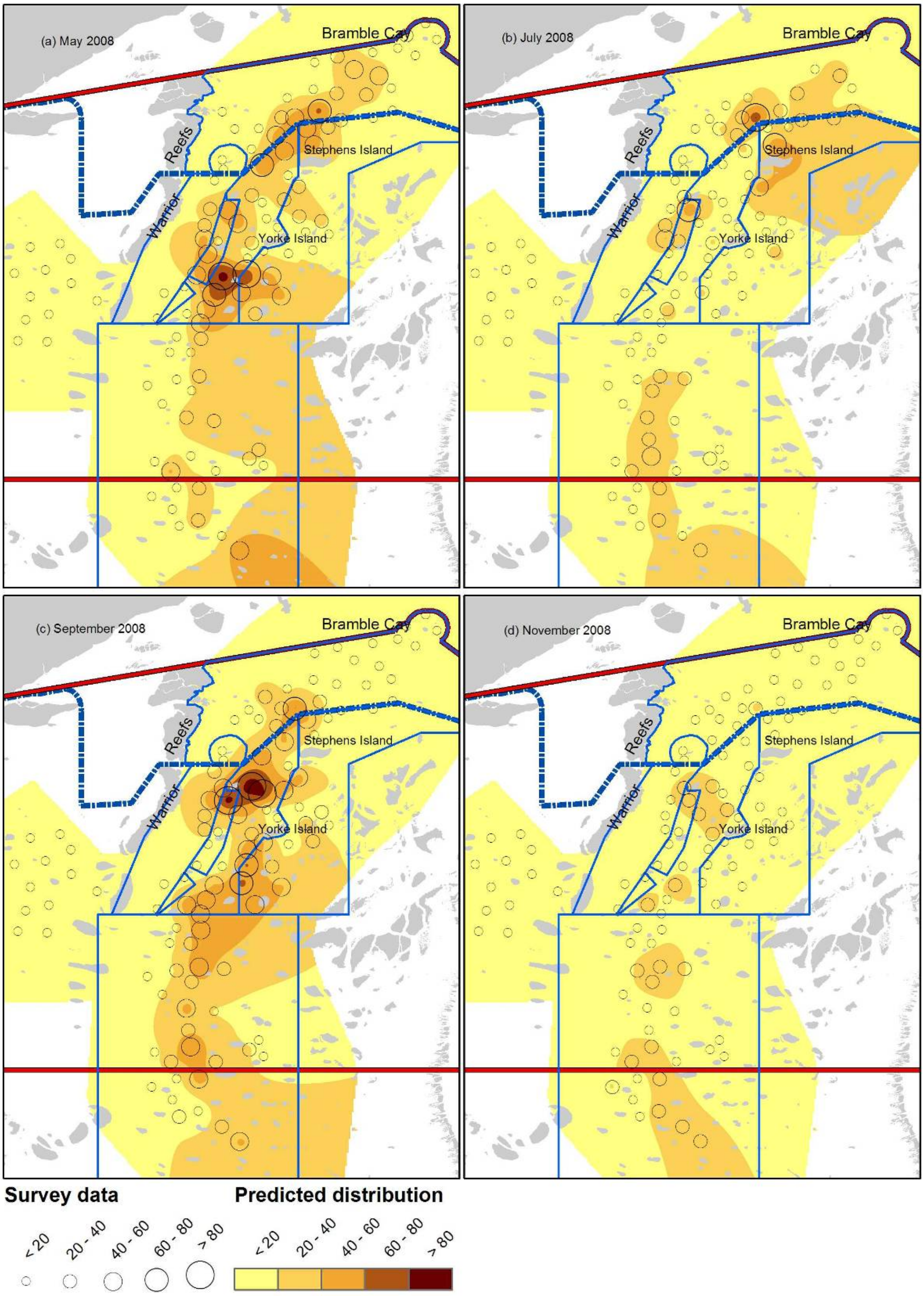


Figure 3.11 Spatial / temporal distribution of endeavour prawn spawning from the 2008 surveys. Population Fecundity Index PFI on a relative scale of 0 to 100. The survey and site with highest egg production (PFI) is scaled to 100.

This page deliberately left blank.

3.3.3 The distribution of the tiger and endeavour prawn stocks

The survey trawl catch rates or Catch per Unit of Effort (CPUE) for each site are a relative index of the stock abundance at each site. The CPUE data for each site were interpolated in ArcGIS to produce raster plots that show the relative spatial distribution of the tiger and endeavour prawns stocks throughout the fishery. There are only minor differences in the spatial and temporal distribution of the tiger (Figure 3.12) and endeavour (Figure 3.13) prawns stocks in Torres Strait. Both species are concentrated in a band that runs from Bramble Cay, southwest to Stephens Island then south to the top of the Queensland east coast trawl fishery. The deep water around Yorke Island has the highest abundances of tiger prawns and there are other patches of high abundance to the west of Stephens Island, the south-west of Bramble Cay and in the southern region of the fishery. In contrast the highest abundances of endeavour prawns occurred in the shallower waters to the south of Dalrymple Island. The areas of highest abundance varied during the season and between years (Figure 3.14 to Figure 3.17).

The raster plots were overlaid with the model regions and the zonal statistics function in Spatial Analyst Toolbox was used to estimate the relative distribution of the stocks across the model regions. Table 3.4 shows the proportion of tiger, endeavour and king stocks in each of the model regions relative to the total stock in the Australian regions (i.e. the proportions in the Australian region sum to 1). The average catch of the Australian region of the fishery during 2003-08 (1240t) was multiplied by proportion of stock in the PNG region (0.18) to estimate the potential catches for the PNG region assuming vessels of the same fishing power and levels of fishing effort as for the Australian regions. The estimated potential catch of the PNG region is about 227t, comprised of 103t tiger prawns, 114t of endeavour prawns and 10t of king prawns.

Table 3.4 Estimates of the potential harvest of the PNG region based on the Australian catches for 2003-04 and the proportion of stock in each region relative to the total stock in the Australian regions.

Region	*prawn*	*tiger*	*endeavour*	*king*
Centre	0.13	0.14	0.12	0.06
EWC	0.09	0.10	0.09	0.00
South	0.57	0.53	0.56	0.74
ExEwc	0.03	0.03	0.03	0.00
Deep	0.19	0.20	0.21	0.19
PNG	0.18	0.18	0.19	0.16
Average Australian catch (2003-08)	1240	584	592	62.93
Estimated catch of PNG region	227	103	114	10
Total	1467	688	706	73

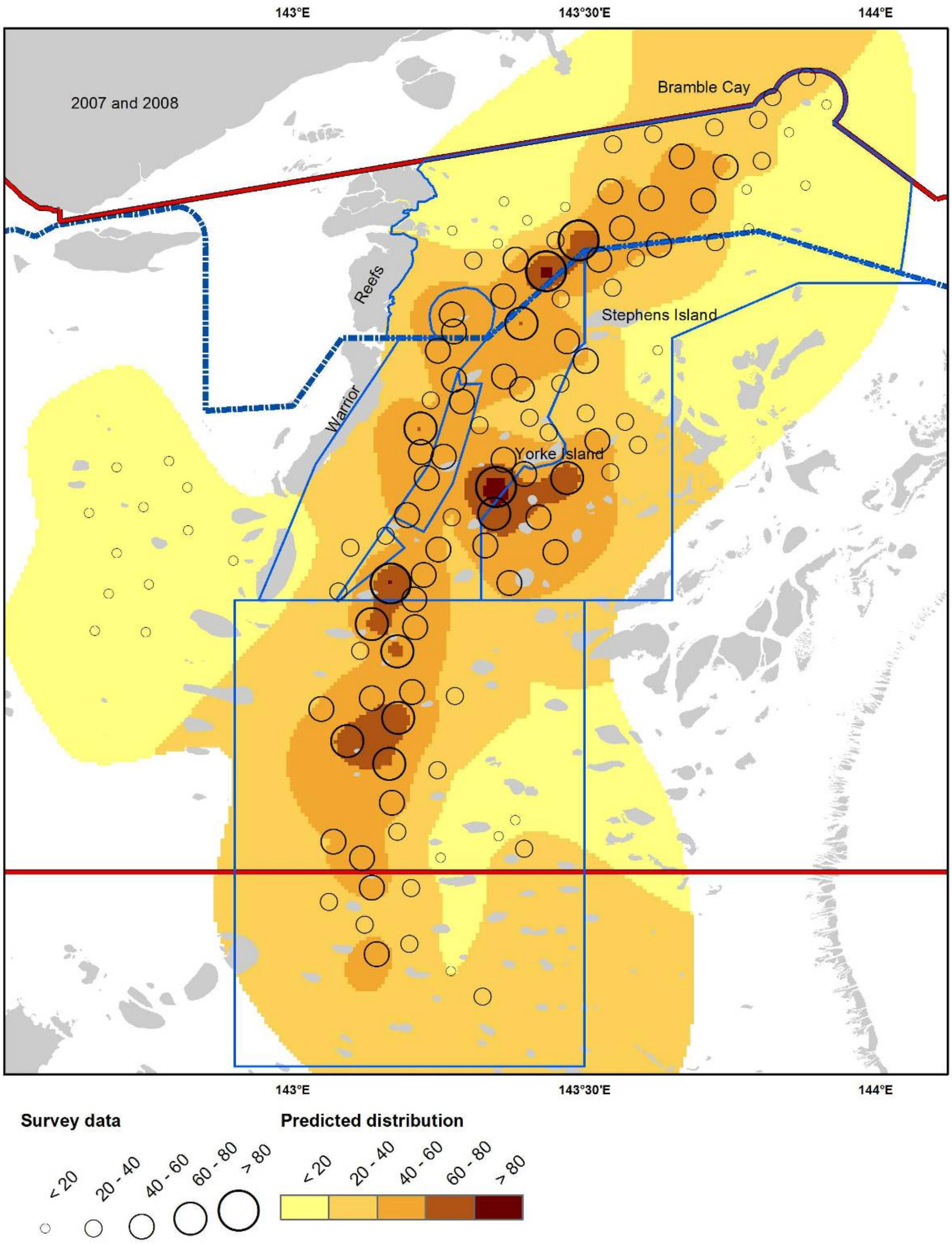


Figure 3.12 The spatial distribution of the tiger prawn stock estimated from the pooled abundance (CPUE) data from all surveys. The indices for both the survey data and the predicted abundance distribution are on a relative scale of 0 to 100. The survey site with the highest CPUE was scaled to 100.

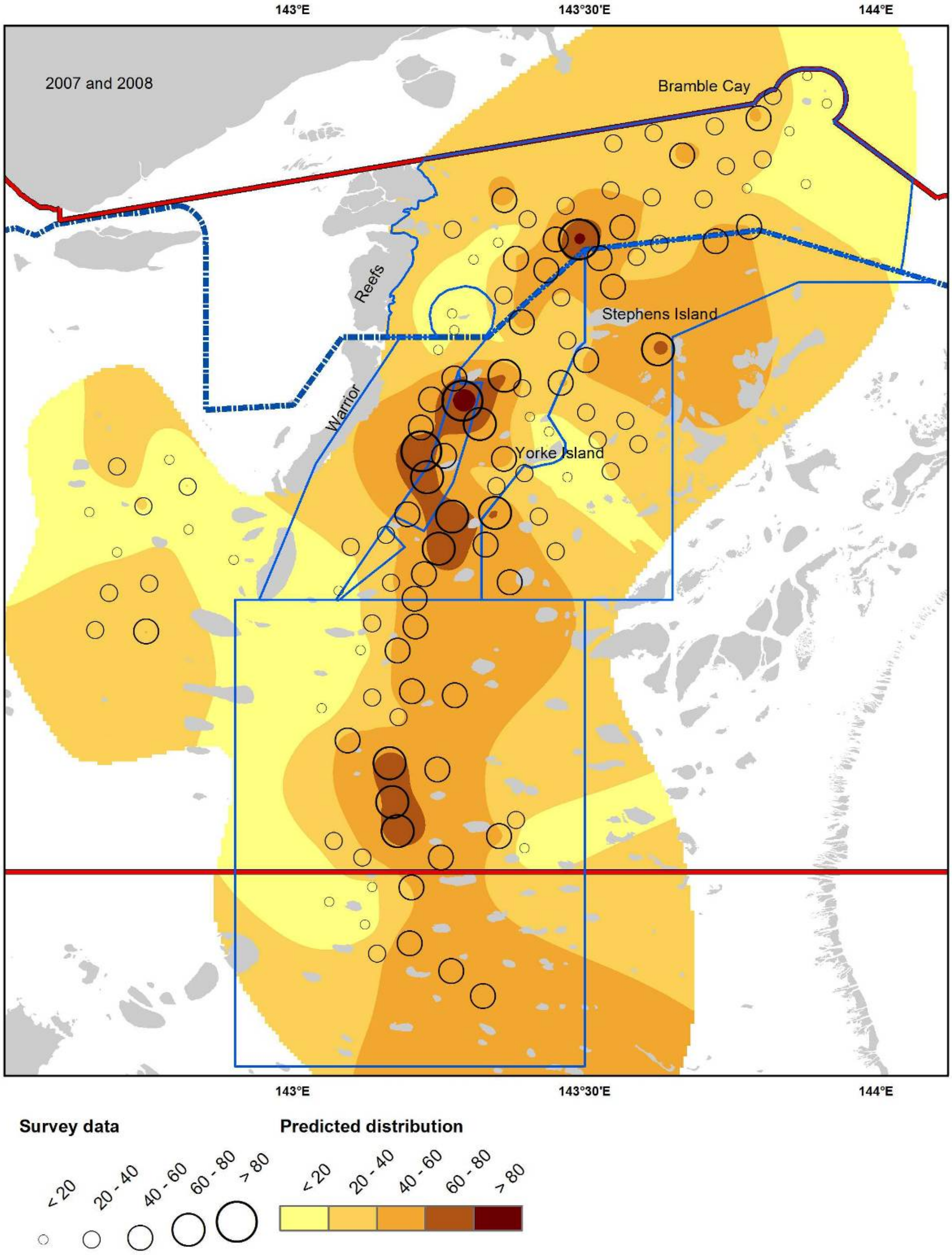


Figure 3.13 The spatial distribution of the endeavour prawn stock estimated from the pooled abundance (CPUE) data from all surveys. The indices for both the survey data and the predicted abundance distribution are on a relative scale of 0 to 100. The survey site with the highest CPUE was scaled to 100.

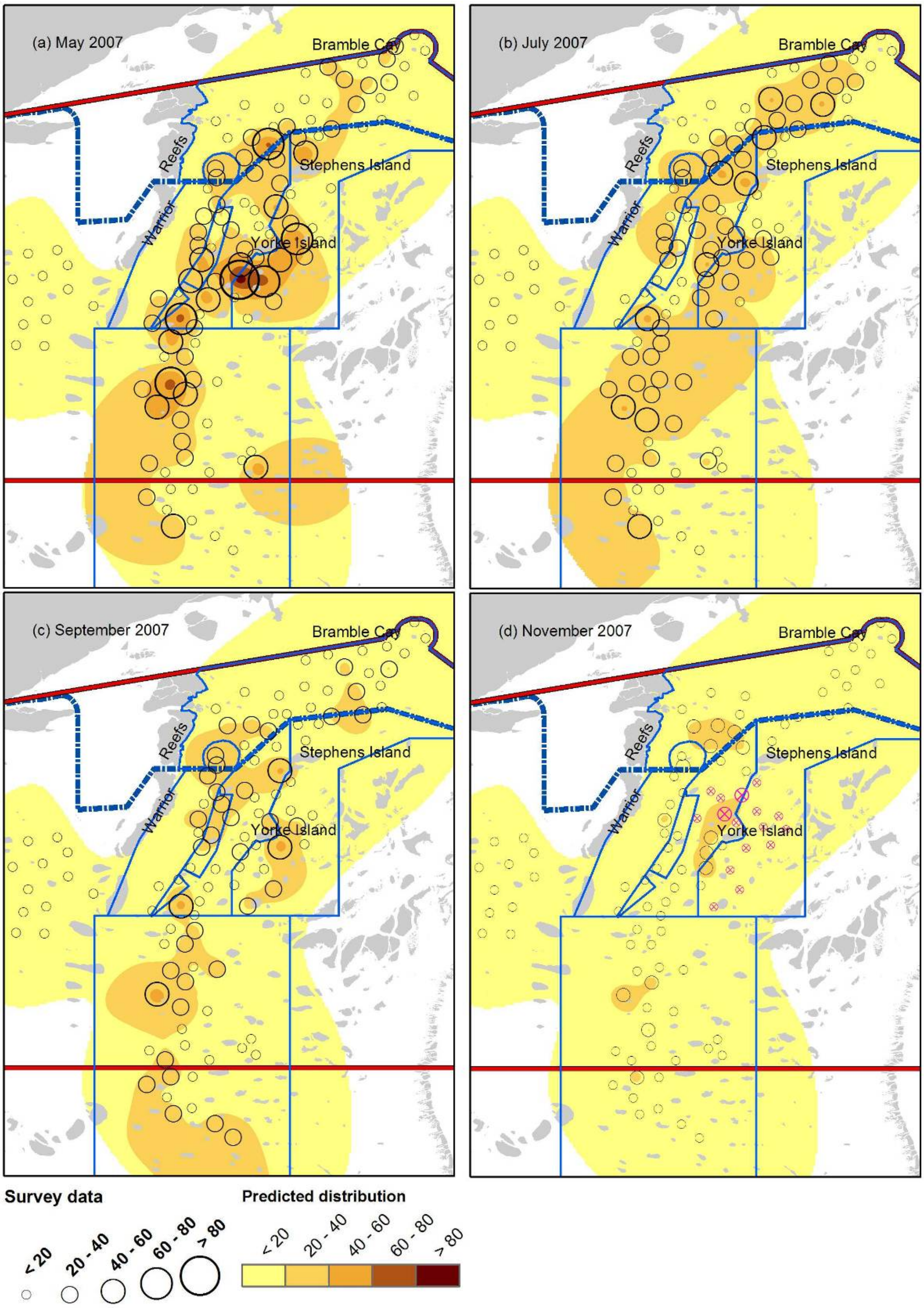


Figure 3.14 The spatial / temporal distribution of the tiger prawn stock estimated from the abundance (CPUE) indices from the 2007 surveys. The indices for both the survey data and the predicted abundance distribution are on a relative scale of 0 to 100. The site and survey for both 2007 and 2008 with the highest CPUE was scaled to 100.

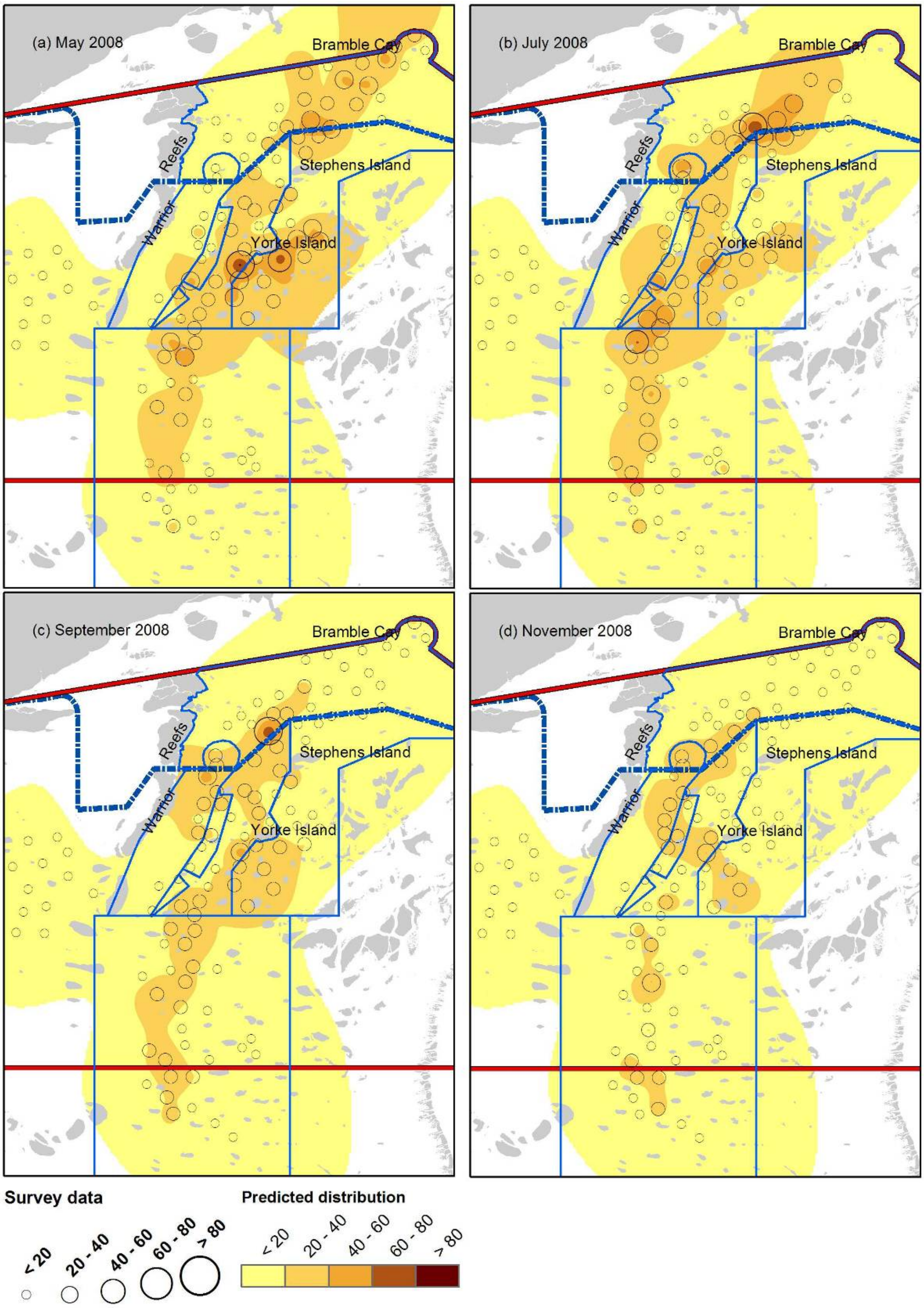


Figure 3.15 The spatial / temporal distribution of the tiger prawn stock estimated from the abundance (CPUE) indices from the 2008 surveys. The indices for both the survey data and the predicted abundance distribution are on a relative scale of 0 to 100. The site and survey for both 2007 and 2008 with the highest CPUE was scaled to 100.

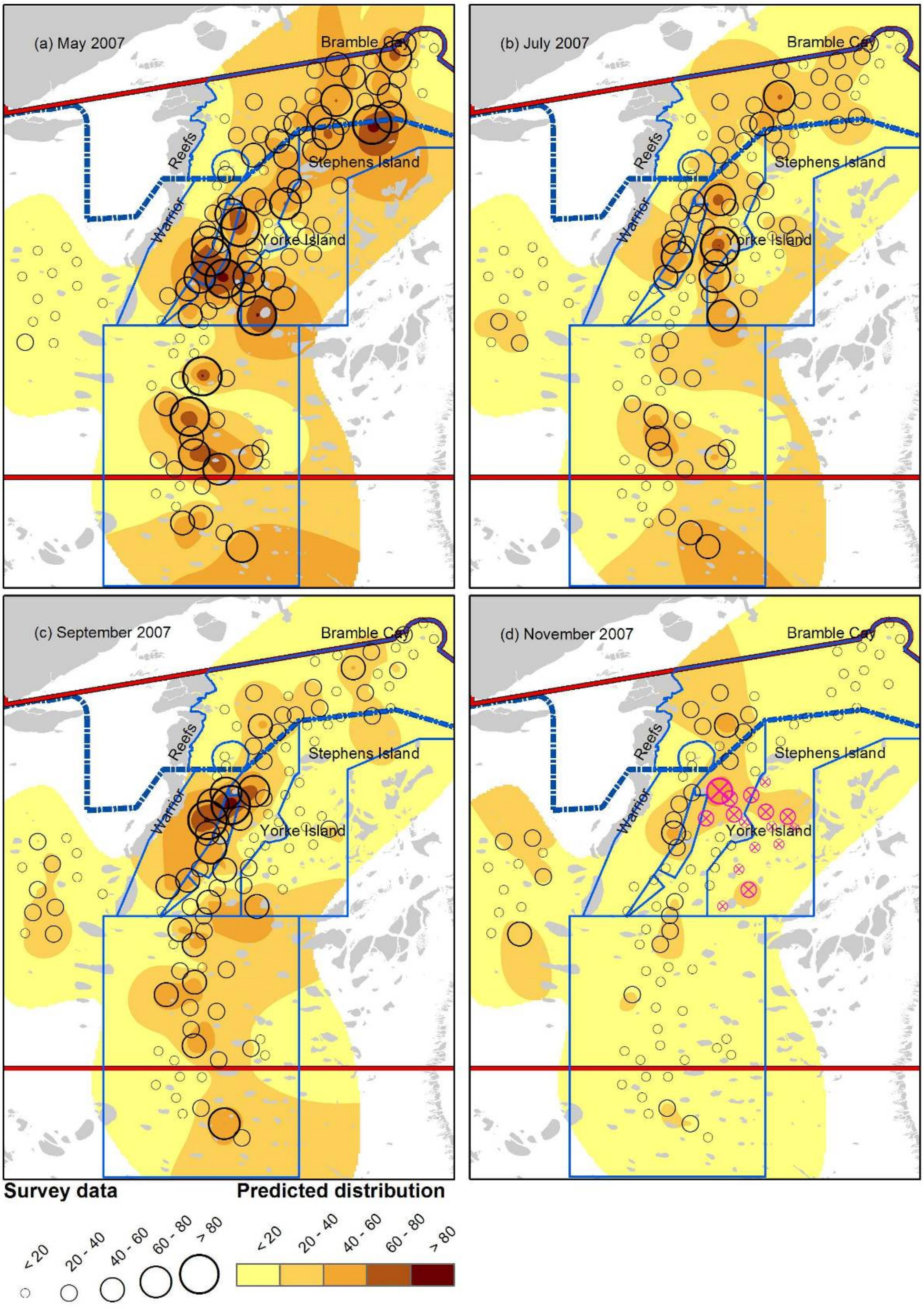


Figure 3.16 The spatial / temporal distribution of the endeavour prawn stock estimated from the abundance (CPUE) indices from the 2007 surveys. The indices for both the survey data and the predicted abundance distribution are on a relative scale of 0 to 100. The site and survey for both 2007 and 2008 with the highest CPUE was scaled to 100.

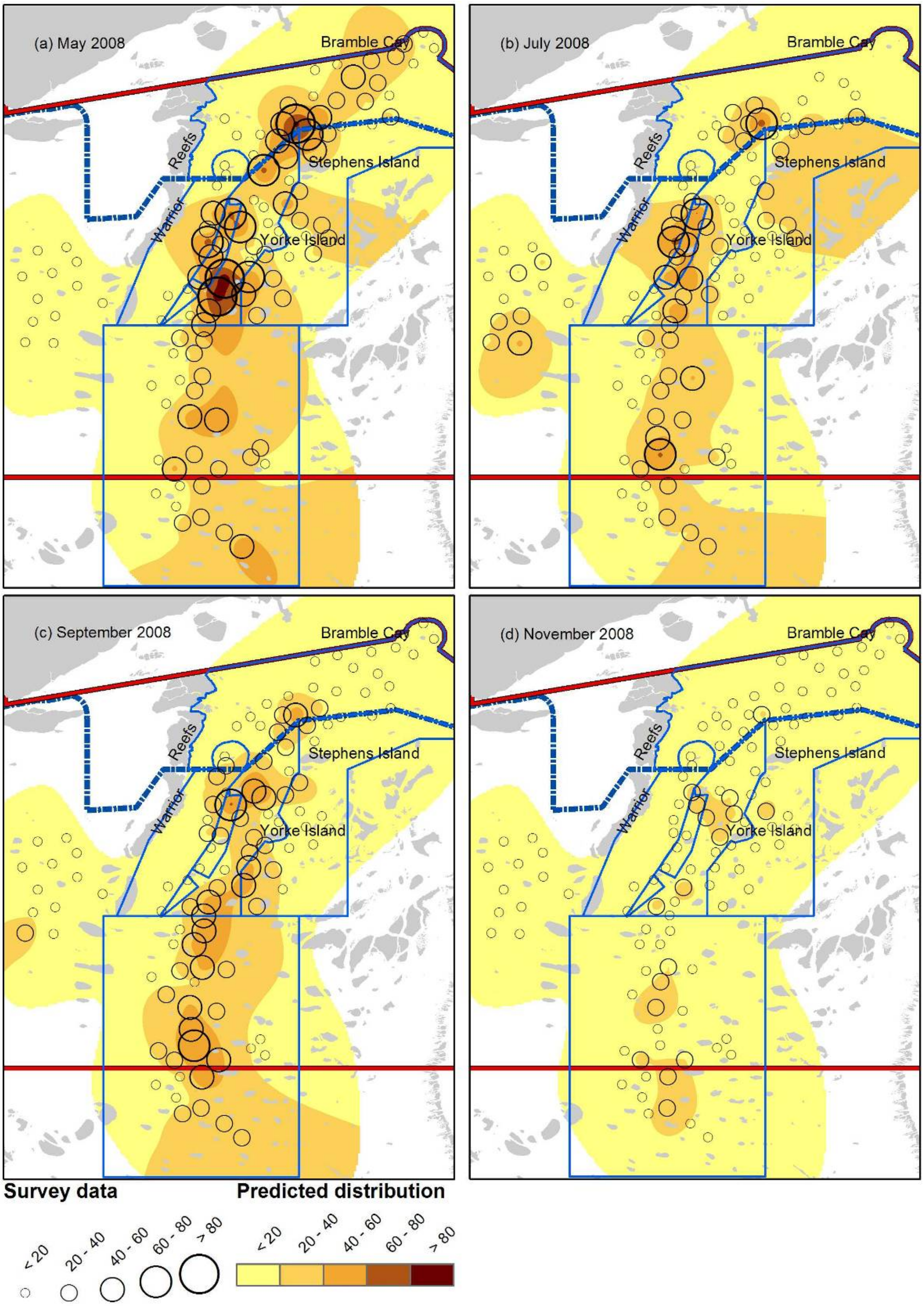


Figure 3.17 The spatial / temporal distribution of the endeavour prawn stock estimated from the abundance (CPUE) indices from the 2008 surveys. The indices for both the survey data and the predicted abundance distribution are on a relative scale of 0 to 100. The site and survey for both 2007 and 2008 with the highest CPUE was scaled to 100.

This page deliberately left blank.

3.3.4 Size distribution of the tiger and endeavour prawn

The mean size of male and female tiger and endeavour prawns at each site were plotted and interpolated then classified in relation to the commercial prawn grades. These grades are based on a count of prawns per pound; the smaller the count the larger the average prawn size and weight. Both the prawn grades and the equivalent carapace length cut-off are indicated on the classification scale. The females of both species grow to a larger size than the males.

The smallest tiger prawns occur in the shallow closure areas on the western side of the fishery and the largest are found in deep waters of the eastern and southern areas. Although there are slight variations this trend is consistent through out the fishing season. These plots provide information of relevance to the proposed extension to the East of Warrior closure (region ExEWC). The pooled data (Figure 3.19 and Figure 3.20) indicates that the southern half of the proposed closure would limit the harvesting of 15/20 female and 21/30 male tiger prawns. The seasonal plots (Figure 3.21 and Figure 3.22) indicate that whole of the proposed closure has small tiger prawns during May but during the later months of the season the small prawns are restricted to the southern half.

Endeavour prawns do not grow as large as tiger prawns hence the limited presence of the U10 grade for this species in the size distribution plots. As for tiger prawns the smallest prawns are prevalent in the western closure areas and the largest occur in the deeper eastern and south-eastern areas of the fishery.

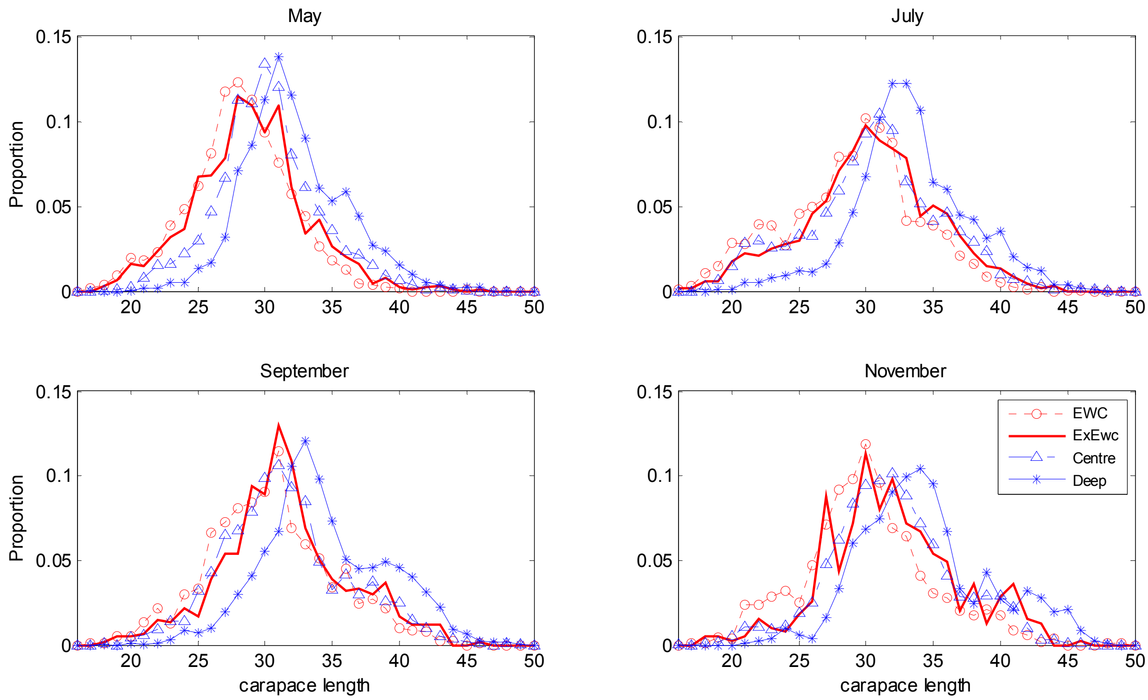


Figure 3.18 The relative size distribution of tiger prawns by month and for the EWC, ExEWC Centre and Deep regions. The Y-axis is the proportion of individuals in each 1mm carapace length class size. Note that prawns <= 25 mm CL are 30+ grade and 26-29 are 21/30 grade.

Figure 3.18 shows the relative size distribution plots of the tiger prawns by survey month (2007 and 2008 data pooled) and the EWC, ExEwc, Central and Deep regions. The plots indicate that the size distribution of tiger prawns in the proposed extension of the East of Warrior closure is similar to that of the East of Warrior closure. Although the size distribution of the Central and Deep regions are shifted to the right indicating a generally large prawn size there are also some small prawns (<= 25 mm CL) in all of the regions.

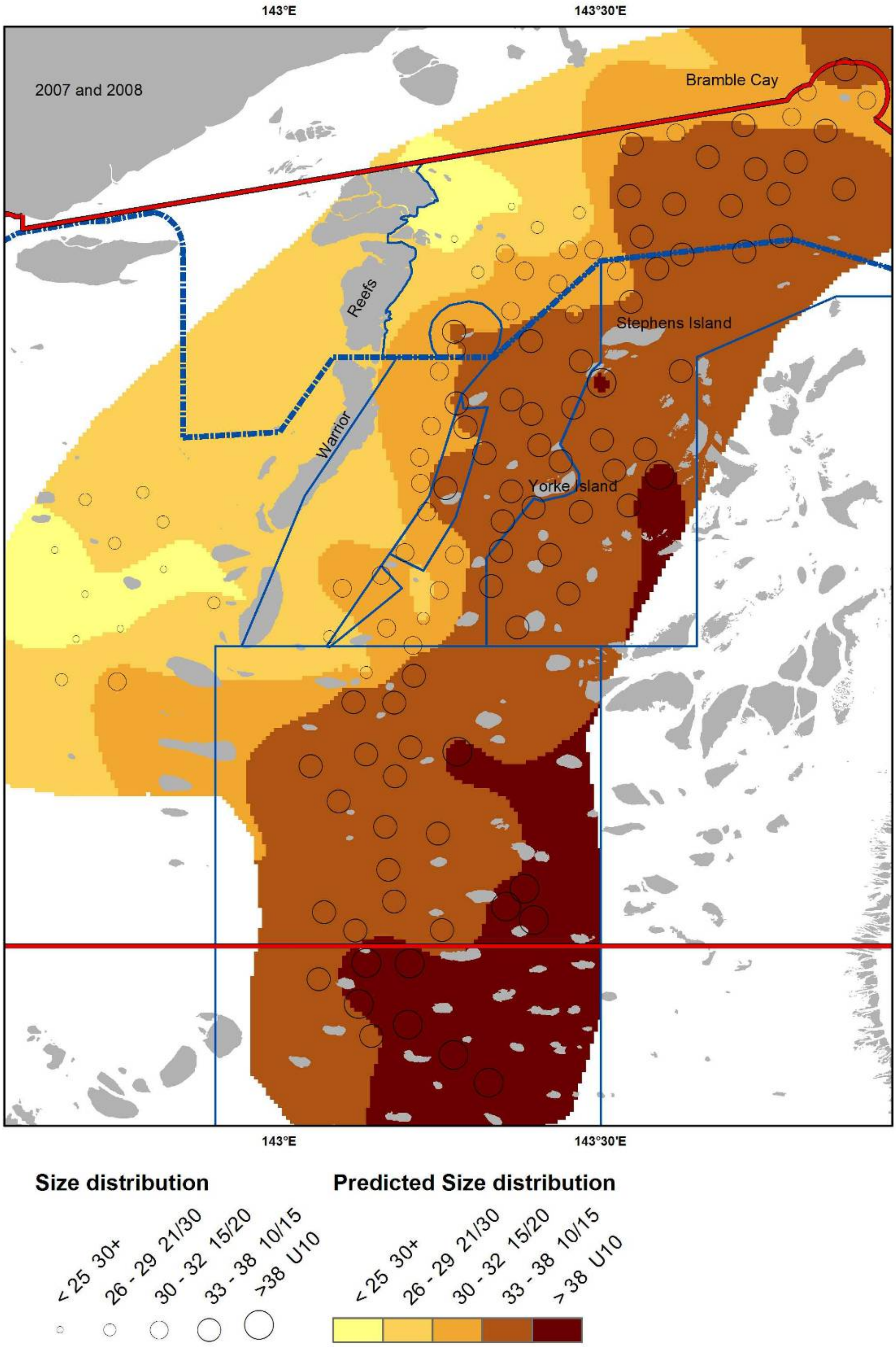


Figure 3.19 The average size of female tiger prawns by carapace length over all surveys, classified by the commercial grades which are a count per pound.

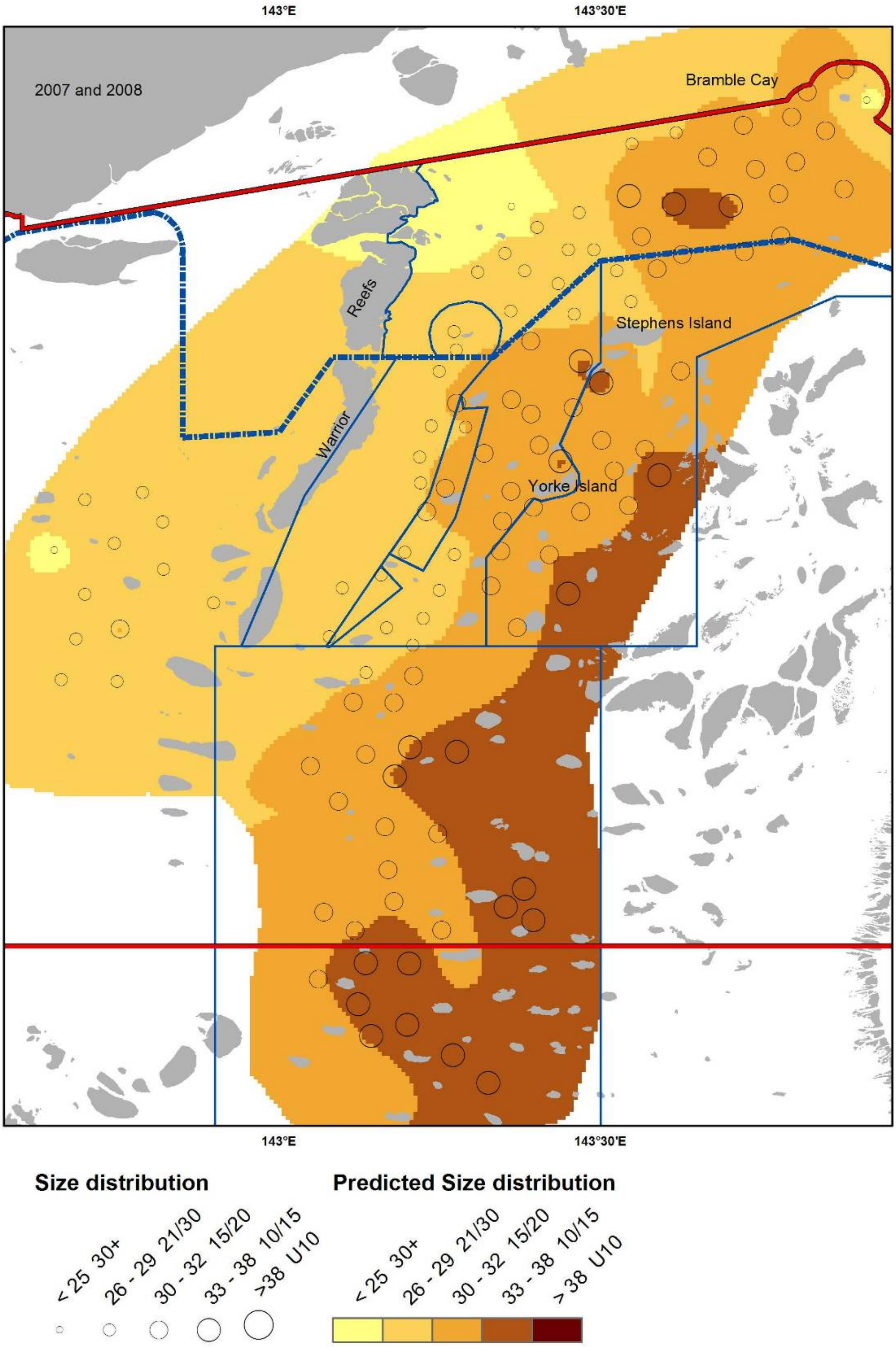


Figure 3.20 The average size of male tiger prawns by carapace length over all surveys, classified by the commercial grades which are a count per pound.

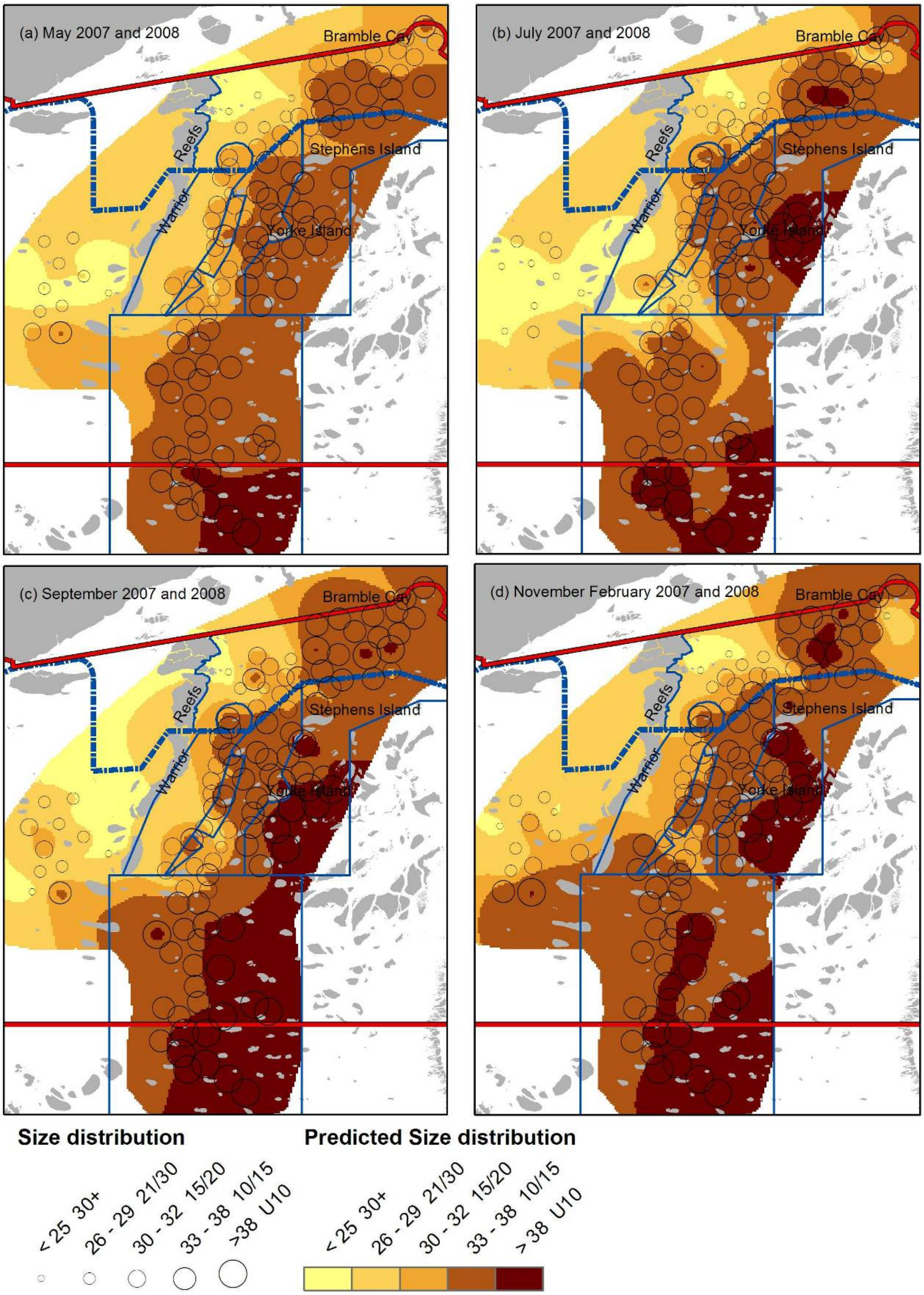


Figure 3.21 The average size of female tiger prawns by carapace length over all surveys shown monthly, classified by the commercial grades which are a count per pound.

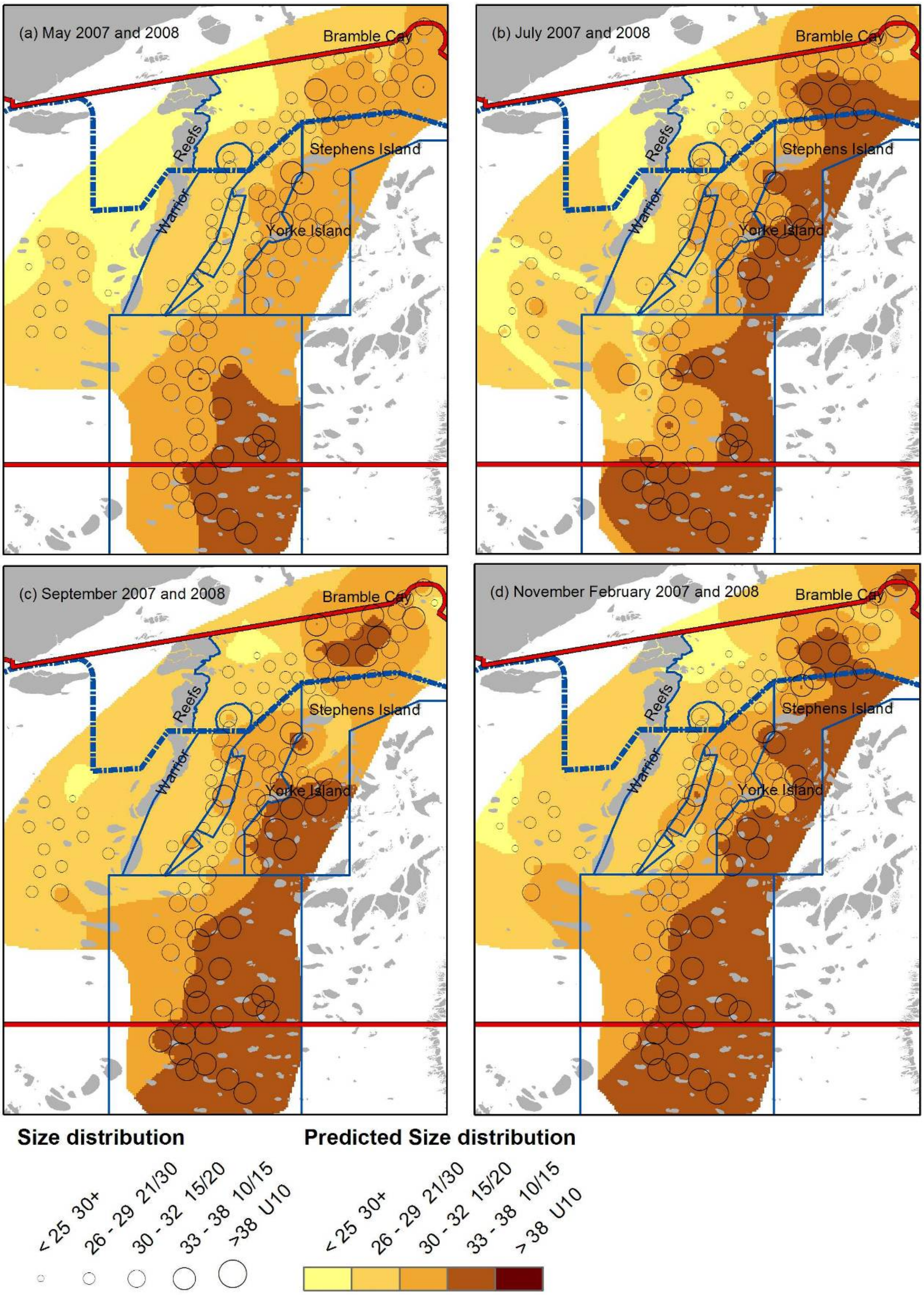


Figure 3.22 The average size of male tiger prawns by carapace length over all surveys shown monthly, classified by the commercial grades which are a count per pound.

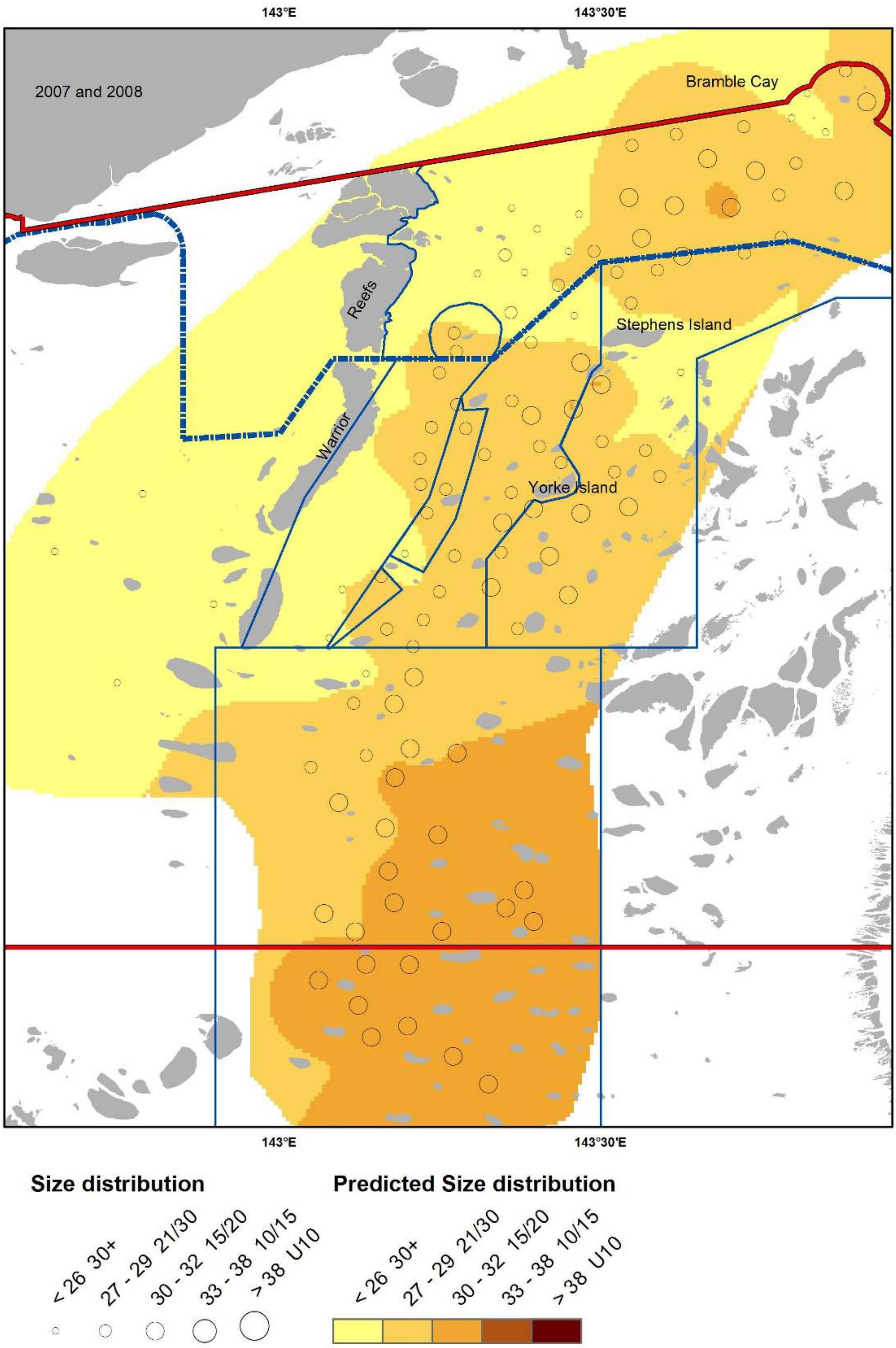


Figure 3.23 The average size of female endeavour prawns by carapace length over all surveys, classified by the commercial grades which are a count per pound.

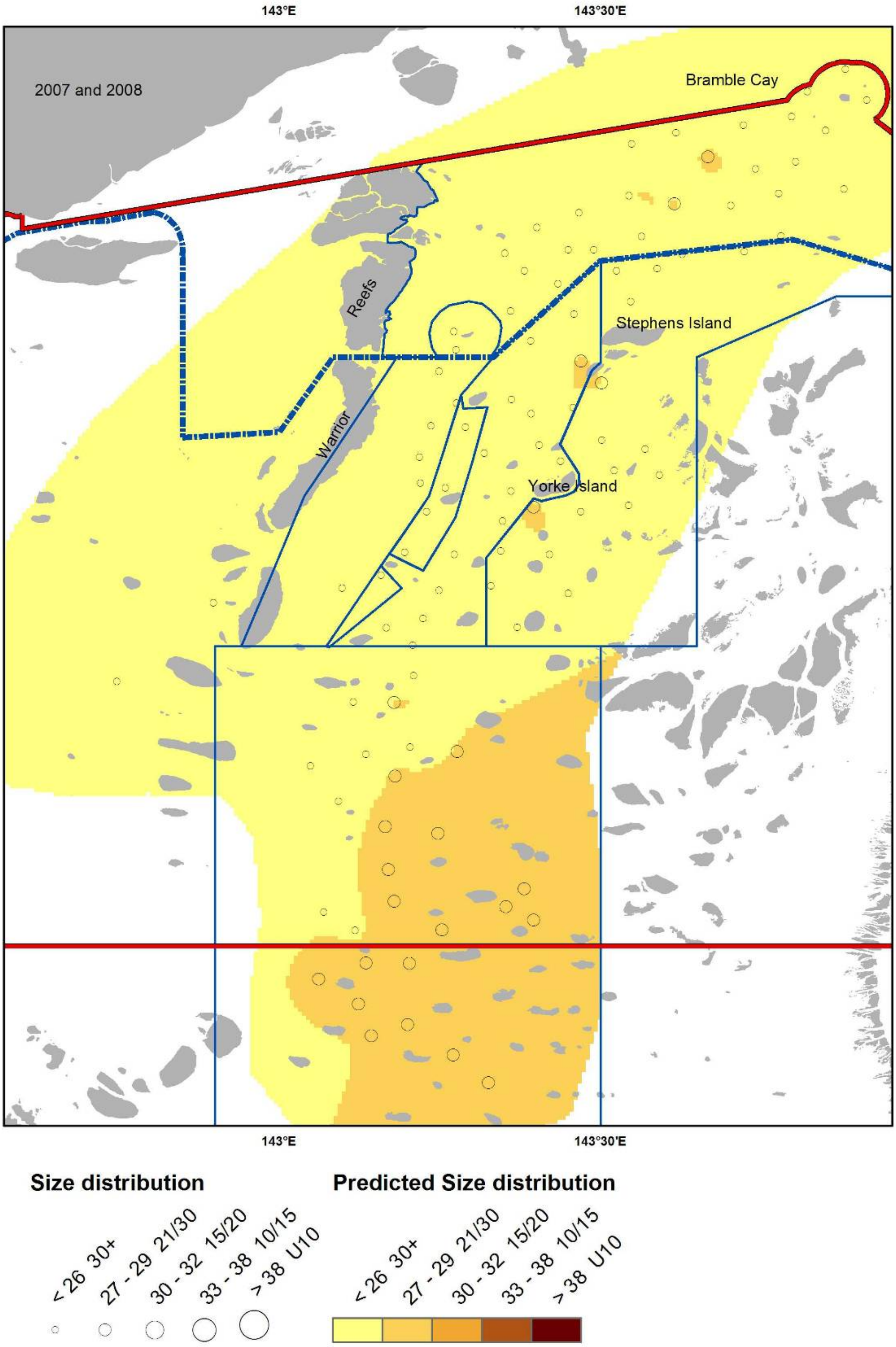


Figure 3.24 The average size of male endeavour prawns by carapace length over all surveys, classified by the commercial grades which are a count per pound.

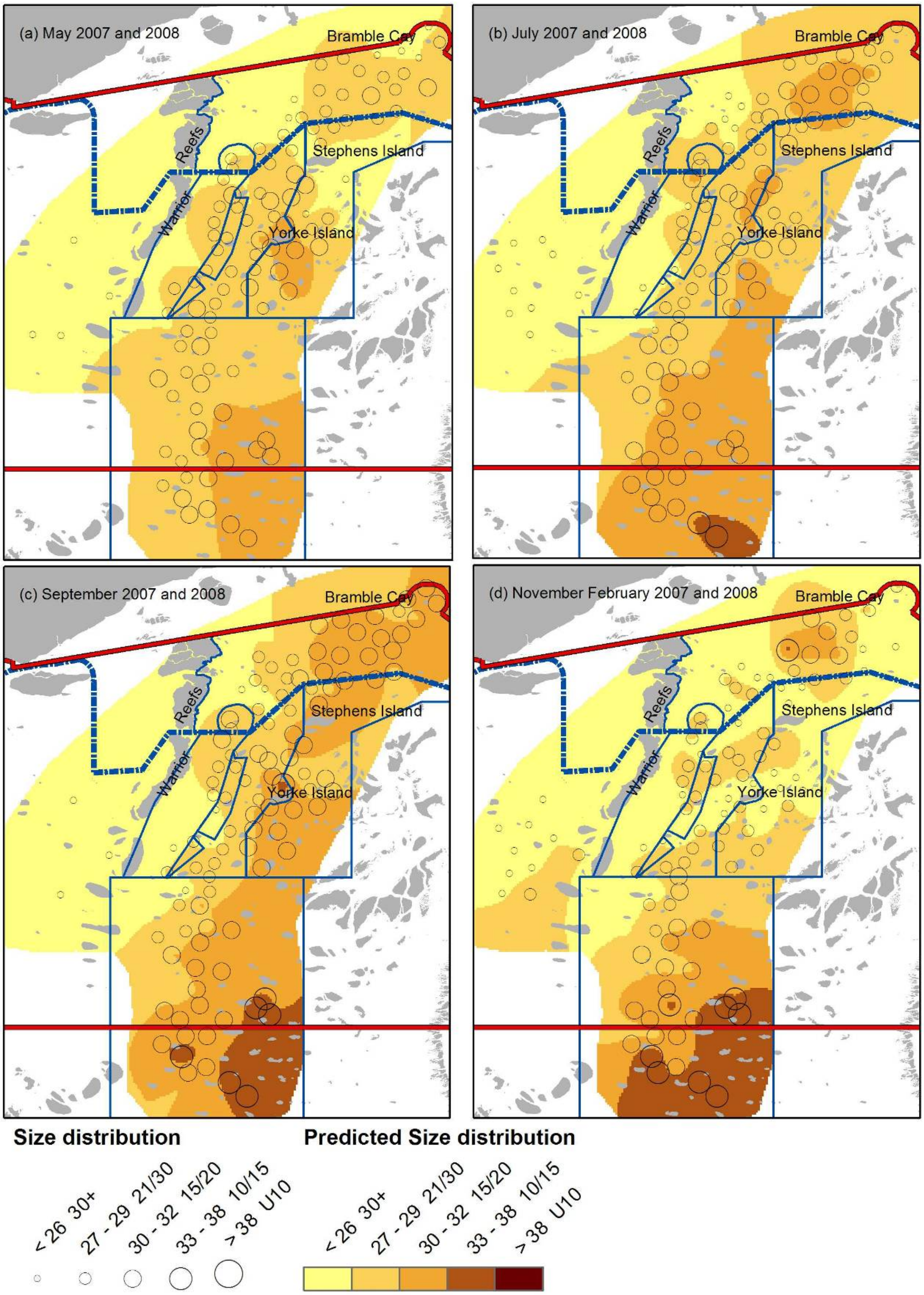


Figure 3.25 The average size of female endeavour prawns by carapace length over all surveys shown monthly, classified by the commercial grades which are a count per pound.

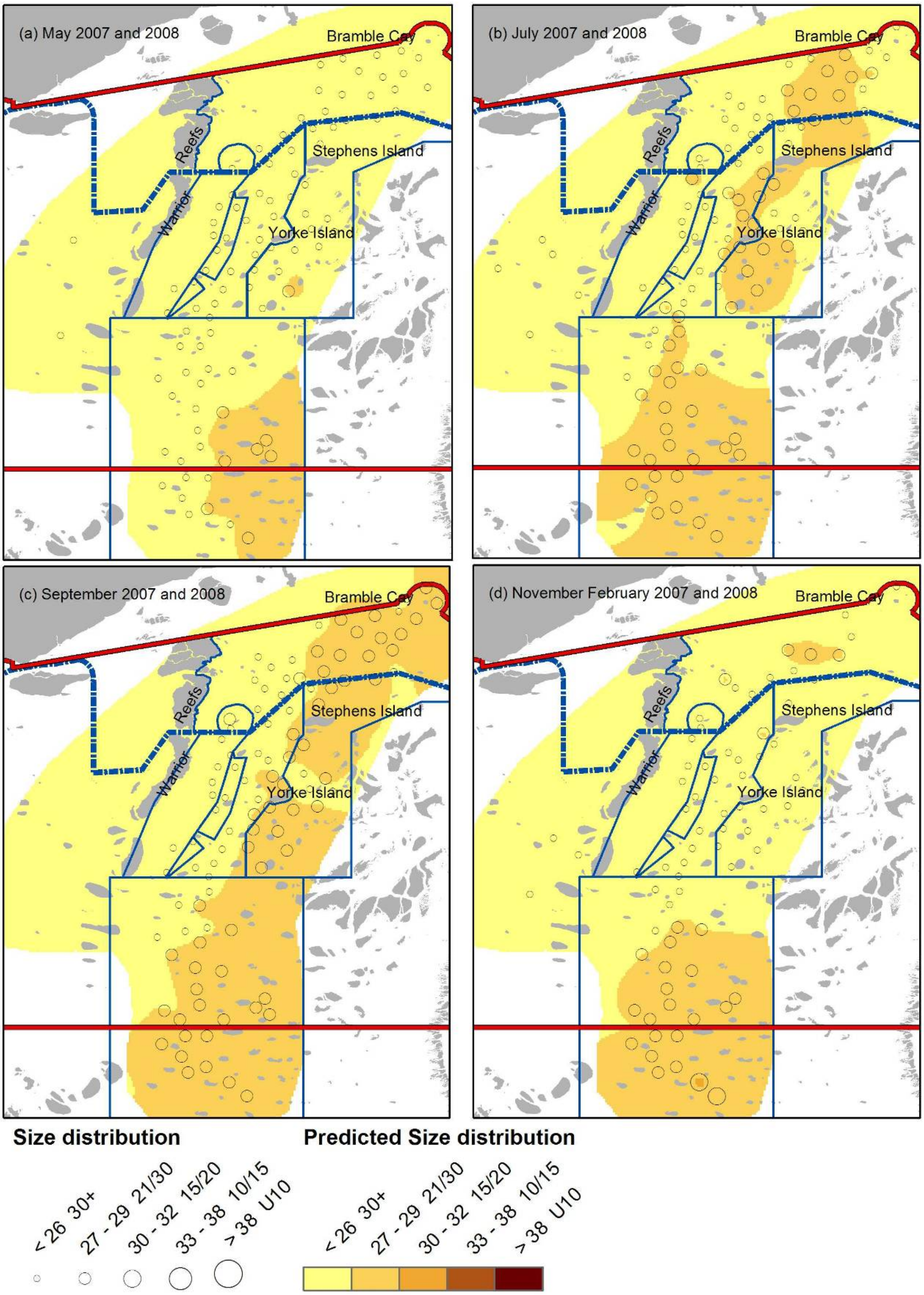


Figure 3.26 The average size of male endeavour prawns by carapace length over all surveys shown monthly, classified by the commercial grades which are a count per pound.

3.4 Discussion

The survey results indicate that the prawn stock of the PNG region is a continuation of the prawn stock in the Australian region as the overall catch composition and catch rates across the fishery are quite similar based on both weight and number of prawns. The regions with the highest catch rate and proportion of tiger prawns were the Central and Deep regions around Yorke Island. At a finer spatial scale there is variability between relatively close sites that reflect the patchy nature of the trawl grounds and is probably the result of variations in sediment type and depth. The deeper sites in the north-east and south-east areas of the fishery produced the highest catches of king prawns. Tiger and endeavour prawns clearly occur together as all of the sites produced at least a few of each species but at a finer spatial level there are areas where tiger prawns are more prevalent and others where endeavour prawns are more prevalent.

The highest levels of spawning (egg production) for tiger prawn occurs in the deep water that runs from Bramble Cay south-west to Stephens Island and then to the south-east of Yorke Island. The relative proportion of tiger prawn spawning occurring in the deep region (proposed spawner closure) ranged from 15 to 35 percent with the highest being May and the lowest November. This is higher than the 12 percent estimated by the spatial simulation model indicating the model may have under estimated the size of the tiger prawn spawning stock in the deep area and hence the benefit of closing the area at high levels of effort. It is worth noting that 12 to 25 percent of the tiger prawn egg production occurs in the PNG region and that this area up until now has been only lightly fished and not at all in recent years. While this area is not fished it servers as a pseudo closure that protects about 15 percent of the tiger prawn egg production.

The survey trawl catch rates for each site are a relative index of the stock abundance and were interpolated in ArcGIS to produce raster plots that show the relative spatial distribution of the tiger and endeavour prawn stocks throughout the fishery. These raster plots were overlaid with the model regions and the Spatial Analyst zonal statistics function used to estimate the distribution of the stocks across the model regions, relative to the stock of the Australian area. The average catch of the Australian region of the fishery during 2003-08 (1240t) was multiplied by proportion of stock in the PNG region (0.18) to estimate the potential catches for the PNG region assuming vessels of the same fishing power and levels of fishing effort as for the Australian regions. The estimated potential catch of the PNG region is about 227t comprised of 103t tiger prawns, 114t of endeavour prawns and 10t of king prawns. This validates the use of 200 tonnes for the nominal catch of the PNG area in the calculations for the cross-boarder catch sharing arrangements.

Size distribution plots show that the smallest tiger and endeavour prawns occur in the shallow closure areas on the western side of the fishery and the largest are found in deep waters of the eastern and southern areas. Although there are slight variations this trend is consistent through out the fishing season. These plots can be used to assess whether the proposed extension to the East of Warrior closure would be of any benefit. The pooled data indicates that the southern half of the proposed closure would limit the harvesting of 15/20 female and 21/30 male tiger prawns. The seasonal plots indicate that the whole of the proposed closure has small tiger prawns during May but during the later months of the season the small prawns are restricted to the southern half. Relative size distribution plots of the tiger prawns by survey month (2007 and 2008 data pooled) indicate that the size distribution of tiger prawns in the proposed extension of the East of Warrior closure is similar to that of the East of Warrior closure. Although the size distribution of the Central and Deep regions are shifted to the right indicating a generally large size there are some small tiger prawns (<= 25 mm CL or 30+ grade) in all of the regions.

3.5 Appendix

3.5.1 The spatial distribution and length-weight relationship of the Japanese tiger prawn (*Marsupenaeus japonicus*) in Torres Strait

Carissa Fairweather and Clive Turnbull

Introduction

The Japanese tiger prawn or Kuruma prawn (*Marsupenaeus japonicus*) is a major species in the Japanese prawn fisheries and throughout the South China Sea (Grey et al. 1983). This tiger prawn species occurs occasionally in Australian waters and is generally combined with tiger prawn landings therefore contributes to the commercial tiger revenue for fishers. In order to quantify the amount, by weight, of *M. japonicus* found in the 2007-08 trawl surveys of the Torres Strait Protected Zone a length-weight relationship was required. A literature search failed to locate length-weight parameters for this species with (Dall et al. 1990) citing only a fecundity estimate derived from total length. Specimens of this species were retained from the trawl surveys and used in this study to develop a carapace length to total weight relationship for *M. japonicus* in Torres Strait. The distribution of this species within Torres Strait is also of interest as it is restricted to small area within the Papua New Guinea section of the fishery. In contrast the other minor tiger prawn species in Torres Strait, the grooved tiger prawn (*Penaeus semisulcatus*) occurs in widely separated parts of the fishery.

Methods

A sample of 224 *M. japonicus* specimens was retained from sites near Bramble Cay after recording the carapace length, sex and ovary condition as per the at sea protocols for the other commercial prawn species (section 3.2.2). The specimens retained from each site were bagged and labelled with the site reference and date, then returned frozen to the Northern Fisheries Centre for further processing. When all eight surveys were complete the specimens were defrosted at room temperature for a minimum of 4 hours and separated into rows of males and females on drainable sorting trays. The sex was determined by examination of the external genital organs. Individual specimens were blotted with absorbent paper to remove excess moisture, as per the methodology used by (Primavera et al. 1998). Carapace length (CL) was measured as the distance from the postorbital margin to the mid-dorsal posterior edge of the carapace to the nearest 0.1mm using Mitutoyo Absolute Coolant proof IP66 digital callipers. Weight was measured to the nearest 0.001g using GR – 200 Analytical Balance linked to Excel® file using RsKey. The length, weight, site, date and sex was recorded in an excel sheet linked to the analytical balance.

GenStat Release 11.1 was used to statistically analyse the data and fit it to the standard two parameter length-weight model used for other prawn species (Dall et al. 1990; Turnbull et al. 2005).

The model fitted was

$$W = aL^b$$

where W is weight, L is the carapace length, a is a curvature parameter and b is an exponential curvature parameter.

Results

The japonicus species in our study where found exclusively in the PNG jurisdiction of the TSPZ and around Bramble Cay. The tiger prawn catch at Site 42, to the east of Bramble Cay (Figure 3.27 and Figure.3.28), consisted almost entirely of *M. japonicus* species over both years. The remainder of the tiger prawn catch at site 42 consisted of a few brown tiger prawns (*P. esculentus*). In contrast the tiger prawn catch of Site 45 which is to the north of Bramble Cay, consisted of the grooved tiger (*P.*

semisulcatus) and the brown tiger prawn (*P. esculentus*). In addition there were a few *P. semisulcatus* in two sites in the west region, the two deep sites east of York Island and three deep sites at southern end of the fishery.

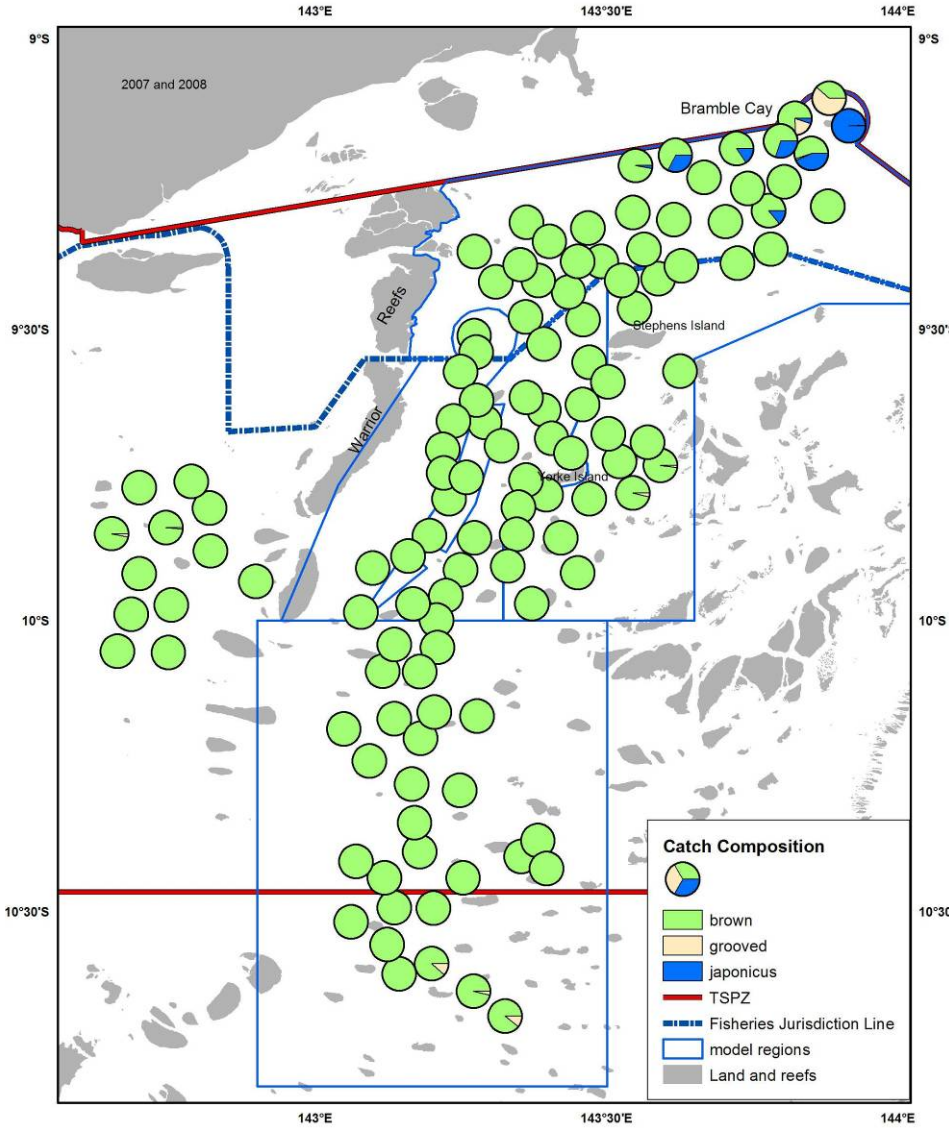


Figure 3.27 Spatial distribution of M. japonicus for all surveys. The sizes of the pie slices indicate the number of prawns by species in each sample. Tiger species include the brown (Penaeus esculentus), grooved (Penaeus semisulcatus) and japonicus (Marsupenaeus japonicus).

Table 3.5 list the parameter estimates, standard error of the estimates, sample size and measures of model fit (percentage variance accounted). Scatter plots of the length and weight data show similar relationships for males and females (Figure 3.29) and the highest percentage of model fit was 97% for the pooled genders, while the lowest was the males with 90%. There was no significant difference between the common ranges of carapace length and weight for the male and female data when the data was log transformed and compared statistically. The sample size in this test, however, was small. The scatter plots for the female and male data (Figure 3.29 b, c and d) indicate sexual dimorphism with the male being smaller than the females.

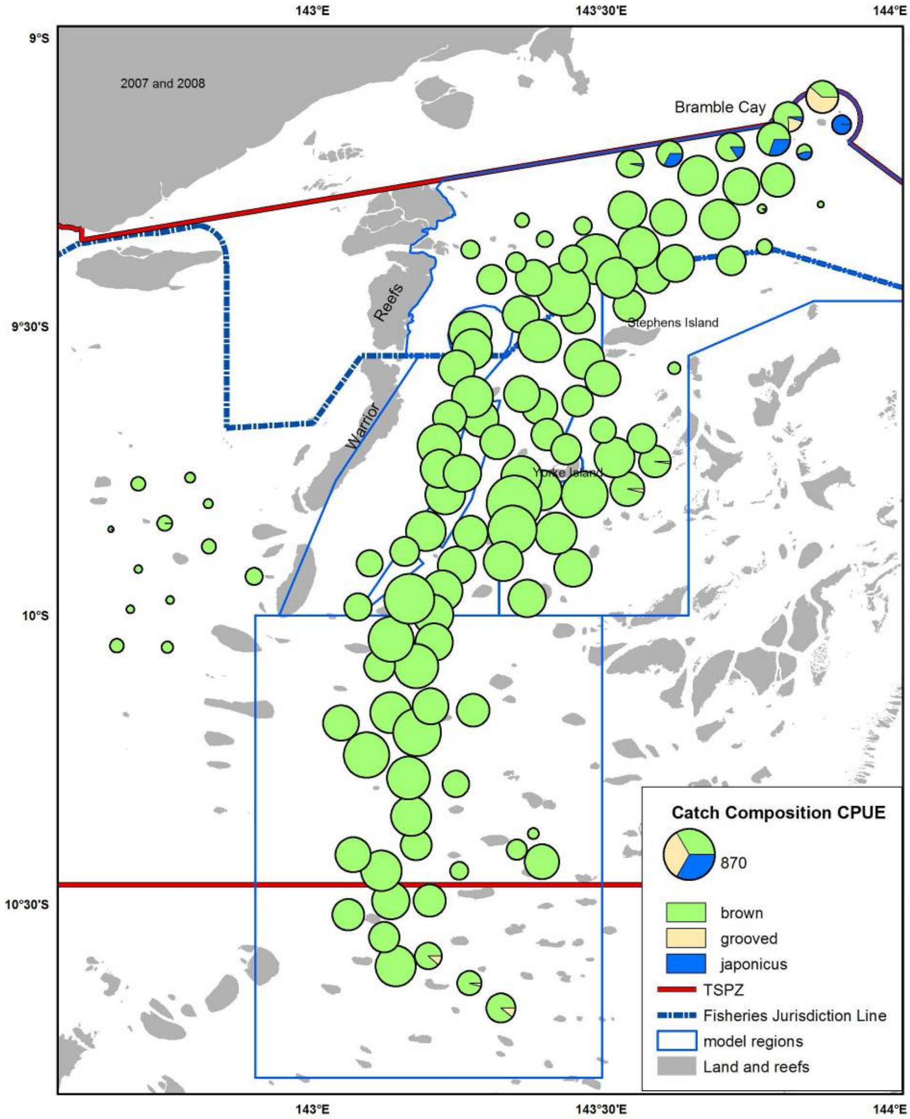


Figure.3.28 Spatial distribution of M. japonicus for all surveys. The size of the pie indicates the CPUE of prawns by species in each sample. Tiger species include brown Penaeus esculentus, grooved Penaeus semisulcatus and japonicus Marsupenaeus japonicus.

Table 3.5 Length-weight parameter estimates for the two-parameter model.

Gender	*a*	*Standard error*	*b*	*Standard error*	*Percentage variance accounted*	*Sample size (n)*
female	0.002735	0.00066	2.5354	0.0628	95.0	111
male	0.001377	0.000466	2.7237	0.0945	90.0	113
both	0.002381	0.000261	2.5713	0.0289	97.5	224

Discussion

We anticipated using the sample of *M. japonicus* to calculate a population fecundity index by quantifying the number of eggs per females. This was not feasible, however, as based on the ovary condition classifications (Tuma 1967; Yano 1988) the majority of female had spent ovaries.

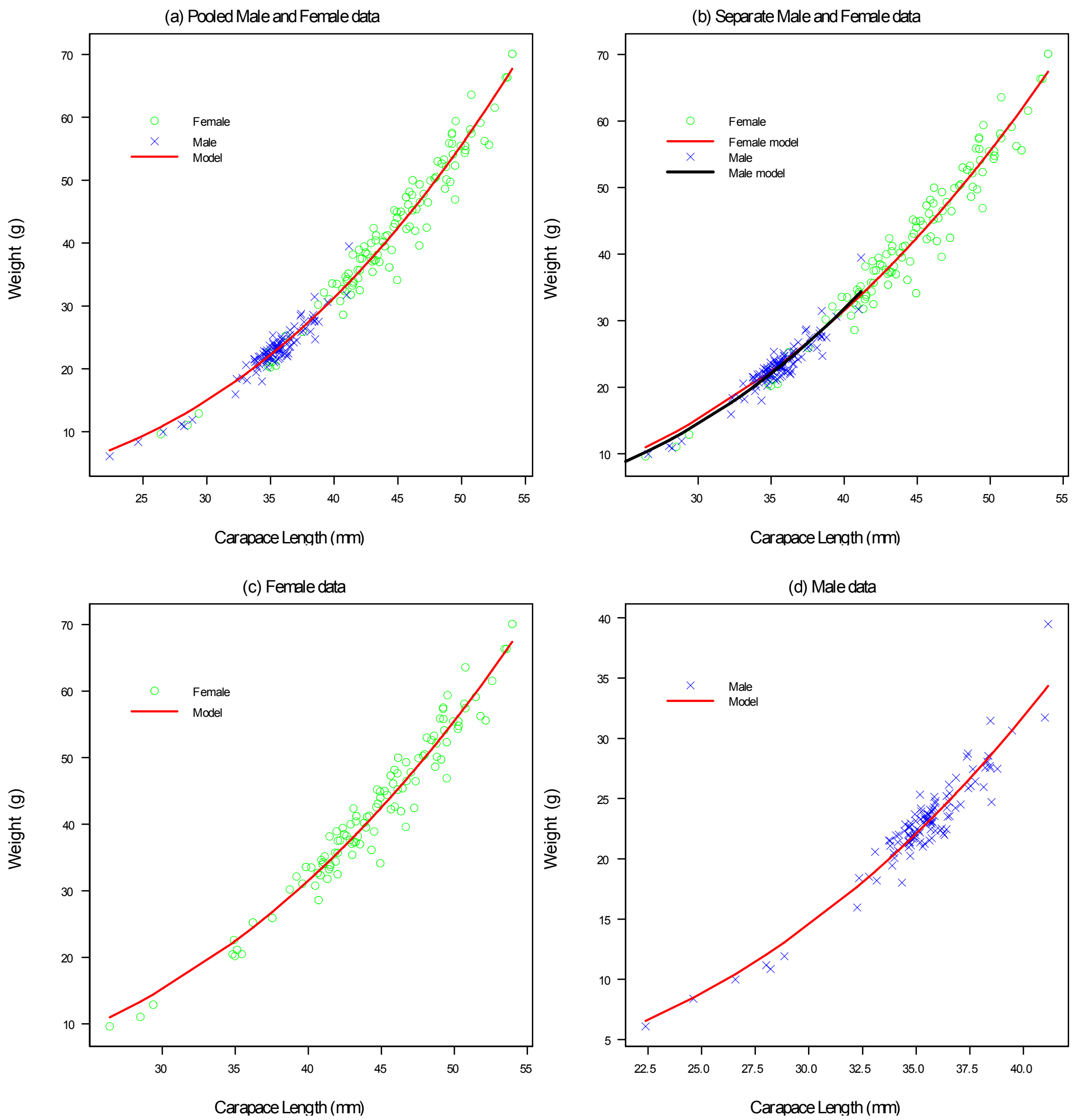


Figure 3.29 Scatter plots of length-weight data for M. japonicus. (a) pooled data for male and female, (b) separate models for male and female, (c) female, (d) male.

The plots of the fitted model are so similar that parameters for both sexes combined could have been used in a length-weight relationship for this species. This is further supported by the combined model having the lowest standard errors, highest model fit and the lack of a significant difference between the two data sets. The test for a significant difference, however, was based on only the carapace length range that included both genders. This reduced the data set by half with only 23 female records being compared. A larger data set would be required for a more robust conclusion.

The scatter plots of the data indicate sexual dimorphism as most of the males were smaller than the females. It is common for most prawn species to display size dimorphism due to sexually mature females containing ripe ovaries that constitute a considerable percentage of body weight (Primavera et al. 1998). As the standard procedure used for the other commercial prawn species is to estimate separate parameters for each gender we used the separate gender parameter estimates whenever it was necessary to apply the length-weight relationship for *M. japonicus*.

4 Simulation modelling and MSE

Mai Tanimoto, Michael O'Neill, Alex Campbell and Clive Turnbull

4.1 Introduction

The Torres Strait Prawn Fishery (TSPF) operates in the international waters of the Torres Strait Protected Zone (TSPZ) between Australia and Papua New Guinea (PNG). The fishery primarily harvests the brown tiger prawn (*Penaeus esculentus*) and the less valuable blue endeavour prawn (*Metapenaeus endeavouri*). The fishery is managed by input controls; primarily a Total Allowable Effort (TAE) along with gear/vessel restrictions and spatial/seasonal closures.

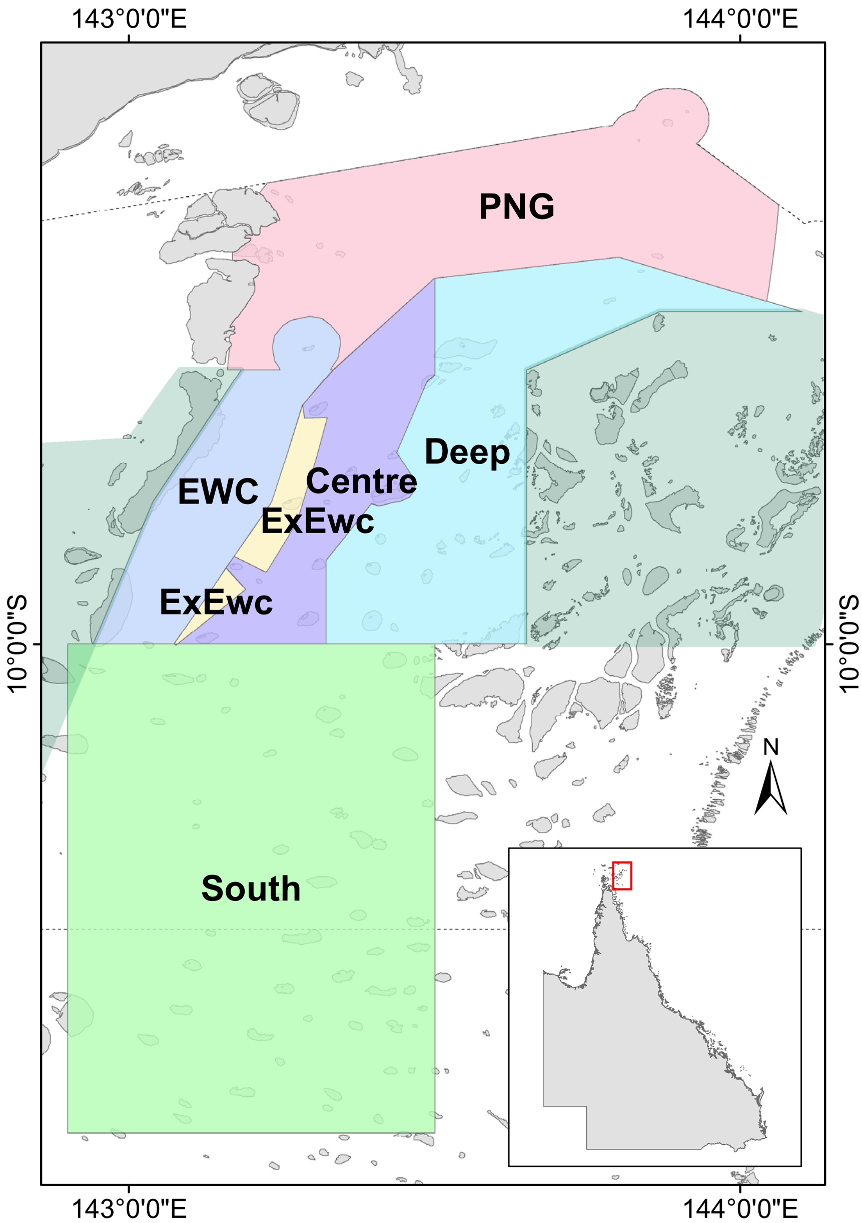


Figure 4.1 Six regions used in the simulation model: Region1 = East Warrior Closure (EWC); Region2= Extension of EWC (ExEwc); Region3= Centre; Region4=Deep; Region5=South; Region6=PNG. The outside of fishing ground was defined as Region7.

Although the Torres Strait Prawn Fishery is primarily controlled by total allowable effort, the level of active effort has always been considerably lower than the 13540 allocated fishing days assigned to the licences in the fishery in 1993. During this decade the size of the *active* fleet has dropped from 74 to 37 vessels and the observed fishing effort from an average of 10264 days during 1997-2001 to less than 4000 vessel nights in 2008. This decrease in the effort resulted in the annual harvest dropping from the average of 1,900 t per annum during the 1997-2001 to 907t in 2008. The largest decrease has been in the endeavour prawns harvest due to fishers targeting the more valuable tiger prawns. The decrease in fishing effort is due to the combined effect of the reduced allocation to Australian vessels, a down turn in the economics of prawn trawling (e.g. declining prawn market price and increasing fuel costs) and a decrease in the infrastructure (supply barges and air services) that support this remote fishery.

An Alternative Management Workshop was held in July 2005 and a number of spatial and temporal management options were discussed (see section 2.4.3 and (O'Neill and Turnbull 2006). One of the options suggested by the industry was a tiger spawner closure was designed to protect spawning tiger prawns by closing the deeper eastern side of the fishing ground (Figure 4.1) once the fishing effort reaches a certain trigger point.

In the 2006-07 federal budget, the Australian Government announced $1 million of special research funding to conduct research into the TSPF that would assess and further develop the spatial management arrangements proposed at the July 2005 Alternative Management Workshop. QPIF successfully tendered for this research funding which was combined with addition funding from the National Fisheries Agency of Papua New Guinea to conduct trawl surveys of the PNG area of the TSPZ during 2007.

We evaluated the effectiveness of the spawner closure and different levels of TAE by developing an open-loop simulation framework named TSPFsim. The trawl survey data reported in Chapter 3 provided the spatial/temporal distribution of the tiger and endeavour prawn stocks. TSPFsim integrated these data with assessments of tiger and endeavour prawns population dynamics (Chapter 5) and quantify the impacts of various harvest strategies with reference to biologically and economically sustainable management objectives.

4.2 Method

4.2.1 General structure

The structure of TSPFsim is similar to that of the Management Strategy Evaluation (MSE) widely adopted in many fisheries (De Oliveira *et al.* 2008; Dichmont *et al.* 2006; Kell *et al.* 2005a; 2005b; Pelletier and Mahevas 2005). It has an *operating model* which mimics the population dynamics of the stock, taking account of various source uncertainties; and a *fishery sub-model*, which dynamically simulates fishing behaviours. The main difference is that TSPFsim is an open-loop model which applies fixed management control throughout the simulation period, rather than allowing a model to alter harvest control rules depending on the management decision rules incorporated in the simulation loop (closed-loop simulation). The model was developed using MATLAB (Math Works 2008).

The key input parameters (catchability q, spawner-recruitment relationship) were estimated from a monthly age- and size-structured stock assessment model. The model was developed for each species separately (single-species model) and has no spatial component. Each model was fitted to the respective standardized catch rate data (1980 – 2003 for tiger; 1980 – 2006 for endeavour). Note that parameters estimated from the deterministic model were used for endeavour prawns (Chapter 5). The model optimization was conducted by Bayesian estimation methods using a Monte Carlo Markov Chain (MCMC) algorithm. To incorporate parameter uncertainties 1000 combinations were sampled from their resulting posterior distributions and imported into TSPFsim (see Section 4.2.4). The main steps in TSPFsim is summarised in Figure 4.2.

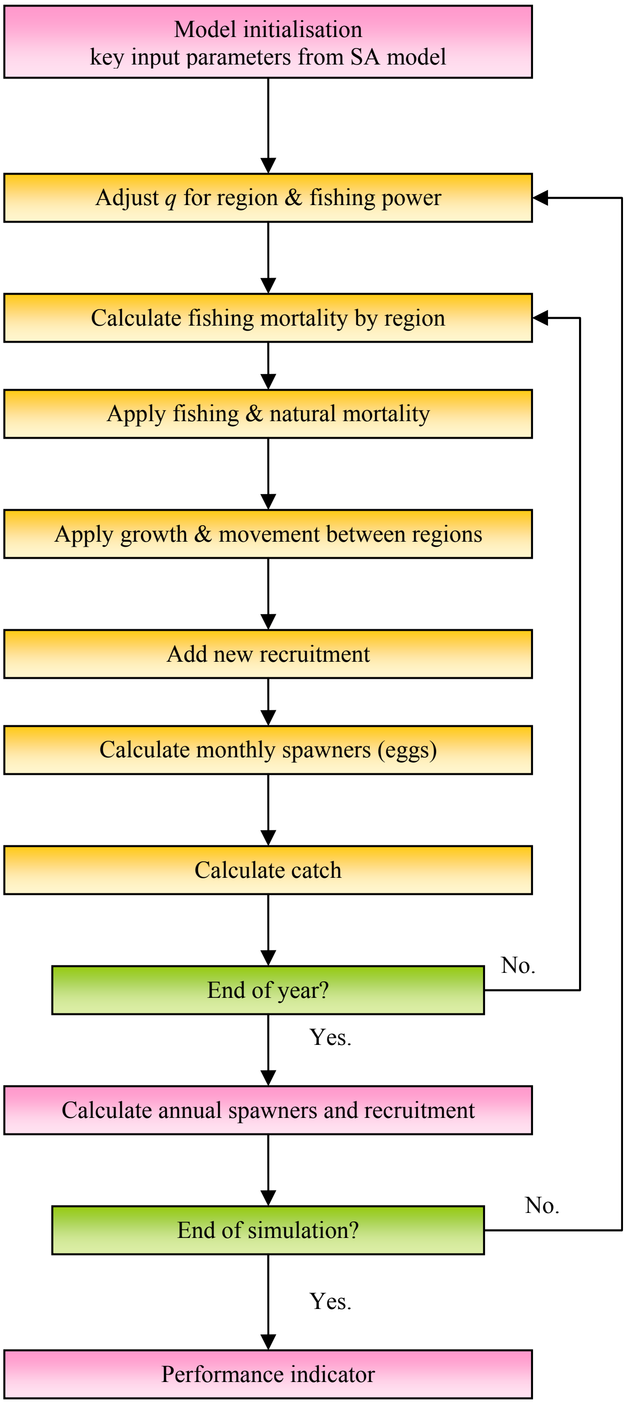


Figure 4.2 Flow diagram of TSPFsim. Pink boxes were overall stock components, yellow boxes were applied on regional bases; green boxes represent logical statements.

4.2.2 Operating model

The equations used in the operating model and symbol notation were summarised in Table 4.1 and Table 4.3, respectively. Simulation was initialised by allocating the latest total prawn abundance (i.e. population in 2007 which was estimated from the age-length structured model) into each region using the fraction of prawn abundance in each region, $sNp_{r,sp}$ (Eq. 4.1), which was estimated from the 2007 survey data (Chapter 3). Note that the prawn biomass was above B_{MSY} for both species at the start of future projection. The dynamic of the population followed (Eq. 4.2). Monthly recruitment was calculated by the product of the within-fishing-year recruitment pattern (Eq. 4.3) and the total number of prawns recruiting in the fishing year (R_y) (Dichmont et al. 1999). A von-Mises directional distribution (Mardia and Jupp 2000) was applied for the monthly recruitment pattern and Beverton-Holt recruitment function was used to estimate annual recruitment stock index (Eq. 4.4). The spawning stock numbers E_y was calculated as the sum of the products of the number of mature females and the fecundity index across the size and effective spawning months (Eq. 4.5). The model assumed the winter-spring spawners (July – Dec) are the major contributor to the recruitment for next year. The proportion of mature female at each length class ($mat_{l,sp,m}$) varies seasonally, which was estimated from the survey data collected in 2007 (Appendix 4.5.2).

The growth of prawns older than the recruitment age of six months was determined by a size-transition matrix ($P_{l,l'}$), which was calculated from a normal probability density function for a prawn in size class l' growing into size l over one month period (Sadovy et al. 2007). The monthly movement between each region was governed by the movement transition matrix ($T_{r,r'}$) which was estimated from the tag-recapture data collected in 1987, 89 and 90 (Mellors 1990; Watson and Turnbull 1993). The transition matrix allowed prawns to move from/to outside of the fishing ground (Region 7). Due to the limited tag-recapture data for endeavour prawns (n = 125 endeavour, n = 2433 for tiger), the movement transition matrix was estimated from species-pooled data (n = 2558). The derivation of the movement transition matrix is explored in Appendix 4.5.1.

4.2.3 Fishery sub-model

The fishery sub model governs the temporal and spatial allocation of annual fishing effort and simulates instantaneous fishing mortality in each region. The regional monthly instantaneous fishing mortality was calculated as the product of monthly fishing effort allocated to each region and respective regional catchability coefficient (Eq. 4.7). Note that fishing only occurs in Region 1 – 6 therefore no fishing mortality is applied to Region 7. TSPFsim incorporated the potential impact of effort from PNG vessels in the PNG water (Region 6). The catchability coefficient was increased in each region by dividing overall q^*_{sp} (which was estimated from the non-spatial stock assessment model) by the proportion of area in each region (Eq. 4.8). This assumes a homogeneous distribution of prawns and fishing effort within each region. It was also adjusted for future increase in fishing power based on the forward projection from historical fishing power trend (O'Neill and Turnbull 2006).

To distribute Australian fishing effort in each month and region, the TAE was first multiplied with implementation uncertainties err_y^{imp}, which was defined as the proportion of annual effort *actually* used by fishers (see Section 4.2.4). This *active* effort was then allocated into each month and region by temporal and spatial fishing pattern, φ_m^{rnd} and ϖ_r, respectively (Eq. 4.9). The temporal effort pattern was randomly simulated from the historical monthly effort trend between 2000 and 2007 (Figure 4.5 in Section 4.2.4). The regional effort pattern was defined by the weighted combination of the historical regional fishing pattern (eff_r^{hist}) and attractiveness of fishing area (Λ_r) observed from previous month (Eq. 4.12). These were weighted equally in the simulation (θ = 0.5). The tiger spawner closure was triggered by the logical index vector Ψ_r. The resulting pattern was normalised to 1 [$\varpi_r(t)$/sum($\varpi_r(t)$)]. At the opening of the fishing season (March), the Australian fishing effort was allocated into each region solely based on the historical fishing pattern as there is no attractiveness estimates available during the seasonal closure (Dec – Feb). The attractiveness of each region was defined as value per unit of effort of monthly catch accommodating the range of prawn price by size, $p_{l,sp}^{\$}$ (Eq. 4.11; Table 4.2). Potential monthly effort by PNG fleets was calculated by (Eq. 4.10), which assumed 100% usage of its potential effort in Region 6 (PNG water). Due to the lack of information on PNG historical effort pattern, we assumed that PNG fleets followed the same temporal effort pattern as Australian fleets (φ_m^{rnd}).

Table 4.1 Equations used in the operating model.

ID	*Equations*
	Initial population (t = 1, y =1)
(Eq. 4.1)	$N_{l,a,r,sp,s}(1)=\{N^*_{l,a,sp,s}sNp_{r,sp}$
	Population dynamics $(t>1)$
(Eq. 4.2)	$N_{l,a,r,sp,s}(t)=\begin{cases}0.5R_{y,sp}P_{l,a,=A_{\min},sp,s}\Phi_{m,sp}sRp^{rnd}_{r,sp} & \text{for } a=A_{\min}\\ P_{l,l'}N_{l',a-1,r,sp,s}(t-1)e^{-(M+F_{r,sp})}T_{r,r'} & \text{for } a=A_{\min+1},\ldots,A_{\max}\end{cases}$
(Eq. 4.3)	$\Phi_{m,sp}=\dfrac{1}{2\pi I_0(\kappa)}e^{\kappa\cos(m-\bar{r})}$
	Spawner-recruitment relationship
(Eq. 4.4)	$R_{y,sp}=\begin{cases}\dfrac{E^*_{sp}}{\alpha_{sp}+\beta_{sp}E^*_{sp}}e^{\varepsilon_y} & \text{for } y=1\\ \dfrac{E_{y-1,sp}}{\alpha_{sp}+\beta_{sp}E_{y-1,sp}}e^{\varepsilon_y} & \text{for } y=2,\ldots,10\end{cases}$
	Spawners
(Eq. 4.5)	$E_y=\sum_{m=7}^{12}\sum_{r=1}^{7}\sum_{l=L_{\min}}^{L_{\max}}\sum_{a=A_{\min}}^{A_{\max}}N_{l,a,r,sp,s=1}mat_{l,sp}fec_{l,sp}$ for $y>2$
	Monthly biomass
(Eq. 4.6)	$bio_{sp}(t)=\sum_{s=1}^{2}\sum_{r=1}^{7}\sum_{l=L_{\min}}^{L_{\max}}\sum_{a=A_{\min}}^{A_{\max}}N_{l,a,r,sp,s}(t)W_{l,sp,s}$ for $t=1,\ldots,T$
	Fishery sub- model
(Eq. 4.7)	$F_{r,sp}(t)=eff_r(t)q_{r,sp}(t)$
(Eq. 4.8)	$q_{r,sp}(t)=\dfrac{q^*_{sp}\,fp^{rnd}_{y,sp}}{\frac{a_r}{A}}$ for $t=1,\ldots,T;\ A=\sum_{r=1}^{6}a_r$
	Effort distribution
(Eq. 4.9)	$eff^{AUS}(t)=E^{TAE}\varphi^{rnd}_m(t)err^{imp}_y$
(Eq. 4.10)	$eff^{PNG}_{r=6}(t)=E^{PNG}\varphi^{rnd}_m(t)$
(Eq. 4.11)	$eff_r(t)=eff^{AUS}\varpi_r(t)+eff^{PNG}_{r=6}(t)$
(Eq. 4.12)	$\varpi_r(t)=\begin{cases}eff^{hist}_r & \text{for } month(t)=Mar\\ \theta eff^{hist}_r+(1-\theta)\Lambda_r(t-1) & \text{for } month(t)=Apr-Nov\end{cases}$
(Eq. 4.13)	$\Lambda_r(t)=\sum_{sp=1}^{2}V^{\$}_{r,sp}(t)\Big/eff_r(t)$
(Eq. 4.14)	$V^{\$}_{r,sp}(t)=\sum_{l=L\min}^{L\max}C_{l,r,sp}(t)p^{\$}_{l,sp}$
(Eq. 4.15)	$C_{l,r,sp}(t)=\dfrac{F_{r,sp}}{F_{r,sp}+M}bio_{l,r,sp}\left(1-e^{-(M+F_{r,sp})}\right)$

Table 4.2 Landing price of prawns in each grade and equivalent size range (as of November 2008, source – Cairns Seafood Company).

Grade	*Tiger prawns*		*Endeavour prawns*	
	CL (mm)	Price($/kg)	CL(mm)	Price($/kg)
U10	> 36	19.5	-	NA
10/20	29 - 36	17.5	> 29	9.5
21/30	23 - 28	14	25 - 28	7
30+	-	NA	20 - 24	6

Table 4.3 Definitions of notations.

Notation	*Definition*
t	Monthly time step (1,2,...,120)
a	Age class in months (A_{min},=6; A_{max} = 24)
l, l'	Size class in months (L_{min},=15; L_{max} =50)
s	Sex indices (1 = female, 2 = male)
sp	Species indices (1 = tiger 2 = endeavour)
y	Annual time step (1, … , 10)
r, r'	Region number (1,…,7)
$N^{*}_{l,a,r,sp,s}$	The initial number of prawns of age class *a* in size class *l* for each species and sex at the beginning of simulation. Estimated from the size and age structured model fitted to the historical data. (Figure 4.4 (e), (f))
$sNp_{r,sp}$	The fraction of total abundance of species sp in region *r*. Estimated from the 2007 survey data.
$N_{l,a,r,sp,s}$	The number of prawns of age class *a* in size class *l* in region *r* for each species and sex *s*.
$P_{l,a=Amin}$	the fraction of prawns in length class *l* for the first age class (A_{min})
$R_{y,sp}$	Annual recruitment of species *sp* in year *y*
$sRp^{rnd}_{r,sp}$	The fraction of prawns recruiting into region *r* for species *sp* (Figure 4.6 (g), (h))
$P_{l,l'}$	the fraction of fish in size class *l'* that grow into size class *l* in one month
M	Instantaneous natural mortality (0.2 month^{-1}); Watson and Turnbull (1993)
$F_{r,sp}$	Instantaneous fishing mortality in region *r* for species *sp*
$T_{r,r'}$	The fraction of prawns in region *r'* moving into region *r* in one month time step
$\Phi_{m,sp}$	Monthly proportion of annual recruits in month *m* for species *sp* (Figure 4.3 (c), (d)). I_0 in Eq. 3 denotes the modified Bessel function of the first kind and order 0, $\overline{r}$ is the estimated mode of the distribution and κ is known as the concentration parameter.
α_{sp}, β_{sp}	Beverton-Holt spawner recruitment parameters for species *sp* (Figure 4.3 (a), (b))
ε_y	Log-normal recruitment error [~ Log(N(0,0.05)] (Figure 4.5 (a)). Variance was estimated from the size and age structured model.
E^{*}_{sp}	The initial number of spawners for each species. Estimated from the size and age structured model fitted to the historical data. (Figure 4.4 (c), (d))
E_y	Annual spawners in year *y*
fec_l	Fecundity at length *l*; Dall, Hill et al. (1990)
$mat_{l,sp,m}$	Seasonal proportion mature at length *l* in month *m* for species *sp*. Estimated from the 2007 survey (see Appendix 4.5.2)
$W_{l,sp,s}$	Length-weight relationships for species *sp* and sex *s*
bio_{sp}	Monthly biomass (kg) of species *sp*
B_y	Annual biomass in year *y*
$eff(t)$	Active monthly effort used in time *t*
$q_{r,sp}$	The catchability coefficient in region *r* for species *sp*
q^{*}_{sp}	The overall catchability coefficient for species *sp* (Figure 4.4 (a), (b))
$fp^{rnd}_{y,sp}$	Fishing power for species *sp* in year *y* (Figure 4.6 (e), (f))
a_r	Area in region *r*
A	Total fishing area (for *r* = 1,…,6)
E^{TAE}; E^{PNG}	Annual total allowable effort (TAE) for Australian fleet; Potential effort by PNG fleet in PNG water (*r* = 6)
eff^{AUS}; eff^{PNG}	Monthly effort by Australian fleet and PNG fleet
err_y^{imp}	Fraction of TAE actually used by fishers in year *y*
$\varphi_m^{rnd}(t)$	Monthly proportion of fishing effort in time *t* (Figure 4.5 (b))
$\varpi_r(t)$	Fraction of monthly fishing effort spent in region *r* in time *t*
eff_r^{hist}	Fraction of historical fishing effort spent in region *r* based on the VMS data
θ	Weighting coefficient (= 0.5)
Λ_r	Attractiveness of region *r* (calculated as normalised proportion)
$V^{\$}_{sp}$	Value of production of species *sp*

$C_{l,sp}(t)$	Catch from length class *l* for species *sp* at time *t*
$p^{\$}_{l,sp}(t)$	Market price of prawns ($ per kg) at length class *l* for species *sp* (Table 4.2)

4.2.4 Uncertainties

A number of key uncertainties were considered in TSPFsim including parameter (conditioning) uncertainty, process uncertainty and implementation uncertainty which associated with management input control (TAE) and actual effort used by fishers.

Parameter uncertainty

We considered uncertainties in a number of key input parameters including:

- Beverton-Holt spawner-recruitment (S-R) coefficient, α_{sp} and β_{sp};
- monthly recruitment parameters, κ and $\bar{r}$;
- overall catchability coefficient, q^*_{sp};
- initial spawning stock index, E^*_{sp}; and
- initial prawn abundance, $N^*_{l,a,sp,s}$.

Figure 4.3 displays the range of S-R curves and monthly spawning patterns for each species. They were calculated from the 1000 combinations of input parameters (α_{sp}, $\beta_{sp,}$ κ and $\bar{r}$) sampled from resulting posterior distributions estimated through the stock assessment process. Note that steepness of the S-R curve was fixed at 0.5 for endeavour prawns due to the lack of fit during the model calibration process (Refer to section 5.1 for details). Sensitivity analysis was conducted for endeavour prawns by comparing the results with steepness set at 0.7 (Appendix 4.5.5). Distributions of other key parameters (q^*_{sp}, E^*_{sp} and $N^*_{l,a,sp,s}$) were shown in Figure 4.4.

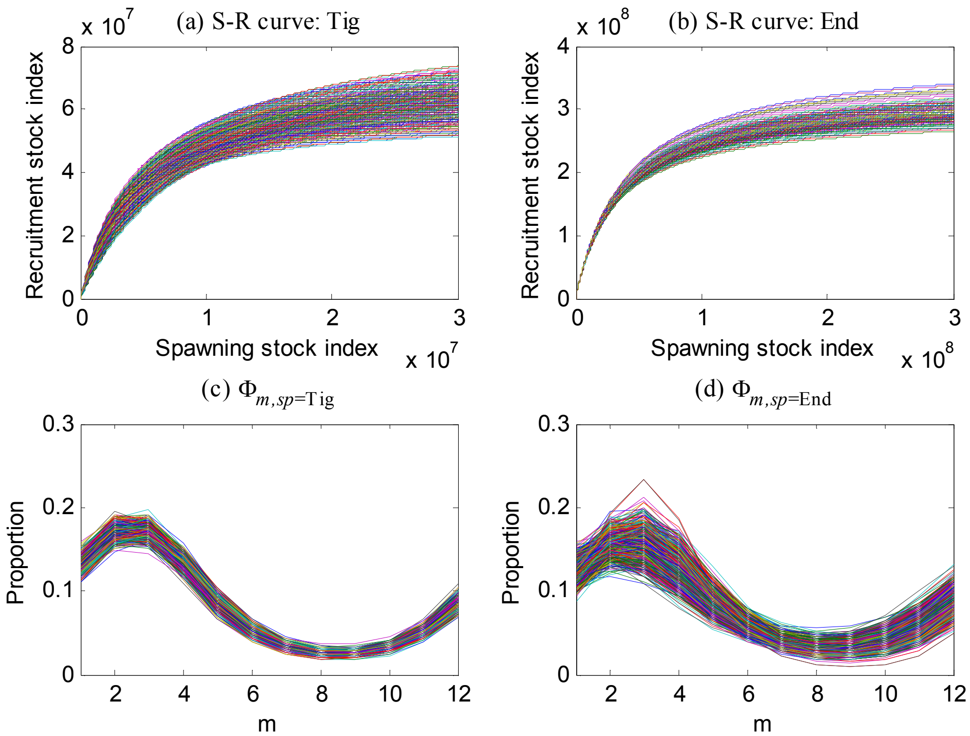


Figure 4.3 The uncertainties considered for: Beverton-Holt S-R relationship for tiger (a) and for endeavour prawns (b); monthly recruitment pattern for tiger (c) and endeavour prawns (d). Note that steepness of endeavour prawn S-R curve was fixed at 0.5.

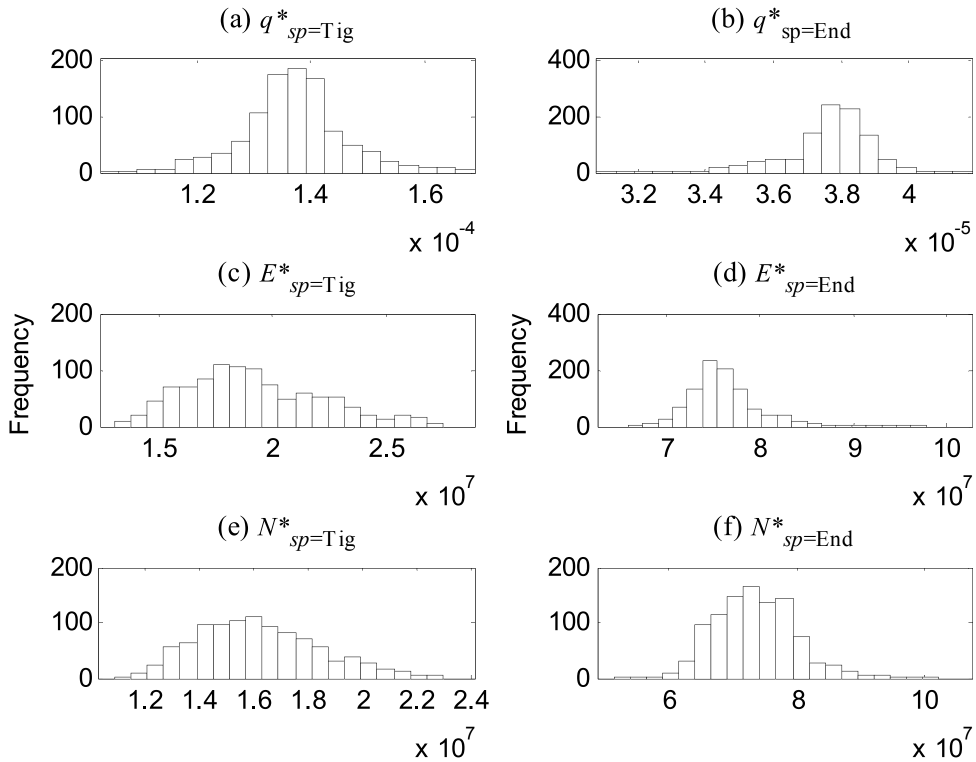


Figure 4.4 The uncertainties in the input parameters for: overall catchability coefficient for tiger (a) and endeavour (b); initial spawning stock index for tiger (c) and endeavour (d); initial prawn abundance for tiger (e) and endeavour prawns (f).

Process uncertainty

Process uncertainty is induced by modelling a stochastic system in a deterministic manner (Haddon 2001). The obvious example is a spawner-recruitment relationship which can vary randomly through time with environmental conditions. TFPFsim incorporated noise in the spawner-recruitment relationship, which were randomly sampled every year from log-normal distribution [~ log(N(0,0.05))] (Figure 4.5 (a)). The error variance (0.05) was obtained from the recruitment error distribution estimated from the stock assessment model. Spatial variations in recruitment were also randomly sampled for each species every month from normal distributions with a mean of spatial proportion of recruits for respective month with a variance of 0.05 (Figure 4.6 (c), (d)).

Fishing behaviour is largely influenced by a number of factors including weather, market conditions, fuel costs and fishing infrastructures, which makes it a stochastic system. Although monthly fishing pattern has been fairly consistent historically, we added 10% variation in its mean pattern for future projection (Figure 4.5 (b)). Changes in fishing power were also considered for each species, each of which were estimated by fitting a 1000 Monte Carlo log regression on the historical fishing power schedule from 1980 to 2005 (O'Neill and Turnbull 2006 p.33) (Figure 4.6 (a), (b)).

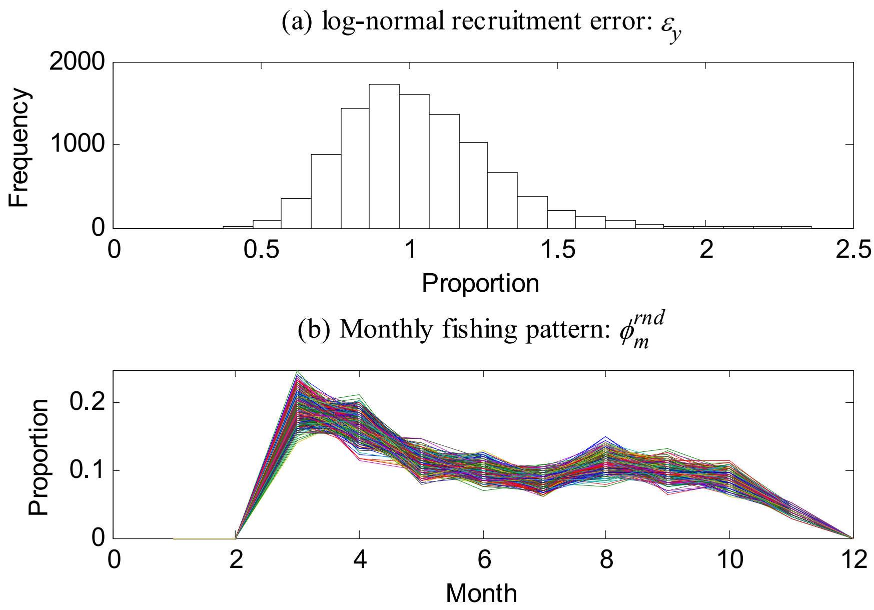


Figure 4.5 The process uncertainties for: (a) annual recruitment error and (b) monthly fishing pattern.

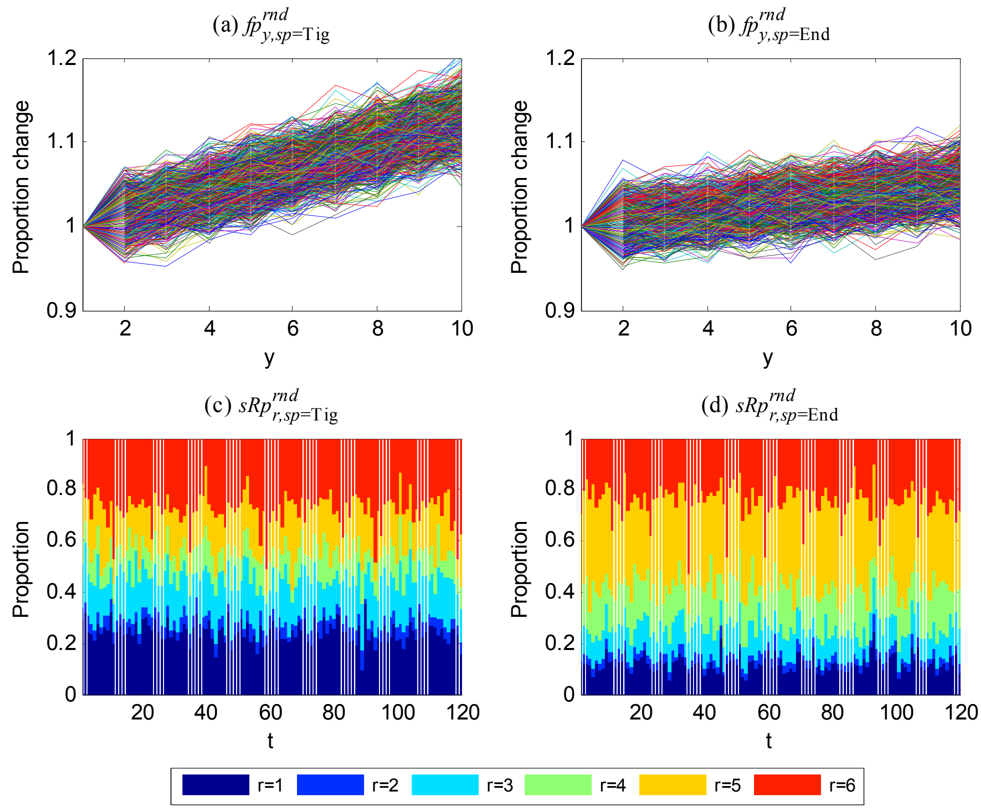


Figure 4.6 The process uncertainties considered for: changes in fishing power for tiger (a) and endeavour prawns (b); and temporal and regional recruitment pattern for tiger (e) and endeavour prawns (f). Note that fishing power change was shown as relative to the first simulation year (y = 1), which was set at 1.

Implementation uncertainties

Implementation uncertainty is important as the TSPF has never used all the allocated nights and the proportion of TAE actually used by the industry has been variable particularly in recent years. Since

2001 the *active* effort used by the industry has declined to less than 6000 nights per year in the last three years. The proportion of TAE used also declined to a low of 44% in 2005, but has increased to about 64 – 70% in 2006 and 2007 due to the reduction in TAE (from 13570 nights to 6867 for Australian vessels). The TSPF appears to be very sensitive to the market prawn price and fuel cost due to the remoteness of the fishing ground. There was a strong positive and negative correlation between the *active* fishing effort and tiger prawn price ($\rho = 0.75$) and fuel price ($\rho = -0.89$), respectively.

The implementation uncertainty was estimated by fitting a logistic regression model to the proportion of TAE fished between 1997 and 2007 and the respective average fuel and tiger prawn market prices (see Appendix 4.5.3). We then conducted 10-year future projections based on three hypothetical scenarios: 1) maintain fuel and prawn price in 2007 (status quo); 2) fuel price goes down by 4% and prawn up by 4% every year (optimistic); and 3) fuel up by 4% but tiger prawn price goes down by 4% (pessimistic) (Figure 4.7). The model allowed a 5% variation for each error type (~ 1900 nights).

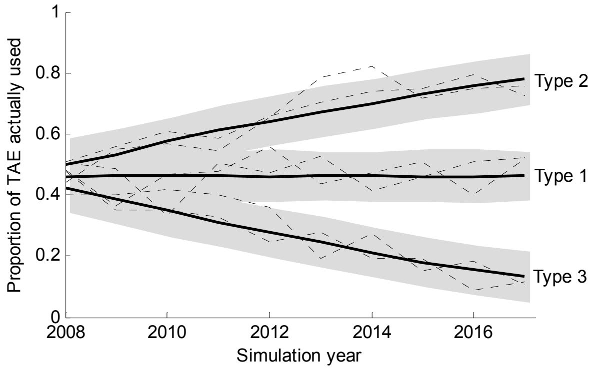


Figure 4.7 Three types of implementation uncertainty tested in TSPFsim. Each uncertainty was signified by the median (solid lines), two simulation replicates (broken lines), and 5th and 95th percentiles (shaded area).

4.2.5 Management Scenarios & Performance Measure

The management scenarios tested in TSPFsim are summarised in Table 4.4. Scenarios 1 – 5 were run for the risk analyses testing the impact of different levels of fishing effort on prawn stocks. Scenario 4 tested a potential impact of PNG effort operating only in Region 6 (PNG). Scenario 6 and 7 apply the tiger spawner closure when effort reaches the trigger point of 9200 and 7000 nights respectively, but allows fishers to continue operating outside the closure until effort reaches 2nd trigger point (12000 nights). Scenarios 1-7 assumed 100% effort usage. Implementation uncertainty was included in Scenario 8 - 10 with trigger effort at 7000 nights.

Table 4.4 Ten management scenarios tested in TSPFsim.

Scenario No. (ms)	*Aus effort*	*PNG effort*	*Imp_error type*	*Trigger effort*
1	4500	0	N/A	N/A
2	6867	0	N/A	N/A
3	9200	0	N/A	N/A
4	9200	1000	N/A	N/A
5	12000	0	N/A	N/A
6	12000	0	N/A	9200
7	12000	0	N/A	7000
8	12000	0	1	7000
9	12000	0	2	7000
10	12000	0	3	7000

We evaluated the performance of each management strategy in terms of:

- the probability that the biomass falls below B_{MSY} in the last year of the simulation projection ($Pr(B_{2017}<B_{MSY})$)
- the probability that the biomass falls below limit reference point (B_{LIM}) in the last year of the simulation projection ($Pr(B_{2017}<B_{LIM})$)
- the ratio of B_{2017} relative to target reference point (B_{TARG}) ($B_{2017}:B_{TARG}$)

- median total harvest and median annual catch rate of the 10–year simulation period.

As defined in the Commonwealth Harvest Strategy Policy (HSP) standards, $1/2B_{MSY}$ and $1.2B_{MSY}$ were used as proxy for limit (B_{LIM}) and target reference point (B_{TARG}), respectively (DAFF 2007 p.22).

4.2.6 Model Verification

The spatial and temporal distribution of total population and number of spawners simulated from TSPFsim was compared against the available monthly survey data collected in May, July, September and November 2007. Spatial interpolation analyses ("TopoToRaster" function in ArcView, ESRI) were conducted on the point survey data to estimate a spatial distribution of prawn abundance and spawning stocks (Chapter 3 - Trawl Surveys). Prawn abundance and spawning stocks were estimated in terms of average catch rates (as number of prawns) and the number of ripe female per net, respectively.

4.3 Results

A comparison of performance measures for each species between ten management scenarios are summarised in Table 4.5 and full trajectories of the 10-year future projection for each scenario are shown in Appendix 4.5.4 (Figure 4.29 - Figure 4.38).

As expected, prawn biomass in the last year of simulation (i.e. B_{2017}) was higher when effort was low and the risk of biomass falling below B_{MSY} increases as effort increases (Table 4.5). For tiger prawns, the risk of biomass falling below B_{LIM} was negligible except for Scenarios 5 – 7 (TAE 12000 nights). The median biomass in 2017 (B_{2017}) was above B_{TARG} at TAE 4500 nights (Scenario 1) and close to B_{TARG} at status quo (Scenario 2). The median B_{2017} was about 3/5 of B_{TARG} ($0.62B_{TARG}$) at TAE 12000 nights (Scenarios 5 – 7). For endeavour prawns, there was no risk of biomass falling below B_{LIM} for all levels of TAE tested. The median B_{2017} was above B_{TARG} at effort level 4500 and status quo (Scenarios 1 – 2) and relatively close to B_{TARG} at 9200 - 10200 nights (Scenario 3 – 4) (Table 4.5). At 12000 nights of effort (Scenarios 5 - 7) there is no increase in tiger prawn harvest compared to status quo (Scenario2) whereas endeavour prawn harvest increased by 8%.

When a TAE of 12000 nights was fully fished every year of the virtual future projection (2008 - 2017), it was highly likely that the tiger and endeavour prawn biomass in 2017 would be below B_{MSY} and 11% of simulations indicated tiger prawn biomass would fall below B_{LIM} (Table 4.5). However, if we consider the likelihood of industry utilising all of the TAE under current economic situation (Scenario 8), the risk of overfishing reduced significantly from 87% to 17% (Table 4.5) and median B_{2017} became above B_{TARG}. If the economic situation becomes favourable to fishers in the future (continuous increase in prawn market price and decrease in fuel price; Scenario 9), the risk of overfishing increased every year with increasing *active* effort, reaching 63% probability in 2017. In contrast, under the most pessimistic situation (decline in prawn price and increase in fuel price), there was no risk of overfishing for both species (Scenario 10) and B_{2017} would be well above B_{TARG}. As the *active* annual effort was always less than the trigger effort, the spawner closure was never implemented in Scenarios 8 and 10.

Figure 4.8 (A) and (B) showed 10 year trajectory of risk probability ($Pr(B_t<B_{MSY})$ for each species and management scenario. For scenarios that applied constant effort without implementation error, the probability increased to a greater extent in first few years then gradually increases in later years. Note that fishing power was generally assumed to increase for the projection period (Figure 4.6 (a) and (b)). The risk curve and performance measures indicated that: 1) under the current management (Scenario 2) the fishery is likely to be biologically sustainable for next 10 years (even with 100% TAE usage), and 2) the endeavour prawn stock was relatively more resilient to the fishing pressure than tiger prawns (Figure 4.9).

Table 4.5 Relative performance measures from the 10 year forward projection of each scenario. Harvest and annual CPUE were shown as relative proportion scaled to 1 at status quo (Scenario 2).

	Tiger prawn					*Endeavour prawn*				
ms	Probability $B_{2017}<B_{MSY}$	Probability $B_{2017}<B_{LIM}$[1]	Ratio (B_{2017}:B_{TARG}[2])	Harvest	Annual CPUE	Probability $B_{2017}<B_{MSY}$	Probability $B_{2017}< B_{LIM}$	Ratio (B_{2017}:B_{TARG})	Harvest	Annual CPUE
1	0.07	0	1.14 (0.8:1.57)	0.91	1.24	0.02	0	1.26 (0.9:1.72)	0.85	1.22
2	0.36	0	0.92 (0.62:1.28)	1	1	0.15	0	1.04 (0.73:1.45)	1	1
3	0.65	0.01	0.76 (0.49:1.09)	1.02	0.84	0.42	0	0.87 (0.6:1.24)	1.07	0.83
4	0.73	0.03	0.71 (0.44:1.02)	1.02	0.78	0.5	0	0.83 (0.57:1.19)	1.07	0.8
5	0.87	0.11	0.62 (0.37:0.92)	1	0.69	0.77	0.01	0.71 (0.47:1.03)	1.08	0.67
6	0.87	0.11	0.62 (0.37:0.92)	1	0.68	0.78	0.01	0.71 (0.47:1.02)	1.08	0.67
7	0.87	0.11	0.62 (0.37:0.92)	1	0.68	0.78	0.01	0.7 (0.47:1.02)	1.08	0.67
8	0.17	0	1.02 (0.72:1.43)	0.96	1.13	0.06	0	1.15 (0.81:1.62)	0.93	1.11
9	0.62	0.01	0.77 (0.5:1.1)	1.01	0.93	0.4	0	0.88 (0.61:1.26)	1.04	0.94
10	0	0	1.57 (1.13:2.15)	0.75	1.39	0	0	1.59 (1.14:2.2)	0.66	1.34

[1] B_{LIM} = ½ B_{MSY} (proxy); [2] B_{TARG} = 1.2B_{MSY}; [3] 90% confidence intervals

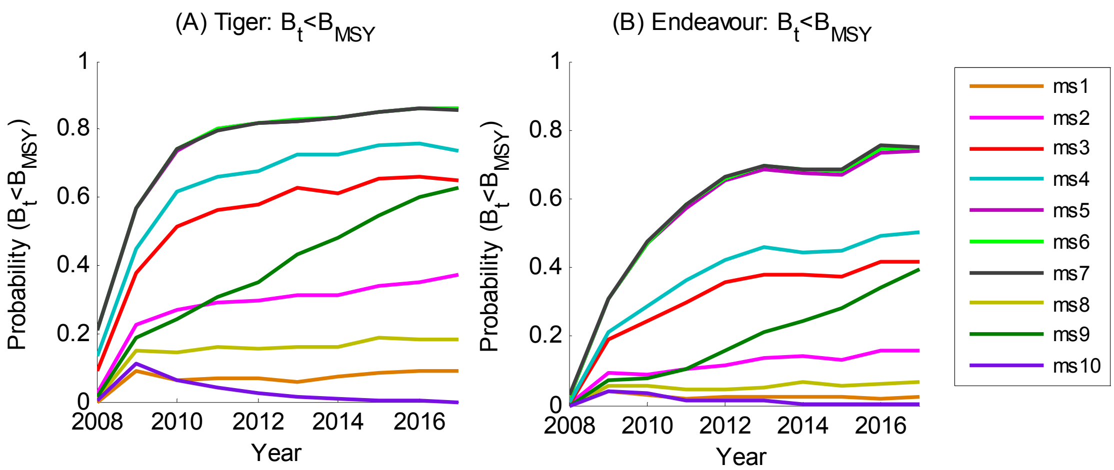


Figure 4.8 Ten-year trajectory of two performance indicator: probability that the biomass falls below B_{MSY} for tiger (A) and endeavour (B).

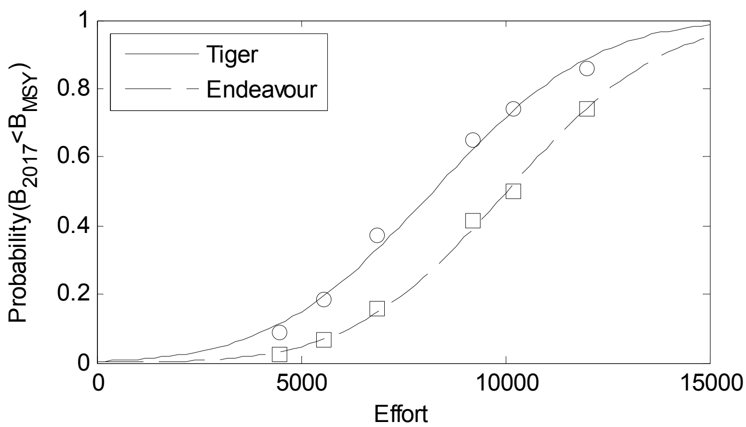


Figure 4.9 Risk of overfishing in 2017 with different level of fishing pressure. The markers and lines indicated model results and fitted curve, respectively.

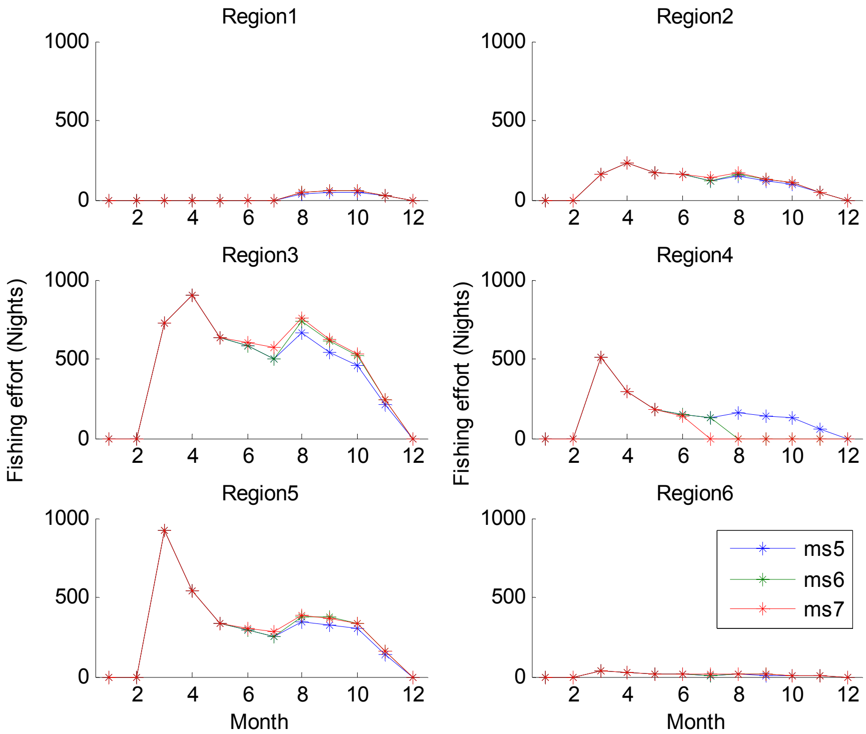


Figure 4.10 Simulated median monthly effort allocated in each region for Scenarios 5 – 7.

The performance measures estimated in Scenarios 5–7 were almost identical, indicating that the spawning closure had little effect on both tiger and endeavour prawn population dynamics (Table 4.5). When the trigger point was set to 9200 nights (Scenario 6), the deep water area (Region 4) was closed for fishing in August for 72% of the simulations and for 100% in September (Figure 4.10). When the trigger point was set at 7000 nights (Scenario 7), the spawner closure was activated in June for about 31% of the simulations and for 100% in July (Figure 4.10). The number of tiger spawners in Region 4 compared to the spawner abundance estimated under no spatial management (Scenario 5) was 5% and 8% higher with 9200 and 7000 night trigger points respectively. On the regional scale, spawners in Region 4 contributed 12 – 13% of total spawners.

Fishing effort allocated in Region 4 was about 17% (2000 nights) each year with no spatial closure, 12% (1400 nights) for a 9200 trigger point closure, and 11% (1300 nights) with a 7000 trigger point closure (Figure 4.10). The fishery sub-model reallocated the majority of the redundant effort into Region 3 (45 – 60%) and Region 5 (30%).

The spatial and temporal trends of prawn density (prawn abundance per unit of area) were a closer fit to the survey data for tiger prawns than for endeavour prawns (Figure 4.11). The correlation between the prawn densities simulated in TSPFsim and estimated from the survey data was 0.91 for tiger prawns and 0.64 for endeavour prawns. In contrast, the spatial and temporal trends of simulated spawner density were relatively different from that of survey data, with correlation of 0.22 for tiger and 0.33 for endeavour prawns (Figure 4.11). In terms of the total number of spawners (density × area), however, TSPFsim spawner trends were highly correlated to the survey data for both species (ρ = 0.88 for tiger, ρ =0.85 for endeavour prawns) (Figure 4.13).

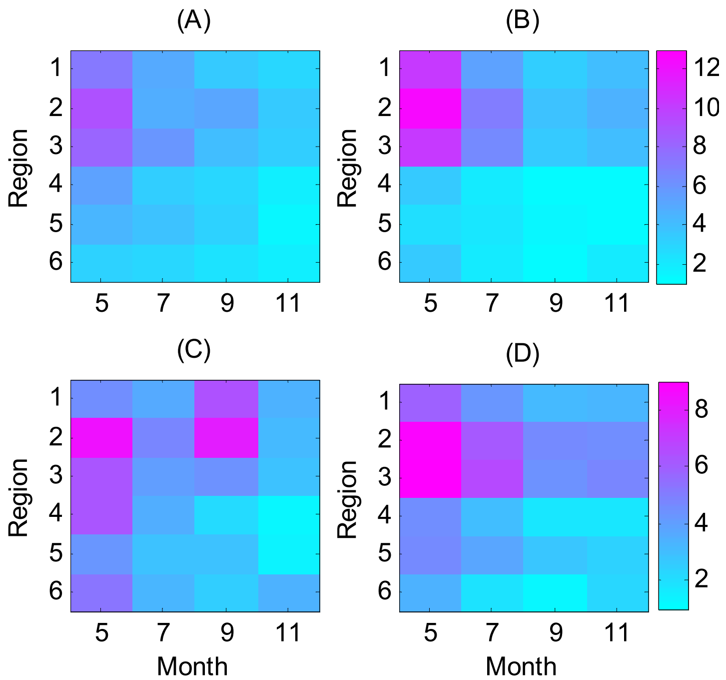


Figure 4.11 Temporal and spatial distribution of prawn density estimated from: (A) survey07, tiger; (B) TSPFsim, tiger; (C) survey 07, endeavour; and (D) TFPFsim, endeavour. Values indicate percentage (%) of abundance per a unit area in each month and region over the sum of monthly abundance in May, Jul, Sep and Nov. Note that the simulation results were based on Scenario 5 (no spatial management).

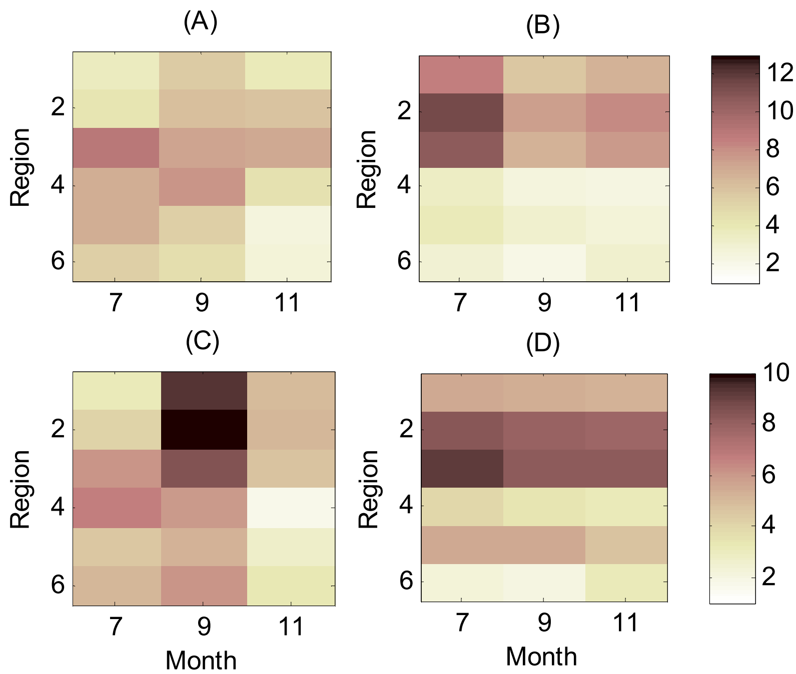


Figure 4.12 Temporal and spatial distribution of spawning stock density estimated from: (A) survey07, tiger; (B) TSPFsim, tiger; (C) survey 07, endeavour; and (D) TFPFsim, endeavour. Values indicate percentage (%) of abundance per a unit area in each month and region over the sum of monthly abundance in Jul, Sep and Nov. Note that the simulation results were based on Scenario 5 (no spatial management).

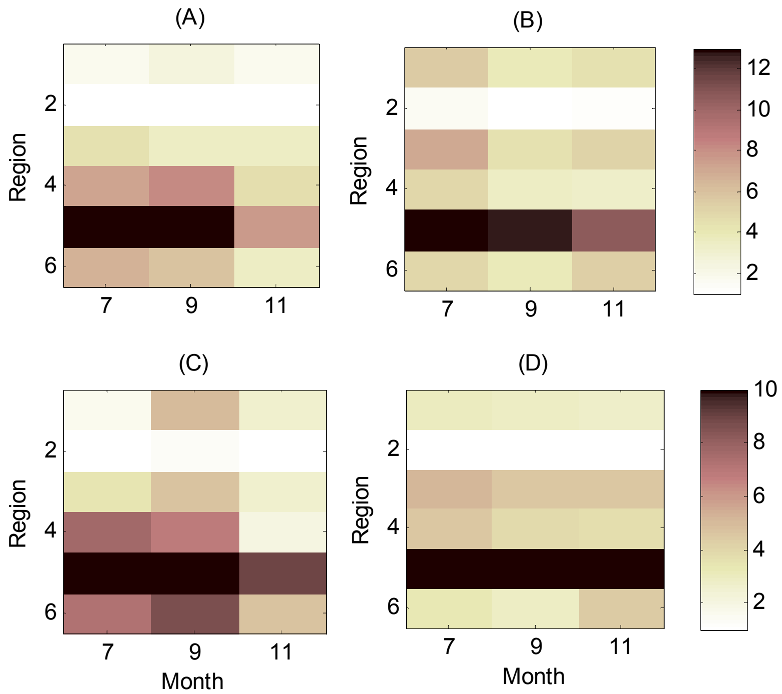


Figure 4.13 Temporal and spatial distribution of total spawning stock abundance estimated from: (A) survey07, tiger; (B) TSPFsim, tiger; (C) survey 07, endeavour; and (D) TFPFsim, endeavour. Values indicate percentage (%) of abundance per in each month and region over the sum of monthly abundance in Jul, Sep and Nov. Note that the simulation results were based on Scenario 5 (no spatial management).

4.4 Discussion

TSPFsim is an open-loop MSE that can explicitly test the effectiveness of the spatial and temporal management of the fishery. One of the biggest challenges of model development was to simulate the movement of prawns between regions. The comparison of temporal and spatial distribution of prawn abundance between TSPFsim and the survey indicated that the overall movement of tiger prawn was relatively well captured by the movement transition matrix. It is important to note that the proportion of prawns moved from one region to others were constant for both species every month and for all size/age classes. This means that we assumed: a) tiger and endeavour prawns move identically; b) there was no seasonal difference in the prawn movement; and c) the smallest size class prawn moved at the same rate as the oldest size class prawns. These assumptions may not reflect reality; for example, the discrepancy between the simulated endeavour prawn abundance and observations from the survey indicates that the movement of endeavour prawn is different from that of tiger prawns (Figure 4.11). The spatial distribution of the tiger prawn was better captured than for the endeavour prawn as the majority of the tag-recapture data, from which the movement transition matrix was estimated, were tiger prawn records. One of the possible reasons for the poor correlation between simulated and surveyed spawning stock (per unit of area, Figure 4.12) was the variable movement between size/age classes (Die and Watson 1992) and different growth rates between regions. Another reason related to temporal discrepancy, is that the seasonal maturity trend included in TSPFsim may not have fully captured temporal variation in the seasonal spawning pattern. How sensitive the violation of these assumptions is on the overall model results is unknown, but capturing seasonally dependent and size/age dependent movement or developing a regional and seasonal growth model is a difficult exercise. It would require further examinations of the available datasets and exploration of a more sophisticated alternative model. The potential ideas include: a) a prawn dispersion model incorporating bathymetry or/and current information of the fishing ground, b) a growth model incorporating seasonal indicators such as water temperature (Mallet et al. 1999; Dion and Hughes 2004; Hesp et al. 2004; Lappalainen et al. 2005). Nevertheless, it is important to note that the more complex a model becomes, the less statistical power the model would have. The current study attempted to estimate prawn movement using the best available data and resources and the overall movement of the Torres Strait prawns was generally well captured by the estimated movement transition matrix.

Although the spawner closure resulted in a 5 - 8% increase in the number of spawners in Region 4, it did not contribute to the overall number of spawners for a number of reasons. Firstly, only 12 – 13% of annual spawners were contributed from Region 4. Secondly, there was a slight reduction in the number of spawners outside Region 4 due to the additional effort re-allocated into other regions after the closure was introduced. This reduction countered the number of spawners protected in Region 4. Lastly, TSPF fishers generally use almost 50% of their allocated fishing effort in the first three month of the fishing season (March – May). The spawner closure was generally triggered in the later part of the season when the fishing pressure was relatively low. It is important to note however that the modelled spawners in Region 4 may be an underestimate of the reality given the discrepancy between of the spawning stock observed from the survey and modelled from TSPFsim.

The distribution of tiger and endeavour prawn stocks overlaps spatially, which makes difficult to control *targeting* effort for each species by the spatial management. The performance measures indicated that endeavour prawns are more resilient to fishing pressure than tiger prawns. However, as the endeavour prawn price is almost half the value of tiger prawns (Table 4.2) and fuel cost is high, there is no incentive for the industry to target endeavour prawns (even after the spawning closure is implemented). In such case the risk of overfishing endeavour prawns is low and TSPF is biologically sustainable for both species as long as more susceptible tiger prawns are managed sustainably.

Comparison of performance measures between management scenarios indicated that the increase in fishing effort is not directly proportional to resulting catch (Table 4.5). As the stock is fished down to lower than B_{MSY}, CPUE lessen so much that extra effort does not contribute to the fishing productivity. The results indicated that the tiger prawn stock is likely to be above B_{TARG} in 2017 at TAE 4500 nights and close to B_{TARG} at status quo notwithstanding continuous increase in fishing power for next 10 years. It is important to note, however, that this does not include implementation uncertainties and the total effort spent in recent years is less than 5000 nights at status quo. The uncertainty analysis indicated that both prawn stocks are likely to be maintained around B_{TARG} even at 12000 nights as implementation uncertainty is likely to be high.

We conclude that the proposed tiger spawner closure would have a minimum benefit for the fishery in terms of reducing the risk of overfishing the tiger prawn stock and maximising the productivity of the fishery. It should be noted that this conclusion was based on the assumption that the model accurately estimated the abundance of spawners in Region 4. Further research and modification of the model, particularly on prawn movement and its size/age dependence, and on the temporal spawning pattern, will be required to better quantify the benefits of spatial closures suggested for the Torres Strait Prawn Fishery. Even if TAE were increased to 12000 nights, it is unlikely that fishers make full use of their allocated nights under the current economic conditions and likelihood of overfishing is low and the spawner closure would not be activated. While the tiger spawner closure was only examined herein, the framework of TSPFsim has the capacity to test the effectiveness of alternative temporal/spatial closures. The model informs the long-term harvest strategy for the prawn fishery by providing stakeholders with estimates of the risk of the stock biomass falling below sustainable levels for a range of fishing effort.

4.5 Appendix

4.5.1 Prawn movement

Model Development

Movement of tiger and endeavour prawns in the Torres Strait were previously investigated by Watson and Turnbull (1993). Based on an eastward and southward movement observed from the tagging data collected in 1987 and 1988, Watson and Turnbull (1993) concluded that tiger and endeavour prawns generally migrate from the west of Warrior reefs into the east of fishing ground.

TSPFsim requires quantitative estimates of prawn movement among fishing areas. We applied a concept of "Eulerian (or box model)" representation of stocks and movement among specific locations (Walters and Martell 2004). The model represents locations of stocks in relatively small grid cells (i.e. 6 minutes grids) and estimates probability of prawns moving among these cells in every time step. It is important to define size of time step short enough so that any individual prawns is unlikely to move more than one spatial cell per step (Walters and Martell 2004). Weekly time step was used for this case study.

Movement transition matrix was estimated using the tag-recapture data collected by Watson and Turnbull (1993) and the unpublished tagging data collected in 1990. Details of data collection were described in Watson and Turnbull (1993) and Mellors (1990). The number of prawns used in the analysis is shown in Table 4.6.

Table 4.6 Summary of the research survey data collected in 1987, 1988 and in 1990.

Species	*Sex*	*Year*	*Number of prawns used*
Tiger	Female	1987	945
Tiger	Female	1988	164
Tiger	Female	1990	77
Tiger	Male	1987	965
Tiger	Male	1988	188
Tiger	Male	1990	94
Endeavour	Female	1988	52
Endeavour	Female	1990	20
Endeavour	Male	1988	38
Endeavour	Male	1990	15

The following steps were undertaken to develop a movement matrix from the survey data:

1. Divide fishing area into 6 × 6 minutes grid cells (Figure 4.14),
2. Assuming a straight movement, obtain a vector between release site and respective recapture site. Calculate prawn movement velocity in x and y components (i.e. how far a prawn move per week in x axis (EW direction) and y axis (NS direction) (Figure 4.15),
3. For the grid cells from which tags were released (release grids), randomly generate 20 coordinate sites within each grid cells using ArcGIS Hawths Tools (Beyer 2004) (Figure 4.16).
4. Assuming a constant movement of prawns within a grid cell, relocate vectors from step 3 to randomly generated sites in each release grids and obtain respective destination coordinates (Figure 4.17). This replication of tagging data will reduce bias due to locations of release sites within a grid.
5. Count the total number of destination points inside each grid cell, and calculate probability of prawns moving from release grids to surrounding grids (*randomtag data*).

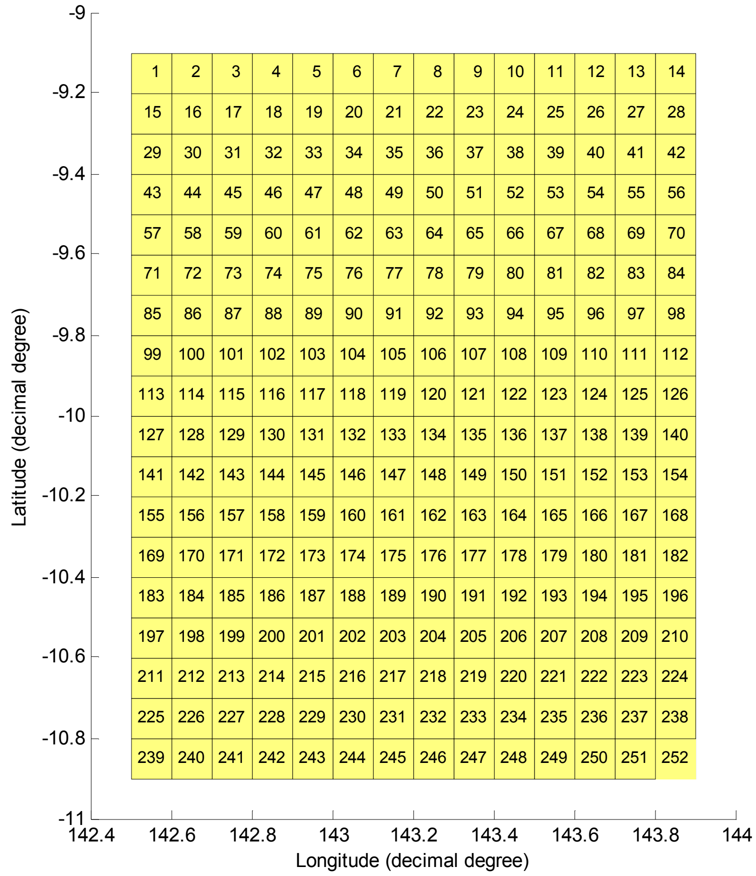


Figure 4.14 Six minutes grid cells used in the movement analysis. The numbers within each square indicates grid ID.

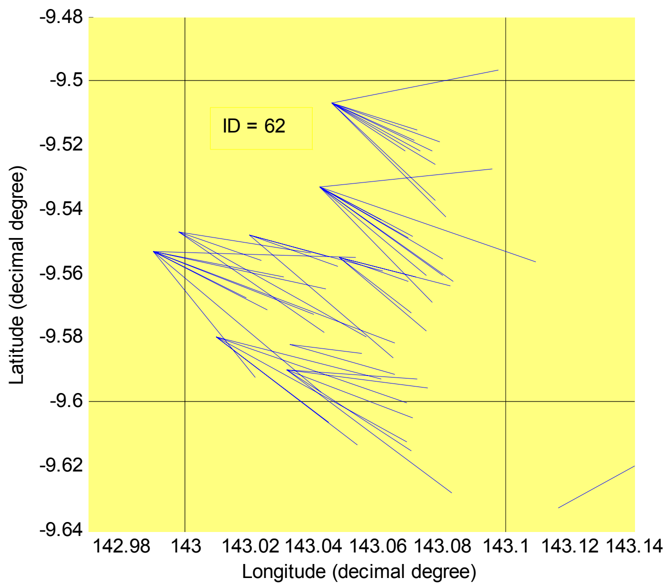


Figure 4.15 Six minutes grid cells used in the movement analysis. The numbers within each square indicates grid ID.

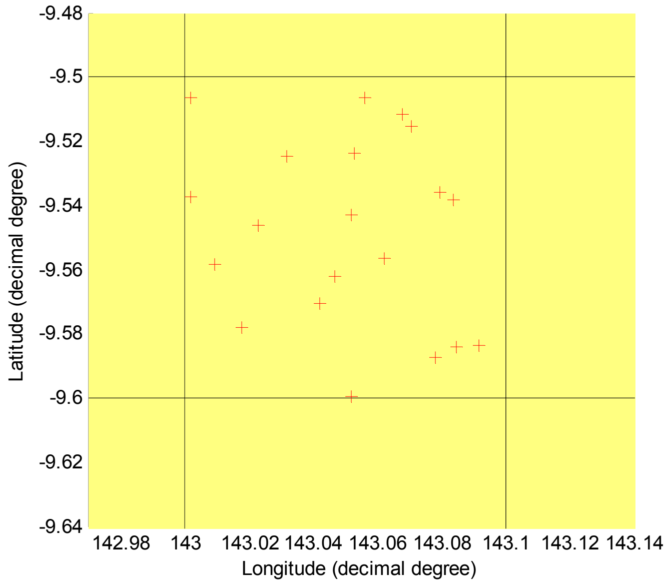


Figure 4.16 Example of randomly generated 20 coordinate sites (ID = 62).

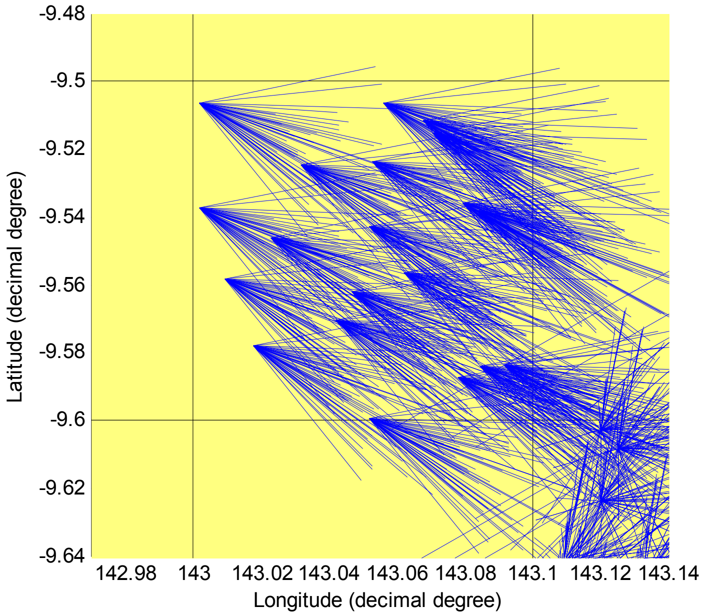


Figure 4.17 Example of movement vector replication (ID = 62).

For cells where no tagging data were available, logistic regression analysis was conducted using the *randomtag* data estimated from step5. The model was defined as:

$$\log\left(\frac{p_{ij}}{1-p_{ij}}\right) = \beta_0 + \beta_i x_1 + \beta_2 x_2 + \beta_3 x_3 + \varepsilon$$

Where p_{ij} is the probability of *j*th prawn released in a grid cell moving into *i*th site (count of prawns in ith site over total count of prawns released in a cell), β_0 is the intercept, β_i is a vector of coefficient for the destination site (i = 1, 2, …, 9), β_2 is for interaction between the destination site and latitude of the release grid, β_3 is for interaction between the site and longitude and ε is the error term. Latitudes and longitudes were defined as the mid point of the release grids. Nine possible destination sites were defined in

Figure 4.18. The model estimates movement of prawns for each grid cell based on respective coordinates (mid point of grid cells).

9 (NW)	2 (N)	3 (NE)
8 (W)	1 (stay)	4 (E)
7 (SW)	6 (S)	5 (SE)

Figure 4.18 Nine possible destination sites. The numbers in each square indicate destination ID.

Once the probabilities were estimated for each grid, they were grouped into each of 7 regions and weekly time steps were approximated to monthly movement in a form of movement transition matrix, T (7×7 matrix).

Results

Results showed significant two-way interaction effects between sites and geographical coordinates (i.e. latitude, longitude) for both species, indicating geographical differences in prawn movements (Table 4.9). Percentage mean deviance was accounted for 95.4% and the goodness-of-fit plots show no sign of extreme outliers (Figure 4.28). The estimated movement transition matrix indicated the same eastward and southward movement pattern (Figure 4.20) as suggested by Watson and Turnbull (1993) and Mellors (1990).

Table 4.7 Test of significance of the logistic regression for prawn movement.

Source	*d.f.*	*Wald Statistics*	*X^2 probability*
site.lat	9	993	<0.001
site.long	9	6278	<0.001

Table 4.8 Parameter estimates of interaction effects (β_2: lat × site, β_3: long × site)).

Parameter	*estimate*	*s.e.*	t	p
Constant	-344.14	9.83	-35.02	<.001
lat.site 1	-0.9781	0.075	-13.04	<.001
lat.site 2	-1.014	0.161	-6.31	<.001
lat.site 3	-0.253	0.181	-1.39	0.164
lat.site 4	1.742	0.108	16.13	<.001
lat.site 5	2.231	0.345	6.47	<.001
lat.site 6	-0.22	0.134	-1.63	0.102
lat.site 7	11.354	0.531	21.37	<.001
lat.site 8	0.366	0.338	1.08	0.28
lat.site 9	9.94	2.28	4.35	<.001
long.site 1	2.3412	0.0651	35.98	<.001
long.site 2	1.972	0.169	11.66	<.001
long.site 3	-3.173	0.192	-16.49	<.001
long.site 4	-4.8671	0.0879	-55.37	<.001
long.site 5	-2.459	0.247	-9.94	<.001
long.site 6	2.068	0.123	16.75	<.001
long.site 7	15.003	0.716	20.96	<.001
long.site 8	13.139	0.501	26.24	<.001
long.site 9	3.13	2.06	1.52	0.128

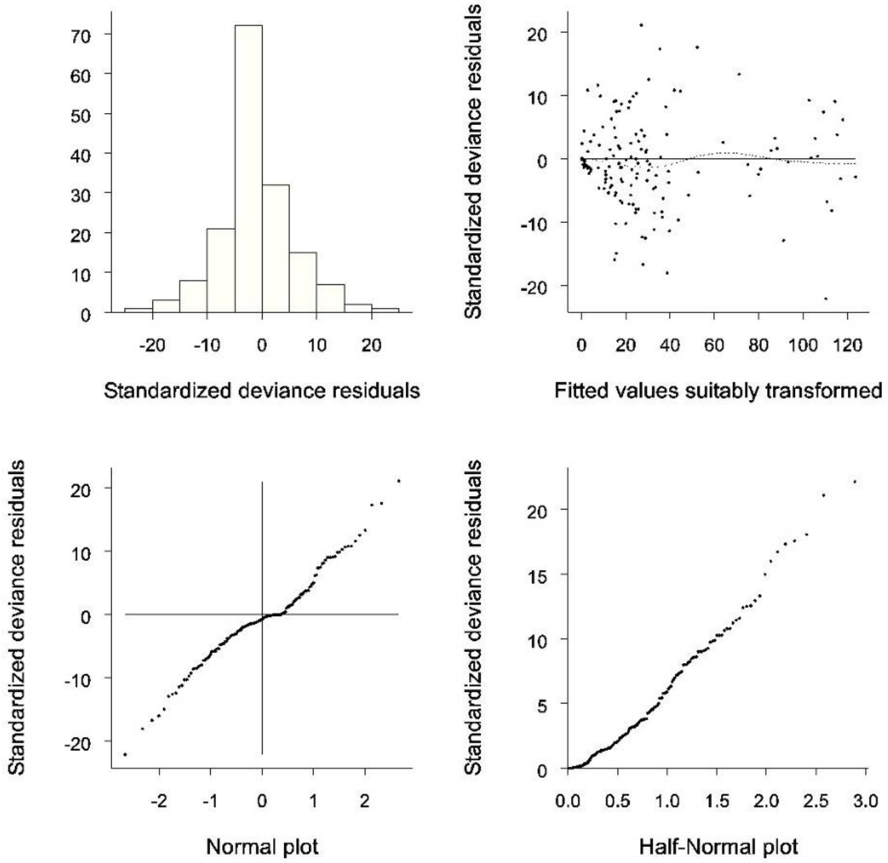


Figure 4.19 Goodness of fit plots for prawn movement analysis.

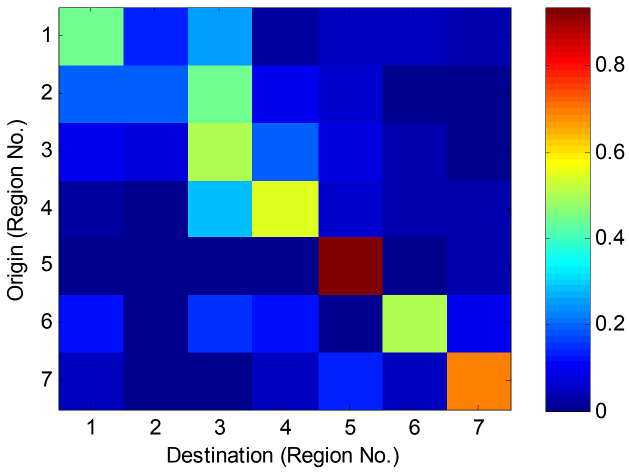


Figure 4.20 Movement transition matrix used in TFPFsim. Values indicate proportion of prawns move from origin (y-axis) to destination (x-axis) in one month period. The main diagonal of a matrix indicates proportion of prawns staying in the same region.

4.5.2 Maturity curve

Model Definition

TSPFsim is a spatially-explicit open loop MSE based on an age and length structured population dynamics. In order to calculate number of spawners for each species, the model requires a maturity curve which defines the proportion of ripe female at each size class. We derived seasonal maturity curve by fitting a logistic regression model to the quarterly survey data collected in 2007. The model was defined as:

$$\log\left(\frac{p_l}{1-p_l}\right) = \beta_0 + \beta_1 x_1 + \varepsilon$$

Where p_l is the proportion of ripe female prawn in size class l, β_0 is the intercept, β_1 is interaction effects between CL and month and ε is the error term. Month was treated as factor (categorical variable). The model was fit to each species individually. Once the model was established for each species, the proportion of ripe female was predicted for every length classes, l.

Results

Results showed a significant interaction effect between month and CL for both species (Table 4.9), indicating proportion of ripe female in each size class differs seasonally. Percentage mean deviance was accounted for 78.8% for tiger and 76.3% for endeavour. While there were four distinct monthly effects on tiger prawn maturity, there were only two seasonal differences on endeavour prawn maturity (Table 4.10; Figure 4.21). Although the residual plot showed some patterns (Figure 4.22; Figure 4.23), the maturity curves were generally a good fit to the data (Figure 4.21) and alternative models (i.e. nonlinear transformation of explanatory variables, CL) did not improve model fit or residual patterns. The poor fit at large CL is associated with very small sample sizes, and the maturity of common size range (Tiger: 20 ~ 40 mm; Endevour: 15 – 35 mm) was relatively well captured by the model.

Table 4.9 Test of significance of β_1 (CL × month) for prawn maturity.

Species	*d.f.*	*Wald Statistics*	*X^2 probability*
Tiger prawn	4	2013	<0.001
Endeavour prawn	4	2748	<0.001

Table 4.10 Parameter estimates of interaction effects (β_1: CL × month)).

	Tiger prawn				*Endeavour prawn*			
Parameter	estimate	s.e.	*t*	*p*	estimate	s.e.	*t*	*p*
Constant	-7.409	0.199	-37.32	<.001	-6.425	0.123	-52.22	<.001
CL × month 5	0.195	0.006	32.09	<.001	0.199	0.004	45.87	<.001
CL × month 7	0.217	0.006	37.22	<.001	0.199	0.004	46.67	<.001
CL × month 9	0.227	0.006	38.87	<.001	0.223	0.004	51.42	<.001
CL × month 11	0.232	0.006	37.23	<.001	0.224	0.005	47.55	<.001

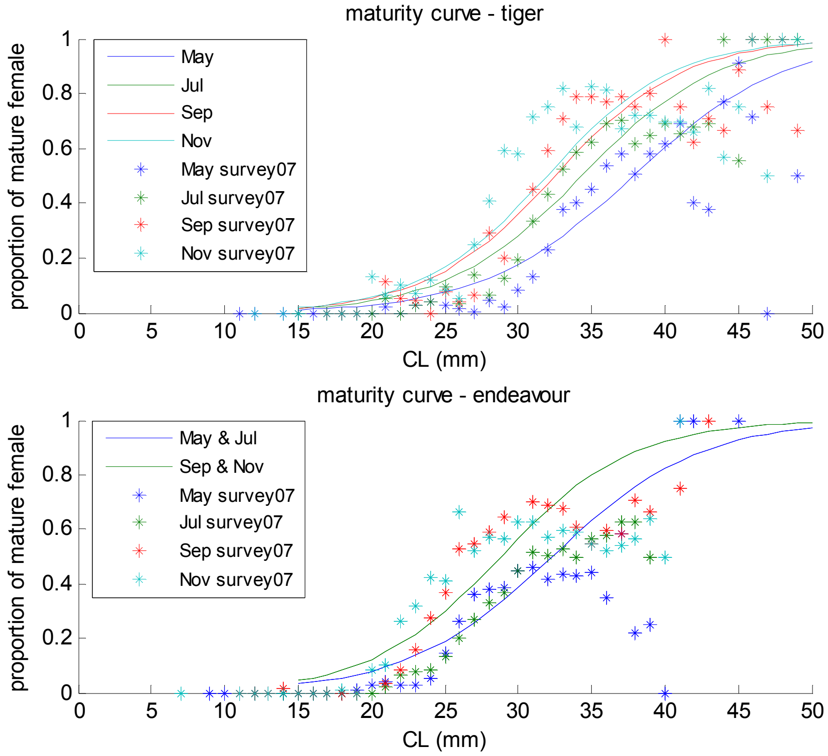


Figure 4.21 Maturity curve estimated for each survey month and species. Asterisks indicate the survey data. Note that maturity curves in May were not used in TSPFsim as the model assumed that only July – Dec spawners were contributing to the exploitable biomass.

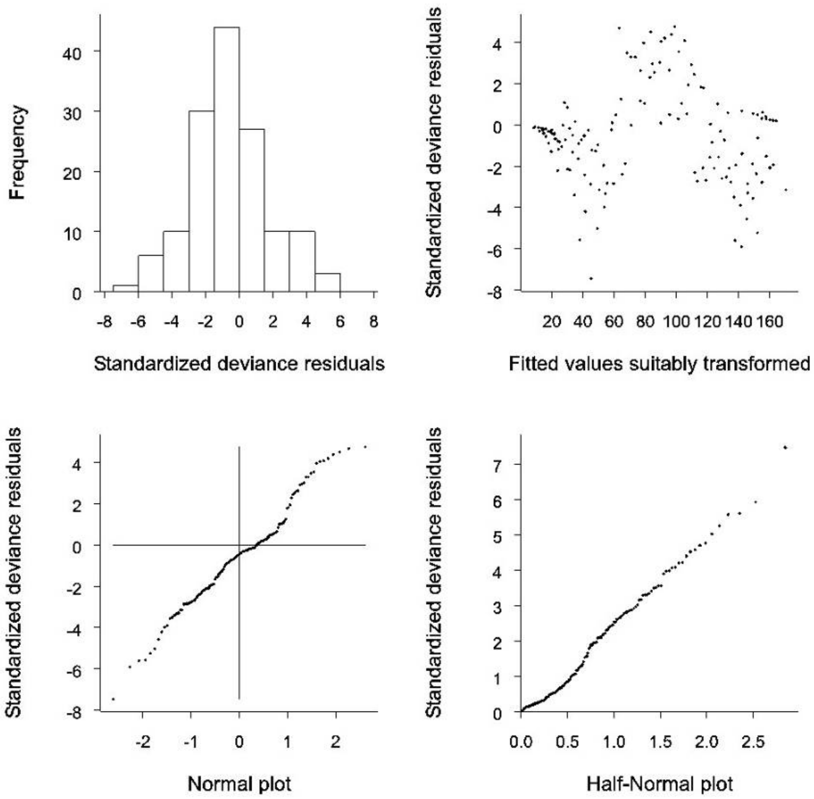


Figure 4.22 Goodness of fit plots for tiger prawn maturity analysis.

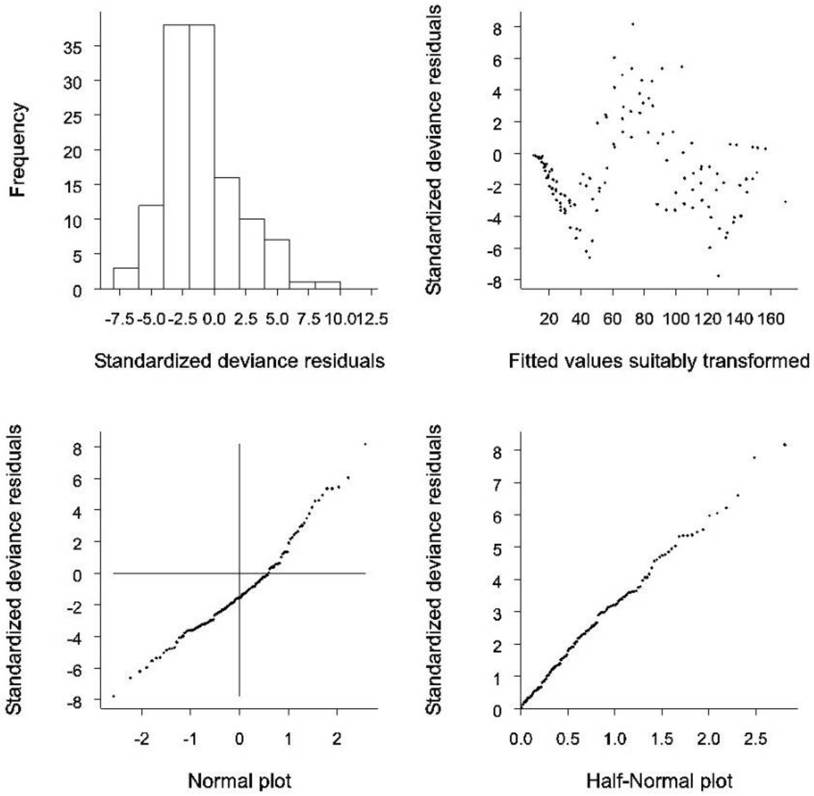


Figure 4.23 Goodness of fit plots for endeavour prawn maturity analysis.

Construction of maturity curve for missing months

The model estimated maturity curves for the survey months (May, Jul, Sep, Nov), but TSPFsim requires maturity information for months when the survey data were not available (Aug, Oct, Dec). For endeavour prawns, we simply assumed:

- May/July maturity curve for August (blue line in Figure 4.21) , and
- September/November maturity curve for October and December (green line in Figure 4.21).

For tiger prawn, we fitted a (quadratic) curve on parameter estimates for the interaction effects (CL × month). Based on the estimated interaction coefficients (Figure 4.24), maturity curve were estimated for missing months (Figure 4.25).

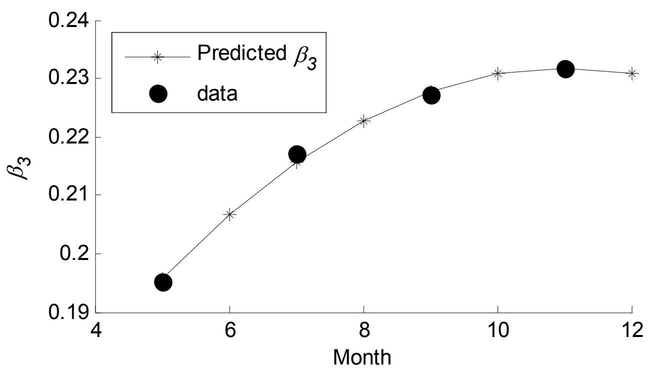


Figure 4.24 Fitted curve on parameter estimates of interaction effects (CL × month) for tiger prawn. Dot points were β_3 estimated from the analysis (Table 4.10).

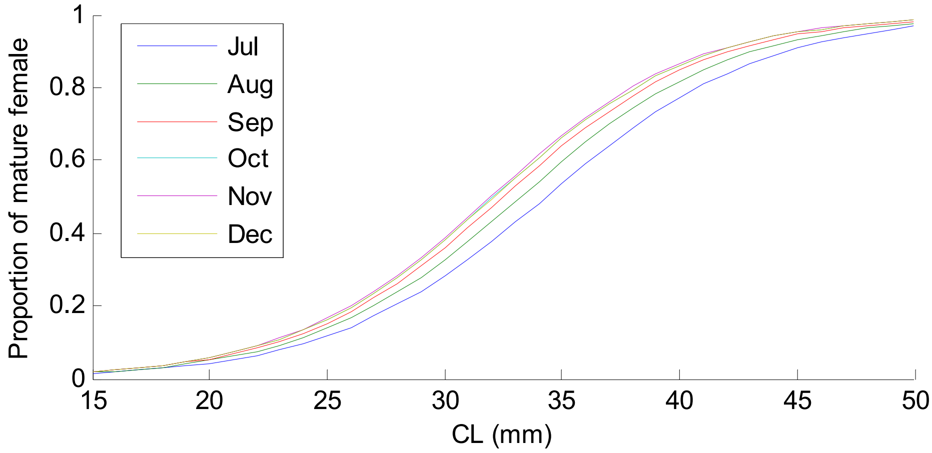


Figure 4.25 Tiger prawn seasonal maturity curve used in TFPFsim.

4.5.3 Implementation uncertainty

Model Definition

The model was defined as:

$$\log\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \varepsilon$$

where p is the fraction of TAE used, β_0 is the intercept, β_1 is coefficient for average tiger prawn market price ($/kg), β_2 is for average fuel price (cents/litre), β_3 is for the ratio of respective TAE to the 2007 TAE (i.e. 6867) and ε is the error term. The third term (β_3) was included as the proportion of TAE actually used by fishers was affected by the level of TAE (the lower the TAE, the more likely it is that fishers make full use of their allocated night and vice versa). Fuel price data were obtained from the AAA website (http://www.aaa.asn.au/issues/petrol.htm) and prawn market price information was provided from ABARE (23/09/2008). Both datasets were adjusted for CPI.

Model Prediction

Once the model was established, 10-year predictions were made based on three types of hypothetical scenarios: 1) maintain fuel and prawn price in 2007 (status quo); 2) fuel down by 4% and prawn up by 4% (optimistic); and 3) fuel price goes up by 4% every year but tiger prawn price goes down by 4% (pessimistic) (Figure 4.26). As we were predicting implementation uncertainty for TAE of 12000 nights the ratio of respective TAE to the 2007 TAE (x_3) was set to be 1.7475 (12000/6867).

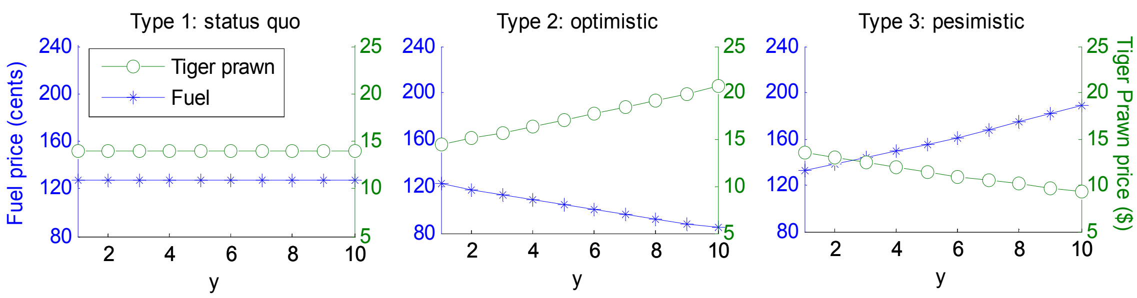


Figure 4.26 Three types of hypothetical fuel and tiger prawn market price for 10-year future projection. Type 1 assumes prices remain the same as in 2007 for next 10 years; Type 2 is the scenario favourable to the fishing industry; Type 3 is unfavourable to the industry.

Results

Results showed that three parameters were all significant (Table 4.11; Table 4.12); tiger prawn price had positive effect and fuel and TAE ratio had negative effects on the proportion of TAE used by the industry (Figure 4.27). Percentage mean deviance was accounted for 83.4%. Proportions of active effort over TAE were higher when TAE was set low (e.g. 6867) (Figure 4.27 (A)) compared to higher TAE (e.g. 12000) (Figure 4.27 (B)). The goodness-of-fit plots were shown in Figure 4.28.

Table 4.11 Results of the logistic regression for the implementation uncertainty.

Source	*d.f.*	*deviance*	*mean deviance*	*deviance ratio*	*approx chi pr*
Regression	3	6343	2114.3	2114.34	<.001
Residual	7	833.9	119.1		
Total	10	7177	717.7		

Table 4.12 Parameter estimates.

Parameter	*estimate*	*s.e.*	*t*	*p*
Constant (β_0)	3.794	0.107	35.6	<.001
Tiger prawn price (β_1)	0.06008	0.00137	43.7	<.001
Fuel price (β_2)	-0.02123	0.000577	-36.81	<.001
TAE_y / TAE_{2007} (β_3)	-1.0079	0.0249	-40.44	<.001

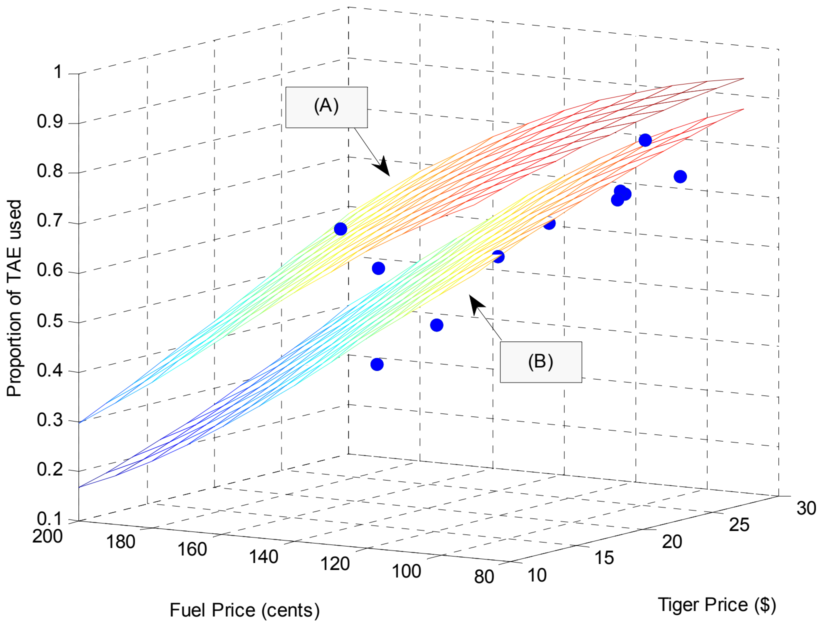


Figure 4.27 The surface of implementation uncertainty with range of tiger prawn price and fuel price predicted from the model with TAE at: (A) 6867 nights, and (B) 12000 nights. Dot points indicate the actual data from 1997 to 2007.

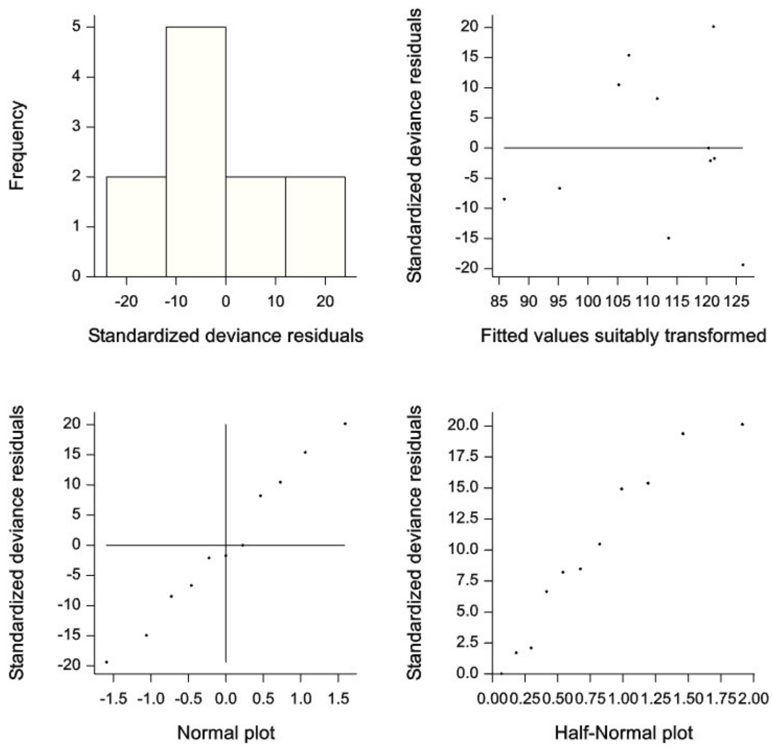


Figure 4.28 Goodness of fit plots for the implementation uncertainty analysis.

Construction of Implementation Uncertainty

Once the predicted mean proportion of TAE used were estimated for each year and scenario, 1000 random numbers were sampled from normal distribution with respective mean and standard deviation at 0.05 (~N($\mu_{y,Type}$, 0.05)) (Figure 4.7 in Section 4.2.4).

4.5.4 Simulation results – individual scenarios

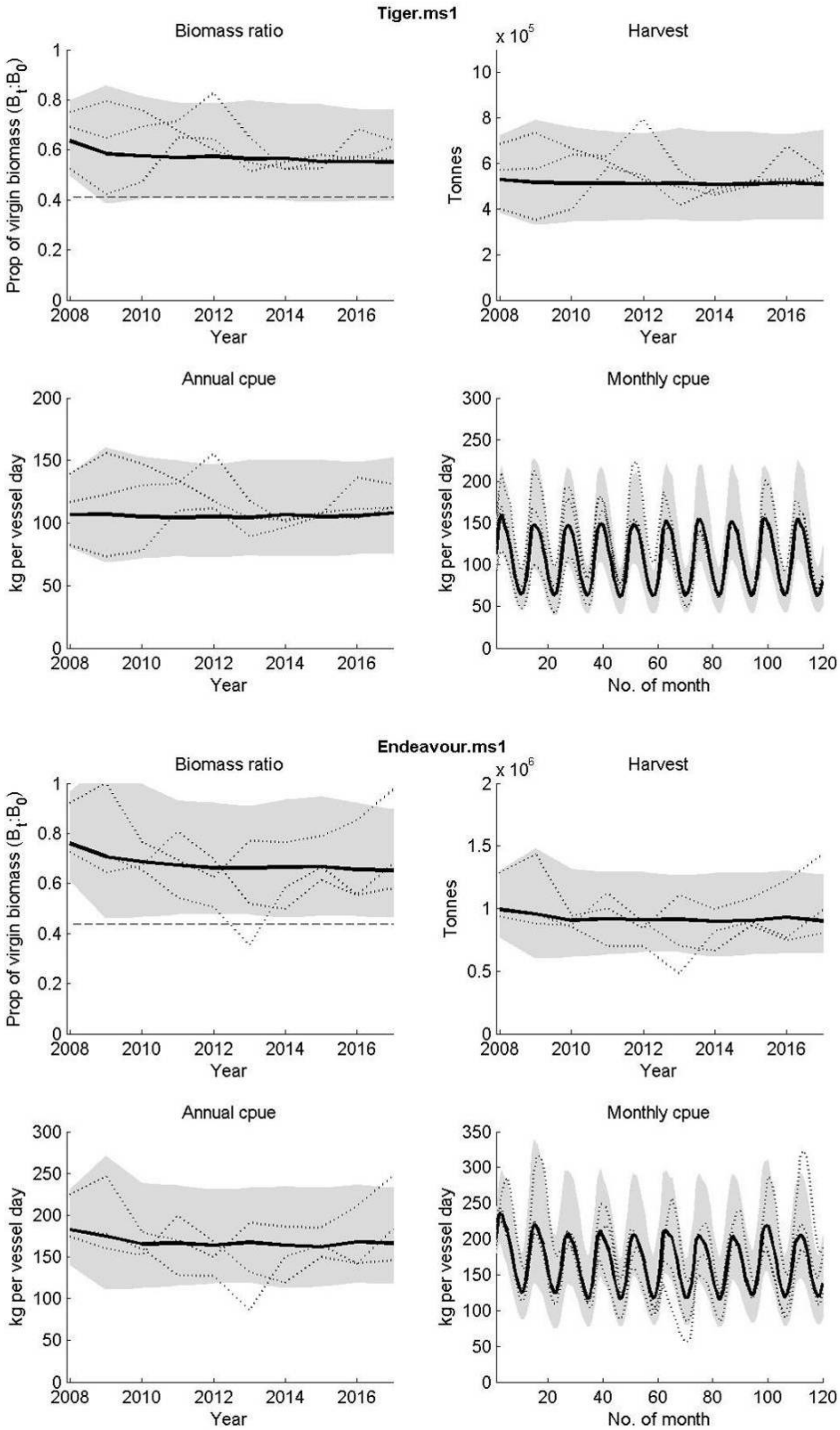


Figure 4.29 The expected biomass and harvest outcomes for tiger and endeavour prawns with fixed TAE at 4500 nights (ms1). Each figure was expressed by the median (solid line), three individual replicates (dotted lines), and 5th and 95th percentiles (shaded area). The dashed line in "Biomass ratio" indicated B_{MSY}.

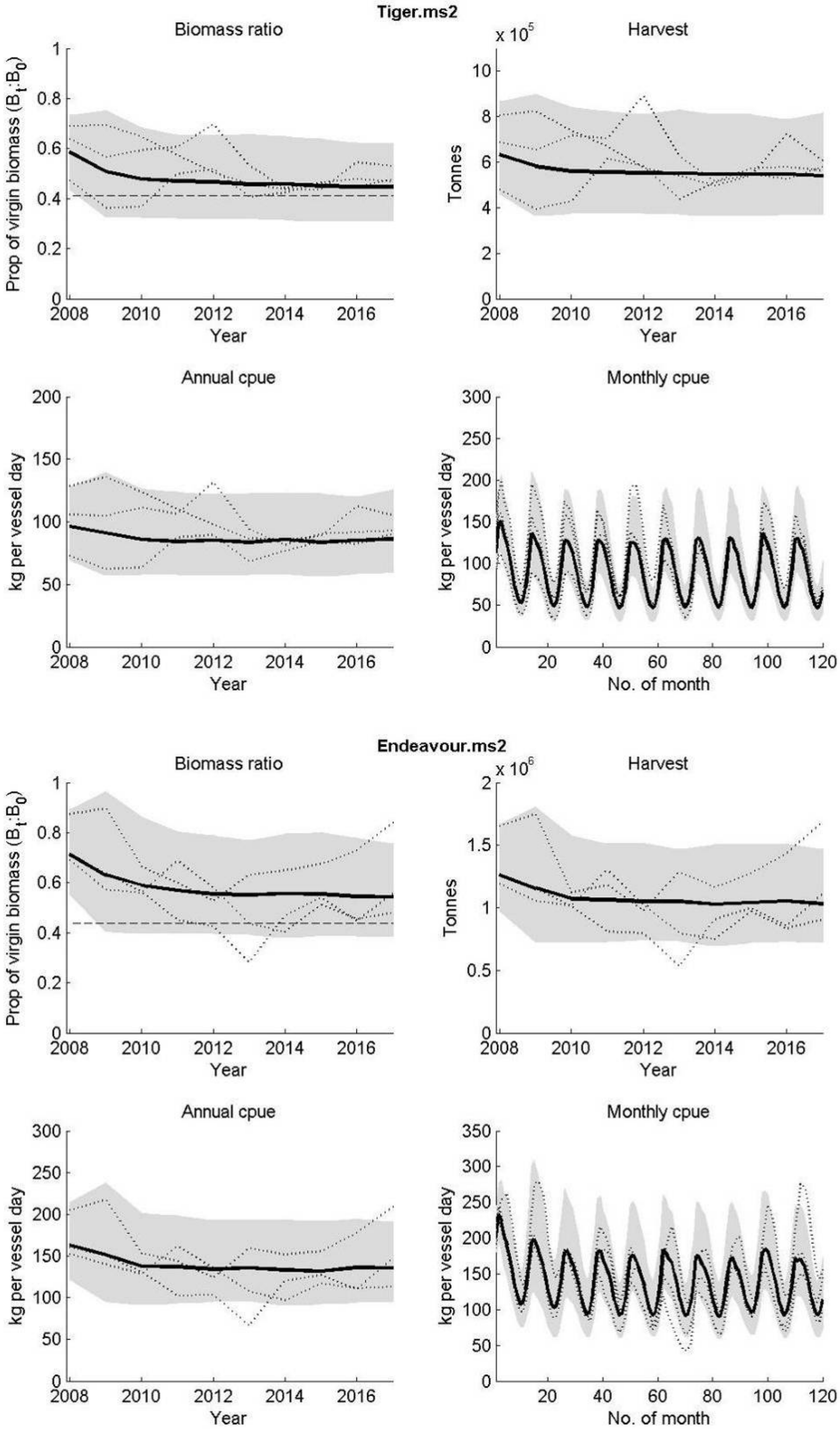


Figure 4.30 The expected biomass and harvest outcomes for tiger and endeavour prawns with fixed TAE at 6867 nights with no implementation error (ms 2). Each figure was expressed by the median (solid line), three individual replicates (dotted lines), and 5th and 95th percentiles (shaded area). The dashed line in “Biomass ratio” indicated B_{MSY}.

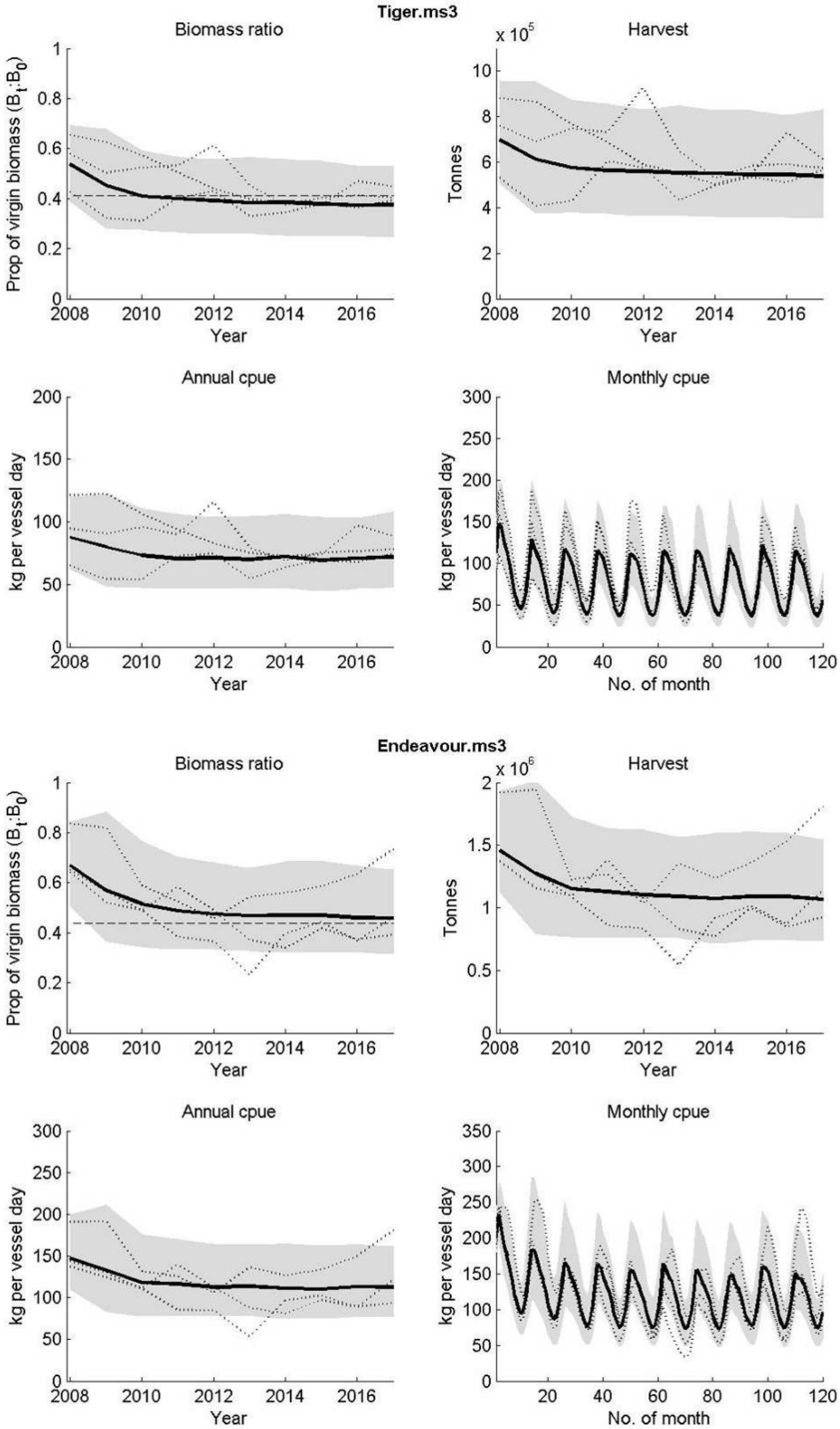


Figure 4.31 The expected biomass and harvest outcomes for tiger and endeavour prawns with fixed TAE at 9200 nights with no implementation error (ms 3). Each figure was expressed by the median (solid line), three individual replicates (dotted lines), and 5th and 95th percentiles (shaded area). The dashed line in "Biomass ratio" indicated B_{MSY}.

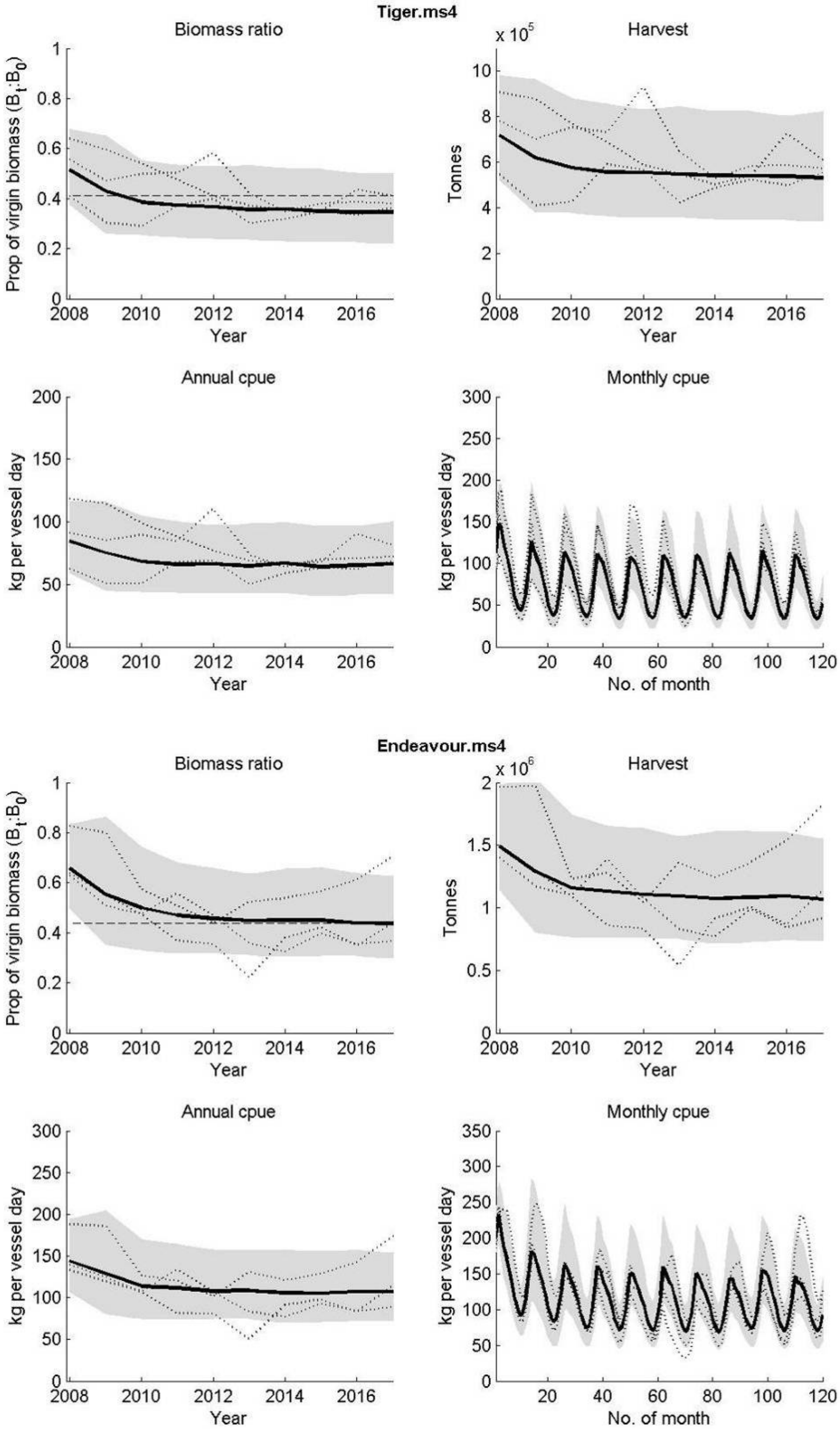


Figure 4.32 The expected biomass and harvest outcomes for tiger and endeavour prawns with fixed TAE at 9200 nights + 1000 nights in PNG water (no implementation error) (ms 4). Each figure was expressed by the median (solid line), three individual replicates (dotted lines), and 5th and 95th percentiles (shaded area). The dashed line in "Biomass ratio" indicated B_{MSY}.

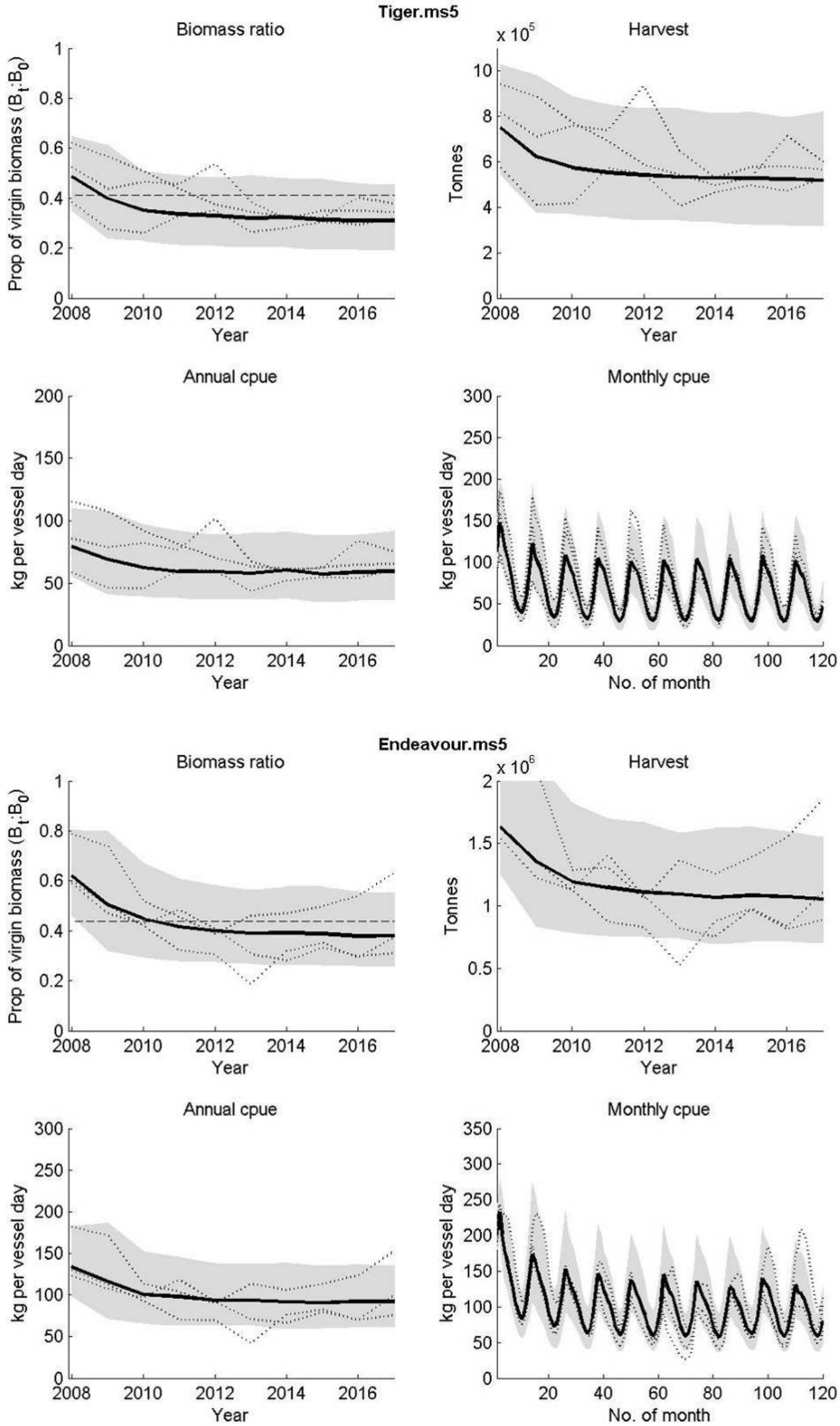


Figure 4.33 The expected biomass and harvest outcomes for tiger and endeavour prawns with fixed TAE at 12000 nights with no implementation error (ms5). Each figure was expressed by the median (solid line), three individual replicates (dotted lines), and 5^{th} and 95^{th} percentiles (shaded area). The dashed line in "Biomass ratio" indicated B_{MSY}.

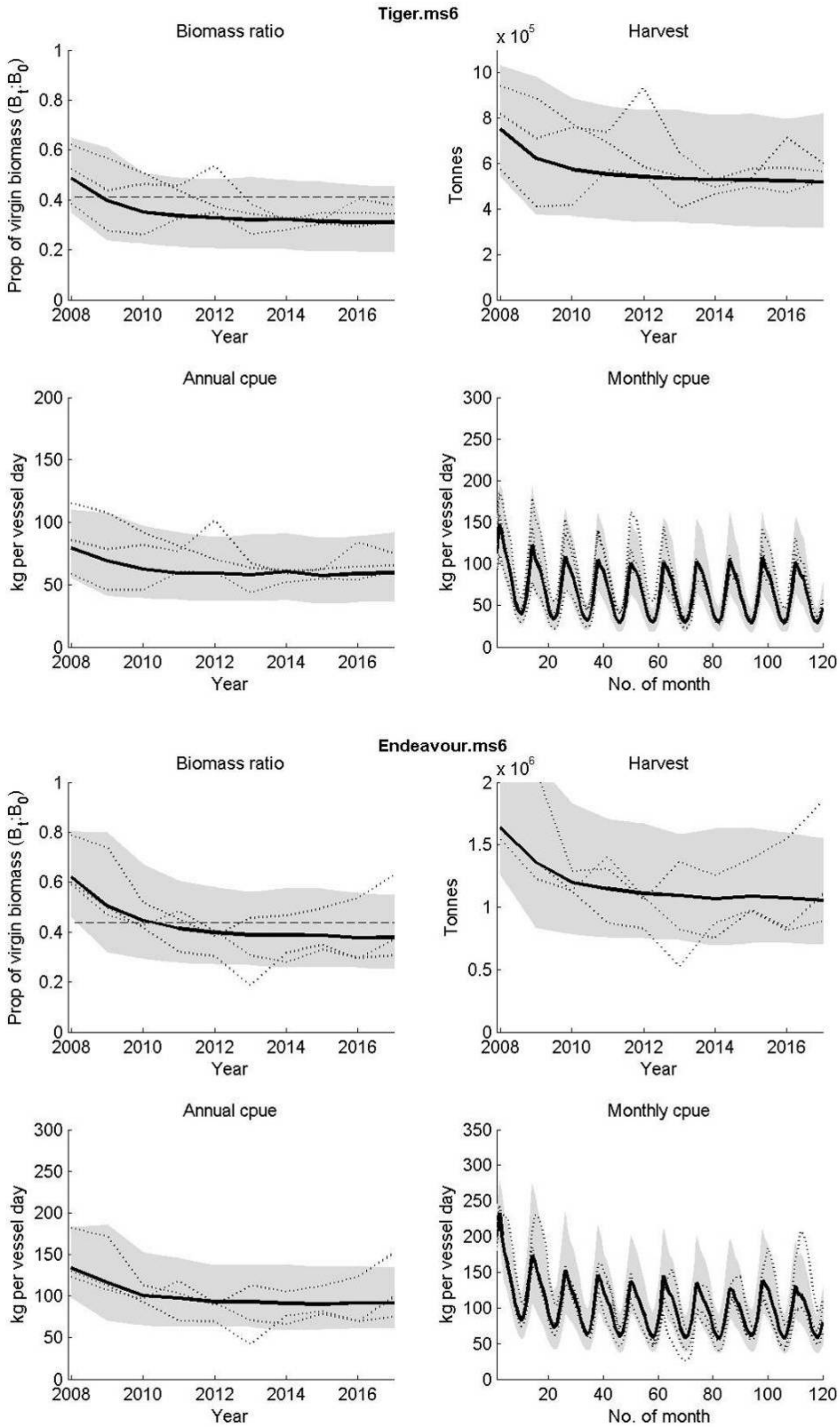


Figure 4.34 The expected biomass and harvest outcomes for tiger and endeavour prawns with fixed TAE at 12000 nights with trigger effort at 9200 nights (no implementation error) (ms 6). Each figure was expressed by the median (solid line), three individual replicates (dotted lines), and 5th and 95th percentiles (shaded area). The dashed line in "Biomass ratio" indicated B_{MSY}.

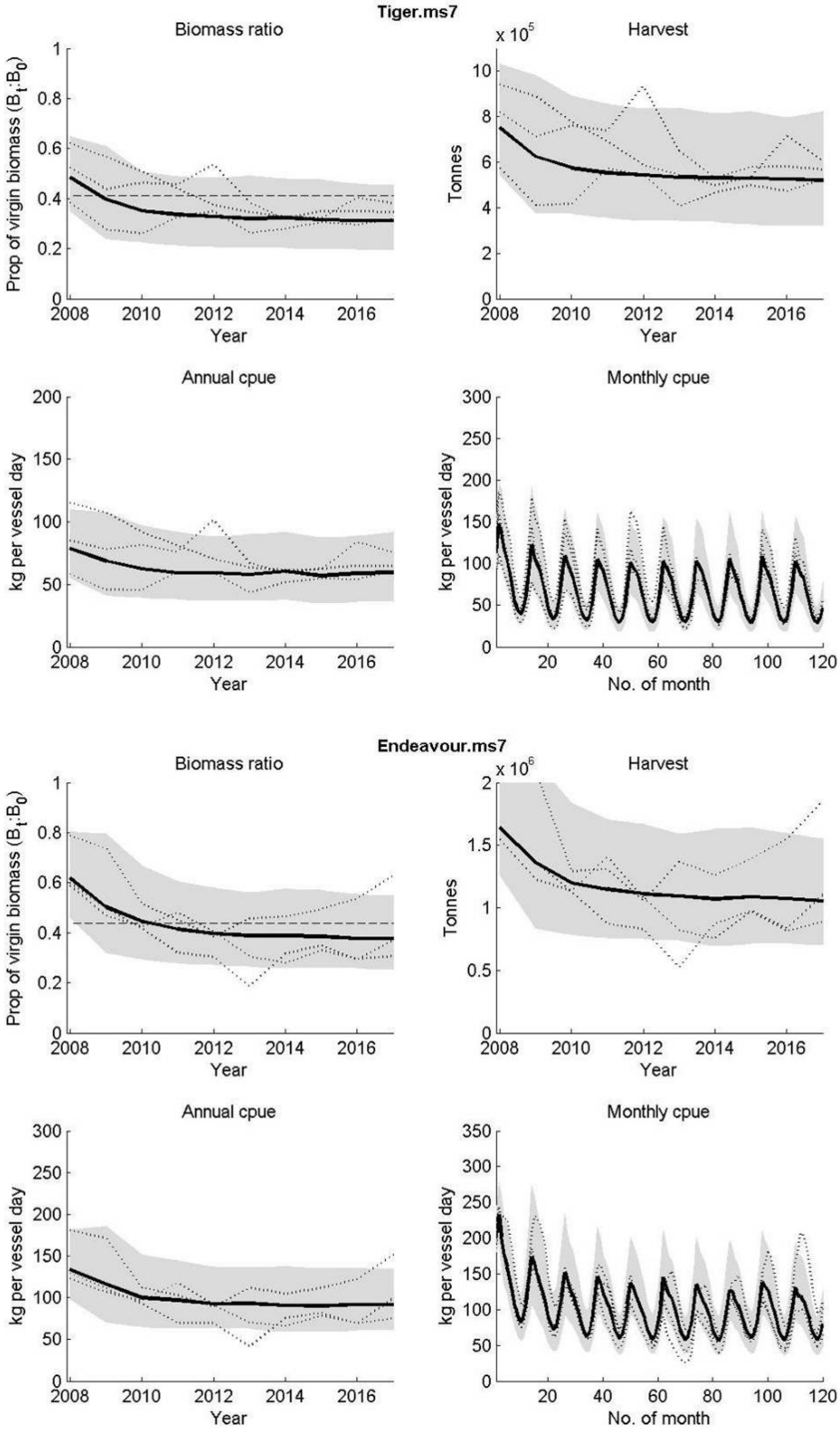


Figure 4.35 The expected biomass and harvest outcomes for tiger and endeavour prawns with fixed TAE at 12000 nights with trigger effort at 7000 nights (no implementation error) (ms 7). Each figure was expressed by the median (solid line), three individual replicates (dotted lines), and 5th and 95th percentiles (shaded area). The dashed line in “Biomass ratio” indicated B_{MSY}.

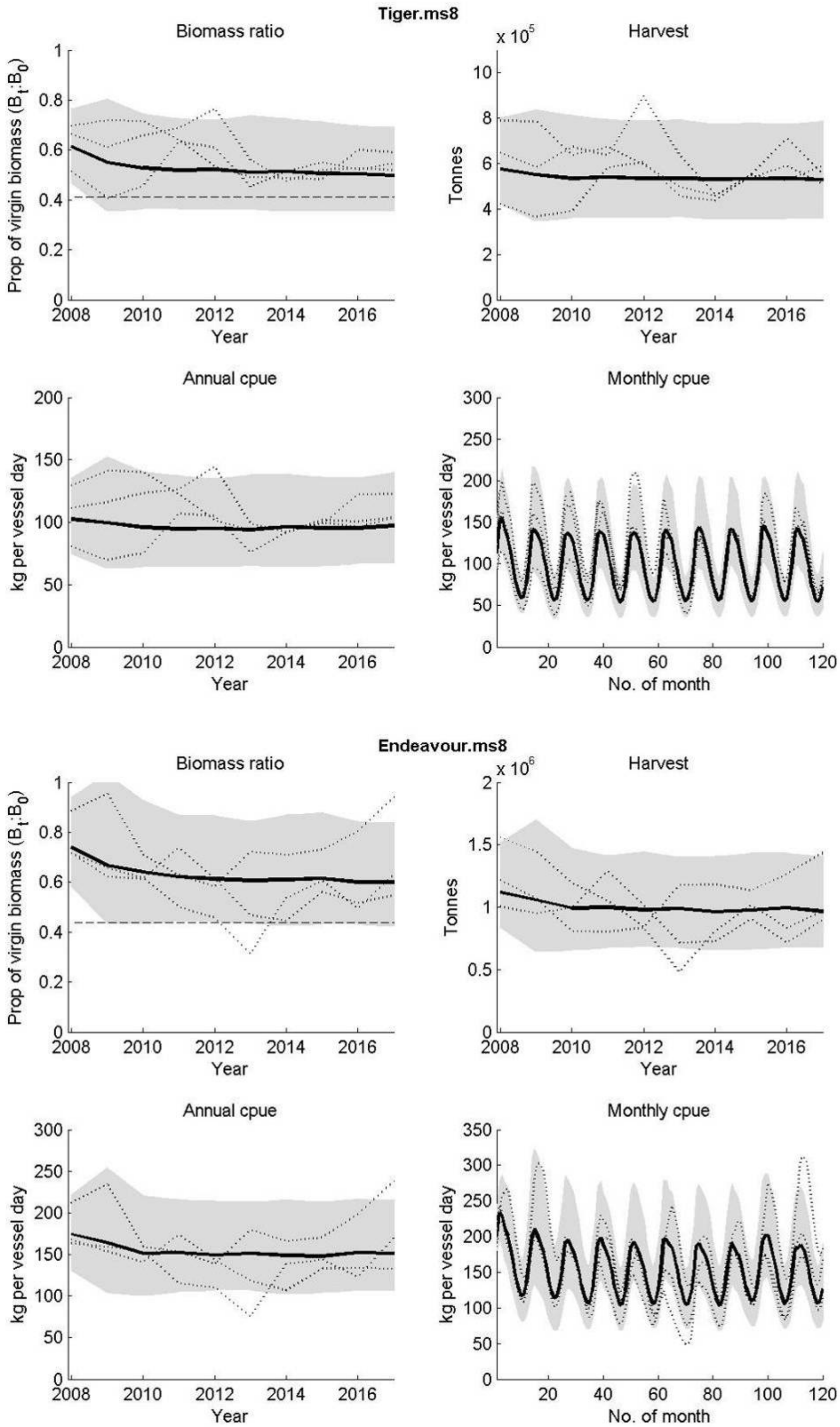
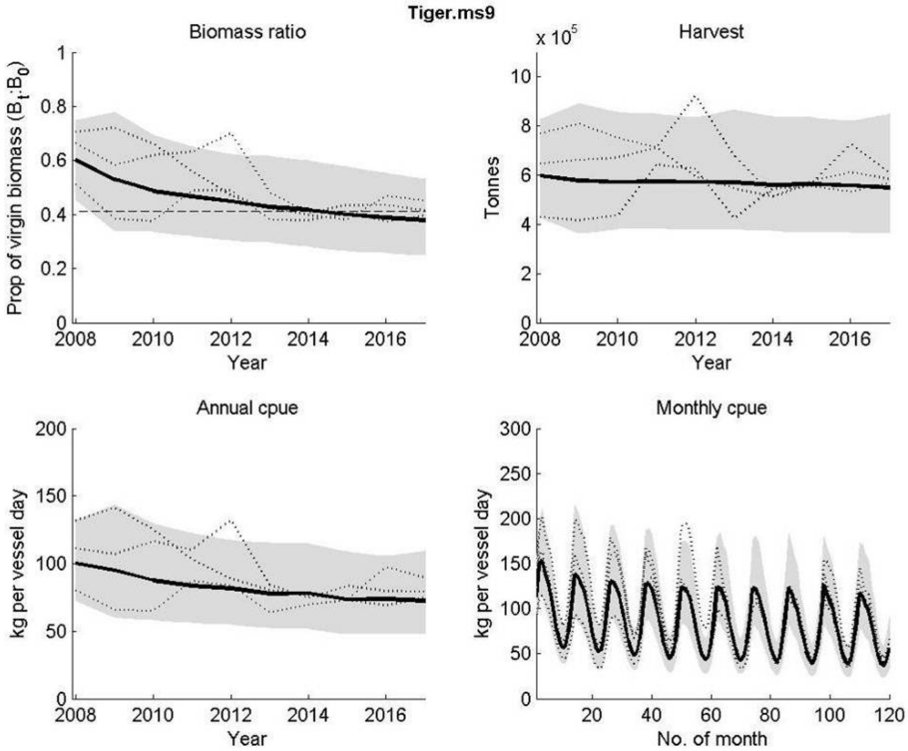


Figure 4.36 The expected biomass and harvest outcomes for tiger and endeavour prawns with TAE at 12000 nights (7000 nights trigger effort) with implementation uncertainty Type 1 (status quo) (ms 8). Each figure was expressed by the median (solid line), three individual replicates (dotted lines), and 5th and 95th percentiles (shaded area). The dashed line in "Biomass ratio" indicated B_{MSY}.



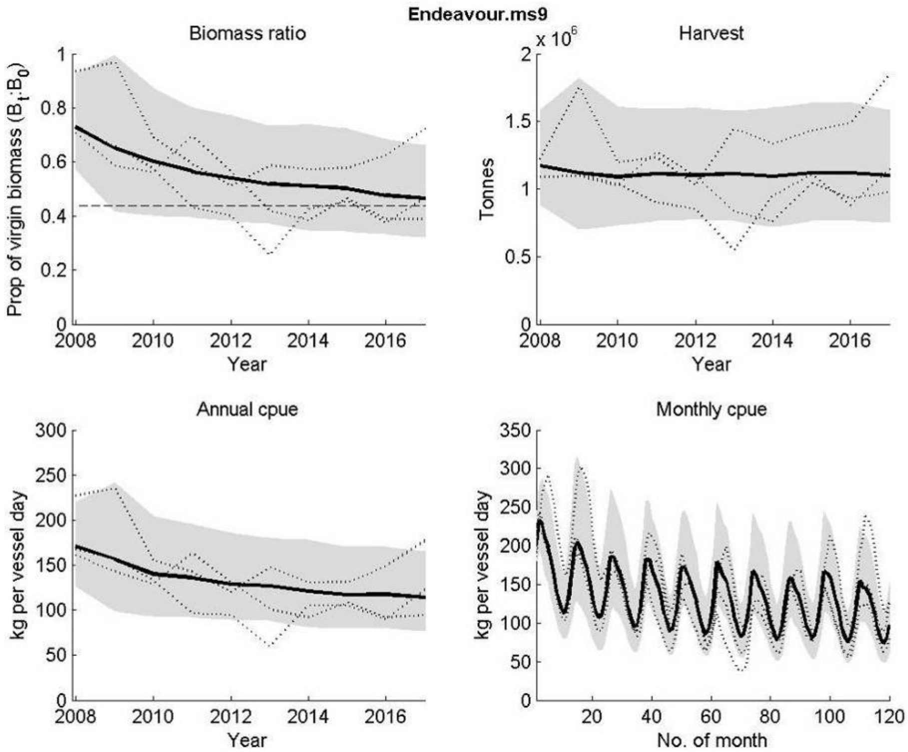


Figure 4.37 The expected biomass and harvest outcomes for tiger and endeavour prawns with TAE at 12000 nights (7000 nights trigger effort) with implementation uncertainty Type 2 (optimistic) (Scenario 9). Each figure was expressed by the median (solid line), three individual replicates (dotted lines), and 5th and 95th percentiles (shaded area). The dashed line in "Biomass ratio" indicated B_{MSY}.

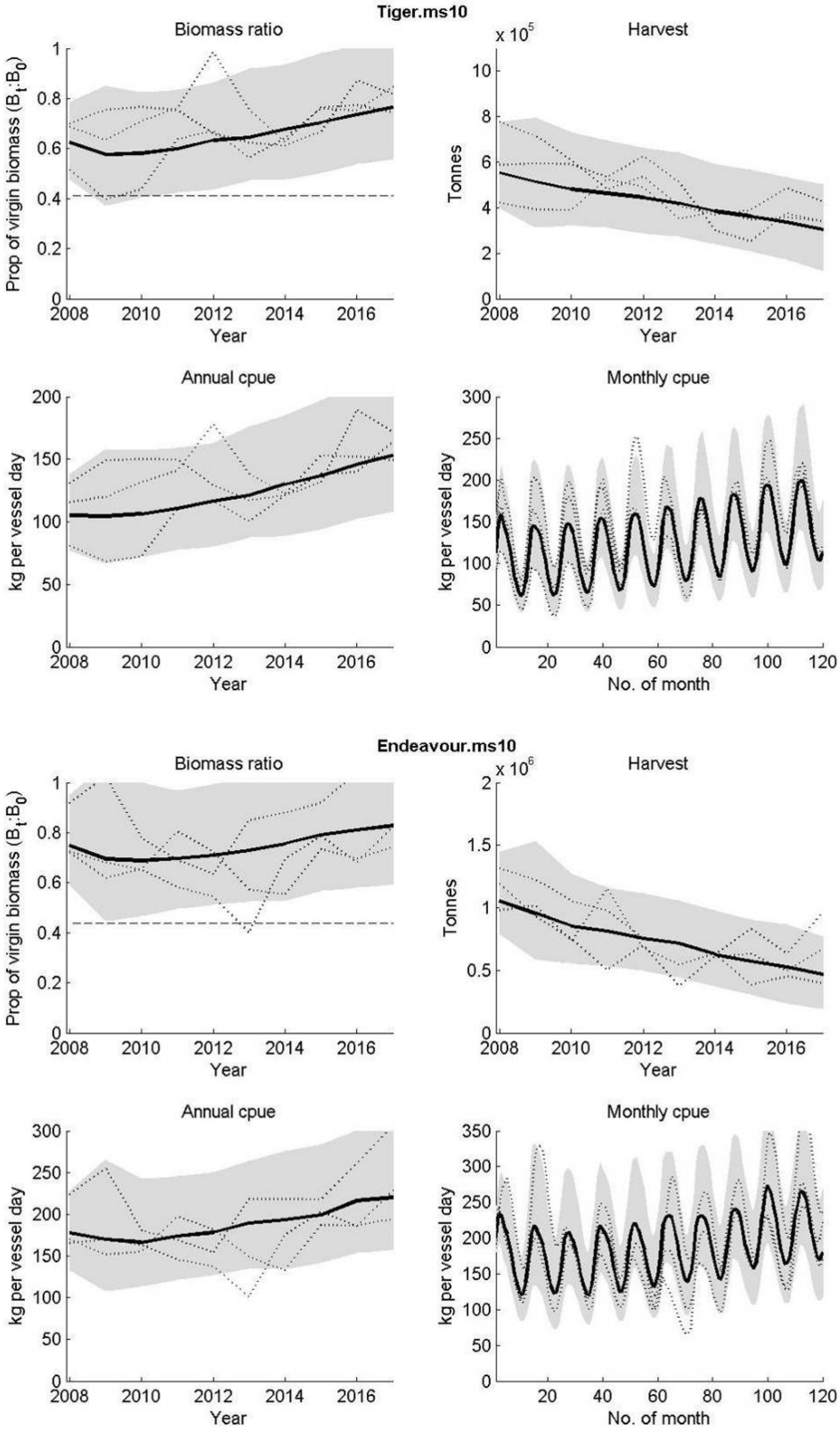


Figure 4.38 The expected biomass and harvest outcomes for tiger and endeavour prawns with TAE at 12000 nights (7000 nights trigger effort) with implementation uncertainty Type 3 (pessimistic) (Scenario 10). Each figure was expressed by the median (solid line), three individual replicates (dotted lines), and 5th and 95th percentiles (shaded area). The dashed line in "Biomass ratio" indicated B_{MSY}.

4.5.5 Endeavour prawn results with fixed steepness at 0.7

This section presents the simulation results for endeavour prawns with fixed steepness at 0.7. As expected the stock is generally more resilient to fishing pressure; the risk of biomass fall below B_{MSY} is lower than the results with fixed steepness at 0.5. With steepness at 0.7, the endeavour prawn biomass is likely to be above B_{TARG} for all scenarios (Table 4.13) and the risk of biomass falling below B_{LIM} is nil.

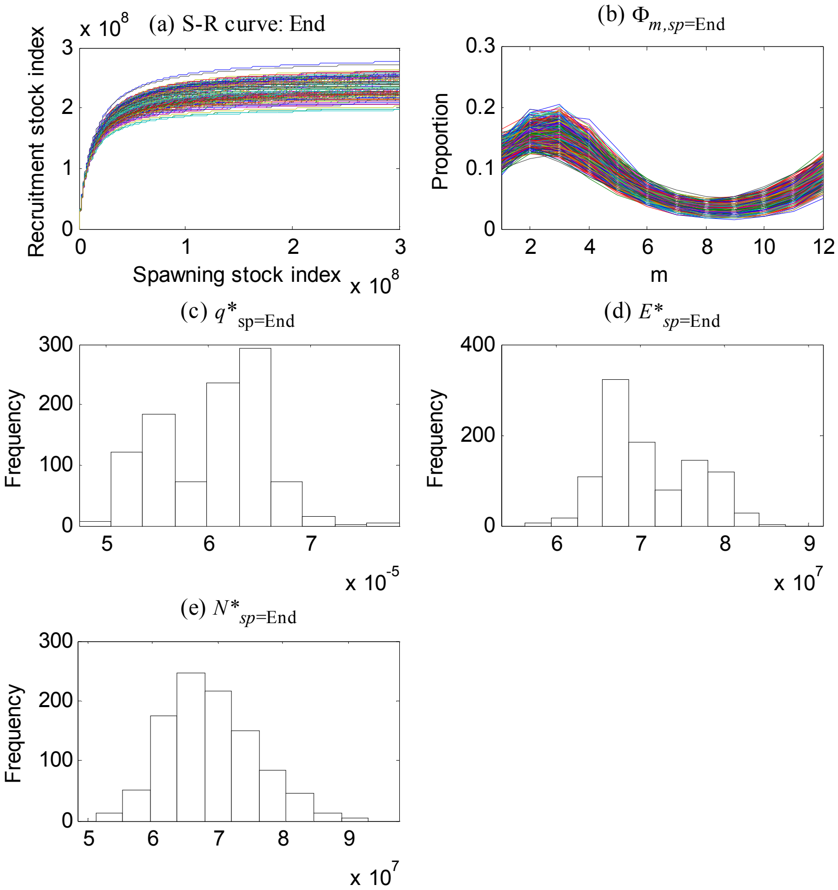


Figure 4.39 The monthly recruitment pattern for endeavour prawns with fixed steepness at 0.7 (a); monthly recruitment pattern (b); overall catchability coefficient (c); initial spawning stock index (d); initial prawn abundance (f).

Table 4.13 Relative performance measures from the 10 year forward projection of each scenario for endeavour prawns (fixed steepness = 0.7). Harvest and annual CPUE were shown as relative proportion scaled to 1 at status quo (Scenario 2).

ms	*Probability $B_{2017}<B_{MSY}$*	*Probability $B_{2017}< B_{LIM}$*	*Ratio ($B_{2017}:B_{TARG}$)*	*Harvest*	*Annual CPUE*
1	0	0	1.45 (1.07:1.96)	0.84	1.19
2	0.02	0	1.24 (0.92:1.69)	1	1
3	0.08	0	1.09 (0.79:1.5)	1.09	0.87
4	0.12	0	1.05 (0.76:1.44)	1.1	0.85
5	0.25	0	0.95 (0.68:1.31)	1.15	0.76
6	0.25	0	0.94 (0.68:1.31)	1.15	0.75
7	0.25	0	0.94 (0.68:1.31)	1.15	0.75
8	0.01	0	1.36 (0.99:1.83)	0.92	1.09
9	0.09	0	1.09 (0.79:1.5)	1.04	0.94
10	0	0	1.8 (1.34:2.43)	0.66	1.31

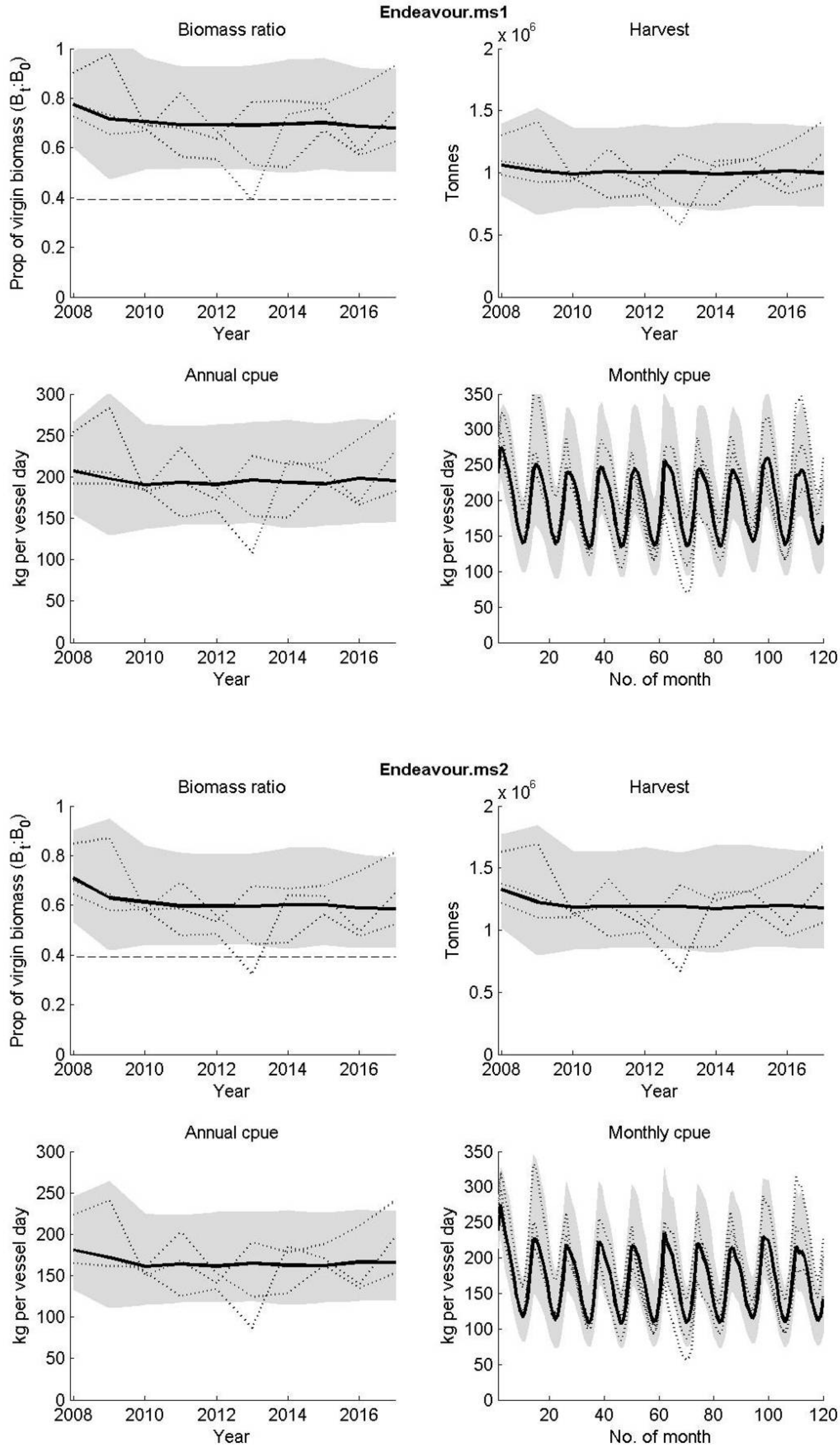


Figure 4.40 The expected biomass and harvest outcomes for endeavour prawns with fixed TAE at 4500 nights (ms1) and at 6867 nights (ms2). Steepness was fixed at 0.7. Each figure was expressed by the median (solid line), three individual replicates (dotted lines), and 5th and 95th percentiles (shaded area). The dashed line in “Biomass ratio” indicated B_{MSY}.

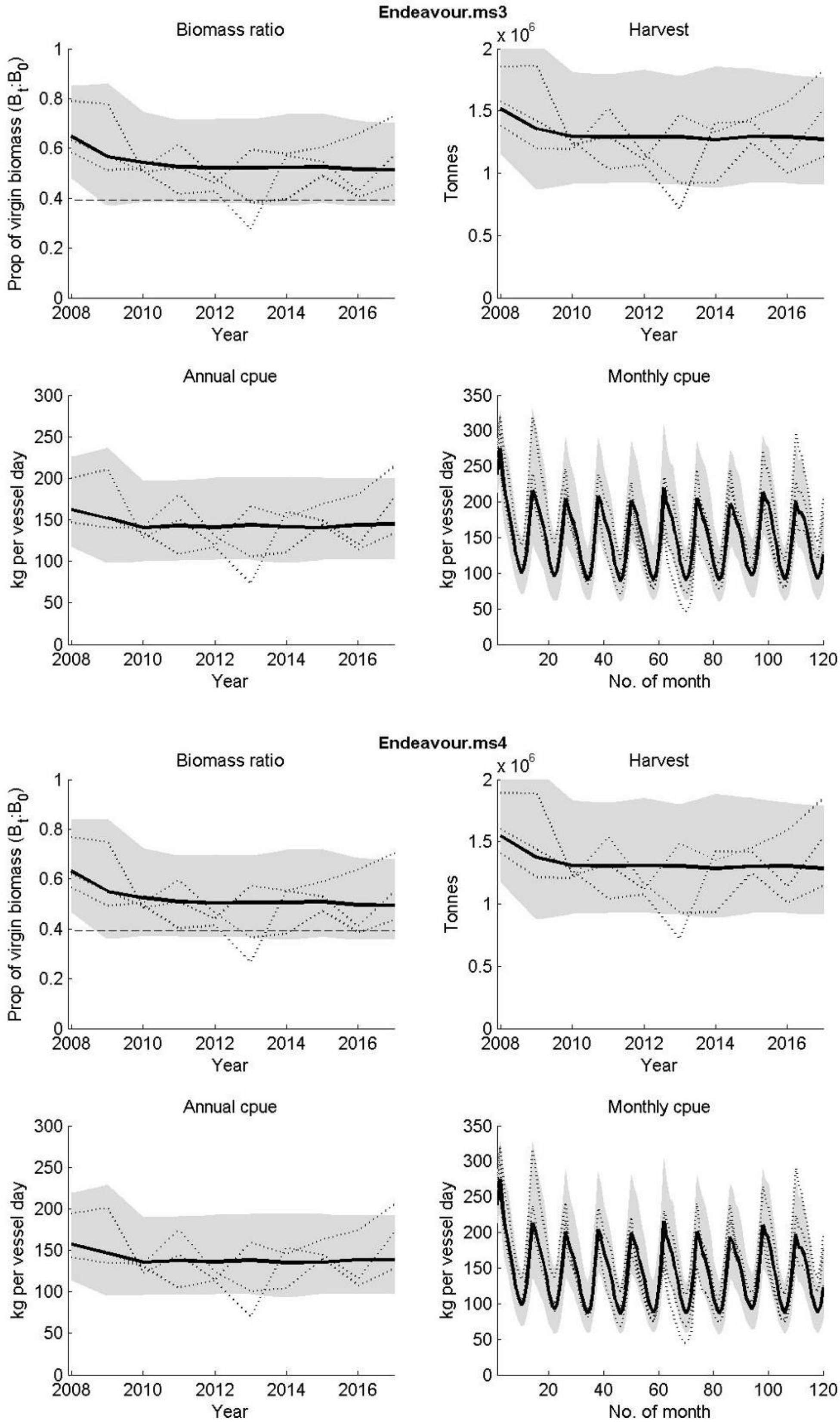


Figure 4.41 The expected biomass and harvest outcomes for endeavour prawns with fixed TAE at 9200 nights (ms3) and at 9200 nights + 1000 nights in PNG water (ms4). Steepness was fixed at 0.7. Each figure was expressed by the median (solid line), three individual replicates (dotted lines), and 5th and 95th percentiles (shaded area). The dashed line in "Biomass ratio" indicated B_{MSY}.

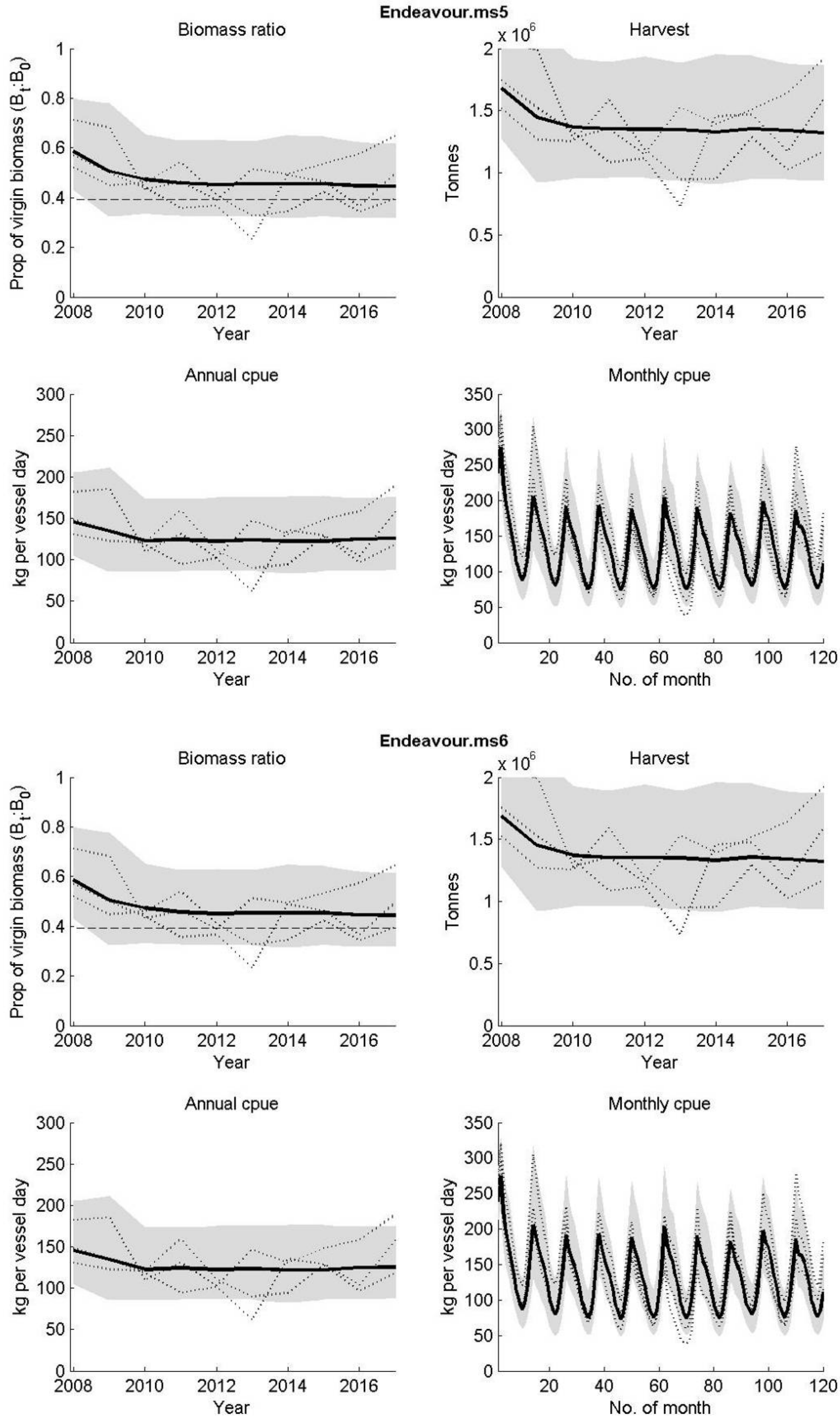


Figure 4.42 The expected biomass and harvest outcomes for endeavour prawns with fixed TAE at 12000 nights (ms5) and at 12000 nights with trigger effort at 9200 nights (ms6). No implementation error was included. Steepness was fixed at 0.7. Each figure was expressed by the median (solid line), three individual replicates (dotted lines), and 5th and 95th percentiles (shaded area). The dashed line in “Biomass ratio” indicated B_{MSY}.

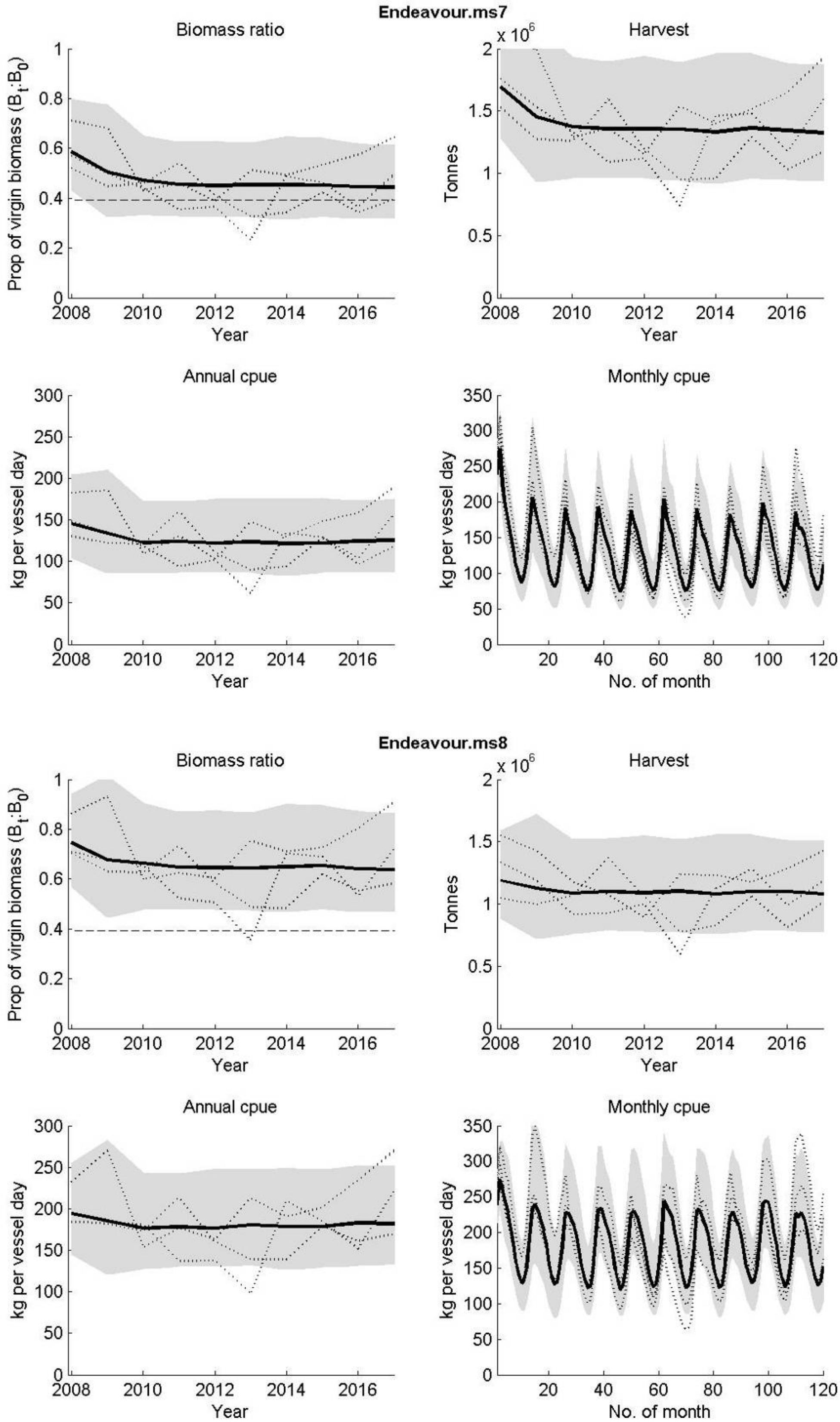


Figure 4.43 The expected biomass and harvest outcomes for endeavour prawns with fixed TAE at 12000 nights (trigger effort at 7000 nights) with no implementation error (ms7) and with implementation uncertainty Type 1 (ms8). Steepness was fixed at 0.7.Each figure was expressed by the median (solid line), three individual replicates (dotted lines), and 5th and 95th percentiles (shaded area). The dashed line in "Biomass ratio" indicated B_{MSY}.

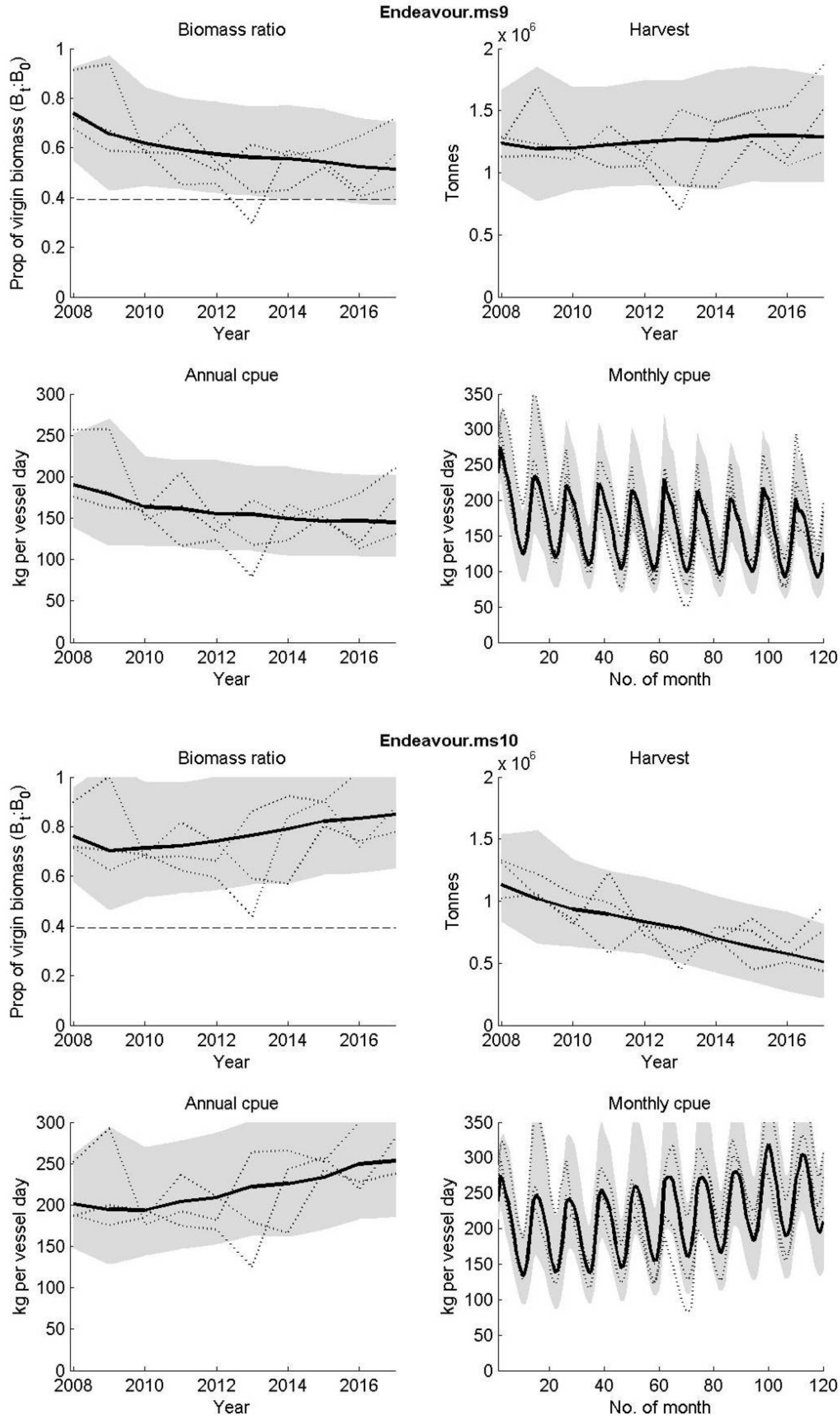


Figure 4.44 The expected biomass and harvest outcomes for endeavour prawns with TAE at 12000 nights (7000 nights trigger effort) with implementation uncertainty Type2 (optimistic) (ms9) and Type 3 (pessimistic) (ms10). Steepness was fixed at 0.7. Each figure was expressed by the median (solid line), three individual replicates (dotted lines), and 5th and 95th percentiles (shaded area). The dashed line in "Biomass ratio" indicated B_{MSY}.

5 Endeavour prawn stock assessment

Mai Tanimoto, Michael O'Neill, Alex Campbell and Clive Turnbull

5.1 Introduction

The Torres Strait Prawn Fishery harvests the brown tiger prawn (*Penaeus esculentus*) and the blue endeavour prawn (*Metapenaeus endeavouri*) with a minor catch of redspot king prawn (*Melicertus longistylus*). Although there was a reliable stock assessment that had been externally reviewed (Die 2003) for the tiger prawn stock, there was no equivalent stock assessment for the endeavour prawn stock. The only available estimate of sustainable endeavour prawn harvest was an estimate of Maximum Constant Yield (MCY); based largely on QDPI trawl survey data collected during 1986-91 (Turnbull and Watson 1995). At the time of the Alternative Management Workshop in 2005, industry representatives strongly argued the need for a current endeavour prawn stock assessment, of the same style as the tiger prawn assessment. The need for this assessment was a flow on from the aim of the workshop; to investigate management strategies that would allow additional fishing for endeavour prawns whilst ensuring a sustainable harvest of tiger prawns.

The stock assessment for the Torres Strait endeavour prawns was initially approached by adopting the existing Torres Strait tiger prawn model (O'Neill and Turnbull 2006). This tiger prawn model used a delay difference model (Deriso 1980; Schnute 1985), which has commonly been used to assess penaeid prawn stocks in Australia including tiger prawns the Gulf of Carpentaria (Dichmont et al. 2005), eastern king prawns in Queensland (O'Neill et al. 2005) and in NSW (Ives and Scandol 2007). The preliminary results of the endeavour prawn delay difference model are presented in Appendix 5.5.2.

Although the estimates of Maximum Sustainable Yield (MSY) from the delay difference model were similar to the average endeavour prawn catch during the 1990's, there was a large level of uncertainty around the MSY estimates and the spawner-recruitment relationship parameters. The preliminary results indicated large uncertainties in the biomass trend and strong collinearity in the parameter estimates. An alternative size and age structured model was developed to overcome these problems. The alternative model follows the dynamics of each sex, size and age cohort separately and enables us to capture the substantial size dependent variation that occurs in reproduction that occurs in these species. Whilst the delay difference model approximated prawn growth by the Brody growth curve, the alternative model applies different growth for each size classes via a growth transition matrix. A Bayesian estimation technique (Monte Carlo Markov Chain (MCMC) algorithm) was used for the model optimisation.

The delay-difference model directly estimated the prawn recruitment for each year from 1989 to 2006 and then fitted the spawning-recruitment curve (Appendix 5.5.2). In contrast the alternative size and age structured model performs these two steps at once, estimating spawning recruitment parameters as well as estimating variations in recruitment (i.e. recruitment error). This stochastic model, however, was unable to estimate a realistic range of steepness of the spawning-recruitment curve and experienced difficulty converging due to the large number of parameters (44) estimated through the MCMC algorithm. A deterministic (no recruitment variation) version of the model was used to reduce the number of parameters and fixed steepness was applied for the spawning-recruitment curve. Fixed steepness of 0.5 was chosen as a base value as the previous delay-difference model estimated steepness of the Beverton-Holt S-R curve as 0.47 and O'Neill and Turnbull (2006) estimated steepness for tiger prawn as 0.58. Additionally, Myers et al. (1999) estimated steepness of the S-R curve for wide range of fish families and found that the steepness tended to be high with an average steepness of 0.69. A steepness of 0.7 was therefore used as a sensitivity analysis.

The results from both the deterministic and stochastic models are presented and form component 2 of the consultancy: produce a stock assessment for the Torres Strait Endeavour Prawn Fishery (*Metapenaeus endeavouri*). The result of this stock assessment and the trawl survey data (Chapter 3), were integrated into the spatial simulation model (TSPFsim: Chapter 4) to quantify the impacts of various harvest strategies with reference to biologically and economically sustainable management objectives.

5.2 Method

5.2.1 Data

The change in fishing power for the years 1980 to 2005 was estimated using data from a variety of sources (Table 5.1). The unloading data provided the endeavour prawn harvest for the years 1978-88 and the logbook data for the years 1980-88 provided the daily vessel catch rate (CPUE) data. Note that this data was variable a subset of the total fishing effort. Prior to 1989 only Northern Prawn Fishery vessels that were a minor component of the fleet were required to fill in logbooks. In addition some of the Queensland / Torres Strait endorsed vessels voluntarily filled in logbooks. We assumed that the logbook data for this period was an unbiased subset of the total fishing effort. The compulsory logbook data post 1988, provided; the total endeavour prawn catch, total fishing effort and CPUE data.

Table 5.1 Summary of data used in the endeavour prawn stock assessment.

Data	*Coverage*	*Use*
Unloading data	1978 - 1988	Total harvest by species category (tiger, endeavour, king)
NPF compulsory logbook	1980 - 1988	Relative index of abundance (CPUE), whole fleet
Voluntary logbook	1980 - 1988	Relative index of abundance (CPUE), subset of fleet
AFMA compulsory logbook	1989 - 2007	Relative index of abundance (CPUE) and total harvest
Gear survey data (O'Neill et al. 2005)	1982 - 2005	Fishing power schedule
AFMA logbook gear sheets	2005	Fishing power schedule

The endeavour prawn harvest during the years 1991-2001 was significantly higher than prior to 1991 (Figure 5.1). Possible explanations for this trend are:

- The introduction of the East of Warrior Closure in 1991 which appears to have increased the yield of endeavour prawns by protecting the smaller sized prawns and limiting growth overfishing (Turnbull and Watson 1991).
- Increased targeting of endeavour prawns during the 1990’s due to a higher value for the product and the establishment of export markets for endeavour prawn.
- Possible discarding of endeavour prawn catch during the early 1980’s due to limited storage space and the lower value of endeavour prawns at that time (per. com. Industry representatives).

During this decade the size of the *active* fleet has dropped from 74 to 37 vessels and the observed fishing effort from an average of 10264 days during 1997-2001 to less than 4000 vessel nights in 2008. This decrease in the effort resulted in the annual harvest dropping from the average of 1,900 t per annum during the 1997-2001 to 907t in 2008. The largest decrease has been in the endeavour prawns harvest (Figure 5.1) due to fishers targeting the more valuable tiger prawns. The decrease in fishing effort is due to the combined effect of the reduced allocation to Australian vessels, a down turn in the economics of prawn trawling (e.g. declining prawn market price and increasing fuel costs) and a decrease in the infrastructure (supply barges and air services) that support this remote fishery.

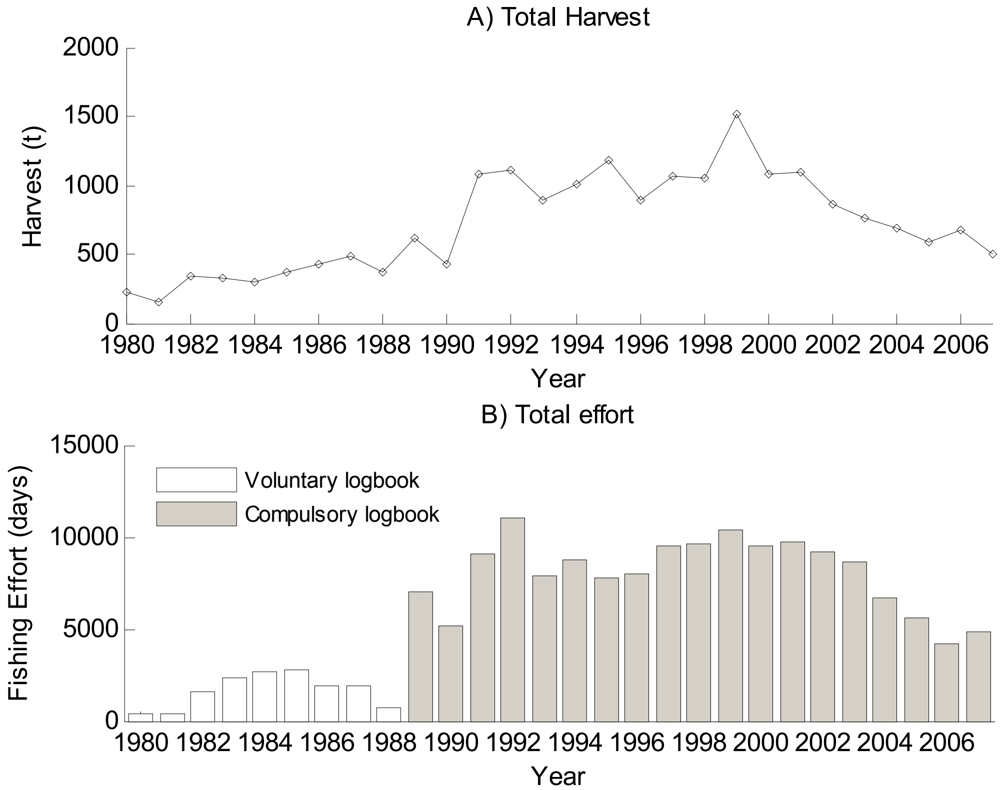


Figure 5.1 The Torres Strait endeavour prawn annual harvest (Top) and effort (bottom) from 1980 to 2007. All records reporting endeavour prawn catch (including partial night fishing) were included (a small number of records that only caught tiger prawns or king prawns were excluded). Note that 1980-88 harvest data is from unloading records.

5.2.2 Standardisation of CPUE

The standardisation model for the endeavour prawn stock was similar to but slightly different from that for the tiger prawn stock (see O'Neill and Turnbull (2006) for details). The main difference was that we included the additional effect of net size in the analysis as suggested by Dr David Die (Die 2003).

The final endeavour model used a general (log) linear model that considered fishing year (same as calendar year), month, five different spatial areas, lunar phase cycles, tiger and king prawn catches, vessel number/ID (record_number), and the vessel gear characteristics as explanatory variables:

$$\log(C_{vayml}) = \beta_0 + \boldsymbol{\beta}_1\mathbf{x}_1 + \boldsymbol{\beta}_2\mathbf{x}_2 + \boldsymbol{\beta}_3\mathbf{x}_3 + \varepsilon \qquad \text{(Eq. 5.1)}$$

where C_{vayml} was the daily catch of the *v*th vessel in area *a,* during fishing year *y, month m* and lunar cycle *l*, β_0 was a scalar intercept and β_1, β_2 and β_3 were vector parameters to be estimated. β_1 was the parameter vector for abundance quantities, in this case interaction effects of fishing area, fishing years and months; β_2 was the parameter vector for catchability quantities, in this case vessel ID and HP and gear characteristics (navigation equipment, bycatch reduction devices, trawl net configurations and net size); vector β_3 was responsible for lunar phase, other prawn catches and duration of fishing per night (full night vs part night fishing); x_1 x_2 and x_3 were the corresponding data matrices; and ε was the error term (NID($0,\sigma^2$)). As recommended by the David Die's 2003 independent review (Die 2003, pp 8-9), five fishing areas (North, EWC, South, Bramble Cay, PNG) were included.

The data retrieval was specified for each vessel and each day where the endeavour prawn catch was greater than zero. As many of these records, in particular those with a low endeavour prawn catch, may have been associated with targeting the other species, tiger and king prawn catch were included as covariates.

It is obvious that the duration of fishing will impact on the level of daily catch. A simple adjustment factor for a full night or part night fishing was therefore included in order to standardise fishing effort to be E=1 (full night).

Lunar cycle is known to affect catches of penaeid prawns including eastern king prawns, tiger prawns, and endeavour prawns (Courtney et al. 1996; O'Neill and Leigh 2006; O'Neill and Turnbull 2006), therefore was included in the analysis in terms of two sine waves ranging between 0 (new moon) and 1 (full moon) (Courtney et al. 2002) (Figure 5.2).

(Eq. 5.1 was fitted to the subset of endeavour prawn logbook data that matched with vessel and gear information. The annual fishing power estimated from (Eq. 5.1) was then offset against all logbook data (including vessels with no gear information) and standardised catch rates were calculated as follows:

$$\log(C_{vayml}) = \beta_0 + \boldsymbol{\beta}_1\mathbf{x}_1 + offset(\log fp) + \boldsymbol{\beta}_3\mathbf{x}_3 + \varepsilon \qquad \text{(Eq. 5.2)}$$

The difference between (Eq. 5.1) and (Eq. 5.2) is the capture system variable β_2 that was replaced by annual increases in fishing power as an offset. This allowed all vessels that operated in the fishery to be standardised, rather than only using a subset of logbook records that could be matched with vessel and gear information. This assumes the vessel characteristics from a subset of records were representative of the whole of the Torres Strait prawn fleet. Due to the limited information on changes in vessels and gear configurations post 2005 the fishing power for 2006 and 2007 was assumed to be the same as for 2005.

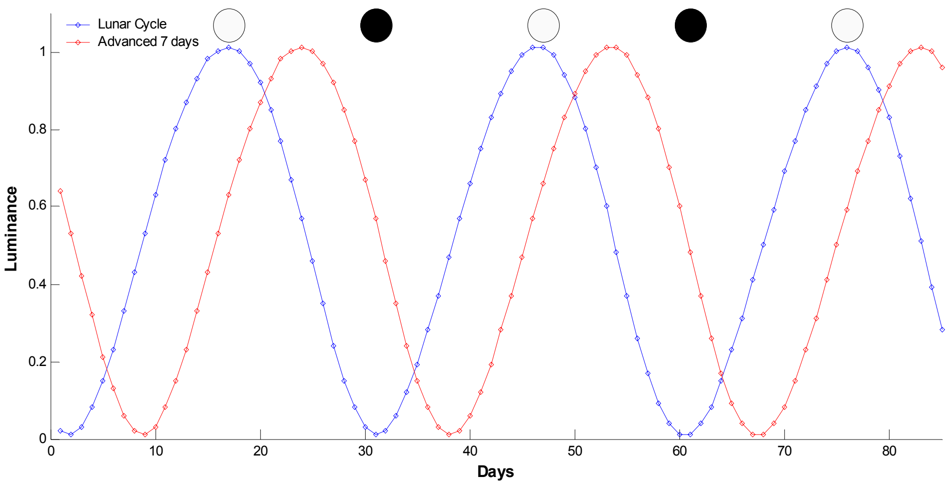


Figure 5.2 The lunar phase cycle (blue line) illustrated over 85 days. The red line illustrates the lunar cycle advanced by seven days. Together these lines were used to model prawn catches allowing for new moon, waxing moon, full moon and waning moon effects [Source: (O'Neill and Turnbull (2006)].

5.2.3 Stock assessment

Size and age structured model

The model assumes the stock was at an unfished equilibrium prior to 1967. The equations (Eq. 5.3) – (Eq. 5.5) were run for ten years to build virgin stock size to its equilibrium (Table 5.2). The virgin biomass (B_0) and initial spawning stock size (E_0) were calculated as the median of the monthly biomass and the total monthly spawning index produced in the last year of the build up period, respectively (Eq. 5.5 and (Eq. 5.6). The annual recruitment was calculated from the previous year's spawning biomass using the Beverton-Holt (BH) stock recruitment relationship shown in (Eq. 5.9). The spawning-recruitment parameters α and β defined by Francis (1992) was used (Eq. 5.7 and (Eq. 5.8). The spawning stock numbers in the previous year, $E_{y\text{-}1}$ was calculated as the sum of the products of the number of mature females (Section 4.5.2) and the fecundity index across the size and effective spawning months (Eq. 5.10). Although endeavour prawns spawn year round, the model assumed the winter-spring spawners (July – Dec) are the major contributor to the recruitment for next year. This was because:

- Seasonal trends of the historical catch, effort and catch rate data (O'Neill and Turnbull 2006, p15) indicated high winter-spring spawners were the major contributor of the new recruits to the fishery;
- Blue endeavour prawns in the eastern Gulf of Carpentaria – tropical waters similar to Torres Strait – spawn in the later part of the year (i.e. between September and December) (Coles and Lee Long 1985);
- The model assumes the age of new recruits as 6 months. This means there is about a 6 month time lag between the spawning season and recruitment events. As the annual recruitment was calculated from the previous year's spawning biomass (January – December in previous year), it is logical to consider spawners only from the later part of the year.

Once the initial population at each sex, age and size class was established (Eq. 5.11), the dynamic of the population followed (Eq. 5.13). Monthly recruitment was calculated by the product of the within-fishing-year recruitment pattern (Eq. 5.12) and the total number of prawns recruiting in the fishing year (R_y) (Dichmont et al. 1999). The mortality due to fishing was calculated in terms of harvest rate U, which was defined in (Eq. 5.14). Note that interpolated harvest estimates were applied prior to 1978 when no harvest data were available (Figure 5.3).

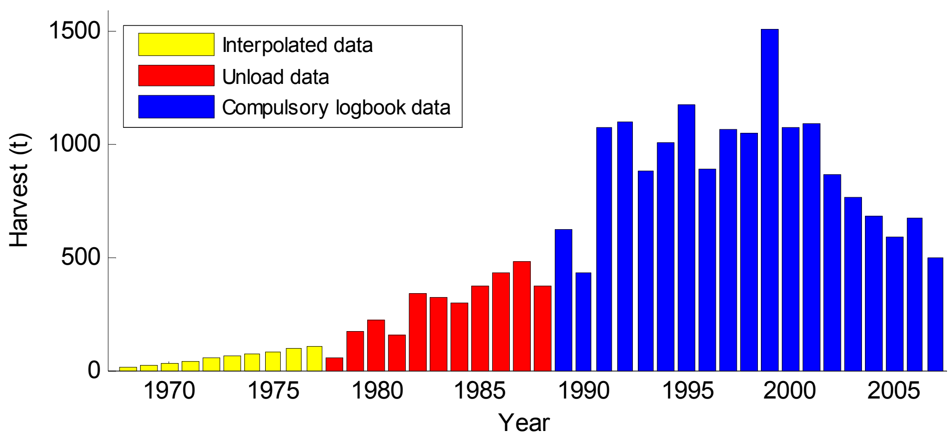


Figure 5.3 Time series of total endeavour prawn harvest applied in the size and age structured model. The model assumes the stock was unfished in the late 1960s. The harvest preceding 1978 was linearly interpolated between 0 (1967) and the average harvest in 1978 and 1979.

Table 5.2 The equations defining the age-size structured model for Torres Strait tiger prawns.

ID	Equations	
	Virgin population built up period	
(Eq. 5.3)	$N^b_{l,a,s}(t^b)=\begin{cases}0.5R_0\Phi_m P_{l,a,=A_{\min},s} \\ P_{l,l'}N^b_{l',a-1,s}(t^b-1)e^{-M}\end{cases}$	for $a=A_{\min}$ for $a=A_{\min+1},\ldots,A_{\max}$
(Eq. 5.4)	$bio^b(t')=\sum_{s=1}^{2}\sum_{l=L_{\min}}^{L_{\max}}\sum_{a=A_{\min}}^{A_{\max}}N^b_{l,a}(t')W_{l,s}$	for $t'=1,\ldots,bup$
(Eq. 5.5)	$B_0=median\left(bio^b(t^b)\right)$	for $t^b=bup-11,\ldots,bup$
	Spawner-recruitment relationship	
(Eq. 5.6)	$E_0=\sum_{m=7}^{12}\sum_{t^b=bup-5}^{bup}\sum_{l=L_{\min}}^{L_{\max}}\sum_{a=A_{\min}}^{A_{\max}}N^b_{l,a,s=1}(t^b)mat_l fec_l$	
(Eq. 5.7)	$\alpha=\dfrac{E_0(1-steep)}{4steepR_0}$	
(Eq. 5.8)	$\beta=\dfrac{5steep-1}{4steepR_0}$	
(Eq. 5.9)	$R_y=\dfrac{E_{y-1}}{\alpha+\beta E_{y-1}}e^{e_y}$	for $y=1,\ldots,41$
(Eq. 5.10)	$E_y=\sum_{m=7}^{12}\sum_{r=1}^{7}\sum_{l=L_{\min}}^{L_{\max}}\sum_{a=A_{\min}}^{A_{\max}}N_{l,a,r,sp,s=1}mat_{l,sp,m}fec_{l,sp}$	
	Initial population (t = 1, y =1)	
(Eq. 5.11)	$N_{l,a,s}(1)=\begin{cases}0.5R_y\Phi_m P_{l,a,=A_{\min},s} \\ P_{l,l'}N^b_{l',a-1,s}(t^b)e^{-M}\end{cases}$	for $a=A_{\min}$ for $a=A_{\min+1},\ldots,A_{\max}$; $t^b=bup$
(Eq. 5.12)	$\Phi_m=\dfrac{1}{2\pi I_0(\kappa)}e^{\kappa\cos(m-\mu)}$	
	Population dynamics (t >1)	
(Eq. 5.13)	$N_{l,a,s}(t)=\begin{cases}0.5R_y P_{l,a,=A_{\min},s}\Phi_m \\ P_{l,l'}N_{l',a-1,s}(t-1)e^{-M}(1-U(t-1))\end{cases}$	for $a=A_{\min}$ for $a=A_{\min+1},\ldots,A_{\max}$
(Eq. 5.14)	$U(t)=\dfrac{tctch(t)}{bio(t)}$	
(Eq. 5.15)	$bio(t)=\sum_{s=1}^{2}\sum_{l=L_{\min}}^{L_{\max}}\sum_{a=A_{\min}}^{A_{\max}}N_{l,a}(t)W_{l,s}$	for $t=1,\ldots,T$
	Predicted catch rate	
(Eq. 5.16)	$\hat{cpue}(t)=q_k bio(t)$	$\begin{cases}\text{for } k=1,\ 158\le t\le 261\ (1980\le y\le 1988) \\ \text{for } k=1,\ t\ge 267\ (y\ge 1989)\end{cases}$
(Eq. 5.17)	$q_k=\prod_t^n\left(\dfrac{cpue(t)}{bio(t)}\right)^{\frac{1}{n}}$	$\begin{cases}\text{for } k=1,\ t=158,\ldots,261\ (n=87) \\ \text{for } k=2,\ t=267,\ldots,479\ (n=162)\end{cases}$

The exploitable biomass was calculated by (Eq. 5.15). Note that all prawns larger than the minimum size class considered in the model (i.e. 15mm) were equally vulnerable to fishing (no selectivity). The growth of prawns older than the recruitment age of six months was determined by a size-transition matrix ($P_{l,l'}$), which was calculated from normal probability density function for a prawn in size class *l'* growing into size *l* over one month period (normpdf(*l'*,*l*,std)) (Punt et al. 1997; Sadovy et al. 2007). The expected monthly growth of each size class was based on the von-Bertalanffy growth curve estimated from the tag-recapture data collected in 1988 and 1990. The standard deviation of the growth increment was set to 1 for both sexes. Once the time series of prawn biomass and number of prawns were calculated, monthly catch rates were predicted using (Eq. 5.16). The catchability coefficient was calculated as the geometric mean of the ratios given in (Eq. 5.17). As the CPUE data does not appear to be a consistent index of abundance over the whole time series different catchability coefficients were calculated for the two data periods: q_1 for pre 1989 and q_2 for the compulsory logbook period (> 1988).

Table 5.3 Notation used to describe the size and age structured model.

Symbol	*Description*
t^b	Monthly time step for built-up period (*bup*=120)
t	Monthly time step (T=492)
a	Age class in months (A_{min},=6; A_{max} = 24)
l, l'	Size class in months (L_{min},=15; L_{max} =50)
s	Sex indices (1 = female, 2 = male)
y	Annual time step (1 = 1967, 41 = 2007)
k	Indices for different logbook period. [1 = the voluntary logbook period (1980-1988), 2 = the compulsory logbook period (1989-2007)]
M	Instantaneous natural mortality 0.2 month^{-1}: Watson and Turnbull (1993)
bio^b,	Monthly biomass (kg) during the built-up period
bio	Monthly biomass(kg)
$N^b_{l,a,s}$	the number of prawns of age class a in size class l during the model built-up period
$N_{l,a,s}$	the number of prawns of age class a in size class l
$P_{l,a=Amin}$	the fraction of prawns in length class l for the first age class (A_{min})
Φ_m	Monthly proportion of annual recruits in month m
$P_{l,l'}$	the fraction of fish in size class l' that grow into size class l in one month
$W_{l,s}$	Length-weight relationships for each sex
fec_l	Fecundity at length l
mat_l	Proportion mature at length l
$tctch$	Monthly catch (kg)
$steep$	Steepness of the Beverton-Holt spawner recruitment curve (0.5 or 0.7)
B_0	Virgin biomass (kg)
E_0	Virgin spawners
R_0	Virgin recruitment
$\kappa, \overline{r}$	Parameters in the von Mises distribution
$cpue$	Monthly standardized CPUE (kg/day) from 1980 to 2006
$c\hat{pu}e$	Predicted monthly CPUE
q_k	Catchability during the period k
R_y	Annual recruitment in year y
E_y	Annual spawners in year y
e_y	Annual recruitment error in year y
α , β	The BH spawner-recruitment parameters
U	Harvest rate

Table 5.4 Endeavour prawn biological parameters used in the size and age structured model

Biological parameters	*Estimates*		*References/data sources*
Von Bertalanffy Growth	L_∞	K (week^{-1})	
Female	42	0.174	Estimated from the tag-recapture data collected in 88 and 90 (Watson and Turnbull 1993)
Male	32	0.162	
Carapace length to weight	*W=aCL^b*		
a_{male}, b_{male}	0.00162, 2.835		(Turnbull et al. 2005)
a_{female}, b_{female}	0.00293, 2.628		(Turnbull et al. 2005)
Fecundity index	*Eggs = aCL - b*		Dall, Hill *et al.* (1990)
a,b	30998, 634000		

Model fitting

The parameters estimated from the model were:

- Virgin recruitment (R_0)
- The estimated mode of the von Mises distribution, $\bar{r}$
- The concentration parameter in the von Mises distribution, κ
- The recruitment error (e_y) estimates from 1980 to 2006.

Note that only first three parameters were estimated in the deterministic model.

The model was fitted to the standardised monthly catch rates from 1980 to 2006 by minimizing differences between predicted and standardised CPUE in terms of negative loglikelihood:

$$-\log \ell = \frac{n}{2}\left(\log(2\pi) + 2\log\left(sqrt\left(\frac{1}{n}\sum_t\left(\log(cpue(t)) - \log(c\hat{p}ue(t))\right)^2\right)\right) + 1\right)$$

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:

$$\lambda_1 = \begin{cases} 0 & if\left(tctch(t) \le bio(t)\right) \\ \sum\left(tctch(t) - bio(t)\right)^2 & otherwise \end{cases}.$$

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 is the minimum annual harvest fraction, CN_y is the accumulated number of prawns caught across the fishing years, and the value 1000 was used to ensure adequate weighting in the optimisation. Three values of 0.2, 0.1, and 0.05 for h were tested as informative priors. While the penalty functions examined resulted in no effect on parameter estimates for the stochastic model, the deterministic model tended to converge to an extremely large, unproductive stock (that have been exploited only slightly) when small value of h was imposed on the second penalty function λ_2. As this was not biologically plausible for a short lived, highly fecund species, the results of the deterministic model was based on the optimisation with a penalty of the minimum annual harvest fraction at 0.2.

A quasi-Bayesian approach was used for parameter estimation. As we know little about the distributions of the free parameters, we used uniform (non-informative) priors for each parameter. A Markov chain Monte Carlo (MCMC) algorithm was used to obtain a 'posterior' by updating these priors with the likelihood function of the model, and the range of each prior was carefully chosen so that the chain of parameters sampled did not hit its upper or lower bound. The model convergence was assessed by the Geweke statistic (Geweke 1992) and the Gelman-Rubin statistic (Gelman *et al.* 2004). The Geweke statistic tests for equal mean for *early* part (the first 10 %) of the chain and *late* part (the second half) of the chain in terms of two-sample Z statistic. If test statistic was significantly different from $Z \sim N(0,1)$ at α =0.05, we concluded parameter estimates had not converged. The Gelman-Rubin statistic (R) was estimated as the ratio of the within-sequence variance to the between-sequence variance. The idea of this statistics is that convergence is achieved when this ratio is very close to one (<1.05 is an often used heuristic). It also estimates an approximate "effective number of independent samples" (*Neff*) taken from each posterior distribution. A number of different parameter starting points were tested, with all converging into the same optimum parameter space.

The main assumptions of the model were:

- Standardised catch rate is proportional to abundance.
- Stock was at unfished stage (equilibrium) in 1967.
- Constant natural mortality and prawn catchability (for each data period).
- Average prawn growth, weight-length relationship, fecundity at size and seasonal maturity at size.
- Age at first recruitment to the fishery is 6 months. All post-recruitment size classes were equally vulnerable to fishing.
- Accurate reporting of the commercial catches.

Equilibrium reference point

The calculation of equilibrium management reference points was based on optimising the dynamics of the model through fishing effort. The prawn population dynamics were simulated to unfished stage using 1000 combinations of key parameters estimated through MCMC algorithm. We then applied monthly instantaneous fishing mortality which was calculated by $q_2 E \varphi_m$, where q_2 was the catchability coefficient during the compulsory logbook period derived from the stock assessment model, E was the total annual effort being optimised, and φ_m was the historical monthly fishing pattern calculated from the logbook records between 2000 and 2007. The recruitment dynamics were calculated according to the respective spawner recruitment relationship. The model was run over ten years with (constant) natural and fishing mortality until the population dynamics stabilised (i.e. reaching equilibrium stage). The product from the 10 years of fishing was the equilibrium catch measured in kilograms. The fishing effort E was optimised to maximise the yield (MSY).

5.3 Results

5.3.1 CPUE Standardisation

Figure 5.4 shows the average trend for each of the vessel and gear characteristics weighted by fishing effort. The average net size was relatively stable at around 20 fathoms until 2002 when a 10 percent reduction in the maximum size (combined headline and groundline length of all nets including the try net) was legislated. Industry had suggested this reduction as means of reducing fishing effort without reducing their allocated days of fishing access attached to each licence. In 2004 the 10 percent reduction was removed as it was creating enforcement problems when vessels were fishing both the Queensland east coast and Torres Strait. As result of these changes post 2003 there was a mix of reduced and full size nets operating in the fleet as many operators continued to use the cut down nets until they needed replacing. The trends of other configurations are described in (O'Neill and Turnbull 2006, p23).

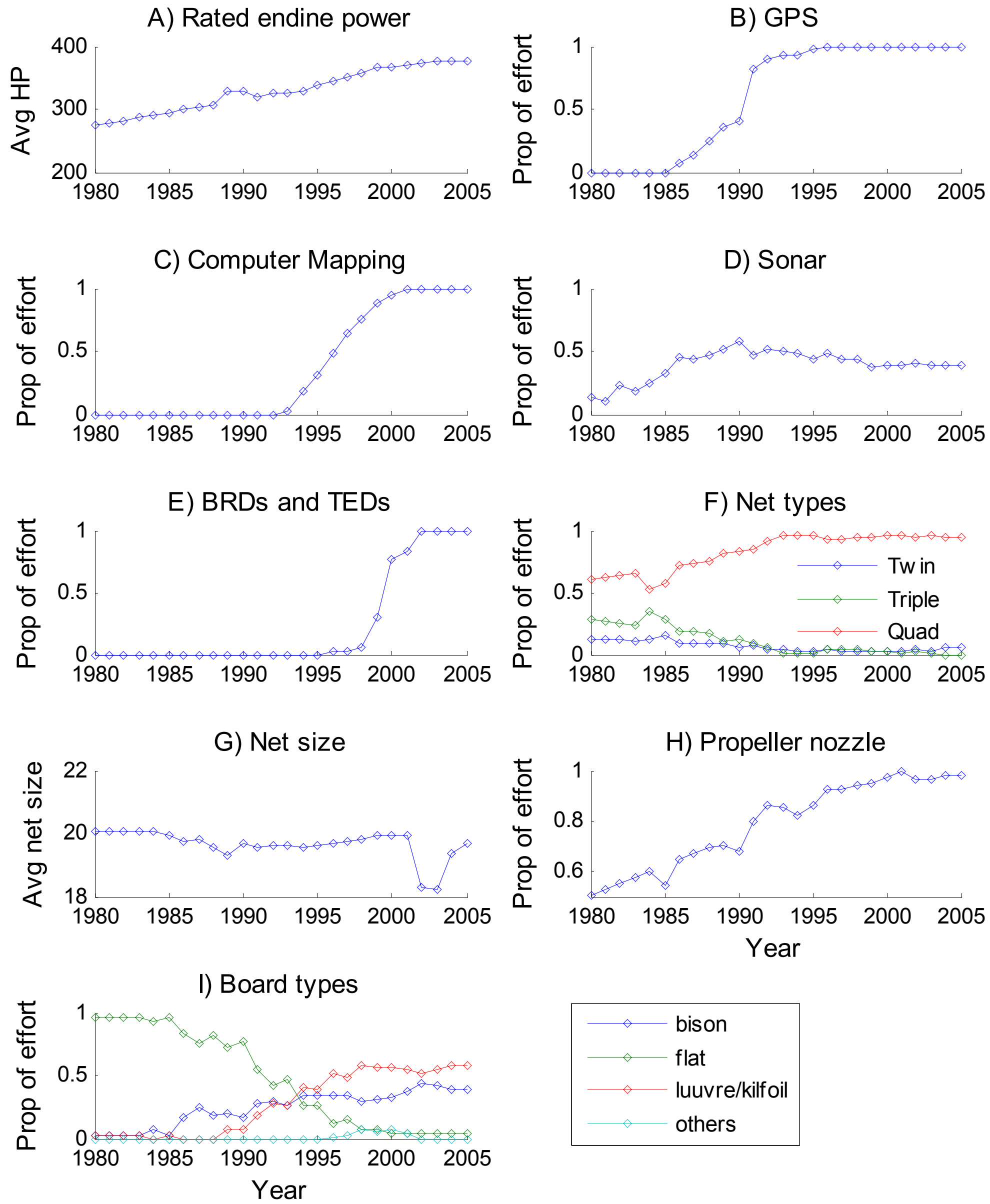


Figure 5.4 Vessel and gear characteristics considered to estimate fishing power. Subplots A) and G) were weighted according to the number of days fished by each vessel in each fishing year. The other plots represented the percent of fishing effort in each fishing year with that particular device.

Parameter estimates for the various fishing gear and technologies were shown in Table 5.5. Although all gear parameters were statistically significant, GPS, Computer mapping and sonar had negative effects. This indicated that endeavour prawn catch rate tended to be lower when these technologies was adopted in the fishery. This is unexpected but possibly explained by the fact that the adoption of these technologies enabled fishers to more effectively target tiger prawns therefore catching less endeavour prawns. As these negative effects are probably a result of a change in the targeting behaviour of the fleet rather than reflecting a true change in fishing power, the data was re-fitted to a "reduced" model without GPS, computer mapping and sonar (Table 5.5) and the fishing power trend of the two models was compared. Bycatch reduction devices (BRD/TED) can result in some loss of prawn catch (Courtney et al. 2007). Therefore it was considered realistic to include the negative effect of bycatch reduction devices in the model.

The comparison of parameter estimates between the full model and the reduced model indicated that the removal of the three negative effects (GPS, Computer mapping and sonar) had a minimum impact on the other gear parameters and the overall goodness-of-fit to the data. There was little difference in adjusted R^2 between two models, indicating that the proportion of variance accounted for by the reduced model (0.399) was as good as that by the full model (0.4). This was not surprising considering the low correlations between removed factors and other gear parameters (Table 5.6) and only 3 degrees of freedom removed from the model. In addition, correlations between removed factors and the abundance term (year) were also low (ρ < -0.15 for GPS, ρ <-0.11 for computer mapping, ρ <-0.05 for sonar). This indicated that confounding of fishing power and stock abundance was not a driving cause of the negative parameter estimates. Parameter estimates for lunar phase show catch rates were marginally higher just after the New Moon and relatively low around the Full Moon (Figure 5.5).

Table 5.5 The summary of analysis, parameter estimates β_2 and standard errors in brackets for the full model and for the reduced model. Note that parameter estimates for record_number (vessel ID) are not shown due to the large number of parameters (112 vessels). n.s. indicates a parameter that was not significant.

Model	*Full model*	*Reduced model*
Sums of Squares β_1 (df)	8382 (329)	8555 (329)
Sums of Squares β_2 (df)	2985 (123)	2955 (120)
Sums of Squares β_3 (df)	1694 (4)	1692 (4)
Residual SS	27492	27522
Residual degree of Freedom	97410	97413
Adjusted R^2	0.400	0.399
Parameter Estimates β_2 (log)		
Rated engine power (HP)	0.505 (0.029)	0.513 (0.029)
GPS	-0.078 (0.013)	-
Computer mapping	-0.053 (0.008)	-
Sonar	-0.06 (0.012)	-
BRD/TED	-0.029 (0.009)	-0.025 (0.009)
Net - twin	0	0
Net - triple	0.162 (0.036)	0.177 (0.036)
Net - quad	0.141 (0.028)	0.13 (0.028)
Boards - bison	0	0
Boards - flat	-0.045 (0.009)	-0.047 (0.009)
Boards - flouvre/kilfoil	0.023 (0.01)	ns
Boards - other less used types	-0.172 (0.023)	-0.176 (0.023)
Propeller nozzle	0.046 (0.012)	0.039 (0.012)
Net size	0.279 (0.081)	0.312 (0.081)

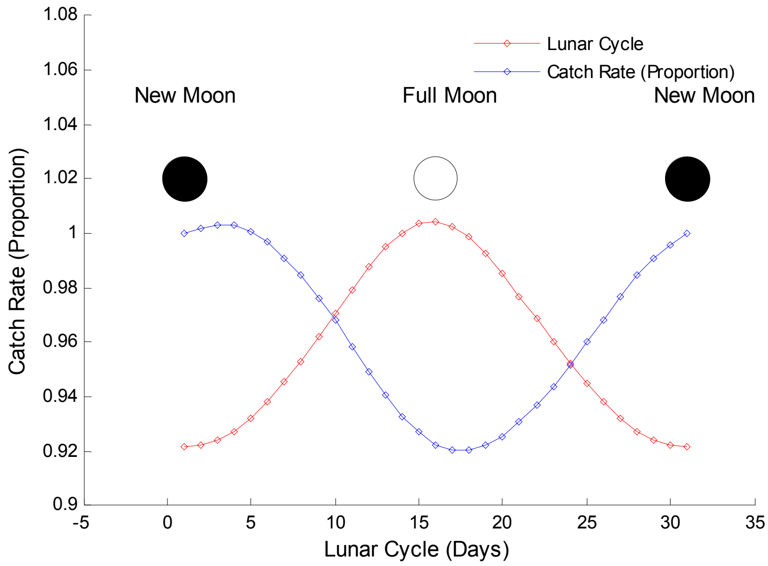


Figure 5.5 The estimated average proportional change in endeavour prawn catch rate with lunar cycle (based on the reduced model). The predictions show higher catch rates associate with just after the New Moon.

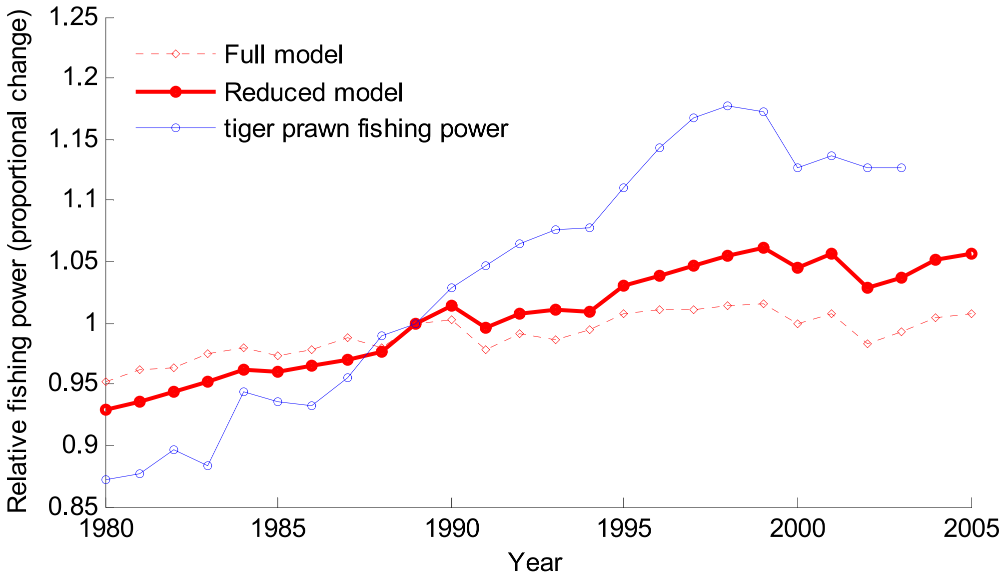


Figure 5.6 Fishing power trends for endeavour prawns (red line) estimated from “Full” and “Reduced” model. Blue line represents fishing power trends for tiger prawns estimated by (O'Neill and Turnbull 2006).

The increase in fishing power for endeavour prawns was less than for tiger prawns. While relatively consistent fishing power increase was observed from the reduced model between 1980 and 2000, approximately a 3% reduction in fishing power was detected in 2002. This was associated with the 10% decrease in net size that occurred in 2002. Overall, fishing power has increased by 13% (the reduced model) and by 6% (the full mode) since 1980 (Figure 5.6).

Table 5.6 The endeavour prawn β_2 parameter correlations (obtained from the full model).

Parameters	*engine (HP)*	*GPS*	*Comp map*	*Sonar*	*BRD/ TED*	*Net triple*	*Net quad*	*Boards flat*	*Boards flouvre/ kilfoil*	*Boards other*	*Propeller nozzle*	*Net size*
engine (HP)	1											
GPS	-0.048	1										
Comp map	0.021	0.045	1									
Sonar	0.075	-0.093	-0.058	1								
BRD/TED	-0.033	-0.028	0.052	0.049	1							
Net - triple	-0.109	0.057	-0.005	0.020	-0.035	1						
Net - quad	-0.072	0.021	-0.027	-0.059	0.010	0.798	1					
Boards - flat	0.040	0.032	0.060	-0.145	0.014	-0.143	-0.001	1				
Boards - louvre/kilfoil	-0.047	-0.102	-0.039	-0.179	-0.006	-0.160	-0.042	0.482	1			
Boards - other	0.061	-0.010	-0.026	0.011	0.023	-0.013	-0.010	0.011	0.025	1		
Propeller nozzle	-0.085	-0.001	0.040	-0.140	0.033	0.024	-0.045	0.000	0.004	0.005	1	
Net size	-0.190	0.078	-0.009	0.000	-0.032	0.059	0.072	-0.042	-0.148	-0.106	-0.081	1

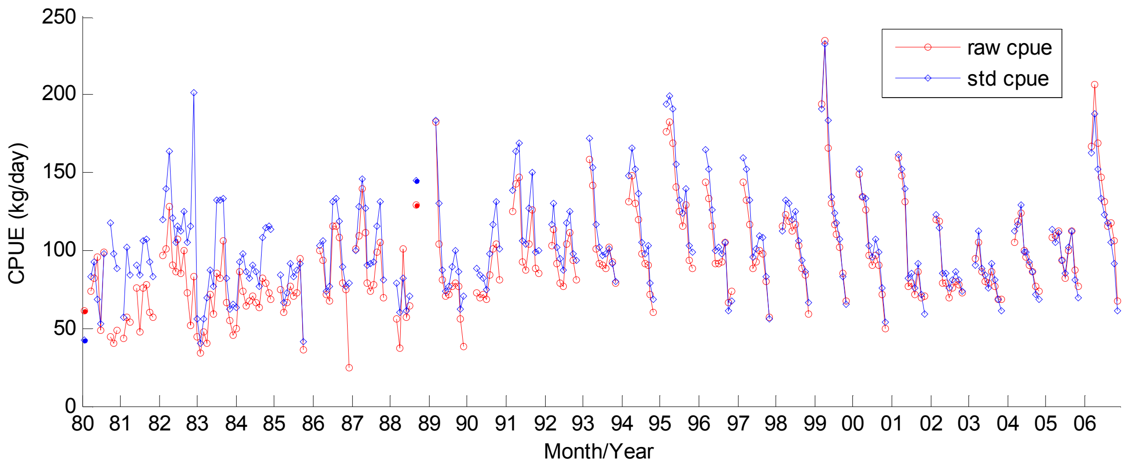


Figure 5.7 Comparison of endeavour prawn raw CPUE and standardised CPUE (estimated from the 'Reduced' model using average vessel operated in 2006 (recordNo 1128).

Figure 5.7 shows the comparison of time series of standardized and raw catch rate using annual fishing power increase as an offset value. The lack of a strong seasonal trend in the CPUE data prior to 1990 is possible a result of;

- The lower level of reporting as the logbook system was only compulsory for part of the fleet.
- Lower total fishing effort.
- The lack of a compulsory seasonal closure during December to March.

5.3.2 Stock assessment

Parameter convergence

The convergence statistics for the stochastic and deterministic models are shown in Table 5.7 and Table 5.8, respectively. Parameter convergence was detected with a relatively small number of model iterations (~ 80,000 samples) for the deterministic model (except for R_0 with steepness at 0.7), but was difficult to achieve with the stochastic model despite extended runs (~ 180,000).

Although the posterior distributions of parameters for the stochastic model appeared to be smooth (Figure 5.8 and Figure 5.9), the convergence diagnostics indicated the model was far from convergence. The Geweke statistic (Z) was significantly different from 0 for most of the parameters ($p < 0.01$), and the Gelman-Rubin statistics were larger than 1.05 for most of the parameters, both indicating parameters were not converged.

For the deterministic model with steepness fixed at 0.5, the Geweke statistic showed that there are no significant difference between mean from the early and the late part of the chain, indicating the model was likely to have converged. The Gelman-Rubin statistics, which were all less than 1.05, also indicated model convergence.

For the deterministic model with steepness fixed at 0.7, both convergence statistics indicated that parameters for the monthly recruitment pattern ($\bar{r}$ and κ) were likely to have converged, but the virgin recruitment (R_0) had not. The visual diagnostics showed that the posterior distribution of R_0 was bi-modal (Figure 5.10).

The log-scaled standardised residuals generally followed normal distribution thus the use of log-normal residuals being considered to be adequate for all models (Figure 5.17 - Figure 5.20; Appendix 5.5.1).

Table 5.7 Parameter convergence diagnostics for the stochastic model with different fixed steepness. Values within bracket indicated standard deviation of posterior distributions.

	Steepness = 0.5					*Steepness = 0.7*				
		Geweke statistics		Gelman-Rubin statistics			Geweke statistics		Gelman-Rubin statistics	
Parameter	estimates	z value	*p*	*R*	*Neff*	estimates	z value	*p*	*R*	*Neff*
R_0	1.92 (0.316)	17.483	<0.01	1.368	215	1.509 (0.316)	43.787	<0.01	1.3	245
$\bar{r}$	0.533 (0.09)	18.006	<0.01	1.038	1387	0.508 (0.09)	16.543	<0.01	1.032	1602
κ	2.945 (0.349)	-3.932	<0.01	1.083	676	3.108 (0.349)	-23.723	<0.01	1.123	482
e_{1967}	-0.095 (0.203)	-11.099	<0.01	1.582	166	-0.009 (0.203)	-41.955	<0.01	1.653	158
e_{1968}	-0.019 (0.208)	40.584	<0.01	1.638	159	-0.008 (0.208)	-69.068	<0.01	1.626	161
e_{1969}	-0.005 (0.215)	8.002	<0.01	1.616	162	-0.018 (0.215)	-15.033	<0.01	1.589	165
e_{1970}	-0.032 (0.219)	51.986	<0.01	1.763	147	-0.006 (0.219)	-35.391	<0.01	1.88	139
e_{1971}	0.031 (0.212)	14.479	<0.01	1.749	149	-0.047 (0.212)	32.802	<0.01	1.659	157
e_{1972}	0.003 (0.221)	3.8	<0.01	1.646	158	-0.024 (0.221)	2.257	0.024	1.649	158
e_{1973}	-0.018 (0.229)	-42.978	<0.01	1.65	158	0.009 (0.229)	16.162	<0.01	1.783	146
e_{1974}	0.046 (0.198)	-56.334	<0.01	1.625	161	0.005 (0.198)	-47.318	<0.01	1.474	185
e_{1975}	0.041 (0.218)	-78.645	<0.01	1.657	157	0.012 (0.218)	-40.224	<0.01	1.749	149
e_{1976}	-0.007 (0.181)	9.429	<0.01	1.448	191	0.005 (0.181)	-22.567	<0.01	1.7	153
e_{1977}	-0.008 (0.184)	47.808	<0.01	1.401	204	0.052 (0.184)	-4.925	<0.01	1.552	171
e_{1978}	-0.086 (0.196)	-3.927	<0.01	1.586	166	-0.053 (0.196)	59.345	<0.01	1.644	159
e_{1979}	-0.318 (0.185)	103.209	<0.01	1.599	164	-0.29 (0.185)	-20.958	<0.01	1.465	187
e_{1980}	0.043 (0.127)	11.923	<0.01	1.394	206	0.01 (0.127)	73.503	<0.01	1.337	227
e_{1981}	0.144 (0.117)	19.185	<0.01	1.262	268	0.153 (0.117)	0.768	0.442	1.32	235
e_{1982}	0.167 (0.114)	87.8	<0.01	1.355	219	0.194 (0.114)	49.584	<0.01	1.331	229
e_{1983}	-0.123 (0.105)	0.256	0.798	1.288	251	-0.089 (0.105)	64.5	<0.01	1.301	244
e_{1984}	0.123 (0.107)	61.613	<0.01	1.231	294	0.147 (0.107)	34.26	<0.01	1.303	243
e_{1985}	-0.198 (0.113)	22.402	<0.01	1.296	247	-0.193 (0.113)	13.545	<0.01	1.385	209
e_{1986}	0.271 (0.103)	46.712	<0.01	1.306	242	0.278 (0.103)	73.503	<0.01	1.281	256
e_{1987}	0.089 (0.109)	69.023	<0.01	1.313	238	0.143 (0.109)	-14.123	<0.01	1.331	230
e_{1988}	-0.213 (0.121)	38.57	<0.01	1.306	241	-0.162 (0.121)	76.232	<0.01	1.443	192
e_{1989}	-0.431 (0.139)	-24.174	<0.01	1.403	203	-0.378 (0.139)	-36.674	<0.01	1.288	252
e_{1990}	-0.079 (0.103)	-29.093	<0.01	1.254	275	-0.137 (0.103)	21.306	<0.01	1.262	268
e_{1991}	0.179 (0.088)	-1.284	0.199	1.264	267	0.184 (0.088)	-24.471	<0.01	1.246	281
e_{1992}	0.004 (0.09)	1.291	0.197	1.212	313	0.016 (0.09)	-15.091	<0.01	1.241	285
e_{1993}	0.008 (0.095)	-4.896	<0.01	1.268	265	0.023 (0.095)	28.201	<0.01	1.208	317
e_{1994}	0.117 (0.095)	-1.088	0.276	1.247	280	0.108 (0.095)	-29.713	<0.01	1.286	253
e_{1995}	0.278 (0.095)	-48.236	<0.01	1.298	246	0.304 (0.095)	9.915	<0.01	1.308	240
e_{1996}	-0.21 (0.108)	35.363	<0.01	1.307	241	-0.17 (0.108)	-11.736	<0.01	1.235	290
e_{1997}	0.068 (0.103)	8.543	<0.01	1.325	232	0.071 (0.103)	-31.087	<0.01	1.252	276
e_{1998}	0.121 (0.097)	-52.314	<0.01	1.275	260	0.109 (0.097)	26.999	<0.01	1.262	269
e_{1999}	0.291 (0.093)	12.332	<0.01	1.284	254	0.319 (0.093)	-41.43	<0.01	1.341	225
e_{2000}	-0.046 (0.102)	-24.755	<0.01	1.289	251	-0.008 (0.102)	2.645	<0.01	1.246	281
e_{2001}	-0.004 (0.1)	19.624	<0.01	1.335	228	0.007 (0.1)	-49.817	<0.01	1.292	249
e_{2002}	-0.091 (0.097)	-11.454	<0.01	1.257	272	-0.127 (0.097)	-19.523	<0.01	1.248	279
e_{2003}	-0.112 (0.1)	-24.226	<0.01	1.276	259	-0.159 (0.1)	2.16	0.031	1.228	297
e_{2004}	-0.054 (0.103)	-3.799	<0.01	1.313	238	-0.101 (0.103)	-9.498	<0.01	1.246	280
e_{2005}	-0.071 (0.101)	1.883	0.06	1.294	248	-0.117 (0.101)	0.041	0.967	1.235	290
e_{2006}	0.06 (0.105)	4.638	<0.01	1.28	257	0.033 (0.105)	28.586	<0.01	1.237	288
e_{2007}	-0.008 (0.192)	-21.514	<0.01	1.527	175	0.013 (0.192)	1.073	0.283	1.719	151

Table 5.8 Parameter convergence diagnostics for the deterministic model with different fixed steepness. Values within brackets indicated standard deviation of posterior distributions.

	Steepness = 0.5					*Steepness = 0.7*				
		Geweke statistics		Gelman-Rubin statistics			Geweke statistics		Gelman-Rubin statistics	
Parameter	Median	z value	*p*	*R*	*Neff*	Median	z value	*p*	*R*	*Neff*
R_0	2.406 (0.085)	1.754	0.079	1.036	1419	2.098 (0.085)	12.031	<0.01	1.096	593
$\bar{r}$	0.816 (0.144)	0.913	0.361	1.007	6522	0.801 (0.144)	1.028	0.304	1.01	4611
κ	2.519 (0.323)	0.584	0.559	1.006	7738	2.484 (0.323)	-0.161	0.872	1.009	5255

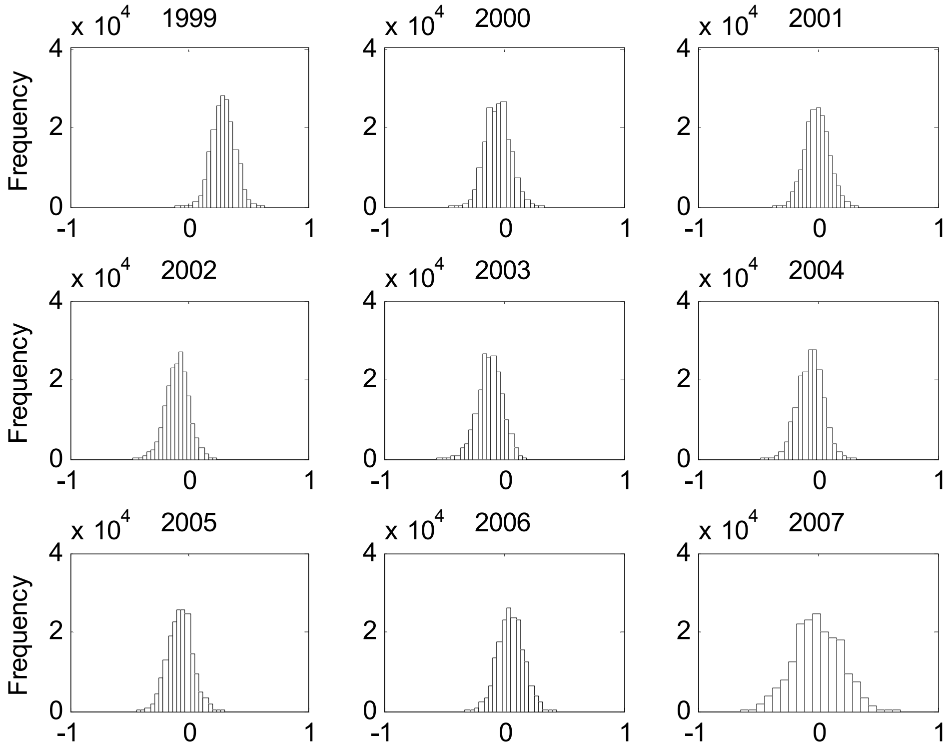


Figure 5.8 Posterior distributions for recruitment error between 1999 and 2007 (based on stochastic model with fixed steepness at 0.5).

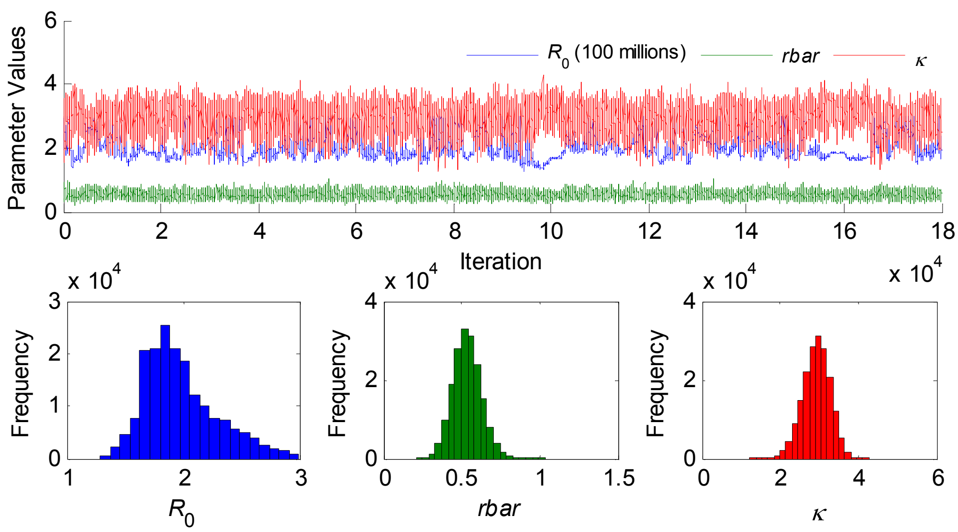


Figure 5.9 Chains of free parameters (top) and respective posterior distributions (bottom) after discarding the burn-in iterations. The results are based on the stochastic model with fixed steepness at 0.5.

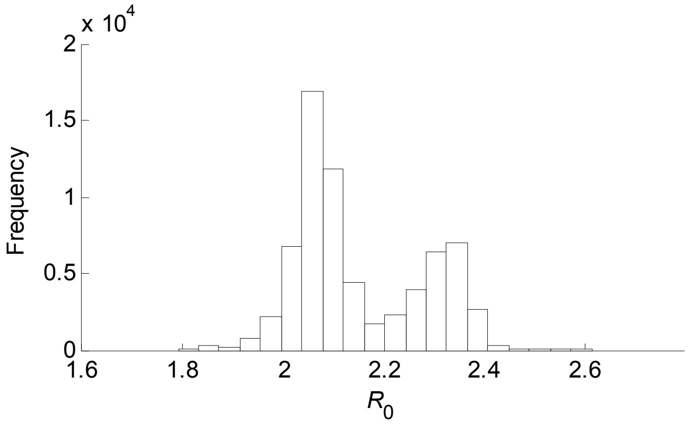


Figure 5.10 Posterior distributions of R_0 from the deterministic model with fixed steepness at 0.7.

Model outputs

A range of estimates of MSY and E_{MSY} were obtained from the stochastic and deterministic model with respective fixed steepness (Table 5.9). The lowest MSY estimate of 899 t was obtained from the stochastic model with steepness at 0.5; the highest estimate of 1368 t was obtained from the deterministic model with steepness fixed at 0.7. The stochastic model was more conservative than the deterministic model. Within each model, higher MSY estimates were obtained with higher steepness.

The estimates of maximum fishing effort (E_{MSY}) ranged between about 8200 and 12480 nights. The stochastic model has larger confidence intervals for MSY and E_{MSY} than the deterministic model due to a large number of free parameters which increased the variability in the spawner-recruitment relationship (Table 5.9).

Predicted biomass trends, expressed as a proportion of virgin exploitable biomass, was similar within each model but differed between models. For each model, the level of biomass was marginally higher for steepness at 0.7. The biomass level that can support MSY (B_{MSY}) was lower for steepness at 0.5 (43% of virgin biomass) than at 0.7 (38% of B_0). The uncertainties in the biomass trend were larger with stochastic model due to the variations in the spawner-recruitment relationships. For all models, the median biomass ratio was above B_{MSY} between 1989 and 2007. The biomass ratio in 2007 was well above B_{MSY}, ranging between 0.71 (stochastic, steepness 0.5) and 0.85 (deterministic, steepness 0.7).

Table 5.9 The spawner-recruitment parameters and equilibrium management parameters for stochastic and deterministic models with respective fixed steepness. Values within brackets indicated 90% confidence intervals.

Parameters	*Stochastic*		*Deterministic*	
steepness	0.5	0.7	0.5	0.7
α	0.10829 (0.10583:0.11025)	0.04669 (0.04565:0.04764)	0.10509 (0.10253:0.10776)	0.04502 (0.04384:0.04606)
β (10^{-7})	0.03896 (0.02863:0.04734)	0.05943 (0.04151:0.07286)	0.03118 (0.02897:0.03222)	0.04249 (0.03772:0.0446)
MSY (t)	899 (745:1208)	989 (817:1402)	1105 (1060:1184)	1368 (1287:1531)
E_{MSY}	8198 (6791:11012)	9022 (7450:12786)	10079 (9667:10800)	12476 (11733:13962)

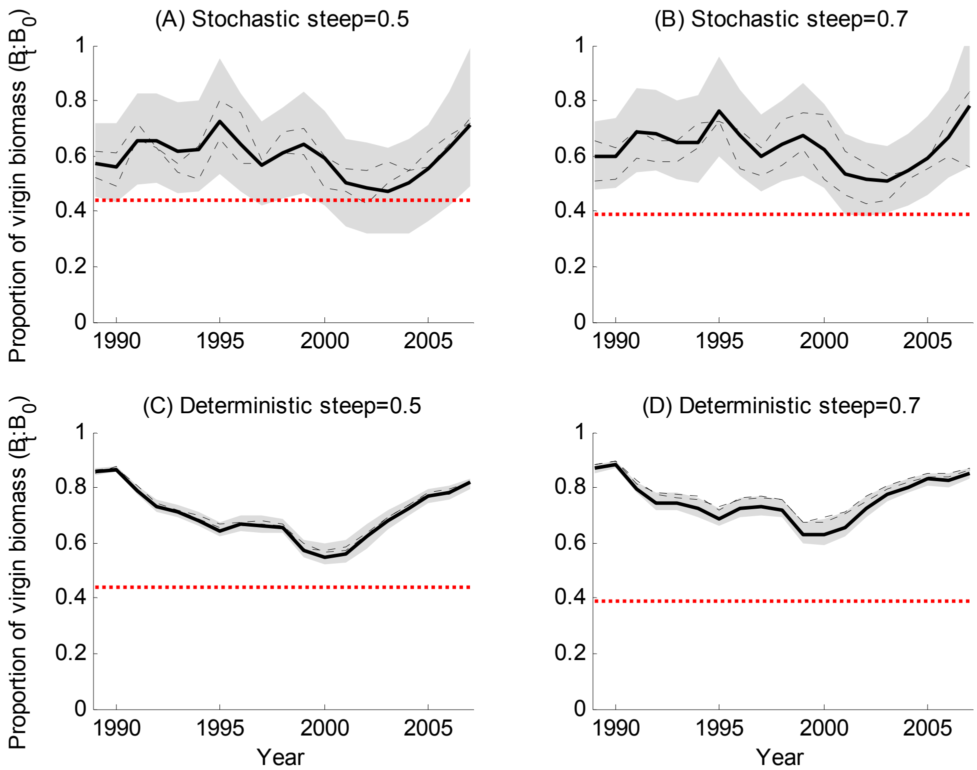


Figure 5.11 Estimated biomass ratio trend for: (A) stochastic (with recruitment error) with fixed steepness at 0.5, (B) stochastic with fixed steepness at 0.7, (C) deterministic (no recruitment error) with fixed steepness at 0.5, (D) deterministic with fixed steepness at 0.7. Each figure was expressed by the median (solid line), two individual replicates (dotted lines), and 5th and 95th percentiles (shaded area). The red broken line indicates B_{MSY}.

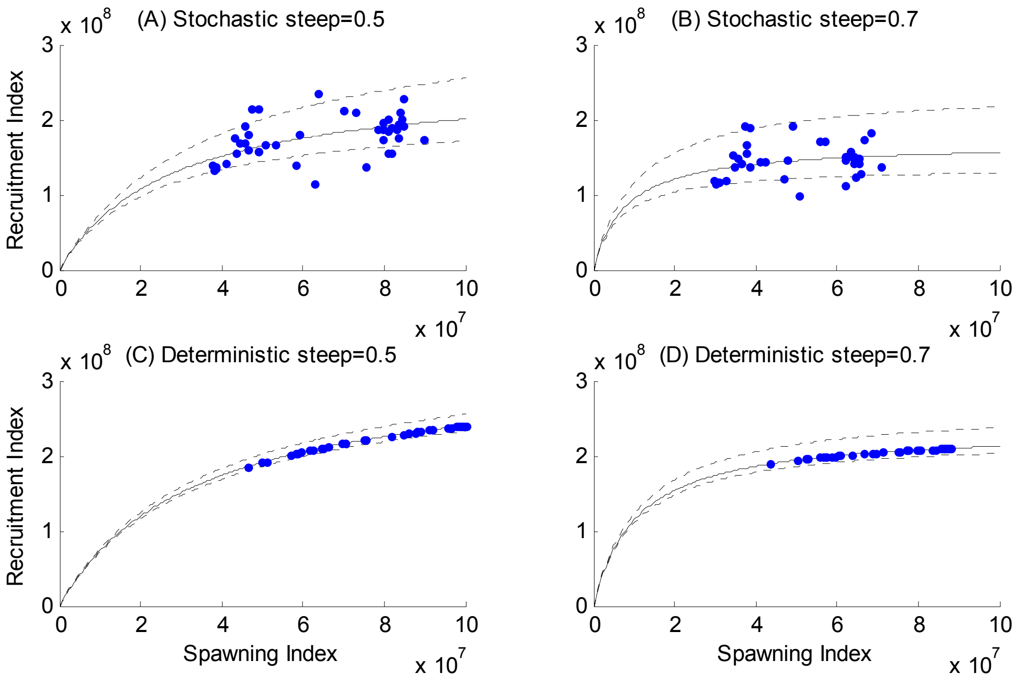


Figure 5.12 The spawner-recruitment relationships for: (A) stochastic (with recruitment error) with fixed steepness at 0.5, (B) stochastic with steepness at 0.7, (C) deterministic (no recruitment error) with steepness at 0.5, (D) deterministic with steepness at 0.7. The relationships were expressed by the median (solid line), 5th and 95th percentiles (dotted lines). Blue dots indicated the actual (median) recruitment index estimated from the model.

The spawner-recruitment relationships estimated from each model were shown in Figure 5.12. Higher uncertainty in the spawner-recruitment relationship was observed for the stochastic model. The actual recruitment estimates (blue dots in Figure 5.12) indicated that the recruitment indices were almost independent of spawning size with steepness at 0.7. Interestingly, two clusters of recruitment index were observed for all model types (Figure 5.13). Each cluster is obviously associated with each of the periods in the data set (per and post compulsory logbooks).

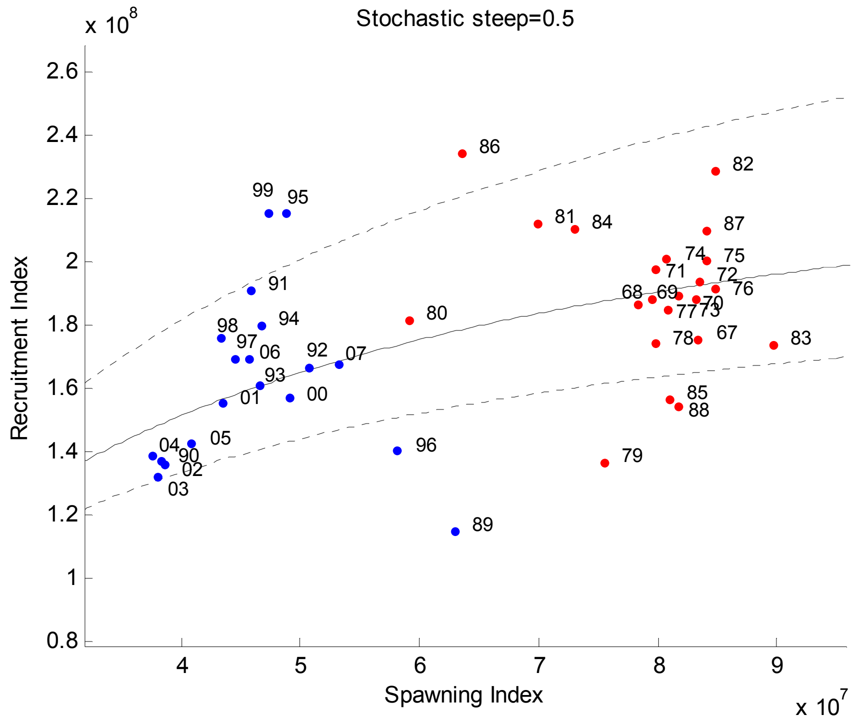


Figure 5.13 S-R relationships for the stochastic model with steepness fixed at 0.5. Red dots indicated recruitment index for the voluntary logbook period (<1989); blue dots for the compulsory logbook period (≥ 1989); zoomed axes illustrate recruitment variation.

Figure 5.14 and Figure 5.15 show correlations between parameter estimates for the stochastic model with fixed steepness at 0.5. Despite the large number of parameter estimated, there is no evident of strong collinearity which was observed in previous model (Appendix 5.5.2).

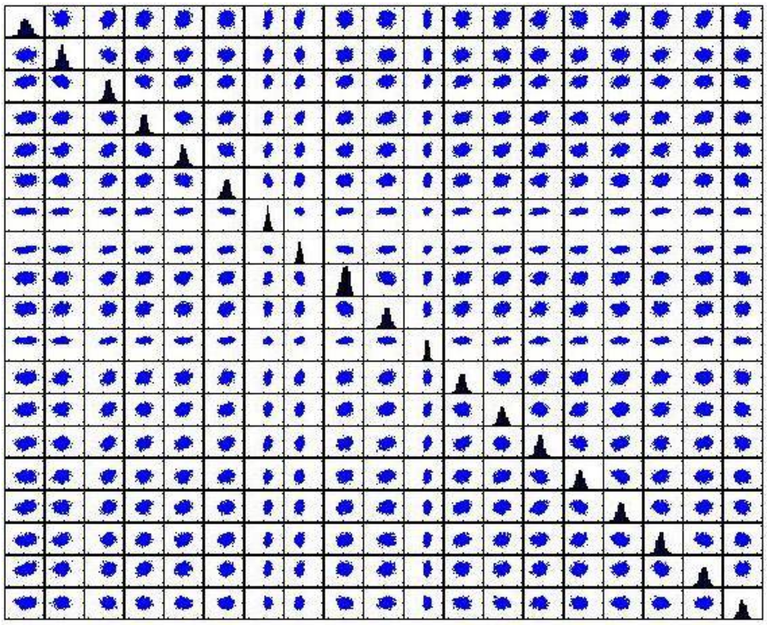


Figure 5.14 Extracted matrix plot of 1000 random values of each model-estimated parameter as sampled from each posterior distribution (based on the stochastic model with fixed steepness at 0.5). The row and column plots of parameters are recruitment residuals from 1989 to 2007.

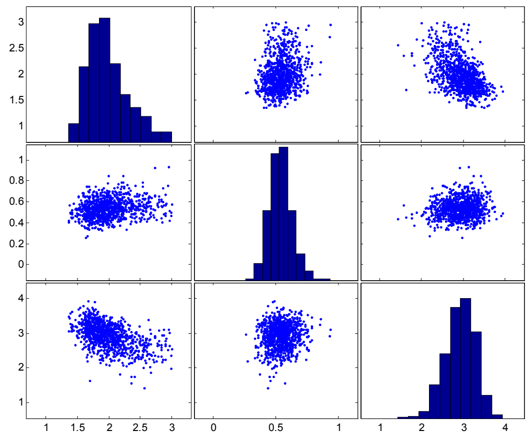


Figure 5.15 Matrix plot of 1000 random values of each model-estimated parameter as sampled from each posterior distribution (based on the stochastic model with fixed steepness at 0.5). The row and column plots of parameters are R_0, $\bar{r}$ and κ.

5.4 Discussion

The fitting of a stock assessment model to the data for endeavour prawns in Torres Strait has been challenging due to the nature of the harvest data available for this species. As the distribution of tiger and endeavour prawns completely overlap there are few daily vessels records that report only one of the species. Although the AFMA logbooks have a target species, field many TSPF fishers do not fill out this field and the reliability of the information where it has been filled out is dubious as fishers target the mix of species which provide the highest return rather than a particular species. At industry meetings fishers have stated that they “target dollars not a species”. Endeavour prawns are of less value than tiger prawns so they tend to be the secondary target species making the CPUE data for endeavour prawns less reliable than the tiger prawn CPUE data. The CPUE data for the years prior to 1989 came from a variable a subset of the total fishing effort, making the catch rates for those years even less reliable as an index of abundance.

Another difficulty with the data is that the endeavour prawn harvest during the years 1991-2001 was significantly higher than prior to 1991. Possible reasons for this trend are; the East of Warrior Closure, increased targeting of endeavour prawns during the 1990's and possible discarding of endeavour prawn catch during the early 1980's.

Catch rate standardisation analysis indicates that the increase in fishing power for endeavour prawns was less than for tiger prawns and that the 10% decrease in net size during 2002-03 resulted in a 3% reduction in fishing power. This is slightly less than the 4 % negative net size effect suggested by Dr David Die (Die 2003) which was based on fishing power studies conducted by CSIRO in the Northern Prawn Fishery. A few navigation systems (GPS, computer mapping and sonar) were found to have a negative effect on endeavour prawn catch rates. A possible explanation is that the adoption of these navigation systems enabled fishers to target with greater efficiency the more valuable tiger prawns in preference to the less valuable endeavour prawns.

The endeavour prawn assessment model was initially developed by modifying the existing tiger assessment model to suit the biology of endeavour prawns (see Appendix 5.5.2). Although the estimates of Maximum Sustainable Yield (MSY) from the delay difference model were similar to the average endeavour prawn catch during the 1990's, there was a large level of uncertainty around the MSY estimates and the spawner-recruitment relationship parameters.

An alternative assessment model was developed using an age and length based model that can better utilise the biological information available for the species. The model follows the dynamics of each sex, size and age cohort separately and enables us to capture the substantial size related variation in reproduction that occurs in these species. A Bayesian estimation technique (Monte Carlo Markov Chain (MCMC) algorithm) was used for the model optimisation.

An interesting improvement over the preliminary model results is significantly reduced collinearity. This is no doubt a product to some extent of fixing steepness (and thus reducing the number of parameters). However, it is likely that another important factor is the use of Monte Carlo Marko Chain approach to estimating the likelihood distribution (as opposed to quasi-Newton optimisation in the case of the preliminary model).

The stochastic model incorporated variations in the spawning-recruitment relationship, but model diagnostics indicate *non-convergence* of the parameter estimates. This is not surprising given that the stochastic model attempts to estimate a recruitment anomaly for each year of the history of the fishery, resulting in a very large number of parameters (44 in total). Although in theory model convergence can be achieved with a large number of parameters, most data sets are simply not that informative. This is especially true for data sets that have large uncertainties, which is the case here as noted above.

There were a few features of the stochastic model results that require careful interpretation, and are symptoms of a common issue with models that attempt to estimate yearly recruitment variation: any interpretation of outputs must take into account the overall contribution to spawning stock from this source. The first notable feature was that the period 1991 through to 2001 appeared to sustain catch levels in excess of MSY without a commensurate effect on the biomass levels. In this instance, the model estimation process has produced recruitment anomalies during this high catch period which compensate for what would otherwise be an overfishing event. In particular, we find that average recruitment anomalies for this period result in recruitments which are roughly 10% inflated from the median. Secondly, biomass drops sharply just prior to this period, coinciding with the introduction of compulsory logbooks. This drop is again associated with a strong recruitment anomaly event, in this case 35% reduction from the median. Finally, negative recruitments are found between 2001 and 2005. This arises from the combination of lower catch rates and catches during this period. The model is unable to explain reduced biomass (inferred from reduced catch rate) purely in terms of high or increased fishing mortality, and uses recruitment anomalies to 'bridge the gap'. This is not necessarily meaningful from a biological or fishery dynamics perspective and it is likely just the best way the model can make use of its large number of parameters. The lower catch rates during this period are possibly due to fishers targeting more valuable tiger prawns. Likewise, the large negative recruitment event in 1989, and the introduction of compulsory logbooks in that same year are unlikely to be independent and that the estimation in the model of a reduction in biomass is probably not real.

As the CPUE data does not appear to be a consistent index of abundance over the whole time series different catchability coefficients were calculated for the two data periods: pre 1989 and the compulsory logbook period (post 1988). The catchability coefficient for the post 1988 period was estimated as higher than for the voluntary period. This resulted in two distinct ‘operating regions’ for the population: one very close to virgin state and the other, post 1989, at roughly 60% of virgin. This explains two distinct cluster of recruitment index observed in the spawner-recruitment relationships (Figure 5.13).

According to both the Geweke and Gelman-Rubin statistics the deterministic model converged when steepness was fixed at 0.5, but both statistics indicated non-convergence of R_0 when steepness was fixed at 0.7. In the latter case we find a bi-modal distribution for R_0 which is likely to have confounded the convergence statistics. Nonetheless this run is less plausible given that it never causes biomass to fall below 60% of virgin and that it results in an MSY which is appears to be unrealistically high given historical catch and effort.

The results show that MSY for endeavour prawns is likely to be between 900 t and 1100 t, depending on the type of model and steepness setting of the spawner-recruitment relationship. The MSY estimated from the stochastic model with steepness 0.5 (900 t) was similar to that of the previous delay difference model (901 t to 940 t) (Appendix 5.5.2). This is not surprising as the previous model estimated steepness at 0.44 and 0.47 (for Ricker and Beverton-Holt models respectively), close to 0.5.

While the delay-difference model had two separate fitting processes (model fitting followed by fitting of the spawner-recruitment relationship based on the model output), the age-size structured model did this in one hit. The delay-difference fitted the CPUE data well, but the spawner-recruitment relationships fitted to the estimated spawning stocks was poor and highly uncertain (Figure 5.24). This resulted in large error/uncertainties in the management parameters. The age-size structured model may seem to have a poorer fit to the CPUE data, but it is clear that it has a better fit to the spawner-recruitment relationship (Figure 5.12). Unfortunately the stochastic age-size model had a problem with model convergence and (as discussed above) there were difficulties in interpreting the results. Whilst the deterministic age-size structure model does not fit as well as the others models and it is ideal to incorporate stochasticity in the spawner-recruitment relationships it is the preferred model for this assessment.

Taking the above issues into account, in particular the potentially spurious recruitment anomaly trends, we recommend the deterministic results over the stochastic results, and in particular the deterministic run with steepness fixed at 0.5. The MSY estimated from this model was 1105t (90% CI 1060:1184) and is plausible given the historical catch and effort trends observed during the 1990s and is similar to the 1994 estimate of Maximum Constant Yield (1035t) for endeavour prawns (Turnbull and Watson 1995). The overall conclusion of the endeavour prawn stock assessment is that the fishing has not impacted the endeavour prawn stock, which confirms Dr David Die’s hypothesis in the 2003 review (Die 2003, p7). The sustainability of the Torres Strait Prawn Fishery would be maintained as long as the tiger prawn stock was managed appropriately.

5.5 Appendix

5.5.1 Residual plots

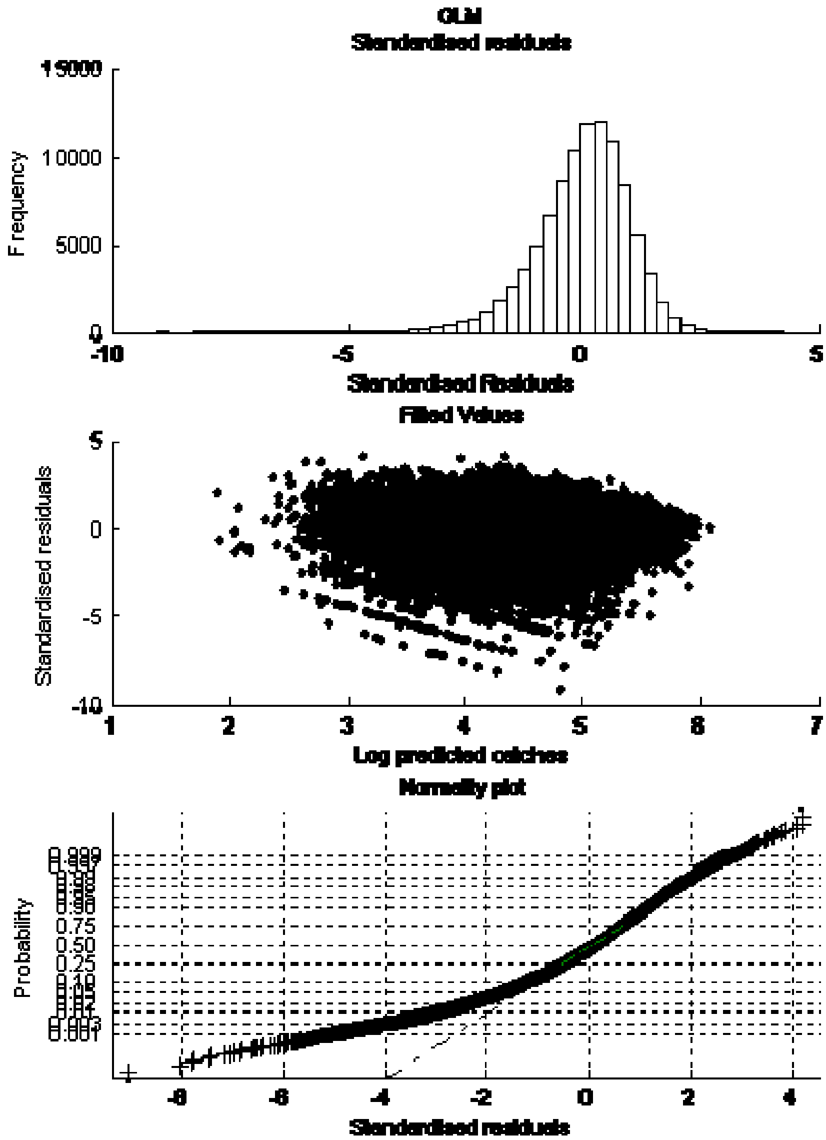


Figure 5.16 Standardised residuals for the endeavour prawn standardisation model.

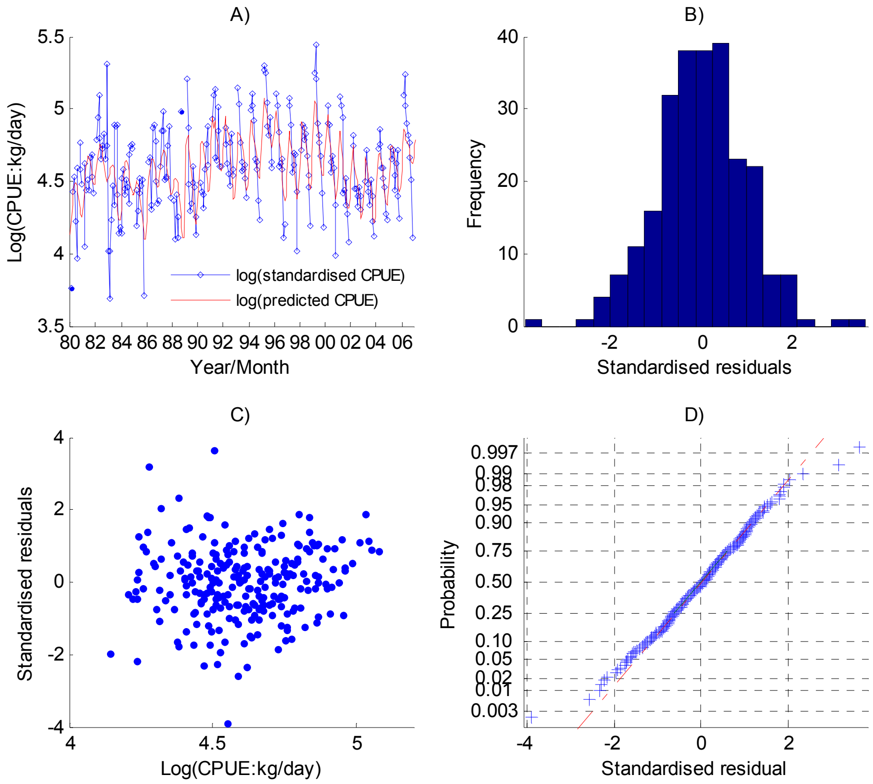


Figure 5.17 The goodness of fit plots for the stochastic model with fixed steepness at 0.5; A) fitted vs observed (std) data and residual plots (B-D).

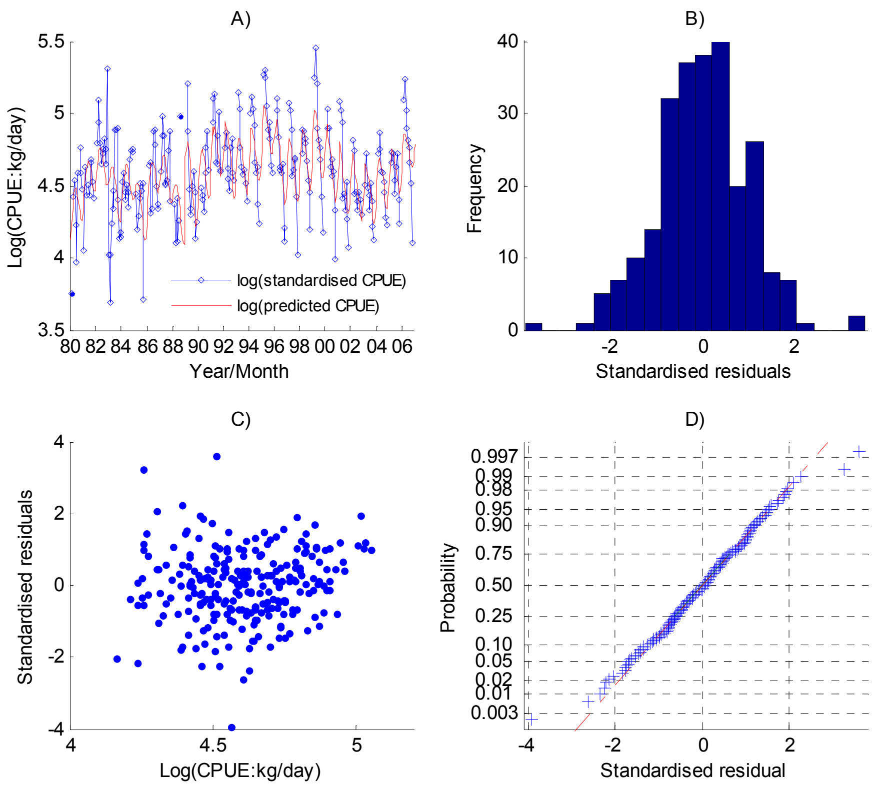


Figure 5.18 The goodness of fit plots for the stochastic model with fixed steepness at 0.7; A) fitted vs observed (std) data and residual plots (B-D).

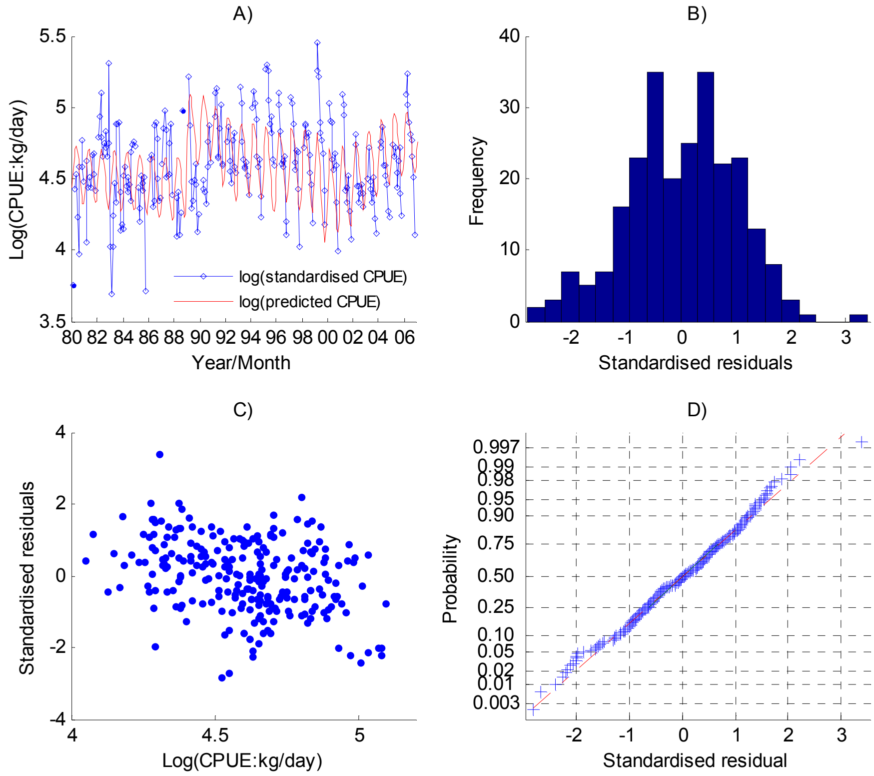


Figure 5.19 The goodness of fit plots for the deterministic model with fixed steepness at 0.5; A) fitted vs observed (std) data and residual plots (B-D).

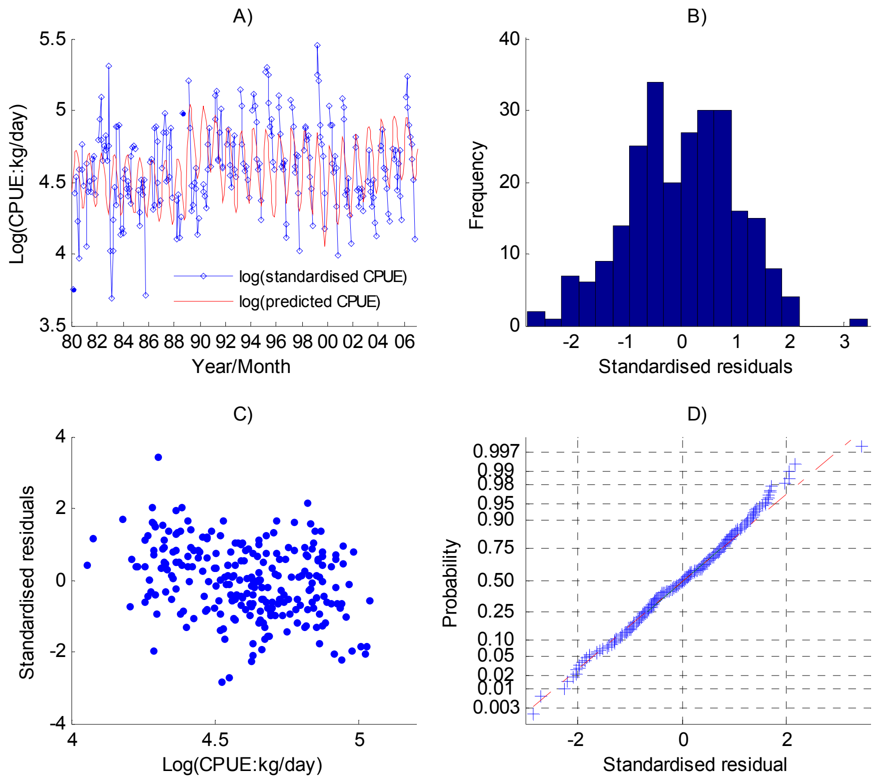


Figure 5.20 The goodness of fit plots for the deterministic model with fixed steepness at 0.7; A) fitted vs observed (std) data and residual plots (B-D).

5.5.2 The endeavour prawn delay difference model

The stock assessment for the Torres Strait endeavour prawns was initially approached by adopting the existing Torres Strait tiger prawn model (O'Neill and Turnbull 2006). The tiger prawn model uses a delay difference model (Deriso 1980; Schnute 1985), which has commonly been used to assess penaeid prawn stocks in Australia including tiger prawns the Gulf of Carpentaria (Dichmont et al. 2005), eastern king prawns in Queensland (O'Neill et al. 2005) and in NSW (Ives and Scandol 2007). A full description of the delay difference model is provided in O'Neill and Turnbull (2006, p 37-38).

Due to uncertainties in the total catch and catch rate for endeavour prawns prior to 1989, the model was fitted to two data periods:

1) All 27 years; 1980 - 2006 and
2) For the period when compulsory logbook data were available (18 years; 1989 – 2006).

In total 30 parameters were estimated for the first dataset (Y27 model), and 21 parameters for the second dataset (Y18 model).

The following parameters were estimated in the analysis:

- Catchability coefficient, q
- The estimated mode of the von Mises distribution, $\bar{r}$
- The concentration parameter in the von Mises distribution, κ
- The recruitment estimates from 1980 to 2006 for Y27 models and from 1989-2006 for Y18 models.

Results

Y27 Model

Despite a relatively good fit the delay-difference model based on a 27-year time series failed to provide meaningful results. The main reason for this being the lack of a significant spawner-recruitment relationship, for either the Ricker or the Beverton-Holt curves. Annual spawners and recruitment index estimates (Figure 5.21) for the period prior to 1989 tended to be much smaller than those estimated for the compulsory logbook period (1989-2006). This is possibly an artefact caused by the discrepancies in the relative index of abundance estimated from the two time periods. It was therefore decided to fit the model only using the standardised CPUE since 1989 onwards (Y18 model).

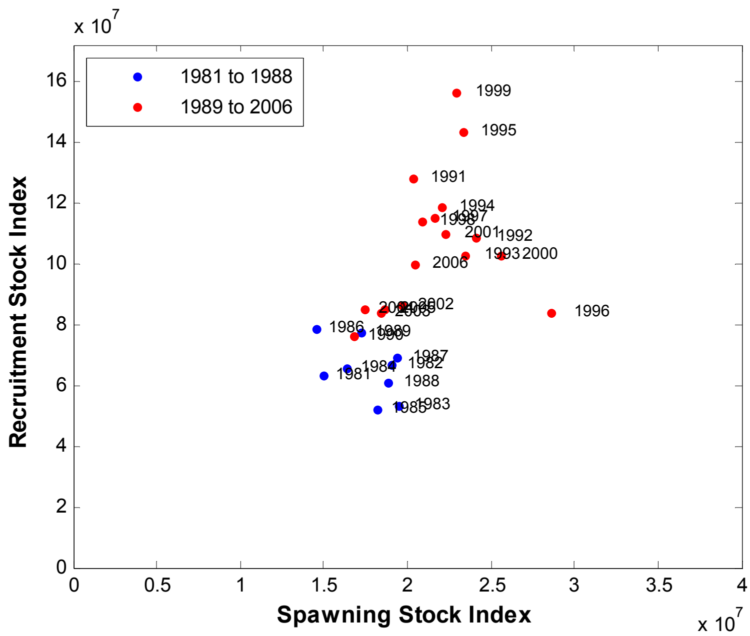


Figure 5.21 Annual spawner and recruitment index estimates.

Table 5.10 The spawner-recruitment parameter estimates for the Y27 model.

Parameters	*Ricker*	*Beverton-Holt*
alpha a	8.5676 (1.9005; 4.51)	0.1167 (0.027; 4.32)
beta b	0.0517 (0.1992; 0.26)	0.0062 (0.0244; 0.26)

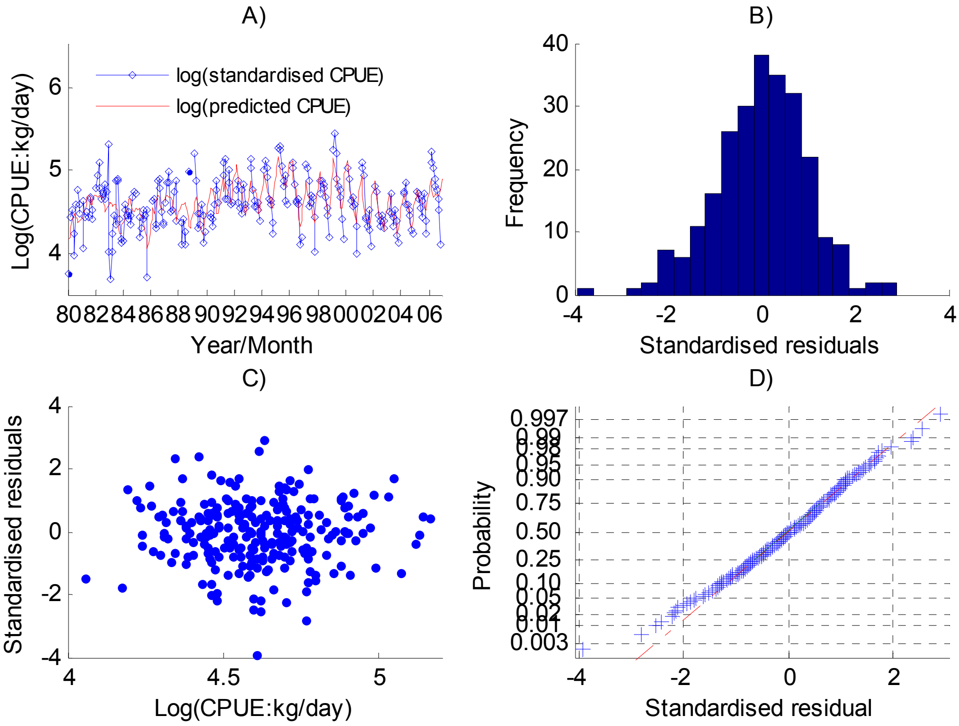


Figure 5.22 The goodness of fit plots for Y27 Model; A) fitted vs observed (std) data and residual plots B)-D).

Y18 Model

The model fitted to the compulsory logbook data period (1989-2006) provided more realistic results. While spawning-recruitment parameters were significant for the Ricker curve, one of the Beverton-Holt parameters (α) was not significant. High uncertainties in the stock-recruitment relationship are evident for both curves.

The measure of steepness, defined as the average productivity of recruitment at 20% of virgin spawning stock size, has large confidence intervals (high uncertainty) for both Ricker and Beverton-Holt models.

Estimates of Maximum Sustainable Yield (MSY) and fishing effort (E_{MSY}) in 2006 were 940 and 980 tonnes, and 9162 and 9540 boat nights, for the Ricker and Beverton-Holt spawner-recruitment relationships respectively (Table 5.11). Large confidence intervals around the MSY and E_{MSY} estimates from the Beverton-Holt are due to the insignificance of the curve fit.

The monthly delay difference model predicted that biomass, expressed as a proportion of virgin exploitable biomass, was above B_{MSY} during the 1990's and around B_{MSY} since 2000. The biomass level in 2006 was just above B_{MSY}.

The log-scaled standardise residuals generally followed normal distribution thus the use of log-normal residuals was considered to be adequate (Figure 5.25: B-D). Figure 5.25(A) shows that the model fits to the data relatively well, although it marginally tended to underestimate the monthly peaks and overestimate the troughs.

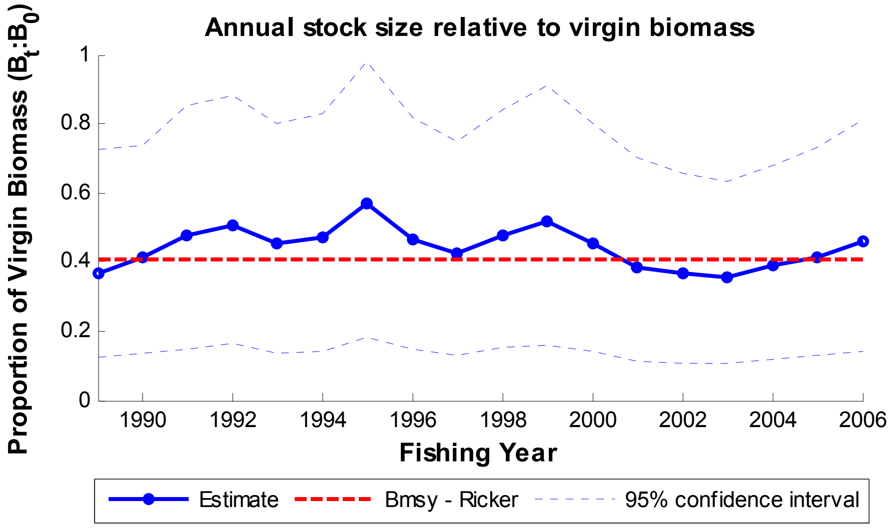


Figure 5.23 Estimated trends in monthly biomass (top) and in biomass ratio (bottom).

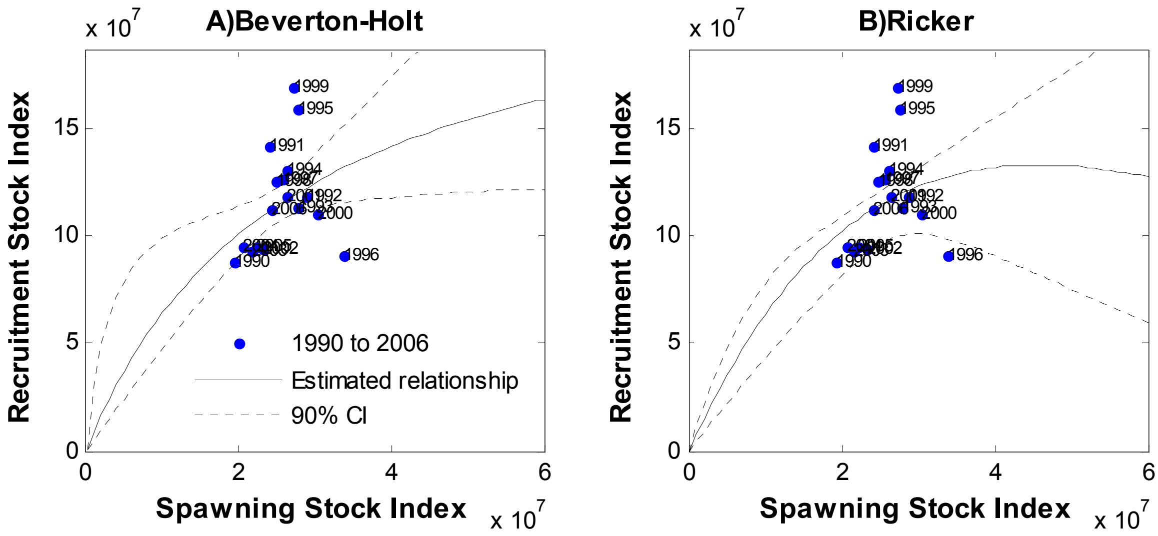


Figure 5.24 The spawner-recruitment relationships assuming A) the Beverton-Holt form, or B) the Ricker form.

Table 5.11 The spawner-recruitment parameters and delay-difference equilibrium-management parameters using Y18 model.

Parameters	*Ricker*	*Beverton-Holt*
Spawner-Recruitment		
alpha a	7.8978 (2.3988; 3.29)	0.1141 (0.0633; 1.8)
beta b	0.2191 (0.1179; 1.86)	0.0423 (0.0251; 1.69)
Steepness	0.44 (0.31; 0.79)	0.47 (0.3; 0.64)
MSY (tonnes)	901 (666; 1022)	938 (775; 1622)
E_{MSY}	8810 (3314; 14938)	8186 (3427; 23437)

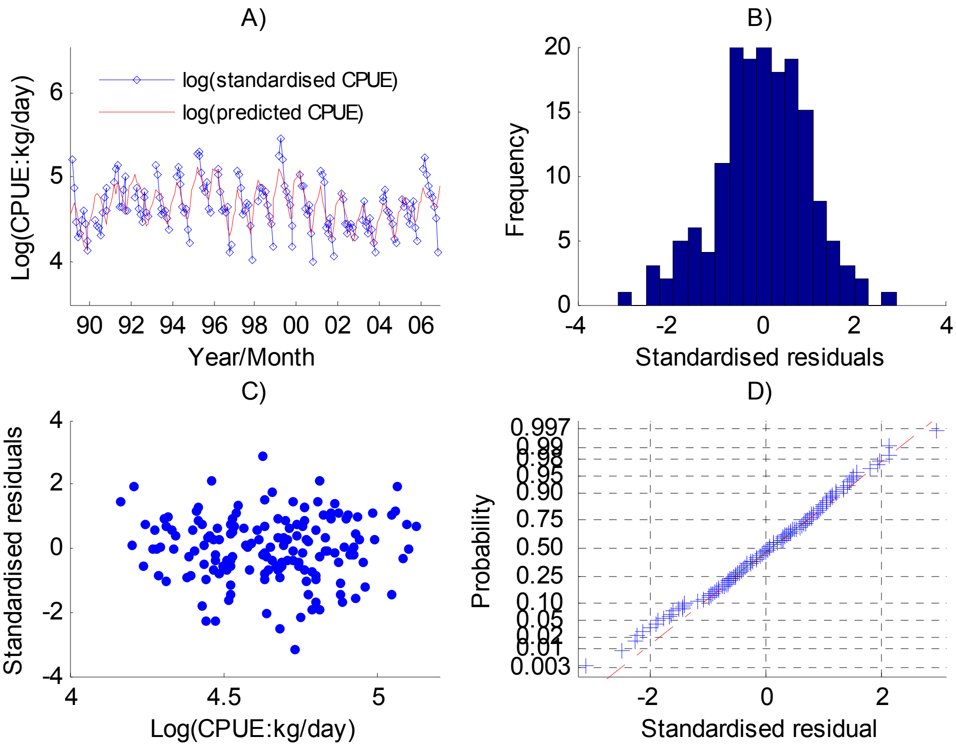


Figure 5.25 The goodness of fit plots for Y18 Model; A) fitted vs observed (std) data and residual plots (B-D).

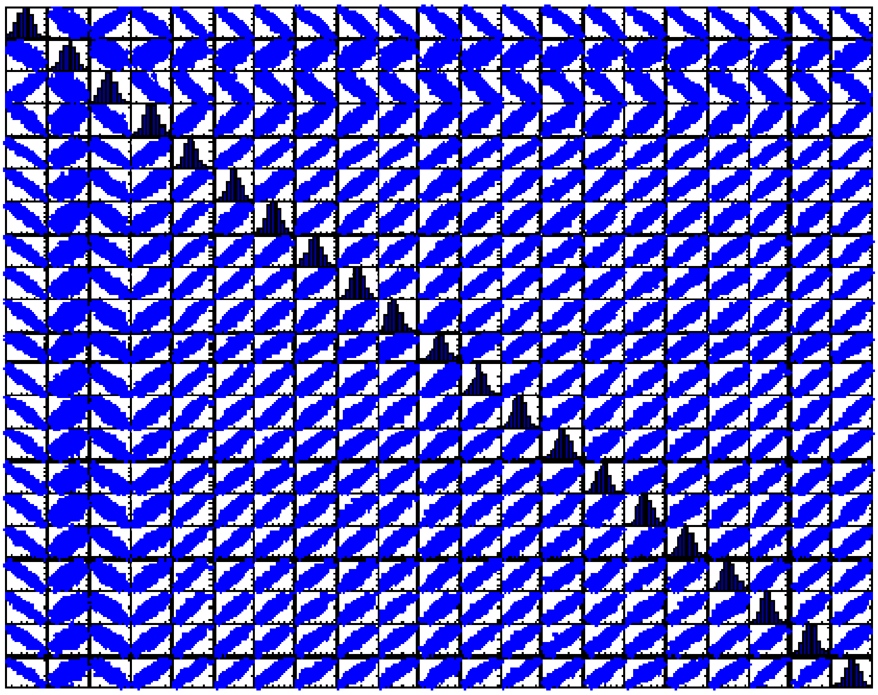


Figure 5.26 Matrix plot of 1000 random values of each model-estimated parameter as generated from the multivariate normal distribution with maximum likelihood estimates and covariance matrix. The row and column plots of parameters are ordered q, $\overline{r}$, κ, $R_{1989},\ldots,R_{2006}$.

Discussion

The delay-difference model based on a time series of 27 years (Y27Model) did not provide realistic equilibrium management parameters. This was because the model failed to detect spawner-recruitment relationships, which are key inputs to determine the status of the fishery. Curiously there were distinct differences in levels of spawning/recruitment indices between the voluntary and compulsory logbook years (Figure 5.21). These differences are not a reflection of the actual spawning/recruitment size, but rather variations in the reliability of the CPUE data as an index of abundance between the two time periods. The model based only on a time series of compulsory logbook data (i.e. Y18 Model) provided more sensible management parameters (Table 5.11), although the large uncertainties in estimated spawner-recruitment relationships remain.

The results of Y18 Model indicated increased endeavour prawn biomass in the early 1990's, reaching the highest level in 1995 due to the high recruitment index estimated for that year. The biomass level was also high in 1999 due to high catch rates. A decline in biomass level was observed since 1999 due to low catch rates but improved since 2003, exceeding B_{MSY} in 2006. Note that large uncertainties in spawner-recruitment relationships resulted in large confidence intervals for biomass estimates and management estimates (Table 5.11 and Figure 5.23).

The biggest concern with the monthly delay-difference model is that parameter estimates were strongly correlated with each other (Figure 5.26). Hilborn and Walters (1992) noted this collinearity is common when fitting delay-difference models to simple time-series data (CPUE, catches, efforts). Collinearity makes interpretation of parameter estimates less reliable since the impact of any parameter on the model output will be confounded among the correlated parameters. In such cases, data can be explained equally well by a wide variety of parameter combinations. For example, the same model fit could be observed from a large stock size (large recruitment) with little fishing impact (small q), or from a small stock (small recruitment) with high fishing pressure (large q). These parameter combinations may result in very different management reference points, therefore further improvement is required to remove collinearity among parameter estimates and increase robustness of the model.

Effort split methods

The original standardisation model includes tiger prawn catches as a covariate, but this seems not to be powerful enough to capture targeting behaviour, particularly for recent years. Therefore alternative standardisation methods were explored.

Model A

The first method simply calculates value-of-production of daily catch for each species and ascribes effort to a species that had higher returns. The prawn beach price data obtained from ABARE (Figure 5.27).

Model B

The second method applied a similar effort split method as that proposed in (Venables et al. 2006). The steps are as follows:

1. value-of-production of daily catch was derived:
   EndvVP= endeavour prawn price*non-zero endeavour catches
   TigerVP = tiger prawn price*non-zero tiger catches)
2. a REML is fitted to the endeavour value-of-production:
   log(*EndvVP*) = month+region5+pnite+lunar+lunaradv+vessel_symbols
   The same model is fitted for log(*TigerVP*)
3. The endev daily production and tiger production are then standardised to an average vessel by dividing each by the corresponding (exponentiated) vessel effect.

4. two types of thresholds are set as: 1) the lower quartiles of the vessel-adjusted *EndvVP* or *TigerVP* for each year and 2) *EndvVP* >*TigerVP* (and vice versa for tiger prawns). Each record is then scored as to whether or not it exceeded the threshold.
5. a GAM is fitted to predict the probability of exceeding the threshold:

$$\log(p_{endv}) = \text{month} + \text{lunar} + \text{lunaradv} + \text{sspline}(\text{latitude}) + \text{sspline}(\text{longitude}) + \text{vessel\_symbols}$$

   The same model is fitted for tiger (p_{tiger}).
6. finally split effort into endeavour-targeted night (endeavour night) and tiger-targeted night (tiger night) as:
   endeavour night = $p_{endv} \geq p_{tiger}$
   tiger night = $p_{endv} < p_{tiger}$

Results

Model A

The monthly endeavour CPUE filtered by value-of-production showed quite different trend compared to the raw (or originally standardised) CPUE (Figure 5.29). The biggest concern is that the proportion of catch records used in the calculation is significantly low particularly for recent years. For example, only 19% of records in 2006 were used, in other words, 89% of records were omitted from the analysis. This filtering method seems to be too forceful and requires further modifications.

Model B

The plot of p_{endv} vs p_{tiger} does not indicate a clear separation of effort (Figure 5.29) and the model's goodness of fit is low. It is possible that this could be improved by applying a different statistical model but further investigation is required to reach any conclusion in this matter. Note that the proportion of records used in the analysis varies significantly between months (Figure 5.31), indicating the majority of records in early months were considered to be targeting tiger prawns but records in later months tend to target endeavour prawns.

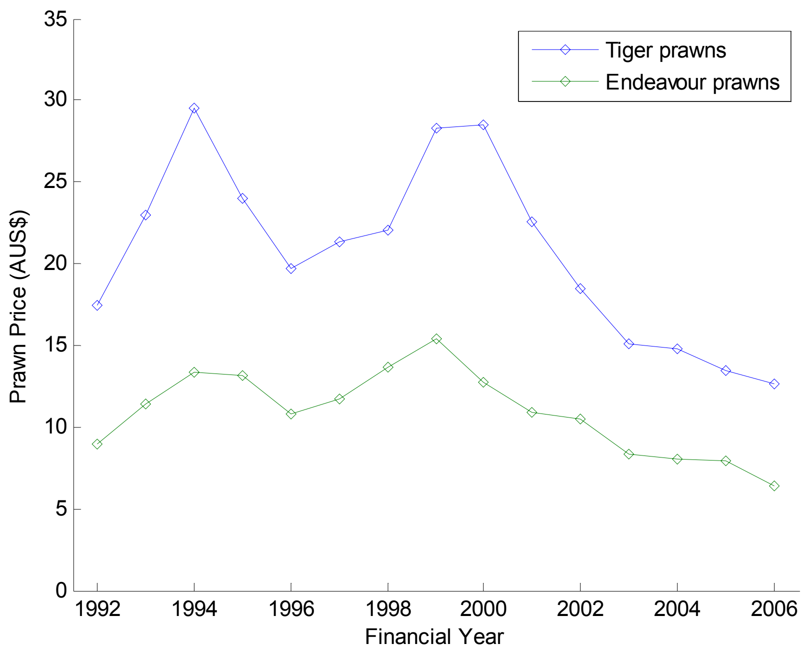


Figure 5.27 Off-loading prices for tiger and endeavour prawns from financial year 1992/93 to 2006/07 (data source: ABARE)

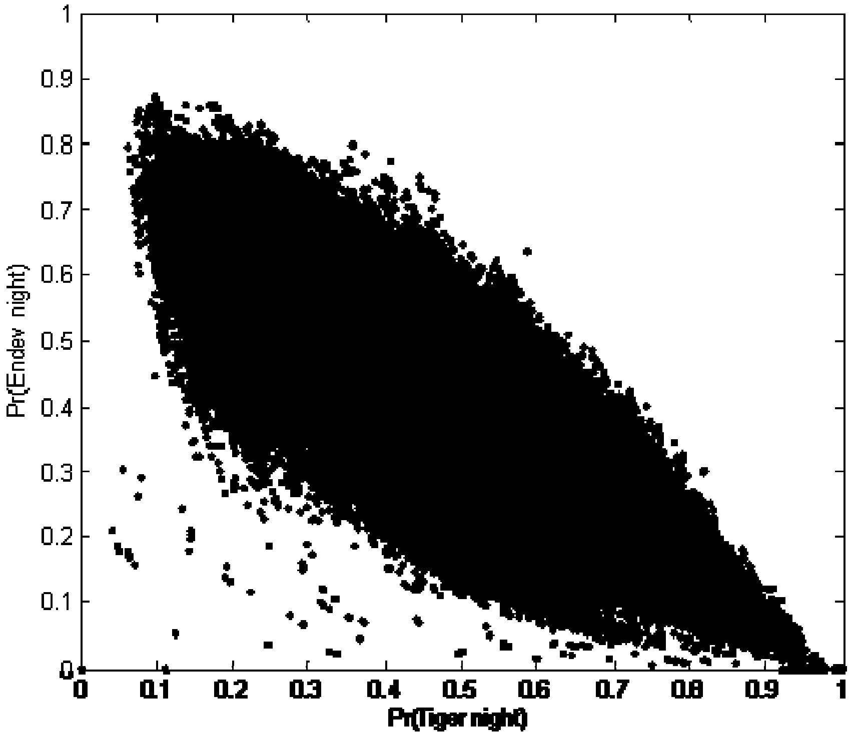


Figure 5.28 Probability of tiger targeted effort versus endeavour targeted effort.

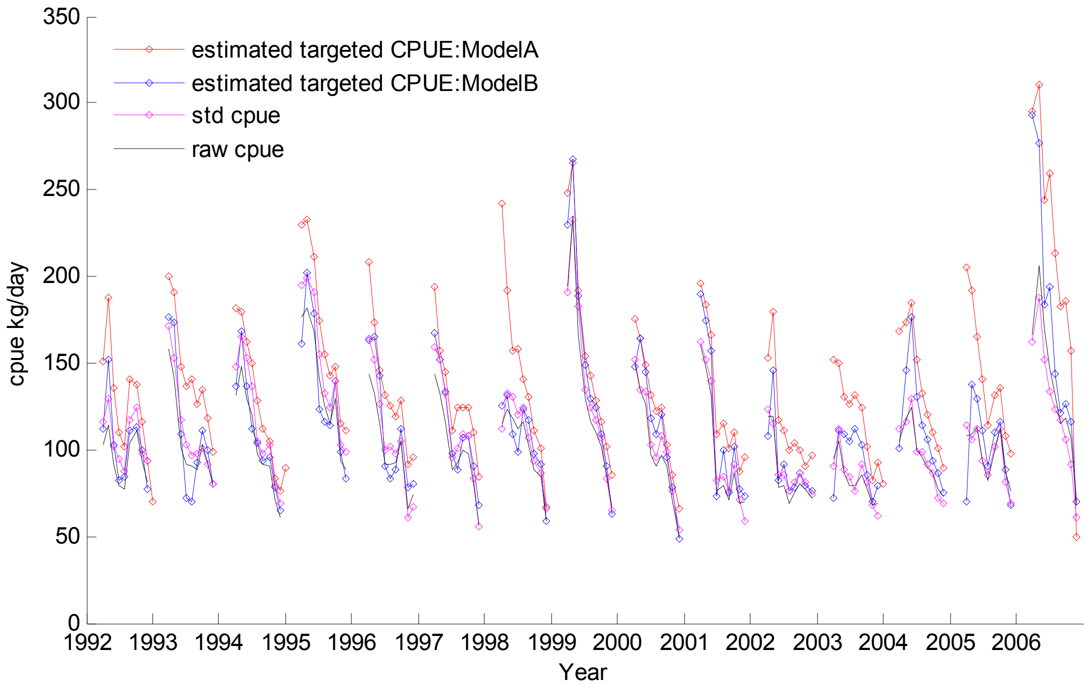


Figure 5.29 Estimated targeted endeavour monthly catch rate with raw and original standardised CPUE.

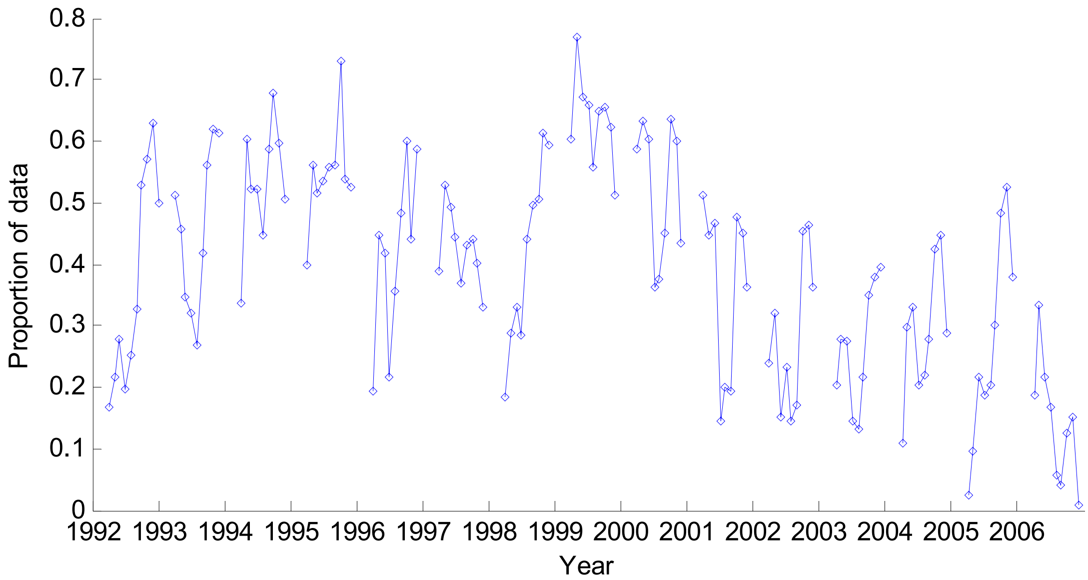


Figure 5.30 Proportion of data used to calculate targeted endeavour targeted CPUE in Model A.

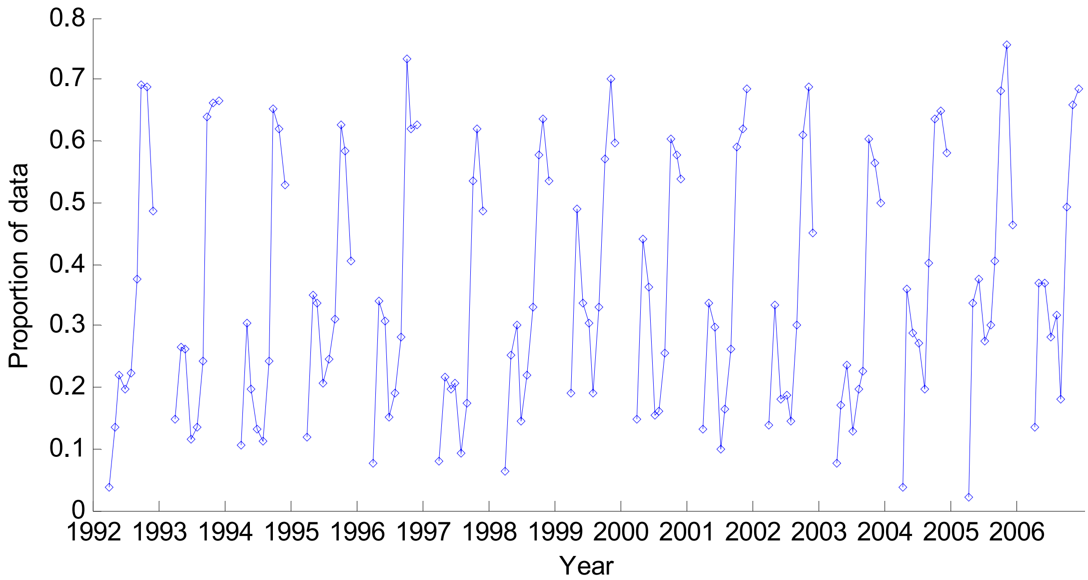


Figure 5.31 Proportion of data used to calculate targeted endeavour targeted CPUE in Model B.

6 References

Beyer, H. L. (2004). "Hawth's Analysis Tools for ArcGIS. Available at http://www.spatialecology.com/htools. ."

Beyer, H. L. (2004). Hawth's Analysis Tools for ArcGIS. Available at http://www.spatialecology.com/htools. (downloaded on 11/10/2007).

Coles, R. G. and W. J. Lee Long (1985). Juvenile prawn biology and the distribution of seagrass prawn nursery grounds in the southeastern Gulf of Carpentaria. Second Australian National Prawn Seminar, Cleveland.

Courtney, A. J., M. G. Cosgrove, et al. (2002). Developing indicators of recruitment and effective spawner stock levels in eastern king prawns (Penaeus plebejus). Brisbane, Fisheries Research and Development Corporation (FRDC) Final Report, Department of Primary Industries, Queensland**:** 70.

Courtney, A. J., D. J. Die, et al. (1996). "Lunar periodicity in catch rate and reproductive condition of adult eastern king prawns, Penaeus plebejus, in coastal waters of south-eastern Queensland, Australia." Marine and Freshwater Research **47**(1): 67-76.

Courtney, A. J., J. A. Haddy, et al. (2007). Bycatch weight, composition and preliminary estimates of the impact of bycatch reduction devices in Queensland's trawl fishery. Brisbane, Queensland Government, Queensland Department of Primary Industries and Fisheries**:** 307.

DAFF (2007). Commonwealth fisheries harvest strategy: policy and guidelines. Commonwealth of Australia.

Dall, W., B. J. Hill, et al. (1990). The Biology of the Penaeidae. London, Academic Press, Harcourt Brace Jovanovich, Publishers.

Deriso, R. B. (1980). "Harvesting strategies and parameter estimation for an age-structured model." Canadian Journal of Fisheries and Aquatic Sciences **37**: 268-282.

Dichmont, C. M., A. R. Deng, et al. (2005). A new approach to assessment in the NPF: spatial models in a management strategy environment that includes uncertainty. Cleveland, CSIRO Marine Research, FRDC 2001/002.

Dichmont, C. M., M. Haddon, et al. (1999). Proceedings of the South-East Queensland Stock Assessment Review Workshop. Brisbane, Queensland, Australia, Department of Primary Industries**:** 179.

Die, D. and R. A. Watson (1992). "A per-recruit simulation model for evaluating spatial closures in an Australian penaeid fishery." Aquatic Living Resources **5**: 145-153.

Die, D. J. (2003). Review of the stock assessment of the Torres Strait prawn fishery., Australian Fisheries Management Authority (AFMA)**:** 33.

Dion, C. and N. Hughes (2004). "Testing the ability of a temperature-based model to predict the growth of age-0 arctic grayling." Transactions of the American Fisheries Society **133**(4): 1047-1050.

Francis, R. I. C. C. (1992). "Use of risk analysis to assess fishery management strategies: a case study using orange roughy (Hoplostethus atlanticus) on the Chatham Rise, New Zealand." Canadian Journal of Fisheries & Aquatic Sciences **49**: 922-930.

Grey, D. L., W. Dall, et al. (1983). A Guide to the Australian Penaeid Prawns. Darwin., Northern Territory Printing Office.

Haddon, M. (2001). Modelling and Quantitative methods in fisheries. New York, Chapman & Hall/CRC.

Hall, N. G. and R. A. Watson (2000). A spatial representation of the tiger prawn (*Penaeus esculentus*) fishery in Shark Bay, Western Australia. Fish Movement and Migration. D. A. Hancock, D. C. Smith and J. D. Koehn. Albury, Australian Society for Fish Biology**:** 212-230.

Hesp, S., N. Hall, et al. (2004). "Size-related movements of Rhabdosargus sarba in three different environments and their influence on estimates of von Bertalanffy growth parameters." Marine Biology **144**(3): 449-462.

Hilborn, R. and C. J. Walters (1992). Quantitative Fisheries Stock Assessment: Choice Dynamics and Uncertainty. New York, Chapman and Hall.

Ives, M. C. and J. P. Scandol (2007). "A Bayesian analysis of NSW eastern king prawn stocks (Melicertus plebejus) using multiple model structures." Fisheries Research **84**(3): 314-327.

Kung, J. P., C. T. Turnbull, et al. (2005). Torres Prawn Handbook 2006. Canberra, Australia, Australian Fisheries Management Authority.

Lappalainen, J., T. Malinen, et al. (2005). "Temperature dependent growth and yield of pikeperch, *Sander lucioperca*, in Finnish lakes." Fisheries Management and Ecology **12**(1): 27-35.

Mallet, J., S. Charles, et al. (1999). "Growth modelling in accordance with daily water temperature in European grayling (*Thymallus thymallus L.*)." Canadian Journal of Fisheries & Aquatic Sciences **56**(6): 994-1000.

Mardia, K. V. and P. E. Jupp (2000). Directional Statistics. Chichester, John Wiley & Sons Ltd.

Math Works (2008). MATLAB The Language of Technical Computing. Natick, Massachusetts, The Math Works Inc.

Mellors, J. E. (1990). Torres Strait prawn project: a review of research 1986 - 88. Brisbane, Queensland Department of Primary Industries.

O'Neill, M. F., A. J. Courtney, et al. (2005). Reference point management and the role of catch-per-unit effort in prawn and scallop fisheries. Final Report on FRDC Project No. 1999/120. Brisbane, Queensland, Australia, Department of Primary Industries and Fisheries**:** 265.

O'Neill, M. F. and G. M. Leigh (2006). Fishing power and catch rates in the Queensland east coast trawl fishery. Brisbane, Queensland, Australia, Department of Primary Industries and Fisheries**:** 185.

O'Neill, M. F. and C. T. Turnbull (2006). Stock assessment of the Torres Strait tiger prawn fishery (*Penaeus esculentus*). Queensland, Department of Primary Industries and Fisheries.

Primavera, J. H., F. D. Parado-Estepa, et al. (1998). "Morphometric relationship of length and weight of giant tiger prawn Penaeus monodon according to life stage, sex and source." Aquaculture **164**(1-4): 67-75.

Punt, A., E, et al. (1997). "Estimating the size-transition matrix for Tasmanian rock lobster, *Jasus edwardsii*." Marine and Freshwater Research **48**(8): 981-992.

Sadovy, Y., A. Punt, et al. (2007). Stock assessment approach for the Napoleon fish, *Cheilinus undulatus*, in Indonesia. A tool for quotasetting for data-poor
fisheries under CITES Appendix II Non-Detriment Finding requirements.
. Rome, FAO Fisheries Circular 1023. **71pp**.

Schnute, J. (1985). "A general theory for analysis of catch and effort data." Canadian Journal of Fisheries and Aquatic Sciences **42**(3): 414-429.

Taylor, S., C. T. Turnbull, et al. (2006). Torres Prawn Handbook 2006. Canberra, Australia, Australian Fisheries Management Authority.

Tuma, D. J. (1967). "A description of the development of primary and secondary sexual characters in the banana prawn, *Penaeus merguiensis* de Man (Crustacea: Decapoda: Penaeinae)." Australian Journal of Marine and Freshwater Research **18**: 73-88.

Turnbull, C. and R. A. Watson (1995). Torres Strait Prawns 1994, Stock Assessment Report, edited by the Torres Strait Fisheries Assessment Group. Canberra, Australian Fisheries Management Authority.

Turnbull, C. T., C. Shootingstar, et al. (2005). Developing indicators of recruitment and effective spawner stock levels in north Queensland east coast prawn stocks. Final Report on FRDC Project No. 97/146. Queensland, Australia, Department of Primary Industries and Fisheries**:** 55.

Turnbull, C. T. and R. A. Watson (1991). The effect of the 1990-91 seasonal and strip closures on catches in the Torres Strait Prawn Fishery. QDPI report to the Torres Strait Prawn Working Group.

Van der Meer, J. (1997). "Sampling design of monitoring programmes for marine benthos: a comparison between the use of fixed versus randomly selected stations." Journal of Sea Research **37**: 167-179.

Venables, W. N., R. A. Kenyon, et al. (2006). Species distribution and catch allocation: data and methods for the NPF, 2002-2004. Canberra, AFMA.

Walters, C. J. and S. J. D. Martell (2004). Fisheries Ecology and Management. Princeton, Princeton University Press.

Watson, R. A. and C. T. Turnbull (1993). "Migration and growth of two tropical penaeid shrimps within Torres Strait, Northern Australia." Fisheries Research **17**: 353-368.

Yano, I. (1988). "Oocyte development in the kuruma prawn *Penaeus japonicus*." Marine Biology **99**: 547-553.