Risk Analysis and Sustainability Indicators for Prawn Stocks in the Northern Prawn Fishery

Dichmont, C.M., Die, D., Punt, A.E., Venables, W., Bishop, J., Deng, A. and Dell, Q.

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MARINE RESEARCH

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Risk analysis and sustainability indicators for prawn stocks in the Northern Prawn Fishery.

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CHAPTER 1: INTRODUCTION **7**

1. Objectives 8
2. Non-technical Summary 8
3. Keywords 10
4. Background 10
5. Need 11
6. Acknowledgements 12
7. Project staff in alphabetical order 12

CHAPTER 2:ON SPECIES SPLIT **13**

8. The Species Split Problem 14
   8.1. An outline of the problem *14*
   8.2. The Wang and Die split procedure *14*
   8.3. Problems with the Wang and Die procedure *15*
9. Survey data 15
   9.1. Origins and extent *15*
   9.2. Conversion to aggregate weights *18*
10. A model-based approach to the species split problem 19
   10.1. Response and predictor variables *20*
      10.1.1. Location 21
      10.1.2. Other predictors and interactions 22
      10.1.3. The final linear predictor model 23
11. A test of empirical and model-based split methods for Tiger prawns 25
   11.1. Discussion *29*
12. Endeavour prawn split models 30
   12.1. A test of the Endeavour split procedures *32*
13. Banana prawns 35
14. King prawns 37
15. Simulation from Tiger and Endeavour species split models 38
   15.1. Generating a parameter vector *38*
   15.2. Generating imputed catches *40*
16. Discussion and further research 41
   16.1. Underlying assumptions *41*
   16.2. Species split methodology *42*
   16.3. Recommendations *43*
17. Reference List 43

CHAPTER 3: AUGMENTATION AND IMPUTATION FOR THE LOGBOOK RECORDS **45**

18. The logbook and landings data 46
   18.1. Spatial organisation of the NPF *46*
19. Inferring target species 47
   19.1. Generalized additive models for reasonable catch probabilities *48*
20. Augmentation and imputation of logbook data 51
   20.1. Wang and Die method of augmentation *52*
   20.2. A new augmentation proposal *53*
      20.2.1. Restricted re-sampling 53
      20.2.2. Allocation of spatially imprecise records to grids 55
21. A spatial assessment of catch and effort for the NPF, 1970-1999 56
   21.1. Stock regions in the NPF *56*
   21.2. Tiger prawn stock regions, catch and effort, 1970-1999 .... *57*
   21.3. Endeavour prawn stock regions, catch and effort, 1970-1999 .... *59*
   21.4. Banana prawn stock regions, catch and effort, 1970-1999 .... *62*
   21.5. Aggregate catch and effort over stocks for all 6 species *66*
22. Comparison with the base case: Tiger prawn group 68

23. DISCUSSION AND FURTHER RESEARCH 75
23.1. Suggested further research *76*
23.1.1. Stock structure in the NPF 76
23.1.2. Augmentation and imputation methods for incomplete data 76
23.1.3. Inferring target species 76
24. REFERENCE LIST 77

CHAPTER 4: FISHING INTENSITY AND DEPLETION STUDIES BASED ON VMS AND LOGBOOK DATA 78

25. INTRODUCTION 79
26. METHOD 81
26.1. Areas *81*
26.2. Data set *82*
26.3. Linking the VMS and logbook data *82*
26.4. Calculation of fishing intensity *83*
26.5. Depletion event analyses *87*
27. RESULTS 87
28. DISCUSSION 100
28.1. Spatial and temporal scale consistency of different data sets *100*
28.2. Fishing intensity *101*
28.3. Depletion analysis *105*
29. CONCLUSION 106
30. REFERENCES 106

CHAPTER 5: THE ASSESSMENT AND RISK ANALYSIS: TIGER PRAWNS 108

31. INTRODUCTION 109
31.1. Types of uncertainty *109*
31.2. Confidence intervals *110*
31.3. The base case *110*
32. METHODS 110
32.1. Population dynamics *110*
32.2. The basic dynamics *111*
32.2.1. Predicted catch in weight 113
32.2.2. Stock and recruitment 114
32.2.3. Parameter estimation 115
32.3. Estimation of MSY *and* E_{MSY} *117*
32.4. Extensions to multiple areas *118*
33. RESULTS 120
33.1. Changes to input parameters and model assumptions *122*
33.1.1. Comparison of the Wang and Die (modified) and Deriso-Schnute assessments 122
33.1.2. Ricker verses Beverton-Holt stock recruitment relationship 123
33.1.3. Fishing power change scenarios 125
33.1.4. Varying the reference year for MSY estimation 127
33.1.5. Transformation of catch data 129
33.1.6. Catchability assumptions 132
33.1.7. Weekly recruitment 134
33.1.8. Multiple stocks 136
33.1.9. Overall summary of sensitivity tests 137
33.2. Incorporating additional process error and variability in the catch and effort data *139*
33.2.1. Error in the catch and effort data 140
33.2.2. Additional sources of process error 142
34. DISCUSSION 144
34.1. Specific issues *144*
34.1.1. The different models 144
34.1.2. Current stock status 146
34.1.3. Key areas of sensitivity 146
34.1.4. Multiple-species considerations 146
34.1.5. Multiple stock considerations 147

34.1.6. Ability to fit the data 147
34.1.7. Implications for the stock assessment process 147
35. CONCLUSIONS 148
36. FURTHER RESEARCH 148
37. REFERENCE LIST 150

CHAPTER 6: FUTURE PROJECTIONS OF THE DERISO-SCHNUTE TIGER PRAWN ASSESSMENT 151

38. INTRODUCTION 152
39. METHODS 153
39.1. Imperfect and perfect knowledge 153
39.2. Future projections 153
39.3. Monte Carlo 154
40. RESULTS 154
40.1. Managing at different effort levels 154
40.2. Recruitment variability 160
40.3. Certainty equivalent versus myopic Bayes 161
41. DISCUSSION 161
42. CONCLUSIONS AND FURTHER RESEARCH 162

CHAPTER 7: FURTHER DEVELOPMENT 164

43. SPECIES SPLIT METHODOLOGY 165
44. STOCK STRUCTURE IN THE NPF 165
45. AUGMENTATION AND IMPUTATION METHODS FOR INCOMPLETE DATA 166
46. INFERRING TARGET SPECIES 166
47. VMS DATA 166
48. STOCK ASSESSMENT 166
49. FUTURE PROJECTIONS 167

APPENDIX A: DESCRIPTION OF THE WANG AND DIE (1996) TIGER PRAWN MODEL AND SOME OF ITS ASSUMPTIONS 168

50. INTRODUCTION 169
50.1. Species split 169
50.2. Logbook catch by species to landings augmentation 170
50.3. Logbook effort augmentation 170
51. INPUT PARAMETERS 171
51.1. Relative weekly recruitment pattern 171
51.2. Relative weekly spawning pattern, maturity and spawning size 173
51.3. Growth 173
51.4. Allometry 174
51.5. Length-at-recruitment, l_r, and mesh selectivity (Somers and Kirkwood, 1991) 175
51.6. Natural mortality 175
51.7. Catchability 175
51.7.1. Catchability and bycatchability 175
51.7.2. Availability to capture 177
51.7.3. Fishing power 178
51.7.4. Overall catchability 178
52. BASIC MODEL DYNAMICS 179
52.1.1. Stock-recruitment relationship 180
53. MAXIMUM SUSTAINABLE YIELD AND RELATED MANAGEMENT OUTPUTS 180
54. SEQUENCE OF WANG AND DIE PROGRAM 180
55. REFERENCE LIST 181

APPENDIX B: BASE CASE 184

56. INPUT DATA 185
57. INPUT PARAMETERS 185

58. REFERENCES: 187

CHAPTER 1: INTRODUCTION

98/109	Risk Analysis and Sustainability Indicators for Prawn Stocks in the Northern Prawn Fishery

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1. Objectives

1 To assess the probability that current NPF prawn stocks are being fished at sustainable levels (as defined by performance indicators of stock status developed by NORMAC) by carrying out a risk analysis.

2 To predict the performance of future NPF management alternatives by comparing predicted stock parameters against NORMAC's performance indicators of stock status.

2. Non-technical Summary

The project outcomes have contributed to:

1. The ecologically sustainable resource base through the use of scientific resource assessments, mitigation strategies, addition of sustainability indicators and performance measures into the Northern Prawn Fishery management plan, and
2. The goal of maximising the economic efficiency of the Northern Prawn Fishery.

These have been achieved by the following project outputs:

1. There is a new robust assessment of the dynamics and status of the tiger prawn species based on a detailed review of the inputs and model assumptions.
2. The distribution and spatial structure of the stock(s) have been established and this information has been factored into a successful new research proposal.
3. There are reliable estimates of all removals and their uncertainty from the fished stock. These estimates have been incorporated into the stock assessment.

There are detailed risk-reward functions that consider the effect of model uncertainty in the reference points. There are tools to investigate management options directly.

This project has been highly successful at determining factors that affect the outputs and outcomes of the model and the uncertainty underlying the model system. The report has been divided into seven broad sections and two Appendices. The first chapter contains the context of the work; the background, need, objectives etc. The main research sections are contained in chapters two to six. Further research recommendations are in Chapter 7. The first of the two Appendices detail the Wang and Die (1996) assessment and the second describes the Base Case used in this report. The first two of the research Chapters investigate in depth the method of splitting the catch and effort into the 6 species major prawn species and augmenting the logbook records (to accommodate missing information) to the known historical landings. Three methods, two of which are new, are investigated and the uncertainty intervals in these methods determined. The subsequent chapters concentrate on tiger prawns.

Chapter 4 investigates the use of Vessel Monitoring System (VMS) data for impacts of trawling and stock assessment studies. Based on recommendations of previous studies, vessels entering three 6-minute by 6-minute grids were polled every 20 minutes. The resultant tracks were calculated and displayed in ARC/INFO. The method developed is new to the NPF.

Chapter 5 is the detailed analysis of the effects of changes to the input data (output from Chapters 2 and 3), the model assumptions and variability. The subsequent output variability of the estimates and management reference points is highlighted. Two new stock assessments were developed, the one is based on the Wang and Die (1996) assessment and the other is a derivation of the Deriso-Schnute assessment. A multi-stock model formulation of these were also developed.

Last, but not least, the Deriso-Schnute assessment is forward projected to a 20-year horizon. This is the first time the standard (albeit modified) assessment of the tiger prawns has been projected. The projections were evaluated in terms of risk (the frequency of the 20th year spawning stock size falling below the spawning stock size at the Maximum Sustainable Yield) and reward (average future catch). Various constant effort (including the effort at the Maximum Sustainable Yield, E_{MSY}) levels were considered. The effects of recruitment variability are also considered.

The report shows that there is little uncertainty in the augmentation method used in the past and surprisingly little difference between the three methods tested. However, there is indication that the species split between *Penaeus semisulcatus* and *P. esculentus* in the last few years has changed substantially, but due to lack of data during that period the results could not be conclusively shown. Sampling of tiger prawn species proportions in the catch is essential as this risk remains undetected and the results on the model output and management advice could be substantial.

The VMS work was novel and highly interesting as little past work on this data type gave us any prior indication of its analysis and usefulness. The high polling frequency data is excellent for fishing intensity studies. Linking the data to the catch and effort logbook information however, was extremely difficult. The spatial scale of the VMS data is much smaller than that of a single logbook record from a night's fishing for one vessel. Combining the high intensity data with surrounding low intensity data was much more useful. Unfortunately, access problems to the data severely compromised the research, and resolving these difficulties should be a high priority to enable this promising research to be completed expeditiously.

The highest risk that would affect the management advice is the level of fishing power. Three levels of constant proportional increases in annual fishing power were compared with two other schemes where annually varying rates were used. These latter effort increase schemes were produced by the Northern Prawn Fishery Assessment Group in conjunction with D J Sterling. In almost all the risks tested, the tiger resources were deemed to be overexploited. The results also show the productivity of the resource to be surprisingly low. The present reference points relating to the Maximum Sustainable Yield could only be estimated with high uncertainty. It is recommended therefore that appropriate reference points for a highly variable short lived and input controlled resource is determined as a matter of urgency.

The future projections show distinct risk-reward relationships for the two tiger prawn species. The mid-season closure has been extremely beneficial for *P. semisulcatus*. This, combined with the fact that little effort is directed towards the species in the first half of the year, allows many prawns to spawn before capture. This is not the case for *P. esculentus* as a large portion of the effort in recent years occurred in the first half of the year. At low levels of effort, the largest component of risk is recruitment variability. This high level of recruitment variability is combined with serial correlation. Constant effort levels can at certain times be sequentially higher than is appropriate for the below average recruitment. The low productivity of the resource does not easily allow full recovery during the above average recruitment years. It is recommended that a more variable management option be investigated in a management Strategy Evaluation framework. The feedback loops will reveal whether increased management variability and/or the availability of certain data would be beneficial (given its cost) by lowering the risk for little or no decrease in reward.

3. Keywords

Northern Prawn Fishery, prawn trawl, uncertainty, species split, stock assessment, risk analysis, projection

4. Background

The Northern Prawn Fishery (NPF) is the most valuable Commonwealth-managed fishery in Australia, with the value of production exceeding $100 million a year. The fishery is managed by AFMA with the help of the NPF management advisory committee (NORMAC). Management of the NPF has for many years focused on the sustainable utilisation of those renewable resources harvested by the Northern Prawn fleet. This has been supported through the provision of scientific advice on the status of target stocks and the impacts of fishing. This advice has been critical for the management of the NPF.

The NPF is based on three prawn species groups, each with at least two species. Common banana prawns are heavily influenced by the environment and less affected by fishing pressure than the other species. Tiger prawns on the other hand have been shown to be prone to recruitment overfishing. Excessive fishing effort in the 1980's led to the decline in tiger spawning stocks which was only halted through large, controversial and costly, fishing effort reductions. These reductions were achieved through a combination of licence buy-backs, proportional licence surrenders and new seasonal closures and bans on daylight fishing. Current assessment of tiger prawn stocks suggest that these adjustments stopped the decline in spawning stock biomass but were not sufficient to allow the stocks to recover to their most productive state. We do not know the status of endeavour prawns and red-legged banana prawns, but it is likely that their stocks will be subject to increased fishing pressure as fishing for tiger prawns becomes less profitable.

There is evidence that in spite of the apparent effort freeze by the A-unit system, effort has continued to increase. There is mounting evidence that the result of this continued increase in fleet efficiency is leading to fishers being able to target the most productive prawn aggregations more effectively, thus increasing the impact of fishing upon the stocks.

Addressing the issue of accurately ascertaining the real effect of fishing effort on prawn stocks is central to meet the two main management objectives of this fishery: maximisation of economic efficiency (MEE) and compliance with the principles of ecological sustainable development (ESD) .

5. Need

To assess whether the MEE and ESD objectives are met there is a need to determine the status of prawn stocks in the NPF and to develop guidelines to clarify whether the present status of the resource requires management action. For this purpose it is clearly important to define precisely what population parameters should be monitored and the biological reference points to which these parameters should be compared.

The Northern Prawn Fishery Assessment Group (NPFAG) has identified that *spawning stock biomass* and *standardised fishing effort* are the two most important indicators that need to be set and reassessed as new information is collected. The NPFAG has also recommended that future advice provided to them by researchers should include a careful estimation of probabilities that each of these targets may be exceeded. Calculation of such probabilities requires a formal risk analysis to be carried out as part of the stock assessment. Additionally, there are a number of future management options that have recently been implemented such as gear restrictions as well as further seasonal and spatial closures.

Although the implications of these options have been considered by NORMAC, their scientific evaluation was not carried out in any structured way. Instead, individual assessments were made of the different options as they were proposed by NORMAC. There is a need to establish a structured framework for management strategy evaluation so that the NPFAG and NORMAC can compare different options in a consistent way. This framework for management strategy evaluation should allow for the integration of risk analysis into the evaluation of management options. The consequences of each management strategy should be quantified and evaluated against the indicator of performance established by the NPFAG. The evaluation should include the estimation of the probability that, in the future, certain undesirable or desirable states of the stocks are reached.

6. Acknowledgements

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Mr Quinton Dell (Risk analysis processor, running and collating model runs, project scientific support)

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Dr Andre Punt (Population dynamics, development of new models with confidence intervals and future options, programming)

Dr Bill Venables (Statistical modelling, development of augmentation and species split methodology)

CHAPTER 2:ON SPECIES SPLIT

8. The Species Split Problem

8.1. An outline of the problem

The logbook records give prawn catches in daily totals for each of the four species groups *Tiger, Endeavour, King* and *Banana.* Each of these species groups is a composite of two dominant biological species, namely, *Penaeus semisulcatus* and *P. esculentus* for Tigers, *Metapenaeus endeavouri* and *M. ensis* for Endeavours, *P. latisulcatus* and *P. longistylus* for Kings and *P. merguiensis* and *P. indicus* for Bananas. For each group the two species occupy different ecological niches and hence stock assessment should ideally be done for each species separately. This in turn implies that from each logbook record a separate catch for each species of each composite group somehow has to be inferred. Of course such inferences will not be without error, so some assessment of the likely error also has to be established. This is the species split problem.

8.2. The Wang and Die split procedure

Previous survey work mainly in the Gulf of Carpentaria (see, for example, (Somers, 1994) and references therein) suggests that for the Tiger prawn group at least the substrate mainly determines the prawn species at any particular location, which therefore remains static in time. This finding is based on data from CSIRO prawn surveys. This survey data has been collected in various ways since 1979 and ranges much more widely than the restricted section of the Gulf of Carpentaria that forms the focus of the Somers study but it does not include the substrate data needed to infer the species accurately given the Somers' hypothesis.

Until very recently the logbook records only give the catch location at a fairly coarse spatial scale. They ascribe the nightly catch for vessel to the $6' \times 6'$ grid in which most of the night's fishing was done. It is known that substrate type can be quite variable, even within some $6'$ grids and that tiger prawn trawls can continue for long periods of time covering a very wide area. The Wang and Die solution to the species split problem was as follows:

1. Use the survey data to give a relative split, by weight, for each species for all grid squares included in the surveys.
2. If a logbook record is ascribed to a grid square for which survey-based split proportion estimates are available, partition the record in the same ratio.
3. In other cases use the split proportions for the geographically nearest grid square for which survey-based estimates are available.

Note that the split is made essentially deterministically and from that point of the process the procedure is the same as if the actual catches of both species were separately, accurately recorded.

It is important to note also that this procedure is ***not*** based on an assumption that the $6'$ grid squares are homogeneous in substrate composition. It does assume that logbook records ascribed to any particular grid correspond to sets of trawls that, on average, cover similar territory with respect to their substrate composition.

8.3. Problems with the Wang and Die procedure

While we agree that the Wang and Die procedure is probably sufficiently accurate for large-scale stock assessment of each species to be realistic, we note the following possible problems and deficiencies that it may entail.

- The grid squares are unevenly surveyed. Some squares are heavily sampled and others not at all. While it can be argued that this kind of unevenness in the accuracy of split proportion estimates will tend to be evened out in the final aggregation process the true effect is unknown. Another way to view this is to note that the survey data is inefficiently used: in selecting only the closest grid square for the split proportions the data for adjacent grid squares is ignored.
- More seriously, there is a strong assumption that the split proportions are effectively constant throughout the season. It is known that the two tiger species have different movement patterns throughout the breeding cycle (Somers et al. 1987) with *P. semisulcatus* moving offshore to breed and back again and *P. esculentus* tending to remain inshore for most of the season. This strongly suggests that constant split proportions for each grid square will tend to over-represent one species at certain times of the year and under-represent it at others in a predictable and systematic way.
- The procedure admits of no easy or obvious way of assessing the possible level of error. The split procedure, at least at the level of weekly aggregation of catch and effort over the whole fishery, is assumed to have negligible error and this assumption is not easily tested in the current framework.

We propose a more formal way of using the survey data in a way that attempts to make optimal use of all relevant information for every split of the logbook records. At the same time the new method will provide an assessment of the error level involved and allow some of the implied assumptions underlying the present procedure to be tested and where they prove to be unreliable, corrective action to be taken. Before doing so, though, we briefly review the sources of survey data used in this project.

9. Survey data

9.1. Origins and extent

For this study the survey data is an aggregation of nine individual data sets and some details of their origin and method of collection are given in Table 1. In all cases subsamples of prawns are taken from within a trawl station and completely classified by species and sex. For each animal the carapace length was recorded. Where the subsample was drawn from a commercial trawl by an on-board observer the size of the sample is generally smaller than for a sample taken from a station on a dedicated research vessel.

We note here that the data from commercial trawls is, for this purpose, probably better than the research vessel data as it is sampled from trawls more like those of the logbook data. In general research vessel trawls are of shorter duration and hence cover a more limited and homogeneous set of substrate types.

Table 1: *Data sets used in species composition modelling for the NPF*

Origin	Method	Coverage	Period
CSIRO *Redfield* cruises	Scientific cruise	Eastern Gulf of Carpentaria	1975-1979
NT Fisheries Western Gulf project	Scientific cruise	North Western Gulf of Carpentaria	1979
KFV quality control	Observer on board commercial vessels	Entire NPF	1980-1983
CSIRO commercial catch sampling	Observer on board commercial vessels	Entire NPF	1988-1990
CSIRO *Maxim* cruises	Scientific cruise	North Western Gulf of Carpentaria	1983-1985
CSIRO Albatross Bay study	Scientific cruise	North Eastern Gulf of Carpentaria	1986-1992
CSIRO banana prawn sampling	Scientist on board commercial vessel	South Western Gulf of Carpentaria	1989
CSIRO *Southern Surveyor* cruises*	Scientific cruise	Entire NPF	1991-1998
CSIRO try-net sampling *	Scientist on board commercial vessels	Gulf of Carpentaria	1996-1997

* This data set has not previously been used for species composition studies.

The survey data collection began in 1976 and for this study the latest data used was collected in 1998.

Table 2 gives the numbers of stations contributing to the survey data for each year between these limits. The same frequency information is displayed in Figure 1. It can be seen that the surveying effort is unevenly distributed over the years, with several peaks of activity.

Table 2: *Numbers of stations for each year of the survey data, 1976-98*

Year:	*1976*	*1977*	*1978*	*1979*	*1980*	*1981*	*1982*	*1983*	*1984*	*1985*	*1986*	*1987*
Stations:	50	930	1244	817	50	0	0	463	1221	253	266	341
Year:	*1988*	*1989*	*1990*	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*	*1998*	***Total***
Stations:	1029	1107	944	275	118	42	172	18	357	1332	289	**11318**

Figure 1: *Annual numbers of stations in the NPB survey data*

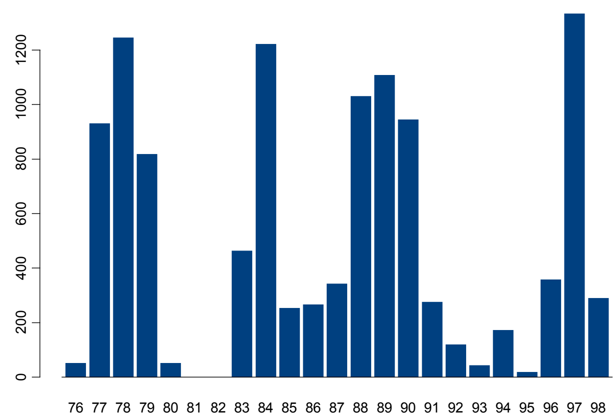


Figure 2: *The location of survey stations by year, 1976-1999*

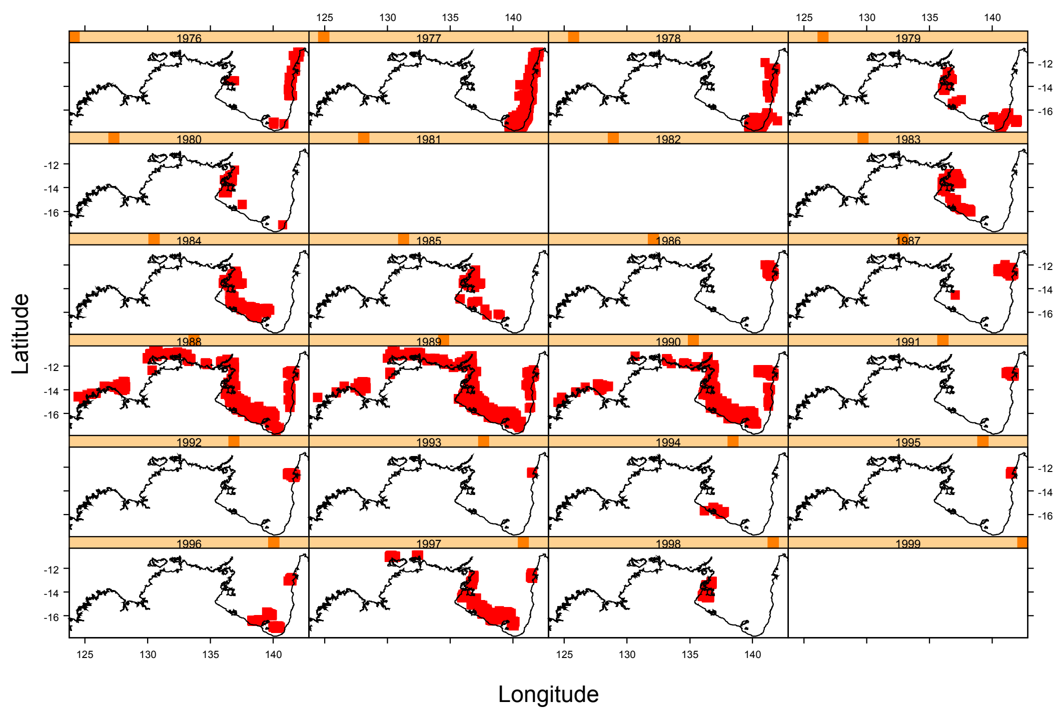


Figure 2 shows the distribution of survey stations by "prawn year" (starting on 1 October of the *previous* calendar year) for each of the 21 survey years between 1976 and 1999. It can be seen that a good coverage of the spatial extent of the NPF was only achieved in the years 1988-90.

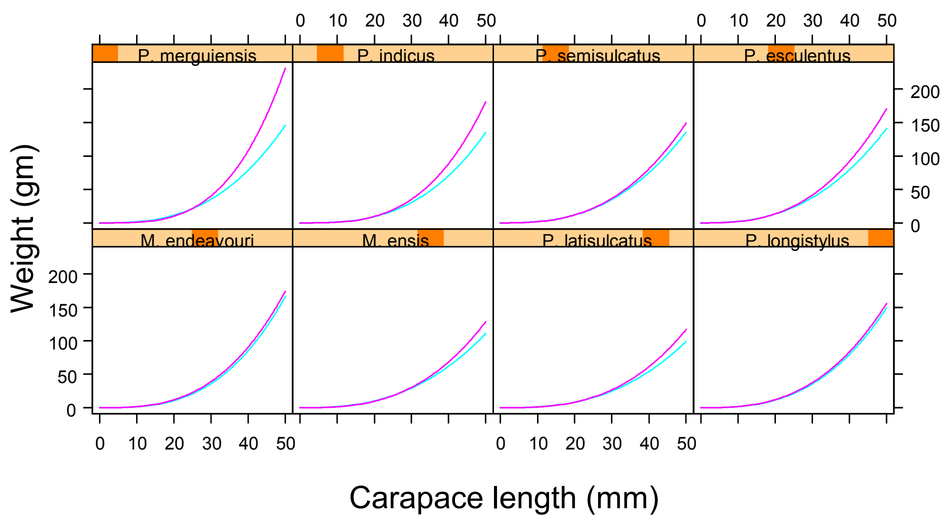
9.2. Conversion to aggregate weights

Since the logbook data only records total weights it is then necessary to convert the individual prawn data into mass aggregates for the station. This is done using calibrated power-law relationships predicting weight of the animal given carapace length and sex (see, for example, (Wang and Somers, 1996) and references therein).

$$W = \alpha L^{\beta}$$

Here W is the weight in grams, L is the carapace length in millimetres and α and β are species- and sex-specific constants listed in Table 3. The curves themselves are shown in Figure 3.

Figure 3: *Length-weight relationship curves for 8 prawn species, females (grey) and males (black)*



Errors in these relationships are assumed to be negligible for the purposes of subsequent analysis. It is known that the relationships are very close fitting and accumulating weights for many animals over a station will tend to even out errors as well.

Table 3: *Length-weight relationship parameters and their origins*

Species	Sex	α	β	Location	Source
701901 *P. meguiensis*	F	0.00175	2.767	Gulf of Carpentaria	CSIRO (1974) (Unpublished data)
	M	0.000197	3.413		
701306 *P. indicus*	F	0.000889	2.914	Joseph Bonaparte Gulf	NT Fisheries (1990) (Unpublished data)
	M	0.000373	3.197		
701307 *P. semisulcatus*	F	0.00265	2.648	Arabian Gulf	(Farmer, 1980)
	M	0.00195	2.746		
701308 *P. esculentus*	F	0.00373	2.574	Shark Bay	(Penn and Hall, 1974)
	M	0.00207	2.764		
701320 *M. endeavouri*	F	0.0008	2.9897	NE Gulf of Carpentaria	Young (1999)
	M	0.0011	2.9235		
701322 *M. ensis*	F	0.0026	2.603	NE Gulf of Carpentaria	Young (1999)
	M	0.0012	2.8284		
701904 *P. latisulcatus*	F	0.001557	2.701	Shark Bay	(Penn and Hall, 1974)
	M	0.0008474	2.8899		
701303 *P. longistylus*	F	0.0015	2.81	Torres Strait	Watson (1990)
	M	0.0017	2.79		

10. A model-based approach to the species split problem

To us it seems natural to use the survey data to develop and calibrate a statistical model for predicting the unknown species proportions. The specific advantages this approach offers include

- The model acts as a basis for interpolation and extrapolation from the survey data in a reasonably optimal way thus allowing the species split to use more of the relevant information than just the crude survey proportions splitting method.
- A parametrically economic model will smooth the data, that is, remove some of the randomness, which is then not passed on to the splitting process.
- An effective statistical model will allow the level of error to be realistically assessed and allowed for in later analyses or simulations.
- A model will allow important hypotheses about the species mixing process to be investigated and it can be more flexibly adapted to take some account of influences that the simple grid proportions method cannot.

For ease of presentation we will start with the Tiger prawn group and consider Endeavour and Banana prawn groups later.

10.1. Response and predictor variables

Our goal is to build a model that will predict, as accurately as possible, the proportions of a logbook catch, by weight, belonging to each particular species. Since in all cases the total catch is a mixture of only two species we may focus on predicting the proportion for one of those two and the other must be the complementary proportion.

For definiteness we will focus initially on the Tiger group and build a model to predict the *P. semisulcatus* proportion. We will see later that a very similar modelling strategy works well for the Endeavour group, but an entirely different modelling technique is appropriate for the Banana group. With the King group the survey information is so sparse and limited that we can find no species split technique that is anywhere near satisfactory for stock assessment purposes. This is not surprising given that the overall catch of King prawns in the NPF is itself relatively small.

Returning to Tiger prawns, it is known that *P. semisulcatus* is the more wide ranging and mobile of the two species (Somers and Kirkwood, 1991). The conclusion of Somers (Somers, 1987) nevertheless is that *substrate type* is the dominant influencing variable for the species split proportion in the sense that the two species do not occur together on the same substrate. While this may be true we find there are good reasons to look beyond *substrate type* for predictor variables for the species split. These include

- Substrate information is only available for a limited region of the Gulf of Carpentaria and a satisfactory species split method is needed for the entire NPF. Even if substrate information were used where it was available, surrogates would need to be used elsewhere. A uniform model covering the entire NPF will be simpler and easier to use.
- Even if the Somers hypothesis is true, there are many regions of the NPF where the substrate type changes quickly or grades from one to another so a single commercial trawl can cover several substrate types even within the one grid square, leading to a mixture of prawns in the net even if none exists on the ground. It is the features of the environment around a grid square that determine this mixture, not just the dominant substrate type.
- The two species breed at generally different times of the year and their movements in response to the breeding cycle are different. Hence the time of year may well be an important variable for determining the split proportion, given that trawls themselves in some areas are expected to range over different substrate types.

Given a station in the survey data we take as the response the observed proportion:

$$Y = \frac{\text{Weight of } P.\,semisulcatus}{\text{Total weight of Tiger prawns}} \tag{1}$$

In other words the conversion from individual carapace lengths to weights and aggregation is regarded here as part of the measurement process and not considered by the model. The model assumes that Y is a random variable with mean value and variance of the form:

$$\mathrm{E}[Y] = \varpi, \qquad \mathrm{Var}[Y] = \frac{\varpi(1-\varpi)}{T/\varphi} \tag{2}$$

The value ϖ in equation (2) represents an ideal proportion about which the response value, Y, is distributed. The form of the variance of this distribution, also specified in, (2), recognizes that the amount of variation will be small if ϖ is near 0 or 1 and larger if the ideal proportion is closer to 0.5. The quantity T in the denominator is the total weight of prawns so according to the model the variation in the distribution of the observed proportion decreases as the total weight of prawns on which it is based increases. This seems intuitively reasonable. The parameter φ in the denominator expression is an unknown scalar constant. A heuristic argument in favour of these model properties we find persuasive is the analogy with a binomial proportion. We argue later that the stochastic behaviour of the observed proportion is similar to that of a binomial relative frequency based on $n = \lceil T/\varphi \rceil$ trials with probability of success ϖ on each, independently and use this as a basis later for simulation.

Rather than specify a definite distribution for Y we postulate a quasi-likelihood model with the above properties. (See, (Anonymous1999), Chapter 6).

The predictor variables will influence the distribution of Y through the ideal proportion ϖ, but since this is a quantity bounded between 0 and 1 it is more convenient to introduce a logistic link function and assume that the predictors act linearly in the same way as in logistic regression. That is

$$\log \frac{\varpi}{1-\varpi} = \eta = \beta_0 + \beta_1 x_1 + \cdots + \beta_p x_p \tag{3}$$

The quantity η is conventionally called the *linear predictor* and the predictor variables, $x_1, \ldots, x_p$ are yet to be defined. Notice that unlike ϖ, η is on an unrestricted scale with $\eta = 0$ corresponding to $\varpi = 0.5$ and $\eta \to \pm\infty$ as $\varpi \to 1$ or 0, respectively.

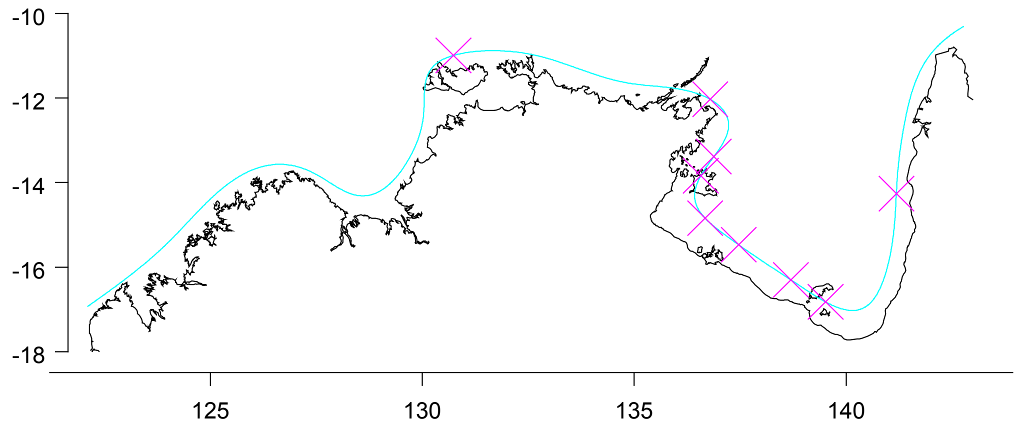
In choosing predictor variables we strive to find ones where a simple model, involving as few interaction terms as possible, will be appropriate.

10.1.1. Location

Rather than use latitude and longitude directly as predictors we find it more effective to represent station locations in the fishery by two quantitative predictors, namely

- The distance to the nearest point on the coastline, that is 'to dry land' (variable Rland) and
- The distance along an arbitrary curve running nearly parallel to the coast of the closest point on the curve to the station (variable Rdist).

Figure 4: *Curve defining position along the coastline in the NPF. The crosses show the nine internal knot positions used for a natural spline term in the linear predictor*



The curve we have chosen to define the variable Rdist is shown in **Figure** 4. It runs through the main fishing areas and is intended to act as a surrogate for major substrate changes along the coastline. Rather than use Rdist itself as a predictor we use a natural spline basis that allows the fitted linear predictor to depend on the variable in a flexible curvilinear way. The crosses in Figure 4 indicate the locations of the knots and to some extent indicate where the curve changes most rapidly as well as where the bulk of the survey information has been sampled. Some experimentation suggests that nine internal knots, at least, may be used and the internal knot positions are shown as crosses on the curve in **Figure** 4**.** These are close to the deciles of the Rdist variable for the stations in the logbook data rather than the survey data.

Similarly for the "distance from dry land" variable, Rland, we choose a natural spline term but with fewer knots, namely four internal knots at the quantiles of the corresponding variable for the logbook data.

10.1.2. Other predictors and interactions

Two other variables we use are

- Depth, as measured using a digital elevation model for the NPF kindly supplied by Fiona Manson. This variable is also fitted within a natural spline with five internal knots at the quantiles of the depths for the logbook data.
- PDay, the "Prawn day", that is, the day number from within the annual prawn season, conventionally regarded as commencing on 1 October. This term should be harmonic and we represent it using two terms of a Fourier series with 12- and 6-month periods respectively. Since both sine and cosine terms are present for both periods, this accounts for four degrees of freedom.

In addition to the four "main effect" terms outlined above the model building process has shown that an interaction term in PDay and Rland is necessary. This is included as product terms of (median corrected) Rland with the 12-month period sine and cosine terms in PDay, thus accounting for a further two degrees of freedom.

10.1.3. The final linear predictor model

The final model form for the linear predictor may be specified as follows:

$$\begin{aligned}\eta = \beta_0 &+ S_{10}(\text{Rdist}) + S_5(\text{Rland}) + S_6(\text{Depth}) \\ &+ H_4(\text{PDay}) + LH_2(\text{Rland, PDay})\end{aligned} \tag{4}$$

where apart from the leading intercept term with 1 degree of freedom, the degrees of freedom associated with each term is shown as a subscript. (Note that a spline term with k knots accounts for $k+1$ degrees of freedom.) The next three terms are natural spline main effect terms with knots at suitable quantiles of the same variable in the logbook data; the fifth is the harmonic term in 'Prawn day' and the last the linear$\times$harmonic interaction term.

The presence of this interaction term technically complicates the interpretation of the main effect terms involving the same variables. However the interaction term is chosen so that its basis is approximately orthogonal to the main effect terms, it has fewer degrees of freedom and the effect it carries, although appreciable, is of smaller magnitude than that of the main effect terms. This means the main effect terms represent a general level averaged over the smaller interaction and thus do have a reasonably clear meaning.

The main effect components are shown individually in **Figure** 5. The solid line is the estimated component in each case and the dotted lines on either side give approximate 95% pointwise confidence intervals for the estimated curve. Where these bands widen it is a sign that the information base is not sufficiently extensive to estimate the curve accurately. The short vertical hairlines at the base of each graph, called the *rug*, show where observations of that determining variable occur.

The contour plot in Figure 6 shows how the split proportion is estimated to vary at a hypothetical location near Groote Eyelandt ($\text{Rdist} = 22.5^\circ$) and at a constant depth of 30m. These components have to be carefully interpreted but the overall impression they give is that grooved tiger prawns (*P. semisulcatus*) are a relatively low proportion of the tiger prawn catch in the southern Gulf of Carpentaria but the overall proportion varies a great deal around the coastline. There is a period of the year when grooved tigers fall as a proportion of catch, but this is more sharply defined in areas far from land than in inshore regions. Grooved tigers are overall a bigger proportion of the catch in deeper water than in shallow and further from land rather than inshore.

Finally it should be noted that despite the relatively large survey database there are still many regions where split proportions are weakly estimated and further monitoring of the situation would appear to be prudent.

Figure 5: *Tiger prawn split model: main effect additive components of the linear predictor. Distances are in 'geographical degree' units and depths are in metres. The vertical scale is the same for all four plots.*

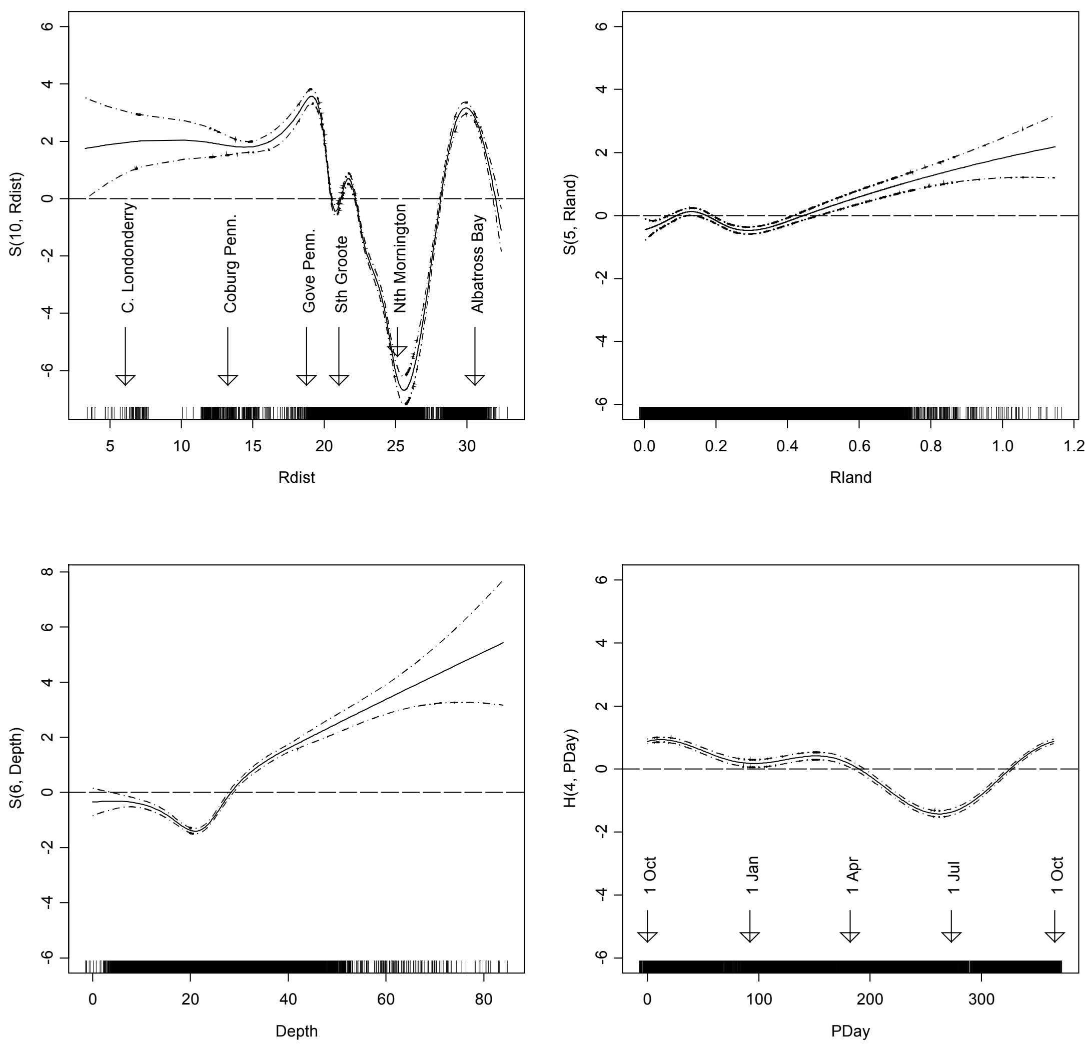
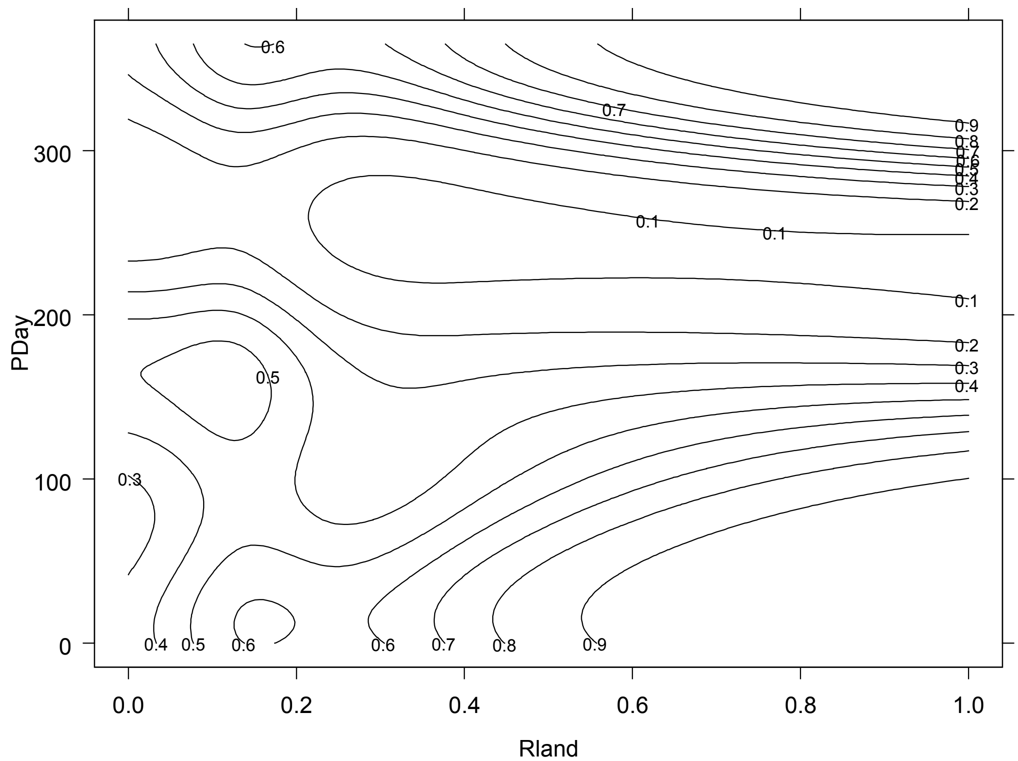


Figure 6: *Combined effect of PDay and Rland on the Tiger split proportion at a hypothetical location in the Gove-Groote Eyelandt region at a constant depth of 30m.*



11. A test of empirical and model-based split methods for Tiger prawns

The survey data is a collection of small samples of prawns from trawls that have been laboriously classified by species and sex and their carapace lengths accurately measured. By contrast the logbook records are typically large, imprecisely classified catches reported only as a total weight for each species class. Small catches are often highly variable so it is difficult to make a realistic comparison of the split methods using only survey data. One way to gain some insight on this is as follows:

1. Divide the data into two groups: the pre-1995 and 1995-1998 data sets. (The present stock assessment procedure is, in fact, based only on the pre-1995 survey data.)
2. Using the pre-1995 data set *only*, re-estimate the statistical model and calculate the grid square proportions.
3. Using the grid square proportions found in 2, predict the weight of one of the Tiger species, say *P. semisulcatus*, for each station in the 1995-1998 data.

4. Using the proportions from the re-estimated model found in 2, predicted the weight of *P. semisulcatus* for each station in the 1995-1998 data.
5. Arrange the stations in some reasonably natural way, such as according to their distance along the coastline (variable Rdist) and group them contiguously so that for each group of stations the total Tiger catch is sufficiently large. We have chosen 3kg as the target Tiger total which is still quite small compared to a commercial catch but will at least start to show the smoothing effect of large catches we need to make the comparisons realistic.
6. Plot the actual total catch of *P. semisulcatus* for each group against the predictions and compare the values with the straight line $y = x$, which would be exactly matched if the predictions were accurate.
7. For more geographic specificity, divide the groups themselves into, say, 9 geographically more coarse groups and perform the plots as 9 sub-plots, each referring to a wider geographic region.

In the following demonstration the fine groups were formed by working from west to east along the Rdist curve and grouping them contiguously so that the fine groups had a total Tiger prawn catch in the region of 3kg. The fine groups were then collected into 9 more coarse groups of about 26 points each. Each of these coarse groups forms a panel in a display.

Figure 7: *Arbitrary grouping of 1995-99 survey stations into 9 groups by distance along the coastline*

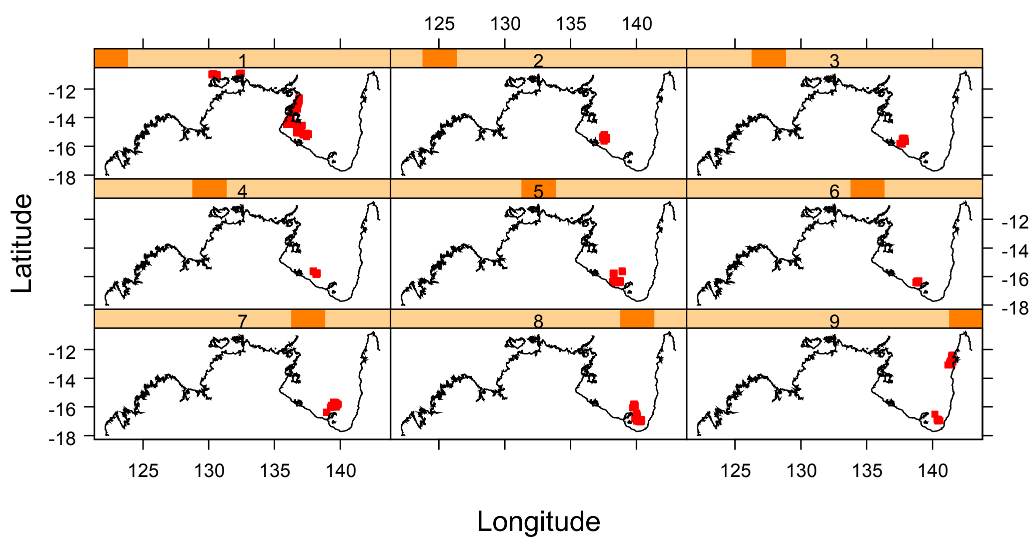


Figure 7 shows the positions of the original stations prior to grouping corresponding to each of the 9 panels in the display. Clearly panels 1 and 9 are widely spread but the intervening panels correspond to fairly compact groups along the southern edge of the Gulf of Carpentaria.

Figure 8 shows the predicted catch of *P. semisulcatus* in this sense using the empirical grid proportions method. It is clear that some volatility exists even after combining survey samples presumably due to the fact that the nearest grid square may well have been lightly sampled. There is also an apparent downward bias in panels 2 to 5 which we discuss later.

Figure 8: *Predicted catch of* P. semisulcatus *for 1995-99 survey data using the empirical grid proportions method, classified by area within the NPF*

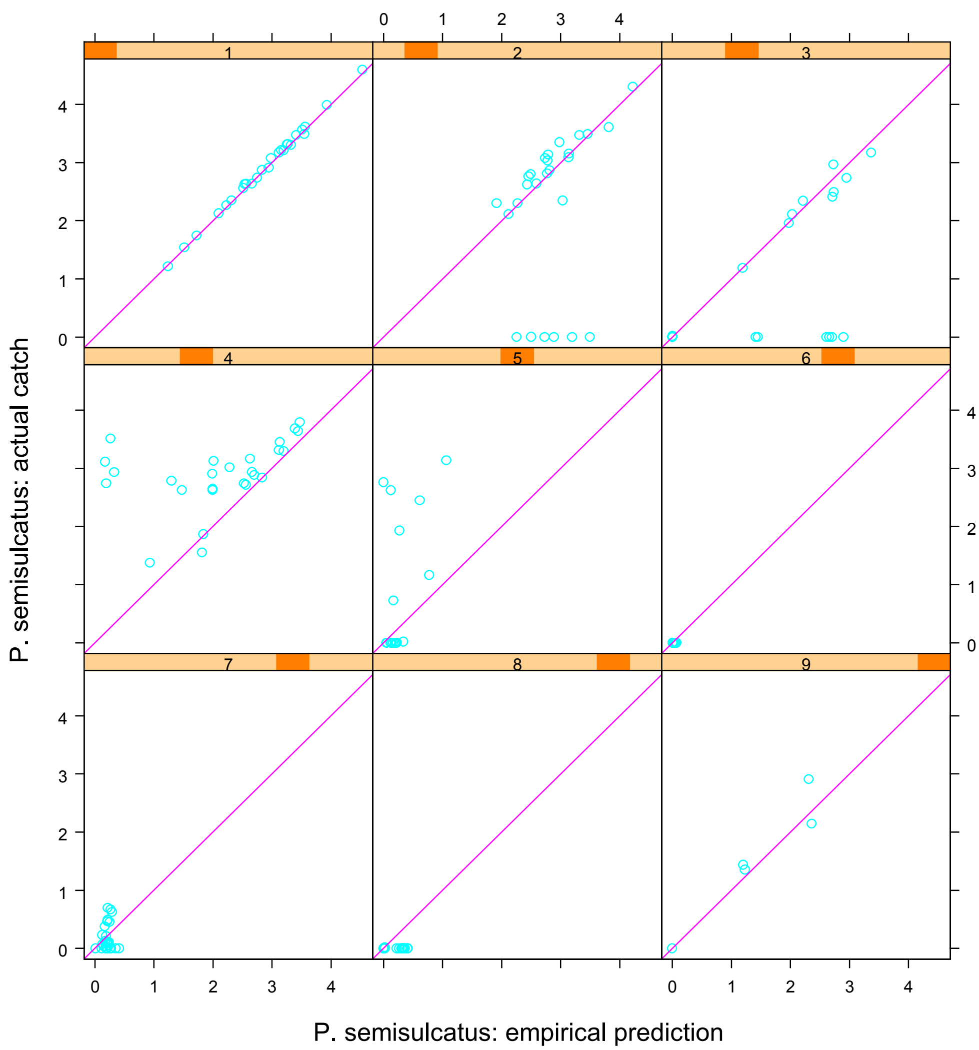


Figure 9 shows the results of the same exercise using the model-based approach. Evidently much of the volatility is removed but the predictions in some panels is still not very good, though possibly adequate for stock assessment purposes.

Figure 9: *Predicted catch of* P. semisulcatus *for 1995-99 survey data using the statistical model, classified by area within the NPF*

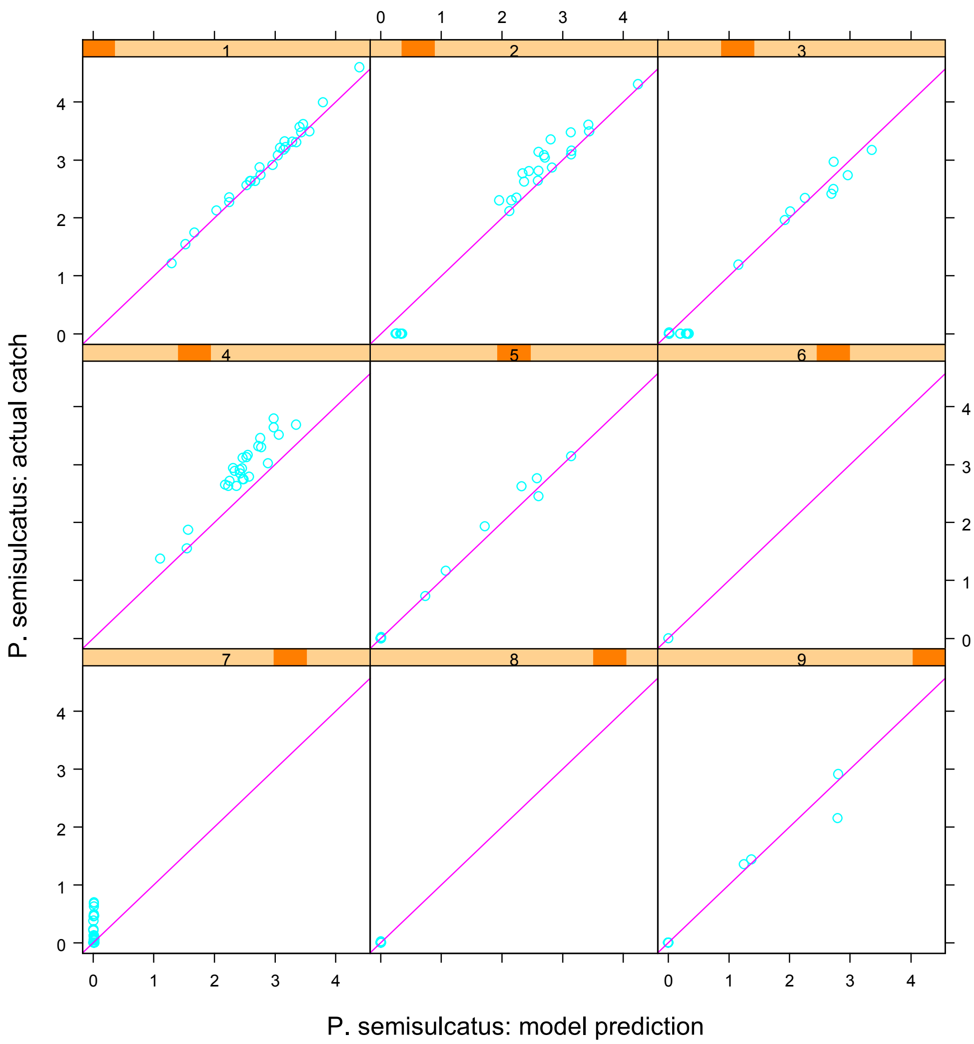


Table 4: *P. semisulcatus percentages of the total sample take in each of the 9 groups estimated by the empirical and model methods, as well as the actual (true) percentages***.**

Group	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Empirical	97.57	93.62	46.23	68.84	7.77	1.10	7.02	3.92	12.82
Model	96.90	71.66	30.60	80.93	18.42	0.04	0.39	0.07	14.83
(Modified)	98.99	77.26	33.69	92.98	19.83	0.02	0.61	0.10	13.88
Actual	98.82	74.77	27.75	95.66	19.14	0.00	6.28	0.03	14.17

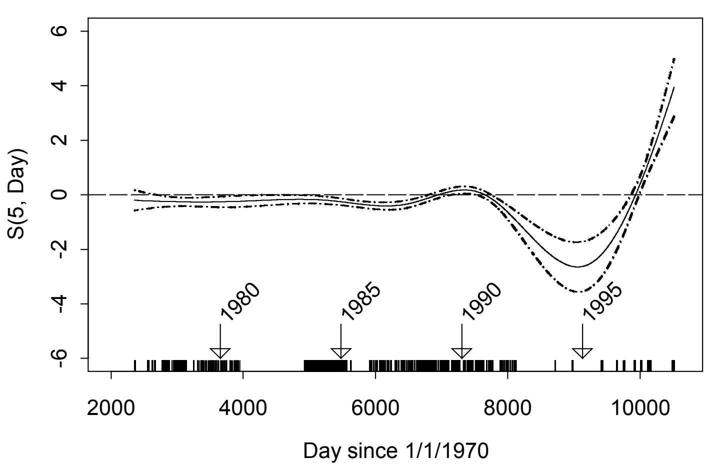
If we further reduce the data by calculating the predicted total *P. semisulcatus* sample take for each panel of the diagrams and the actual total and express these as percentages of the total Tiger prawn sample take the results are shown in **Table 4**. (The row marked "(Modified)" in this table will be discussed below.

The panels differ markedly in the proportions of Grooved Tiger prawns in each; the only place where the empirical method does appreciably better than the model-based approach is panel 7, for which most of the stations are directly north of Mornington Island.

11.1. Discussion

The tendency for both methods in this demonstration to predict lower proportions of Grooved Tigers than appears in the samples in some panels is of some concern. One way to investigate this is to fit a model to the entire data set that contains a smooth term in the time since 1/1/1970, that is the number of days. This is a way of checking for an overall long-term trend in the proportions that the current modelling procedure assumes is negligible. This is also true of the empirical proportions method, of course. We assume a natural spline term in the 'day count since 1/1/1970', Day, variable with 5 interior knots at quantiles of the logbook Day distribution. The extra component of the fitted model is shown in **Figure 10.** It suggests strong stability up until 1990, followed by a period of instability where there was a sudden drop in the proportion of Grooved tigers followed by an even more dramatic rise.

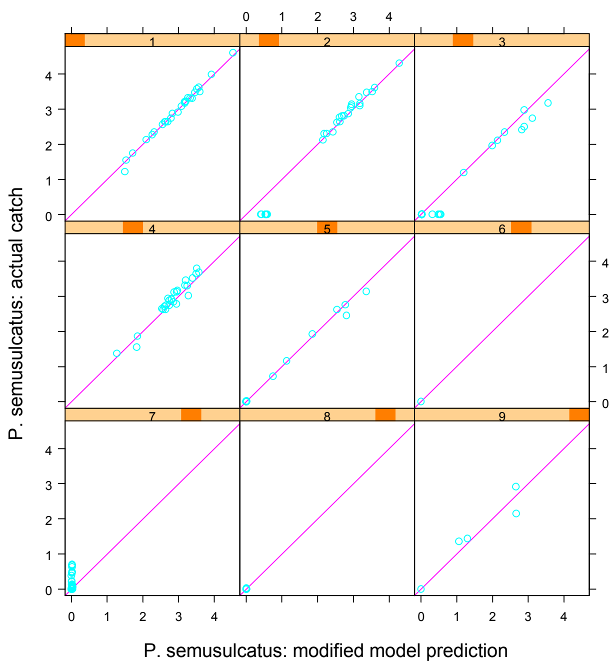
Figure 10: *Long-term trend component in Tiger logistic split proportion*



We hesitate to claim at this stage that this dramatic looking instability in the overall proportions is real, as it only established by a relatively light surveying effort and several possible explanations as a confounding effect with other uncontrolled factors have yet to be ruled out. Nevertheless it does indicate that continuing survey data is urgently needed to settle this question and more importantly to monitor the stability of the split proportions over time.

Our method of estimating the parameters of the model from the pre-1995 data and testing the model predictions on the 1995 and later data will clearly not be sensitive to this potential instability, which has really only appeared in the data since 1994. One way of checking whether this kind of adjustment will remove the apparent biases in the previous model predictions, however, is to keep this long-term trend component as a fixed, given part of the model in both the estimation phase and in the predictions. If we do this we obtain the line marked "(Modified)" in **Table 4** and the comparison shown in **Figure 11.**

Figure 11: *Predicted catch of* P. semisulcatus *for 1995-99 survey data using the modified statistical model, classified by area within the NPF*



Some improvement in the comparison was almost assured by the fact that this model now partly depends on the data used for the comparison itself. Nevertheless it does show a substantial improvement and larger than might have been expected if the correction were in reality not needed. Panel 7 is still not well accommodated, though, and seems to correspond to a small area north of Mornington Island with a small but persistent quota of Grooved tiger prawns that is systematically omitted by the model. We are reluctant to expend further degrees of freedom in the model to rectify this, however, as the weight of animals involved is relatively small and there are many other highly local regions with this possible phenomenon and, of course, an unknown number in regions not surveyed.

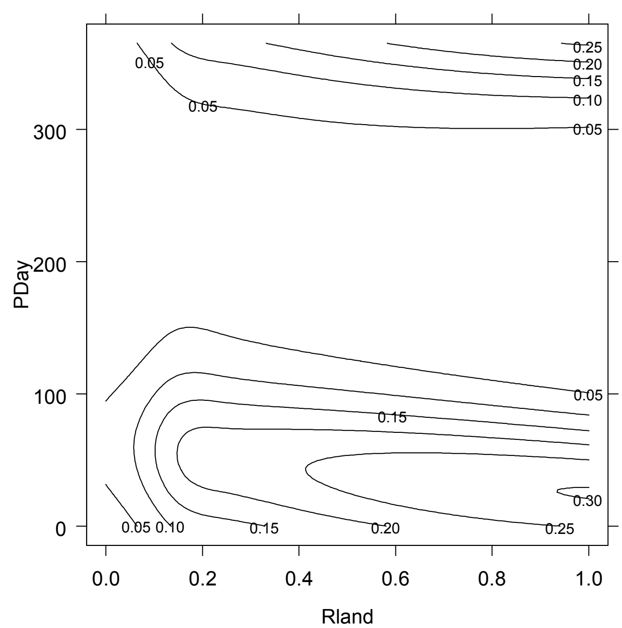
12. Endeavour prawn split models

The Endeavour prawn group are a mixture of *Metapenaeus endeavouri* and *M. ensis*. As they are a commercially less valuable group, they tend to be caught incidentally with Tiger prawns rather than specifically targeted to any great degree. As a group they also behave in some respects similarly to the Tiger group. *M. ensis* is the more mobile species; like *P. semisulcatus* it has a regular pattern of movement off shore at various times of the year whereas *M. endeavouri* is like *P. esculentus* and tends to be more sedentary and favour shallower waters. It seems entirely likely that the two component species partition the environment and use it in a very similar way to the way the two component Tiger prawn species do. (See, for example, (Somers, 1994) and references therein.)

The survey data for the Endeavour group is not as extensive as for the Tiger group and what data there is makes clear that one species, *M. ensis*, is much more rarely caught than the other. This makes it difficult to construct very precise split models.

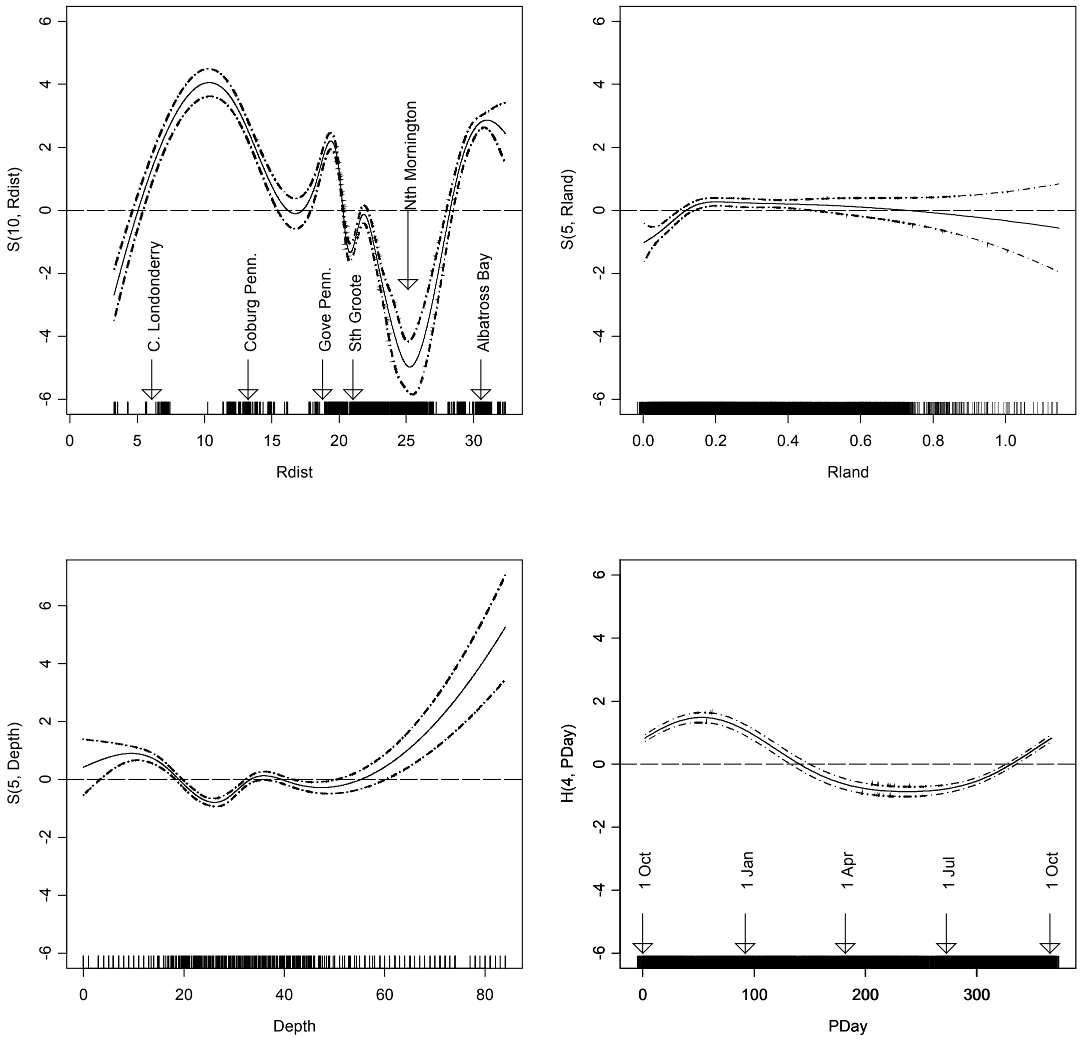
For several reasons including simplicity and comparability we decided to use exactly the same form of split model as we used for the Tiger group. This decision was justified by the normal model construction techniques as well. The 'main effect' additive components are shown in Figure 13**.** The interaction effect of Rland and PDay is shown in Figure 12.

Figure 12: *Combined effect of PDay and Rland on the Endeavour split proportion at a hypothetical location in the Gove-Groote Eyelandt region at a constant depth of 30m***.**



The similarity of these components to those for *P. semisulcatus* in the Tiger group is clear but not strikingly similar. The marginal effect of distance from land is now quite weak and mainly carried in the interaction with prawn day. The main difference is that the proportion for *M. ensis* is uniformly smaller than that for *P. semisulcatus*. This is clear, for example in the contour diagram shown in Figure 12 where the contour lines range from 0.05 to 0.30. The corresponding diagram for *P. semisulcatus* has levels ranging from 0.10 to 0.90.

Figure 13: *Main effect additive components for Endeavour prawn quasi-likelihood split model.*



12.1. A test of the Endeavour split procedures

We will use the same procedure as we used in the Tiger prawns case to assess the accuracy of the Endeavour split procedures. Using the pre-1995 data we will re-calibrate our model and calculate grid square proportions and use the result to predict the weight of *M. endeavouri* in the data from 1995 and later. We choose *M. endeavouri* rather than *M. ensis* because it is by far the more commonly caught species.

Stations in the post-1994 data set will be amalgamated into groups of about 1.5kg total endeavour prawn weight. We choose 9 panels of about 20 groups each working along the coastline surrogate from west to east. These 9 resulting panels are not precisely the same as for the Tiger prawn group, but are very similar.

Figure 14: *Comparison of actual caught weights and empirically predicted prawn weights for M. endeavouri.*

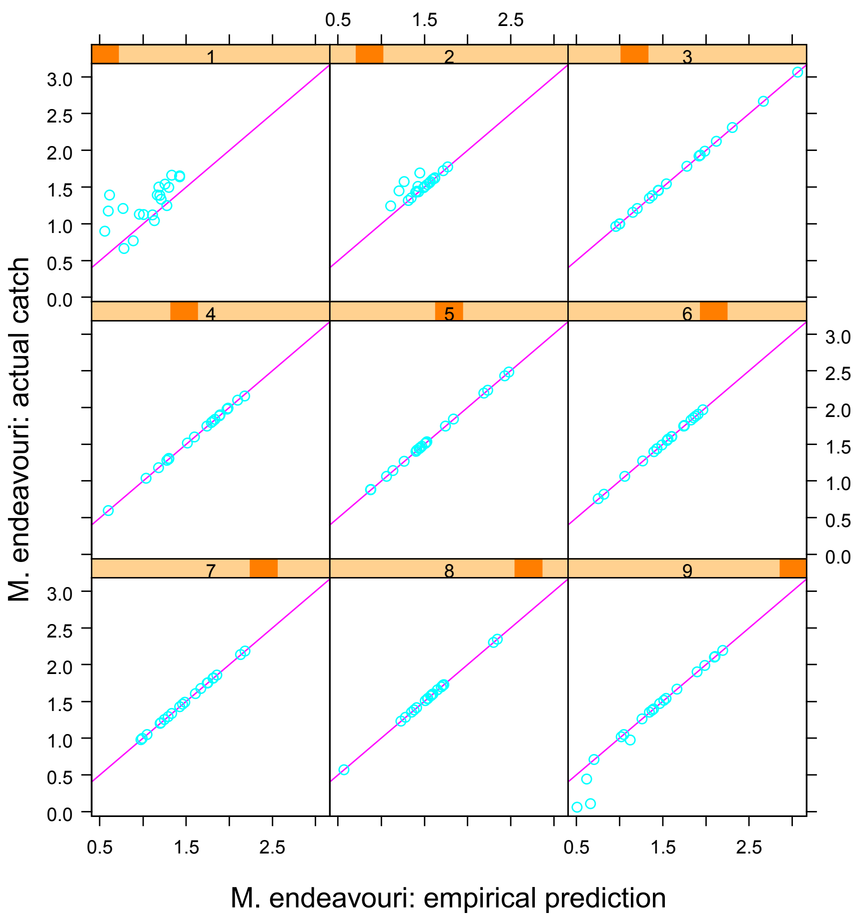
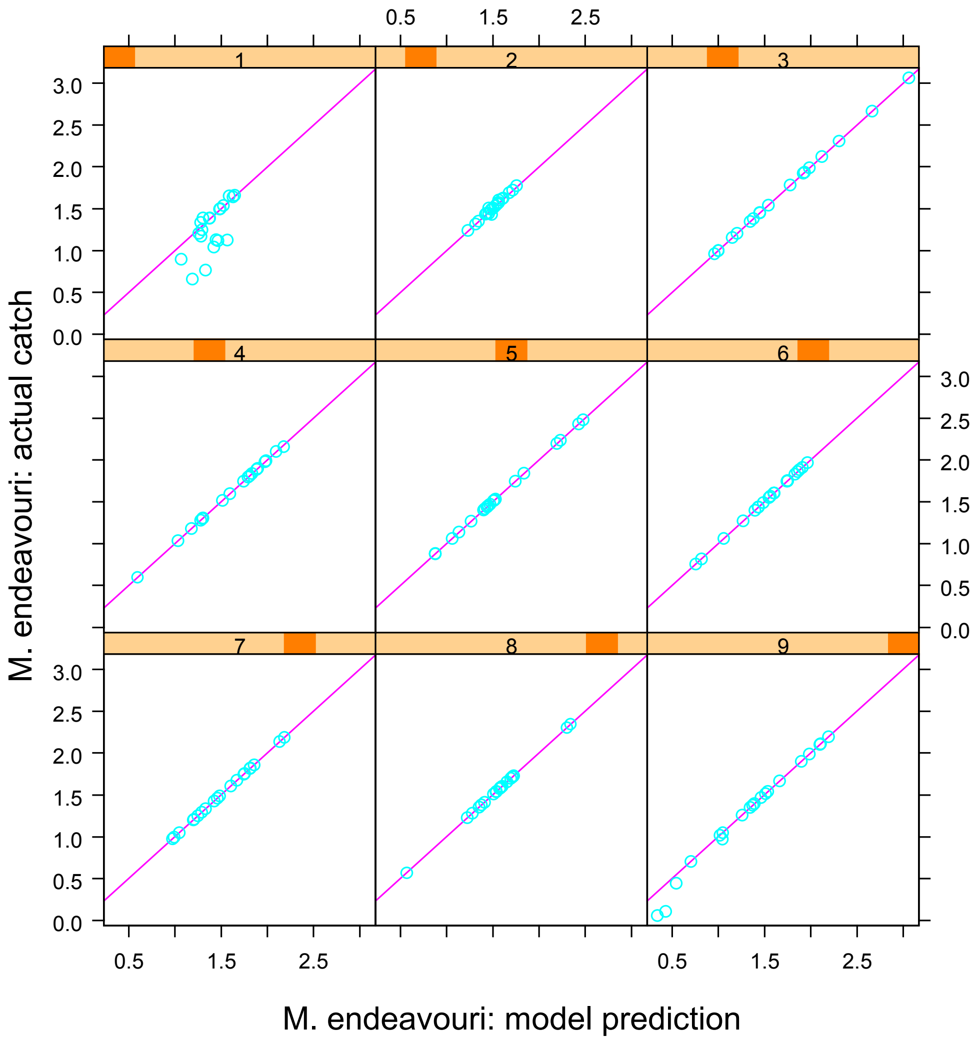


Table 5: *Empirical and model-based estimates of total proportions for* M. endeavouri *for the 9 comparison panels.*

Group	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Empirical	69.46	96.06	100.00	100.00	100.00	100.00	100.00	100.00	89.58
Model	91.78	99.10	99.94	99.94	99.94	99.94	99.95	99.94	87.74
Actual	82.96	99.52	100.00	99.93	100.00	100.00	100.00	100.00	85.24

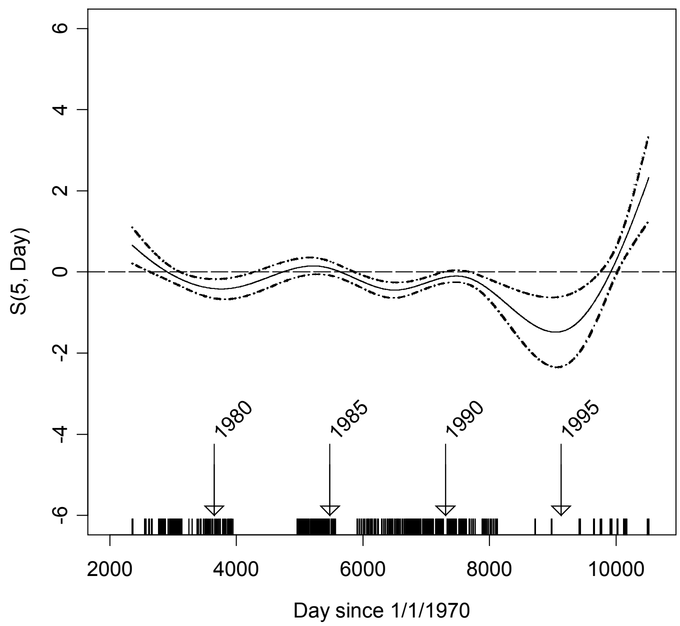
Figure 15: *Comparison of model predictions and actual catches for M. endeavouri in 9 panels*



The total percentages for *M. endeavouri* for each panel are shown in Table 5, and the corresponding information for the model-based predictions are given inFigure 15. It is quite clear that the "perfect fits" are in some respects meretricious in the sense that the proportions are trivially very near unity and both empirical and model-based approaches are picking this up. The first and last panels are more variable, though, and some more realistic comparison is available from them.

We also did a test to see if a long-term trend might be necessary in this case as well. The estimated additive component is shown in **Figure 16**. Again it shows an incipient instability towards the end of the period but this adjustment is off a very low base and even if significant cannot be claimed as practically important from a split point of view, yet. It is another indication, however, that some overall movement in species proportions in the catch may be underway and should be closely monitored as a matter of scientific and possibly commercial importance.

Figure 16: *Possible long-term trend component for the Endeavour split model***.**



13. Banana prawns

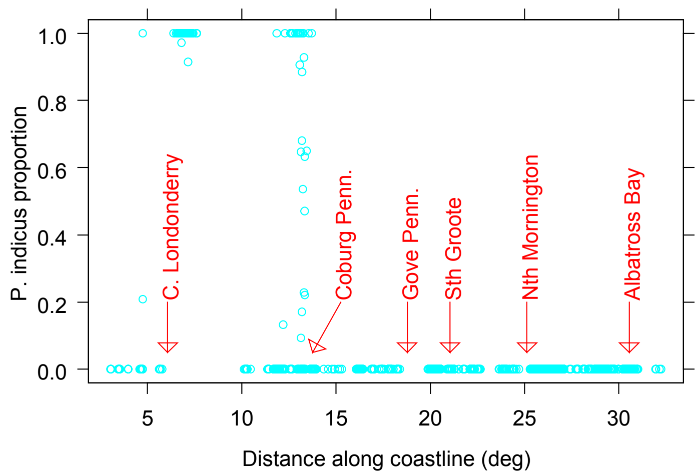
Although this study will not consider Banana prawns to any great extent we did consider species split procedures for this species group. There were 4025 stations in the survey data with Banana prawn catches recorded and the vast majority of these were single species catches. The frequency table for which species were caught is shown in Table 6.

Table 6: *Frequencies for stations with one or other or both Banana prawns caught*

		P. indicus	*Totals*
		139	139
P. merguiensis	3869	17	3886
Totals	3869	156	4025

With such strong species separation in the survey stations, a model of the type we have used for Tiger and Endeavour groups is both unnecessary and difficult to fit as most of the proportions will be either 0 or 1. A plot of the proportion of P. indicus in the Banana catch against distance along the coastline (Rdist) as given in Figure 17 clearly shows a strong separation with no catches of *P. indicus* east of the Coburg peninsula and the only mixed catches occurring mainly in the gap between the Coburg Peninsula and Melville Island. Even here in all but six stations one or other of the two species dominates the catch.

Figure 17: *Proportions of P. indicus against station location for Banana prawn catches.*



Since *P. merguiensis* and *P. indicus* are usually caught by different gear types as well we suggest that the possibility of a mixed catch may safely be discounted and a model approach devised based on the assumption of a pure catch. The model will then focus on predicting which of the two species has been caught.

We suggest a decision tree model (Anonymous1984) for this situation, as it appears to accommodate most of the unusual features of the situation in a natural way in particular the very discrete and sharply defined species boundaries.

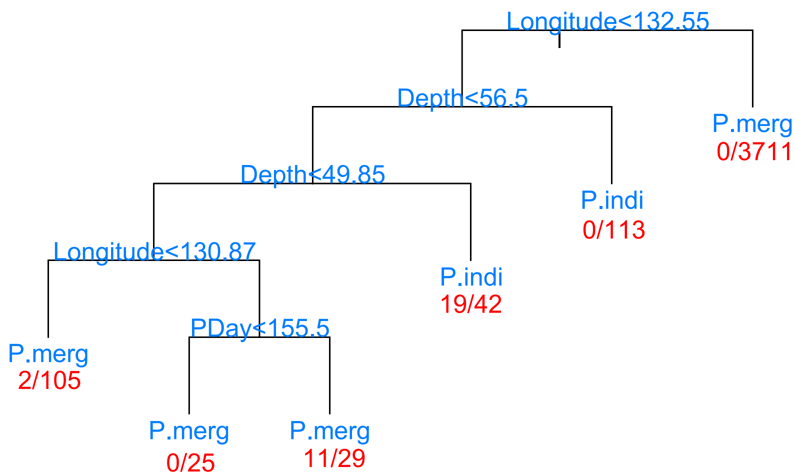
When the usual algorithm is used to form the decision tree, the first branch is on Depth, presumably since only *P. indicus* is found in relatively deep water. This leaves open the possibility of predicting *P. indicus* if Banana fishing is ever done east of the Coburg Peninsula in deep water. However *P. indicus* has never been recorded so far east in the NPF, so it would seem to be preferable to make the first split artificially on Longitude at the base of the Coburg Peninsula (132.55° E) thus avoiding this possibility.

Tree models are usually grown larger than the ultimately intended size and pruned to some justified size guided by cross validation. This procedure suggests a tree of about 6 nodes and the result is shown in Figure 18. We may paraphrase the diagram as follows:

1. If the station is east of the Coburg Peninsula, the predicted species is *P. merguiensis*,
2. West of Coburg, if the catch is in water deeper than 56m the predicted species is *P. indicus,*
3. If the catch is in water between 49.85m and 56.5m the predicted species is still *P. indicus*, though the confidence is lower,

4. If the catch is in water less than 49.85m deep then
    a. If the catch is further southwest than Cape Londonderry the predicted species is *P. merguiensis*.
        i. If the catch is between Cape Londonderry and the Coburg Peninsula, in water shallower than 49.85m and in the first 5 months of the "Prawn year" the prediction is confidently *P. merguiensis*;
        ii. if it is in the latter part of the Prawn year the prediction is the same but with less certainty.

Figure 18: *Tree model for Banana prawns species split with error rates in the training sample*



The decision rules in Figure 18 the dichotomies indicate the conditions for traversing the left-hand branch of the tree and the complementary condition indicates the right-hand branch should be taken. The species at each terminal node is the predicted most likely and the figures in red below each terminal node are the error rates in the training sample for that node, that is, the proportion of times the predicted most likely species was not observed.

Since Banana prawn assessments are not considered in the present report we will not take this proposal any further at this stage.

14. King prawns

This species group is by far the smallest and least studied of the groups. The survey data is sparse and does not allow statistical models to be constructed or calibrated. The catch is always very much the minor component of the prawn catch in the NPF, almost at negligible levels for stock assessment purposes. This species group cannot be further considered in this report.

15. Simulation from Tiger and Endeavour species split models

In the analysis that follows a major goal is to make realistic appraisals of the levels of uncertainty in the whole data accumulation and stock assessment process. Much of the work will be done by simulation. At key stages we will need to generate an imputed data set for use in the stock assessment process in such a way that repeats of the process will yield different data sets in a way that reflects the uncertainty present.

The major discussion will focus on Tiger and Endeavour prawns species groups. For these two groups the major sources of error or uncertainty to come from the species split process are

1. The uncertainty due to the fact that the parameters in the species split models have been estimated from finite survey data somewhat haphazardly collected and
2. The error due to the fact that the species compositions of the logbook records are themselves realisations of unknown and unobserved random processes.

There are other sources of error, of course, in particular that due to flaws in the choice of model itself, but we believe that our studies above have shown that these are at least of a lower order of magnitude than the two given above.

Our simulation generating process also has two stages:

a) Generate a parameter vector in such a way as to reflect uncertainty in the estimation process and

b) Given the parameter vector, generate a realisation of the species split process to subdivide the logbook record.

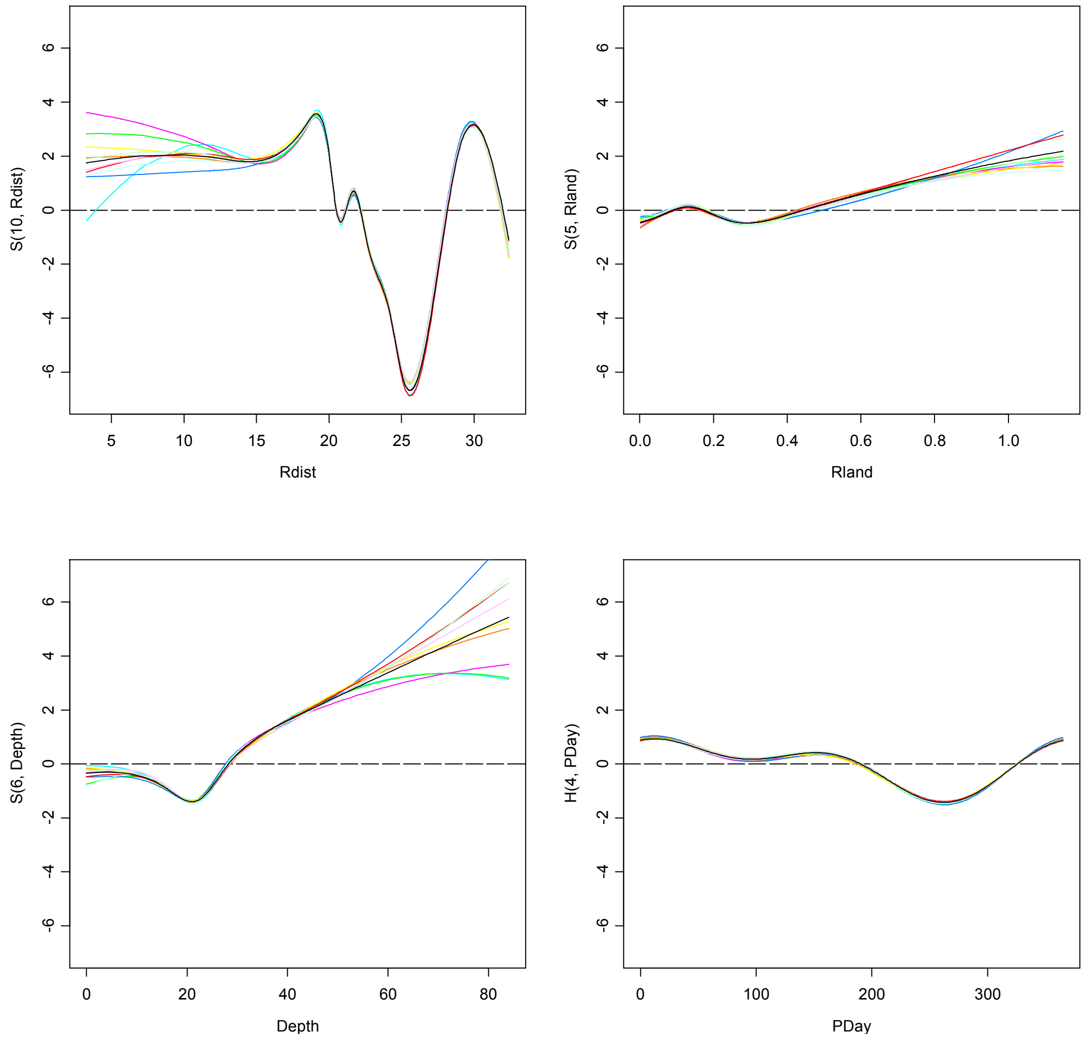
We discuss both of these separately below.

15.1. Generating a parameter vector

The estimation procedure we have used, essentially maximum likelihood, is based on a frequentist paradigm in which uncertainty is viewed in terms of error rates in repeated sampling. This technique provides an estimate of the parameter and an estimate of the variance matrix associated with the repeated sampling error process. The standard large-sample theory also suggests that the error distribution of the parameter estimates can be well approximated by a multivariate normal distribution, which is why the estimate vector and variance matrix suffice to specify the error distribution.

For our present purposes a Bayesian standpoint is more appropriate as it regards the parameter vector as an unknown realisation of a random variable and uncertainty is conveyed by the conditional distribution of that random variable given the data, the so-called “posterior” distribution. For non-informative priors it is well known (and in any case easy to show) that the Bayesian posterior distribution is well approximated by the estimated error distribution of the maximum likelihood estimator. Hence we propose to generate a parameter vector for simulation purposes as follows:

Figure 19: *Simulated additive components for the linear predictor from the approximate Bayesian posterior*



- Generate an observation from a multivariate normal distribution with mean the maximum likelihood estimator and variance matrix the usual frequentist estimate of the large sample variance matrix, say β.

- From the coefficient vector generate the linear predictor, $\eta = \mathbf{x}^{\mathrm{T}}\beta$, and hence the split proportions through the inverse logistic transformation:

$$\varpi = \frac{\exp(\eta)}{1 + \exp(\eta)}$$

The implications of this component of the simulation are best viewed through its effect on the additive components of the linear predictor. Figure 19 shows the original estimated main effect components in black and 10 simulated components superimposed in different colours. Where the original pointwise confidence limits were narrow there is not very much movement in the simulated component but where they were wide the simulated component is freer to move.

Clearly this component of variation is relatively small, although this may be deceptive. If the catch is large, even a small change in the proportion can result in a large absolute (though not relative) change in the imputed catches.

15.2. Generating imputed catches

Having generated a candidate theoretical split proportion the actual split proportion for any logbook record will have a distribution with this value as its conditional mean. In principle we need to generate from a distribution that leads to the quasi-likelihood we have used in the analysis. Unfortunately most quasi-likelihood models do not correspond to a true sampling distribution, including our case.

On the other hand the quasi-likelihood model does imply that the true distribution from which the sample proportions are drawn has the following properties:

1. The mean is $\mu = \dfrac{\exp(\eta)}{1+\exp(\eta)}$,
2. The variance is $\sigma^2 = \dfrac{\mu(1-\mu)}{T\ /\ \phi}$ where T is the total catch,
3. The distribution belongs to the generalized linear modelling family.

If $n = T\ /\ \phi$ were an integer, the distribution of the binomial proportion, $Y\ /\ n$, where $Y \sim \mathrm{B}(n, \mu)$, would have all three properties. By a natural continuity argument we argue that the following approximate procedure will at least inject a degree of randomness into the imputed values that will realistically reflect the uncertainty in the situation:

- Generate an actual split proportion as $\tilde{\varpi} = Y\ /\left\lceil \dfrac{T}{\varphi} \right\rceil$, where $Y \sim \mathrm{B}(\left\lceil \dfrac{T}{\varphi} \right\rceil, \mu)$ and divide the logbook catch by assigning

  $$\text{Weight of } P.\,semisulcatus = T\tilde{\varpi}, \quad P.\,esculentus = T(1-\tilde{\varpi})$$

  where T is the total catch.

There are two small points to note here.

1. The survey data is in grams but the logbook data is in kilograms, so there has to be a change of units in enacting this formula.
2. We take φ as known, as estimated as the dispersion parameter from the generalized linear model. This is, we claim, a justified convenience as it is doubtful if generating a simulated value for φ each time would inject very much more randomness into the outcomes. We must admit as well that it is unclear what sort of distribution should be used to simulate the Bayesian posterior for φ although there are several natural candidates that could be considered.

The estimated values for the scale parameter, φ, are

	$\hat{\varphi}$	Error d. f.
Tigers:	514.91gm	9173
Endeavours:	245.29gm	7174

These were obtained using the suggestion of (Anonymous1989) namely

$$\hat{\varphi} = \chi^2 / d$$

where χ^2 is Pearson's chi-squared statistic and d is the error degrees of freedom. An intuitive way to appreciate these estimates is to think of the split proportions as binomial proportions where, roughly, every half-kilogram of Tiger prawn catch is the equivalent of an independent trial and likewise every quarter-kilogram of Endeavour prawn catch.

16. Discussion and further research

Although taxonomically close, the two species of Tiger prawn are behave very differently and use the marine environment in different ways (Somers, 1994). The Grooved tigers, *P. semisulcatus*, appear to be more mobile than the relatively sedentary Brown tigers, *P. esculentus,* and have regular offshore movements in response to the breeding cycle. It is not at all clear that a sudden and dramatic decrease in either species could be offset either commercially or environmentally by a matching increase in the other. This is why it is important at least to attempt a stock assessment of both species separately but indirect stock assessments, based on imputed catches for both species, are inherently difficult. The species split information on which they are based must not only be of high quality but must also be regularly updated to guard against unforeseen changes over time.

16.1. Underlying assumptions

The empirical species-split model based on very local observed proportions in the survey data clearly assumes that split proportions for any grid square are

a) constant within a fishing season (absence of any within-season effect),

b) constant from one season to the next (absence of any long-term trend) and

c) faithfully estimated by short-trawl survey data for use with long-trawl logbook data.

The statistical modelling approach as well as comparative biological studies of the two Tiger species make it clear that a) is at best only approximately true but it may be easily accommodated using the statistical model.

Assumption b) is more difficult. The statistical model at least superficially suggests that there has been increasing volatility in the overall split proportions, for both Tiger and Endeavour prawn groups, at least in areas where both species are appreciably represented. This apparently dramatic finding has to be tempered by the realisation that survey sampling has in recent times been patchy both in time and in spatial coverage, especially compared with the 1988-90 seasons, for example. At this stage we do not feel sufficiently confident of this to claim that the effect is real, but it is a clear warning that close monitoring of the situation is urgently needed. If a long-term trend with increasing volatility does proved to be a real effect it implies, for instance, that most of the historical data currently used for the species split problem is no longer of much value as it estimates split proportions that are not fixed in time.

Assumption c) is also serious and remains an untested assumption and probably untestable by any currently available evidence. The survey data does use a range of sampling techniques but in an apparently serendipitous way making it inimical to the kind of comparative studies that testing this assumption would entail. Such a study would in any case be retrospective and hence logically not as cogent as a properly designed and controlled prospective study.

16.2. Species split methodology

While we still contend that the simple species-split method based on local grid-square proportions has probably been adequate for large-scale assessment of the Tiger stocks, as has been done to date, we claim that the statistical model approach offers a way to improve the procedure substantially and, more importantly, may offer a way of making local stock assessments focused on stocks in smaller, well-defined regions, more feasible. We do not claim that our species split models are necessarily optimal, but we do claim that they are a palpable improvement over the previous method for no real cost and that the ideas behind them offer a way of developing better models in the future as more and better data become available. They may also offer an effective way of aiding the design of future survey work.

For the case of Tiger and Endeavour prawns, where the species are much more mixed and occur more widely, we found that quasi-likelihood generalized linear models offered a good way of developing species split models but for Banana prawns, where the animals are very nearly mutually exclusive, a tree-model offers a simpler and more effective alternative. There is much scope for developing these tools further and even combining them, but this would be most effective with more and better designed survey data. Two natural extensions of the quasi-likelihood models we have not explored but which in our view may be potentially valuable are

- Extending the model to allow for random effects. At present the quasi-likelihood models assume a deterministic mean structure enveloped in a cloud of essentially measurement errors. It may be more realistic (and it may well make more effective use of sporadic data) if we were to assume that random variation were occurring at several levels and modelling this variation in its own right rather than trying to impose an essentially deterministic structure, apart from the measurement errors.

- Developing an explicitly Bayesian model *ab initio*. We already make a notional switch from frequentist to Bayesian models when we go from estimating and testing to simulation. It may be better to work with explicitly Bayesian models from the start and to use the prior distributions in a positive way to incorporate background information to come from sources not presently utilized.

16.3. Recommendations

We recommend that further research be undertaken into species split methodology and additional data be systematically acquired to enable this. Specifically

1. There should be a small, carefully planned and well-designed programme of acquisition of additional species split data. This should as far as possible come from skilled observers on commercial vessels taking low impact samples from specified commercial trawls. The sample design should cover all fished areas and should evenly cover the fishing season in time. We envisage a scheme in broad terms as follows:
   a) Areas and times for sampling should be chosen in such a way as to optimise the information base for calibration and development of species split models.
   b) Skippers visiting those areas at those times should be required, for a fee pre-negotiated with the industry, to supply a small, randomly selected sample of, say 5 kg of Tiger and of Endeavour prawns from the trawl catch of the specified night in the specified area.
   c) The samples should be supplied as soon as possible to a skilled third party in the state they are when the logbook records are made. This third party should classify the sample into species and sexes and for each animal record carapace length *and* weight.
   d) The data should be used to calibrate and develop refinements to species-split models as well as weight at length curves. Of particular interest would be to check for any long-term trend in the overall species proportions, so the programme has to run for several seasons at least.
2. In parallel with 1 above there should be further statistical research into optimal species split models as a problem in its own right and not simply as a preliminary step to stock assessment. Changes in species split proportions have management implications directly, as well as through the influence they have on stock assessment. The kinds of developments suggested here would be primarily random-effects and Bayesian extensions to the generalized linear quasi-likelihood models of the type proposed in this report, but the problem should be open-ended and specified in terms of the desired outcomes rather than the methodology to be developed.

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CHAPTER 3: AUGMENTATION AND IMPUTATION FOR THE LOGBOOK RECORDS

18. The logbook and landings data

In the NPF, active skippers are required to supply records of their catch and whereabouts on a nightly basis. For our purposes the record contains, ideally,

- The ***location*** of the principal area fished on the night, usually to a precision of a $6' \times 6'$- grid square. In recent years specific latitudes and longitudes are given.

- The ***catch*** for each of the four prawn species groups: Tiger, Endeavour, Banana and King.

There is provision for skippers to report their intended ***target*** but this information is voluntary and is not given often enough for it to be useful for stock assessment purposes. It would also have been useful if fishers were provided with a mechanism for reporting the ***gear type*** they had in use. Note that there are two qualitatively different types of gear in use, one primarily for Banana prawns and the other for the Tiger, Endeavour and King groups.

In addition to the logbook data there is an independent assessment of the entire catch for each of the four species groups for the calendar year called the ***landings data***. Neither logbook nor landings are entirely free of reporting error, though the landings are generally regarded as accurate and for our purposes we will assume this to be the case.

In this chapter we will detail methods adopted to deal with some of the recognizable uncertainty in the logbook records. Our purpose is to *impute* surrogate data for that which is either missing or incomplete. The imputation method itself will involve some random choices and the property we hope to achieve may be stated as follows:

> *If the imputations are repeated and used as an input into a simulation, the uncertainty in the logbook data will be communicated to the simulation process as faithfully as possible.*

18.1. Spatial organisation of the NPF

For administrative purposes the NPF is spatially organised into groupings of increasing precision. It is not necessary for us to specify these precisely here (Sharp et al.) but only to note that

- The most precise grouping is by ***grid square***; these are $6' \times 6'$ in extent and aligned with one decimal place latitude and longitude coordinates.
- The ***area*** is the grouping of next highest precision. An ***area*** is a contiguous collection of about 36 grid squares, but this varies.
- The ***region*** is a contiguous collection of areas all within the one ***province*** and
- There are two ***provinces*** essentially the Gulf of Carpentaria and the rest.

These spatial groupings form an *aligned* sequence of partitions of increasing precision. That is any grid square within the NPF belongs to one and only one area, region and province.

The extent of the NPF itself changed several times. There were changes to the definitions of areas, regions and provinces as well, principally at 1/1/1980. The Landings we use have been pro-rated to refer to the Northern Prawn Fishery as currently defined, and excludes the Kimberley portion of catch. Uncertainty in the logbook records

The sorts of deficiencies we recognize in the logbook data are listed below:

1. Catch records are missing entirely from the annual record of catch. This is detected only by the aggregate of the logbook records falling short of the landings. We have a method of imputing records for missing logbook records that we detail below.
2. The skipper, whether deliberately or not, understates or overstates the catch. We have no way of detecting or adjusting for this but we believe it to be a relatively minor source of error variation.
3. Catch records are attributed to a false or inappropriate location. We have no general way of detecting or adjusting for this kind of error but we believe it to be a relatively minor source of error variation. (In some cases the record location is on dry land. This makes it possible to detect the error but there is no way of correcting for it. Such records are fortunately very few.)
4. Catch record locations are imprecisely recorded. In nearly all cases this implies that the logbook record is merely ascribed to the area rather than to the grid square within the area, but in a few cases it may be recorded only at the region or even province level. We have a way of imputing locations for such imprecisely recorded data that we detail below.

Before detailing how we propose to deal with these uncertainties in the data we need to discuss the way we propose to handle the question of target species.

19. Inferring target species

The traditional way of inferring target species in the NPF, also adopted by(Wang and Die, 1996), uses the actual catch record according to the following rule:

For any logbook record denote the catches of Banana, Tiger, Endeavour and King groups by B, T, E, and K respectively. Then the target species group is assumed to be

- ***Bananas*** *if* $B > T + E + K$ *or* $B + T + E + K = 0$ *and*
- ***Tigers*** *otherwise.*

Furthermore, within the species group, the target species is assumed to be the one with the highest split proportion; the secondary species within the species group is the bycatch target species.

Based on the NPF experience this may be a reasonable way to infer catch, but we find a rule that infers the target from the outcome of the catch questionable in principle. We would prefer an inference method that does not rely upon the individual catch outcome.

Our proposal also begins with a definition of a *target species group* and at a second stage resolves it into a primary target species and bycatch target species. Furthermore we only consider Banana and Tiger groups explicitly. If the target species group is Tiger we assume that the Endeavour is also targeted, since the two are generally caught together.

Kings are not caught in sufficient quantity to qualify for consideration in this project.

Intuitively it seems reasonable to suppose that a particular species group is targeted if the chance of achieving a *reasonable catch* of that species group is sufficiently high. This notion requires us to specify what constitutes a *reasonable catch*. Since the fishery is managed by calendar year and since there are large fluctuation in abundances from year to year we propose a definition that also varies with the year itself.

> *A* **reasonable catch** *of a particular species group for a particular calendar year is defined to be any catch that exceeds the lower quartile of the non-zero catches of that species group for that year.*

In other words, we take all non-zero catches for, say, Tigers for that year, and take the value that is exceeded by 75% of them.

Table 1 gives the quartiles and maximum logbook catches for Tigers and Bananas for the years 1970-1999. The distribution is clearly positively skewed, in part due to the fact that we have no individual boat information so the catches are marginalized with respect to boat size. It would clearly be better if we could make the definition of reasonable catch relative to boat size but this information is unavailable in the record.

19.1. Generalized additive models for reasonable catch probabilities

Having defined a reasonable catch for each main species group, the next step is to develop predictive models relating the probability of a reasonable catch to the determining variables. For this purpose we take the same determining variables as we used for the species split problem, namely

- Rdist: distance along the coastline from an origin in the west of the NPF,
- Rland: distance from dry land
- Depth: the depth within the grid square to which the record pertains,
- PDay: the day within the 'Prawn year'.

There is a minor problem with spatially imprecise logbook records for which the first three variables are themselves not precisely recordable. We have adopted a simple solution of using the values for a location central to the collection of grid squares within which they are known to be located. For our purposes here this is apparently an adequate solution, although more elaborate schemes are possible.

Table 7: *Annual quartiles and maximum (in kg) of the non-zero catches of the two main species groups*

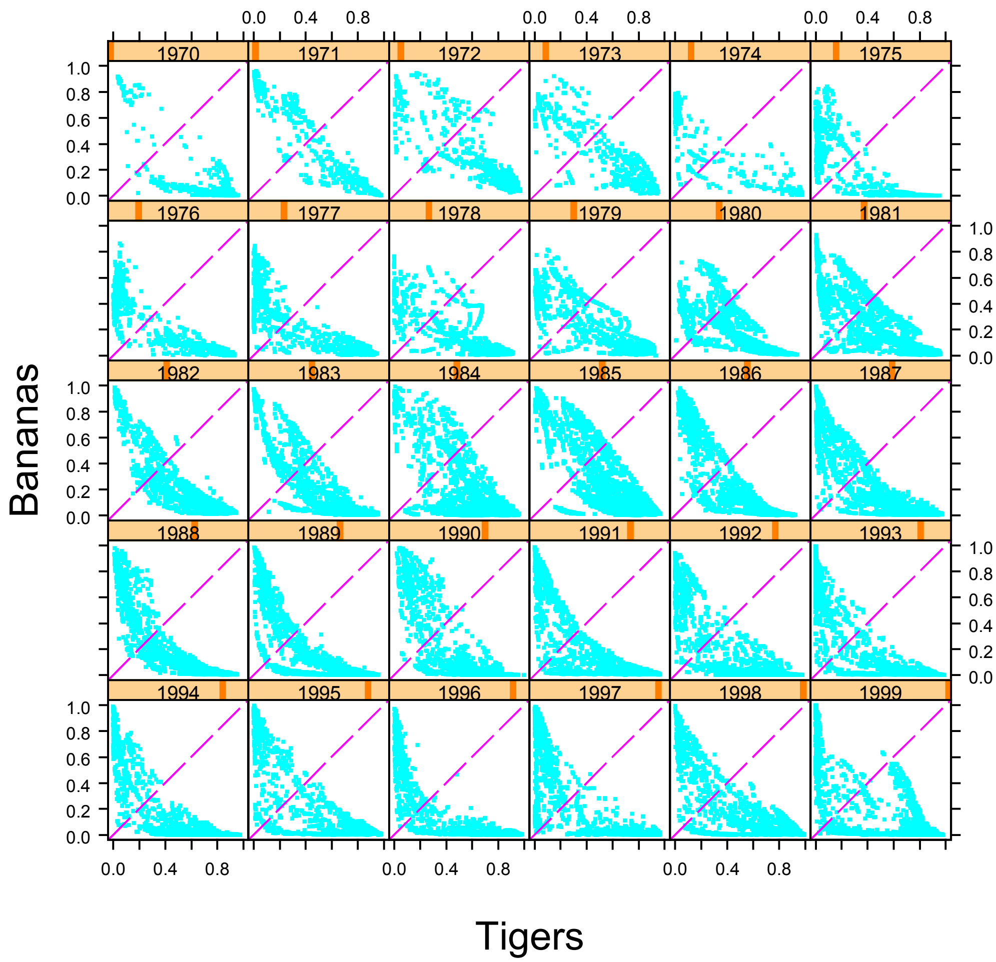
	Tigers				*Bananas*			
Year	*25%*	*50%*	*75%*	*Max.*	*25%*	*50%*	*75%*	*Max.*
1970	108.0	164.0	245.0	2214	51.0	227.0	886.0	11818
1971	67.0	123.0	209.0	1595	136.0	456.0	1393.0	27273
1972	83.0	147.0	245.0	1311	29.8	171.0	741.0	13182
1973	101.0	182.0	293.8	1320	45.0	272.0	909.0	12727
1974	103.5	177.0	282.0	926	282.0	1136.0	2727.0	18182
1975	82.0	130.0	201.0	1077	136.0	455.0	1364.0	10001
1976	82.0	136.0	211.0	1298	136.0	455.0	1241.0	12845
1977	101.0	201.0	330.0	2386	123.0	545.0	1591.0	13636
1978	93.0	155.0	231.0	4376	41.0	182.0	682.0	9091
1979	102.0	181.0	295.0	2361	52.0	273.0	909.0	11818
1980	80.0	132.0	208.0	2601	30.0	120.0	452.5	12000
1981	75.0	136.0	215.0	2900	40.0	180.0	600.0	12345
1982	72.0	120.0	182.0	1390	25.0	125.0	430.0	11000
1983	84.0	140.0	210.0	1390	26.0	120.0	350.0	7345
1984	72.0	120.0	180.0	1386	52.0	192.0	560.0	8255
1985	65.0	108.0	169.0	910	36.0	160.0	533.0	7282
1986	52.0	84.0	120.0	1176	36.0	140.0	406.0	7350
1987	91.0	143.0	204.0	1050	50.0	210.0	630.0	10933
1988	80.0	120.0	165.0	3600	43.0	182.0	564.0	9000
1989	75.0	108.0	144.0	663	56.0	270.0	912.8	17230
1990	90.0	127.0	170.0	579	54.0	211.0	511.5	7020
1991	120.0	170.0	235.0	9000	84.0	390.0	1231.0	15000
1992	90.0	131.0	180.0	850	70.0	220.0	546.0	10000
1993	100.0	143.0	193.0	2535	120.0	390.0	900.5	18000
1994	110.0	156.0	210.0	2000	75.0	280.0	663.0	8700
1995	150.0	217.0	290.0	3165	90.0	400.0	1170.0	13000
1996	87.0	131.0	180.0	680	108.0	364.0	1000.0	15027
1997	117.0	170.0	228.0	1000	100.0	378.0	994.0	15000
1998	109.0	169.0	231.0	6500	61.0	270.0	750.0	18000
1999	100.0	153.0	210.0	910	140.0	377.0	893.0	13000

Each logbook record then provides a value for each of the determining variables and two binary variables indicating whether they did or did not achieve a reasonable catch in each of the two major groups. The form of model we adopt is a generalized additive model logistic regression:

$$\log \frac{p}{1-p} = T_9(\text{Rdist}) + T_5(\text{Rland}) + T_5(\text{Depth}) + T_5(\text{PDay}) \tag{5}$$

where p is the probability of achieving a reasonable catch for either main species and $T_k(x)$ is a smoothing spline in the variable x with notionally k degrees of freedom. Smoothing splines differ from natural splines in that they have a separate knot at each distinct $x-$value but they are estimated with a roughness penalty so that they do not interpolate the data and the notional expenditure of degrees of freedom is roughly k. This makes them more flexible than natural splines but inference on them is difficult.

Figure 20: *Estimated probabilities of a "reasonable catch" of the Banana prawn group versus the Tiger prawn group. 10% sample stratified within calendar years.*



Another point that could cogently be argued is that (2.1) should contain interaction terms as well as main effect terms. We have found that adding interaction terms here makes little difference to the final outcome and can make the estimation of terms considerably unstable. Our judgment here is that little is lost by omitting them.

These models are really being used as simple smoothing devices that will get us a serviceable ***local*** estimate of p. For a given logbook record, let $\hat{p}_T$ denote the estimate of the probability of achieving a reasonable catch in Tigers and $\hat{p}_B$ the corresponding estimate for Bananas. We infer the target in the obvious way as follows:

$$\text{If } \hat{p}_T > \hat{p}_B \text{ the target is Tigers, otherwise Bananas} \tag{6}$$

This definition is only fully reasonable to the extent that the two estimates tend to be complementary. Figure 20 shows the two probabilities plotted against each other for the

30 years of the survey. Since there are over 600 000 records this only give a 10% sample in each year. Close inspection of most years shows a strong tendency for the points to lie close to either vertical or horizontal axis, though there are enough points "in the middle" to obscure this graphically. The points at least show it is uncommon for both estimates to be near unity.

20. Augmentation and imputation of logbook data

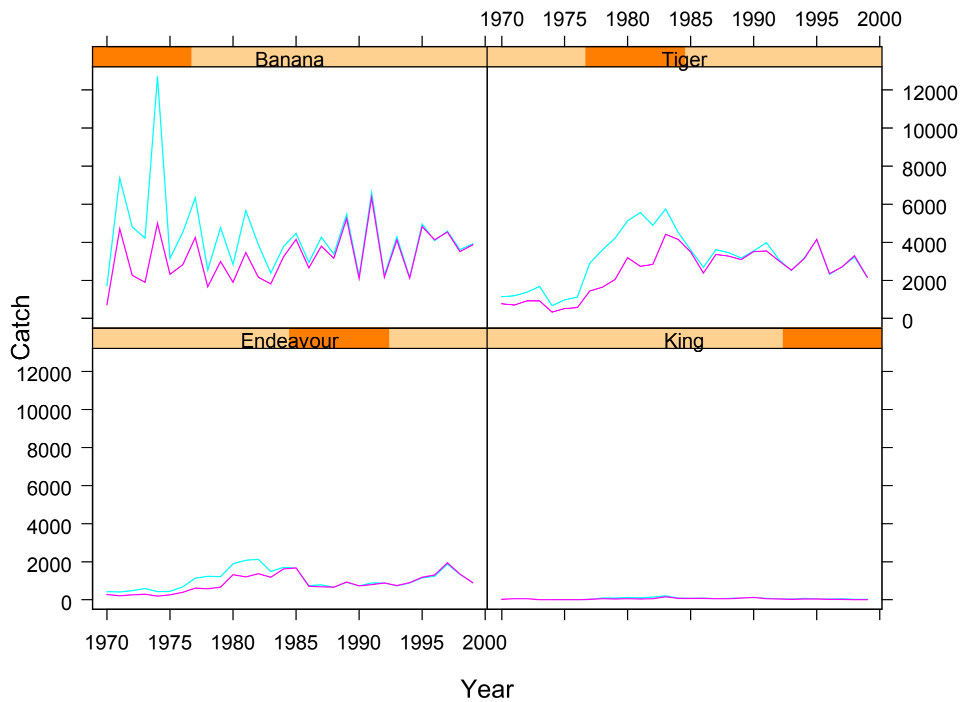
The landings data is a separately calculated set of estimates for the annual total catch for each of the four species groups, for all years. These data are shown in Table 8.

Table 8: *Landings data for 1970-1999 (in tonnes).*

Year	*Banana*	*Tiger*	*Endeavour*	*King*	*Year*	*Banana*	*Tiger*	*Endeavour*	*King*
1970	1702	1138	417	NA	*1985*	4469	3592	1671	77
1971	7364	1183	400	NA	*1986*	2935	2682	748	85
1972	4801	1380	472	NA	*1987*	4257	3617	772	65
1973	4226	1672	594	NA	*1988*	3381	3458	669	81
1974	12711	666	434	4	*1989*	5466	3173	909	85
1975	3160	973	444	6	*1990*	2221	3550	735	128
1976	4519	1118	675	5	*1991*	6605	3987	879	81
1977	6345	2900	1125	28	*1992*	2254	3084	880	47
1978	2535	3599	1240	82	*1993*	4292	2515	733	35
1979	4775	4218	1213	94	*1994*	2157	3162	872	72
1980	2835	5124	1891	111	*1995*	4961	4125	1150	58
1981	5672	5559	2073	95	*1996*	4078	2311	1235	41
1982	3875	4891	2124	144	*1997*	4587	2694	1870	51
1983	2382	5751	1488	207	*1998*	3606	3218	1327	20
1984	3770	4525	1714	83	*1999*	3904	2136	885	21

Source: Sharp et al 2000. Northern Prawn Fishery and Kimberley Prawn Fishery Data Summary 1999. AFMA Canberra. (Table 1)

Figure 21: *Landings records (above) and annual aggregates of logbook data for 4 species groups*



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The aggregate logbook records will normally be less that the landings figure. This is so but in recent years the two have become essentially identical. Up to the mid-1980s the gap between logbooks and landings was typically very wide. Figure 21 displays the relative sizes of the landings data and the aggregates of the logbook data.

20.1. Wang and Die method of augmentation

We do not wish to review the method by which Wang and Die reconciled the logbook data with the landings data here in any detail since several methods were used and we are not sure of the status of any particular variant. For this discussion it suffices to note that all methods simply involved an expansion factor to bring the reported catches up to the same grand total as the landings data.

For some purposes this may be an adequate procedure but it will be unable to capture any of the uncertainty in the data. No difference is noticeable between the case where the reporting is essentially accurate and complete so no expansion factor is necessary and another where the spatial distribution of the whole (and hence the species split) is largely determined by a small fraction of the catch, namely the accurately recorded part.

We believe it is possible to do better than this, though it is still an open question if the improvement is substantial.

20.2. A new augmentation proposal

We propose a re-sampling method of reconciling logbook and landings data based on the ideas underlying the statistical technique known as *bootstrapping*. Once again we do not aim to provide a single enhanced data set that will in itself shoulder the entire augmentation but rather we use a procedure for generating an imputed data set which, if we repeat the procedure a large number of times and use the imputed data sets as inputs to a later stock assessment process will reliably transmit to the later process a realistic picture of the uncertainty in the data as well. The governing principles to which we have tried to adhere are as follows:

- The imputed data sets will conform to the real data as closely as possible. In particular all known and partially known records will appear in every imputed data set.
- The imputed data sets will rely on the actual data in a symmetric way.

The meaning of this second principle will become clearer after we outline the procedure we propose, to which we now turn.

The process advances in two stages:

1. We re-sample the known and partially known logbook records in a restricted way so that when the re-sampled records are added to the known records the landings totals for Tigers and Bananas are achieved as closely as possible.
2. Records in the resulting data set whose grid square is not precisely known but only up to a set of grid squares is randomly allocated to one of the grid squares in the known set with probabilities proportional to the known fished frequencies in the entire data set.

20.2.1. Restricted re-sampling

For any year where there are deficits between logbook totals and landings we propose to augment the logbook data set with $k_T + k_B$ additional readings got by re-sampling the records that are present, *with replacement*. The sampling is restricted in the sense that k_B will be chosen from the records where the inferred target is Bananas and k_T from the Tiger target records. Our aim is to do this in a way that makes the augmented logbook records have the same totals as the landings, at least for Tiger and Banana prawns. Let B_{log}, and B_{land}, be the logbook total and landings for Bananas and similary T_{log} and T_{land} for Tigers. So the deficits we aim, primarily, to make up with the $k_T + k_B$ re-samples are $B_{\text{land}} - B_{\text{log}}$ and $T_{\text{land}} - T_{\text{log}}$.

When the target is Bananas the record will very often have a small Tiger prawn catch recorded as well and similarly for Bananas when Tigers are the target. Let A_{IJ} be the average catch of group I when the target is group J, (where I and J are either T or B). If we choose k_B and k_T so that

$$
\begin{aligned}
A_{BB}k_B + A_{BT}k_T &= \max(0, B_{\text{land}} - B_{\log}) \\
A_{TB}k_B + A_{TT}k_T &= \max(0, T_{\text{land}} - T_{\log})
\end{aligned}
\tag{7}
$$

then *on average* the Tiger and Banana deficits will be removed. Rather than perform the sampling in one operation, however, we recommend a more cautious and tentative strategy, namely:

1. Start with a step size of $s = \frac{1}{2}$.
2. Solve (7) for k_B and k_T, but actually draw only $k_B^s = \max\{0, (1-s)k_B\}$ and $k_T^s = \max\{0, (1-s)k_T\}$ records from the Banana and Tiger target records, respectively.
3. Update $B_{\log}$ and $T_{\log}$ by adding in the re-sampled records. If both exceed, say, 99% of the respective landings figure, go to step 5 below.
4. Halve the step size, $s \to s/2$ and return to step 2 above.
5. Adjust all records in the augmented logbook data set by multiplying the catches for each species group by a constant factor so that logbook totals and landings are exactly equal. That is, for Tiger catches, say, the factor will be $cf = T_{\text{land}} / T_{\log}$. In practice the factors for Tigers and Bananas are nearly always very close to unity and for Endeavours and Kings often still reasonably close to unity.

Notice that sampling in stages like this is only easy if it is done with replacement. There are two other reasons why we use sampling with replacement, though. First, it injects more variability into the process and in this sense is conservative (which is much the same reason as why it is used in bootstrapping) and secondly, for some years sampling without replacement would not be enough records to effect the augmentation.

An example of the process in action is given in Table 9. This is for 1979, a year when under-reporting in the logbooks was particularly high. Initially the reported Tiger catch was 51.3% below landings, the Banana catch 37.5% below, the Endeavour catch 45.3% below and the King catch 65.4% below. In the first step 1364 logbook records from the Banana targets and 4690 from the Tiger targets were selected. This brings the logbook records for all four species groups closer to the landings, essentially halving the difference for Tigers and Bananas as expected. After four such steps the tolerance is achieved in both Tigers and Bananas, slightly over-achieved in Endeavours and better but still quite far from the landings in Kings. The final correction factors are essentially unity for Tigers and Bananas, a small scaling down for Endeavours and a big scaling up for Kings.

This kind of progress and outcome is the norm for 1979 suggesting, perhaps, that some King prawns were caught separately from the other three groups and systematically omitted from the logbook records but included in the landings.

Table 9: *Progress of a logbook to landings augmentation re-sampling for 1979*

Step		*Banana*	*Tiger*	*Endeavour*	*King*
1	Logbooks	2987	2054	664	32
	Landings	4775	4218	1213	94
	Rel. diff. (%)	-37.45	-51.30	-45.26	-65.44
	$k_B^s = 1365$, $k_T^s = 4690$				
2	Logbooks	3946	3106	1008	49
	Landings	4775	4218	1213	94
	Rel. diff. (%)	-17.37	-26.37	-16.86	-47.46
	$k_B^s = 937$, $k_B^s = 3636$				
3	Logbooks	4600	3917	1270	62
	Landings	4775	4218	1213	94
	Rel. diff. (%)	-3.67	-7.13	4.73	-33.78
	$k_B^s = 222$, $k_B^s = 1159$				
4	Logbooks	4782	4168	1354	66
	Landings	4775	4218	1213	94
	Rel. diff. (%)	0.14	-1.19	11.59	-29.55
	$k_B^s = 0$, $k_B^s = 217$				
(Tolerance achieved)	Logbooks	4794	4214	1368	66
	Landings	4775	4218	1213	94
	Rel. diff. (%)	0.40	-0.08	12.79	-29.26
Corrections factors:		0.9960	1.0008	0.8866	1.4136

20.2.2. Allocation of spatially imprecise records to grids

Having augmented the logbook records so that they essentially match the landings it remains to assign the spatially imprecise records to a specific grid. Again we seek a procedure for doing this that will reflect the inherent uncertainty by the variations that occur in repeated performances of the process, but will also respect known properties and constraints.

For example we should not assign records to grids that are untrawlable if at all possible. It should also be kept in mind that the main reasons we need a precise allocation are to allow more precise species split and to provide a better basis for a spatial assessment of the stocks. The first reason is relatively minor in most cases, since species split proportions typically vary only slowly over the local areas (although in some parts of the

NPF there are dramatic shifts in relatively short distances at certain times of the year) and the second is only rarely a serious consideration since stock regions themselves are very broad.

Each imprecise record does have a known set of grids from which it may have come. In the case of records only known to the province level this set is quite large but records known at the area level could only come from a very small and compact set of grids. Our procedure is as follows:

1. Using every precisely known record in the 30 year history under study, calculate the total number of times each square was known to be fished (a) when the target was Tigers and (b) when the target was Bananas.
2. If possible, allocate an imprecisely known record to one of the grids from which it might have come with probability proportional to the fishing frequency of the precisely known records for its putative target group. (This will usually be possible.)
3. If there are no known fishing records for that target group for that set of grid squares, enlarge the set of fishing records to include those from both target groups.
4. If there are still no precisely known fishing records for grids of the set, leave the record at the geographic centre of its known set.

Step 2 will usually result in a credible allocation for each unknown record. Very occasionally some enlargement of the set is necessary as per step 3 and grids left unallocated as per step 4 are limited to about 2 or 3 records per annum in the 70s, at most.

Note that if an imprecisely known record is included several times in the augmented data set by re-sampling, each instance is independently allocated to a grid square. In other words at the allocation stage each record is treated as if it were a separate logbook record in its own right.

21. A spatial assessment of catch and effort for the NPF, 1970-1999

This section will concentrate on a sequence of 77 imputed completions of the logbook records by the methods described in section 20.2 above. A sample of this size has the handy property that the expected probability content between the 2nd and the 76th value is very close to the conventional 95% used for confidence intervals. Having ‘guard’ values at either end reduces the variance of the probability content appreciably. In what follows the uncertainty intervals shown will be these two order statistics from the imputed values.

We first need to discuss a series of partitions of the NPF into separate stock regions for the main species.

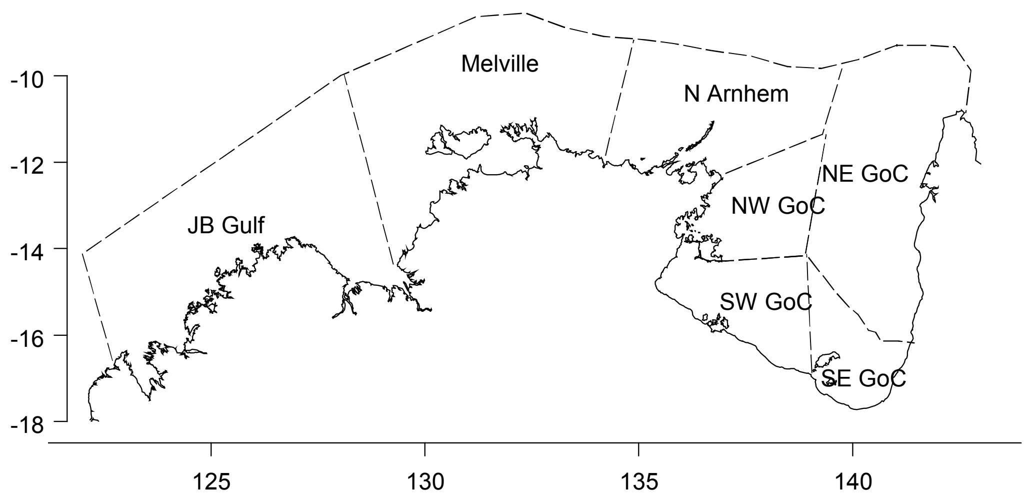
21.1. Stock regions in the NPF

Most assessments of prawn species in the NPF have considered the entire fishery as constituting a single stock. This is biologically unrealistic but the kind of detailed knowledge needed for a confident partition of the NPF into discrete stocks, if such exist, is still a topic for research. (This is a question that the proposed genetic marker approach to stock assessment in the NPF will certainly clarify if it proceeds.) It is nevertheless important to look at spatial structure for the catch and effort data and accordingly the research team sought the consensus opinions of senior researchers with extensive experience in the NPF as to where credible stock boundaries might be drawn for the six main species. The team here records its thanks to Dr Neil Loneragan, Dr Burke Hill and Mr Brian Taylor for their input into this exercise.

21.2. Tiger prawn stock regions, catch and effort, 1970-1999

The consensus was that both tiger prawn species have the same stock boundaries with seven reasonably discrete stocks in the NPF. These boundaries are shown in Figure 22. The temporary names we have given to these regions are not standard but are coined here simply to reduce the need to refer back to these diagrams when viewing catch and effort data in future sections.

Figure 22: *Stock boundaries for the 7 Tiger prawn stocks in the NPF*



The annual catch and nominal effort (that is, boat days unadjusted for effort creep) are now given in Figure 23, Figure 24, Figure 25 and Figure 26. It is clear that *P. semisulcatus* is largely caught in the north western Gulf of Carpentaria and around Albatross bay whereas the southern and south-eastern Gulf are the main places where *P. esculentus* is caught.

Notice that the uncertainty levels are low for recent years and moderate even for years when the proportion of missing or imprecise records was high. Note also that all the uncertainty is due directly or indirectly to species split.

Figure 23: *Annual catch of P. semisulcatus, 1970-1999 with uncertainty ranges*

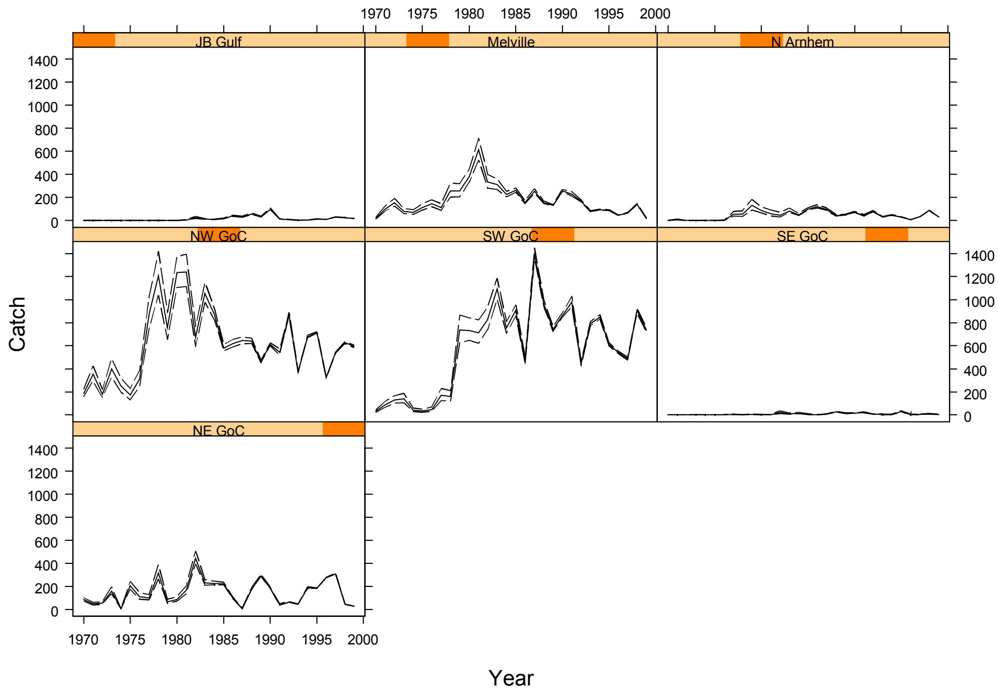


Figure 24*: Annual nominal effort given to P. semisulcatus in 7 stock regions*

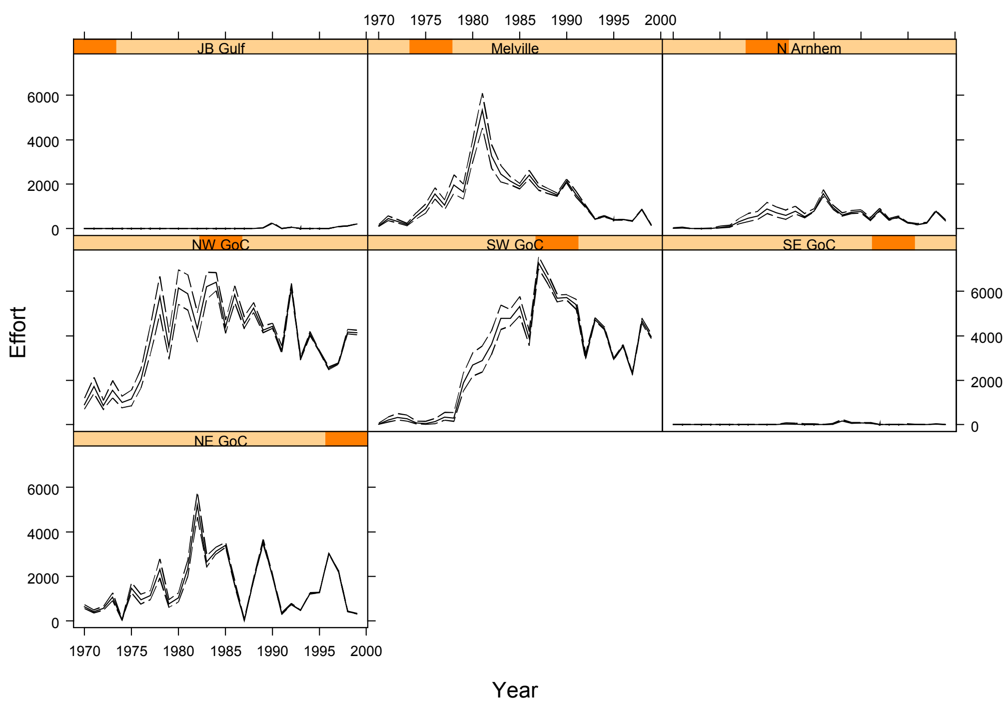


Figure 25: *Annual catch of P. esculentus in 7 stocks*

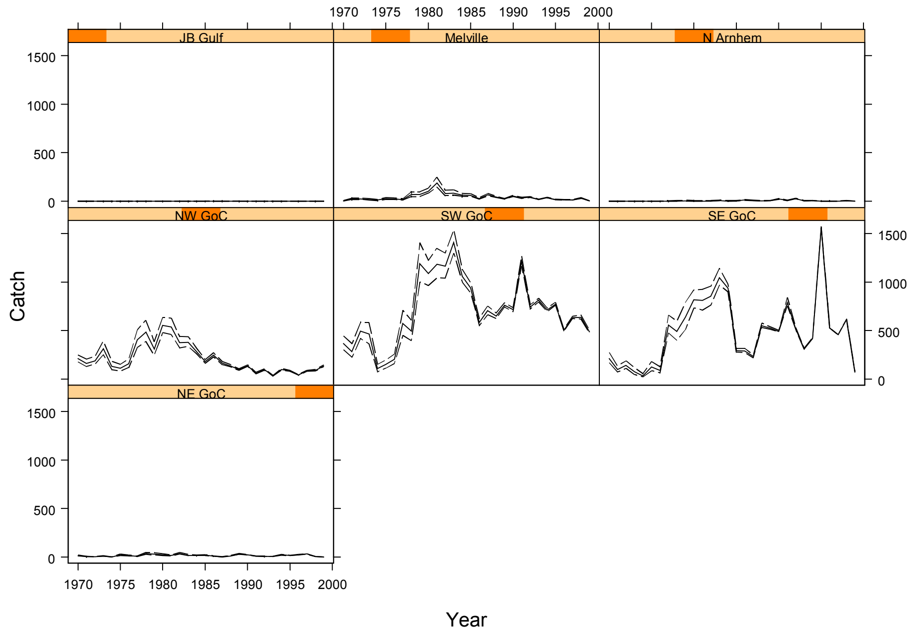
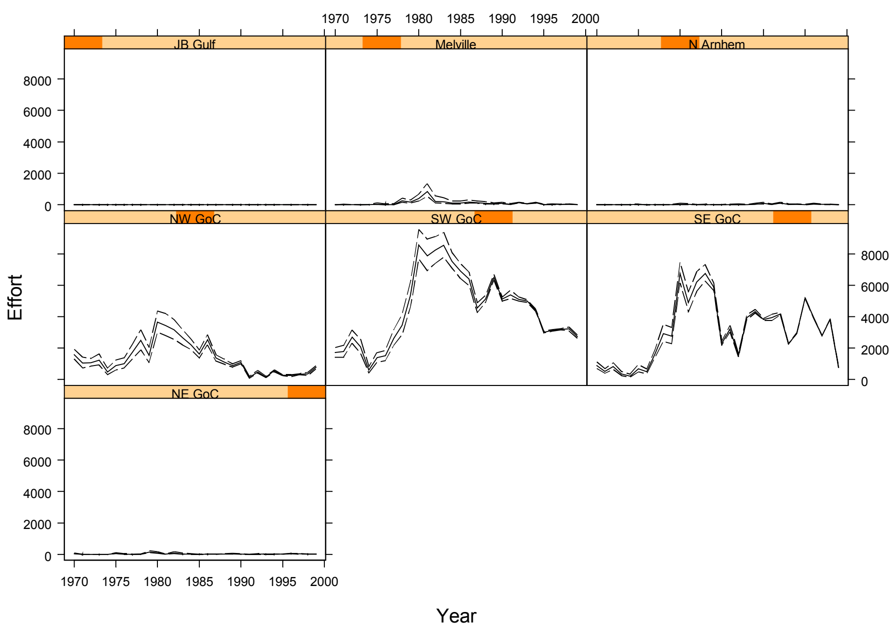


Figure 26: *Annual nominal effort given to P. esculentus in 7 stocks*



21.3. Endeavour prawn stock regions, catch and effort, 1970-1999

One species of Endeavour prawn, *M. endeavouri*, is considered to have the same stock boundaries as both species of Tiger prawns (see Figure 22). For this species the catch and effort histories are shown in Figure 27 and Figure 28 respectively. The pattern is vaguely similar to *P. esculentus*, with the stronghold in the southern Gulf.

Figure 27: *Annual catch of M. endeavouri in 7 stocks*

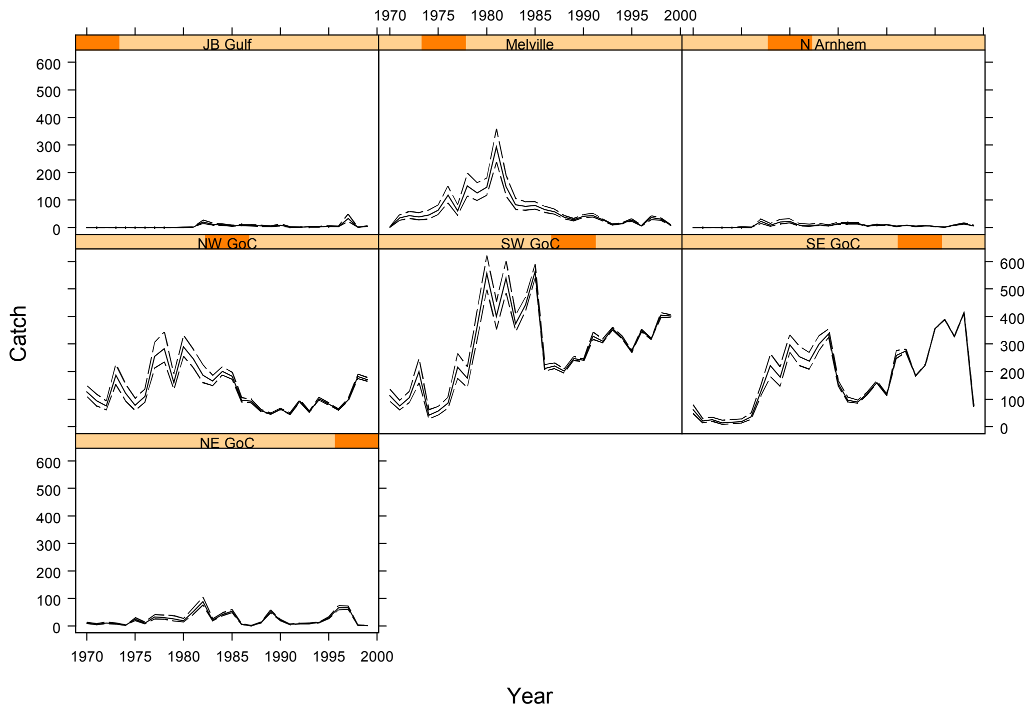
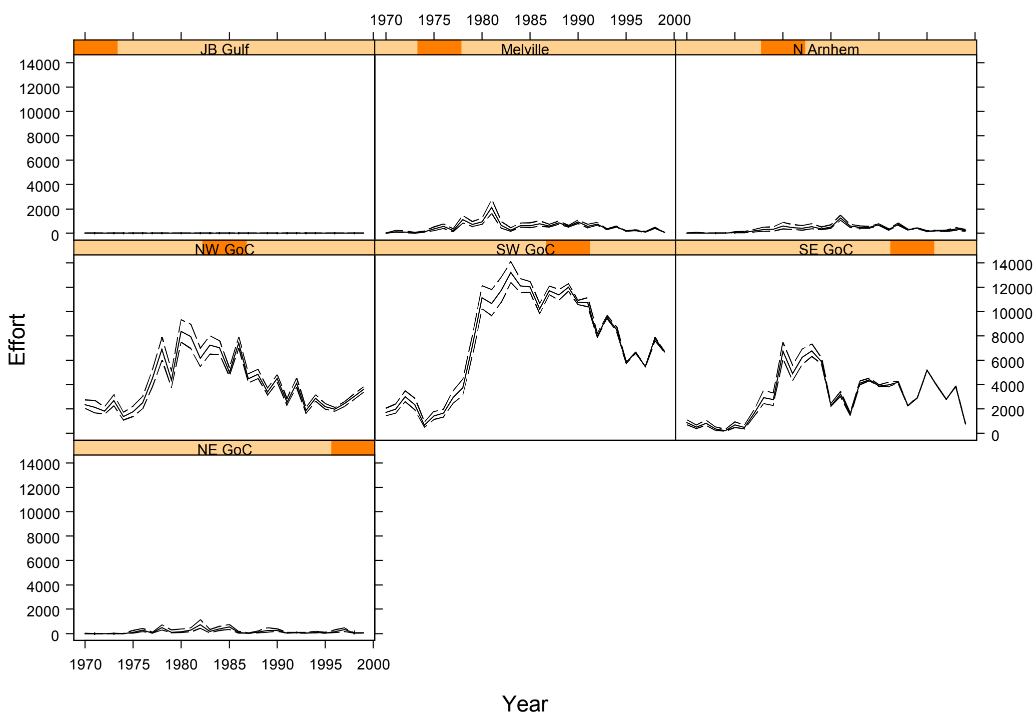
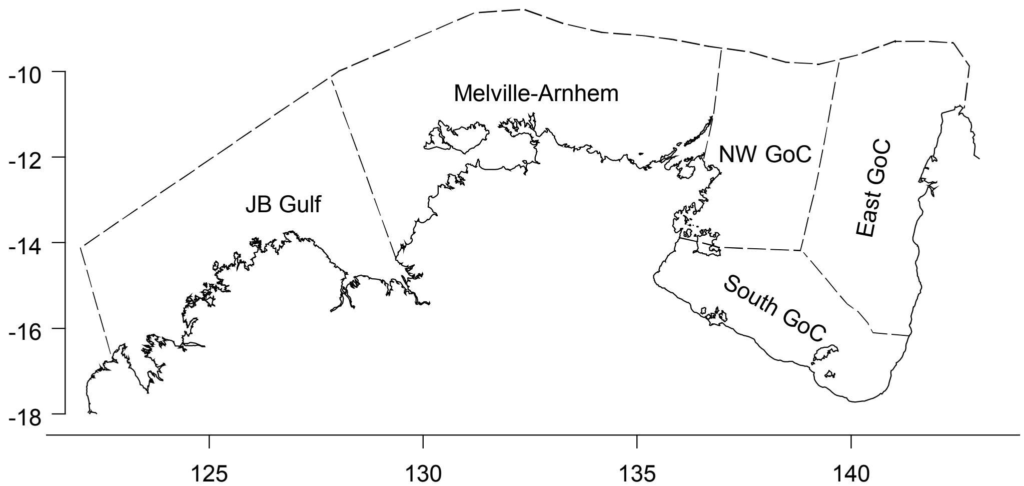


Figure 28: *Annual nominal effort given to M. endeavouri in 7 stocks*



The second Endeavour species, *M. ensis*, is more mobile than the first and 5 slightly larger stock regions are suggested. These are shown in Figure 29 below. Again the names shown here are not standard and only used for mnemonic purposes.

Figure 29: *Stock boundaries for 5 M. ensis stocks in the NPF*



This species is apparently much less frequently caught in the NPF than *M. endeavouri*. The history of catch and effort is shown in Figure 30 and Figure 31. There are similarities in the catch and effort patterns to *P. semisulcatus*, though big differences as well.

Figure 30: *Annual catch of M. ensis in 5 stocks*

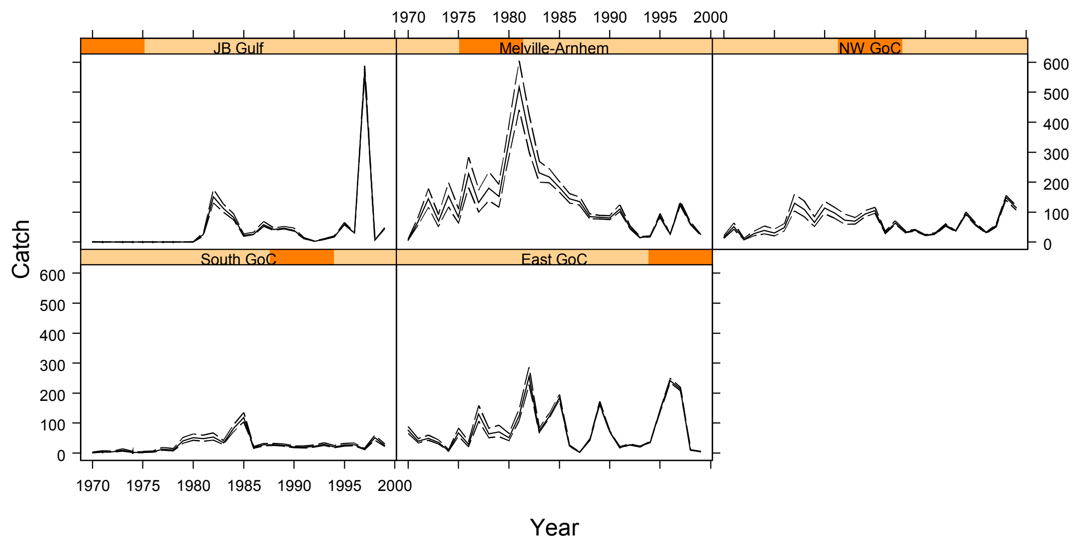
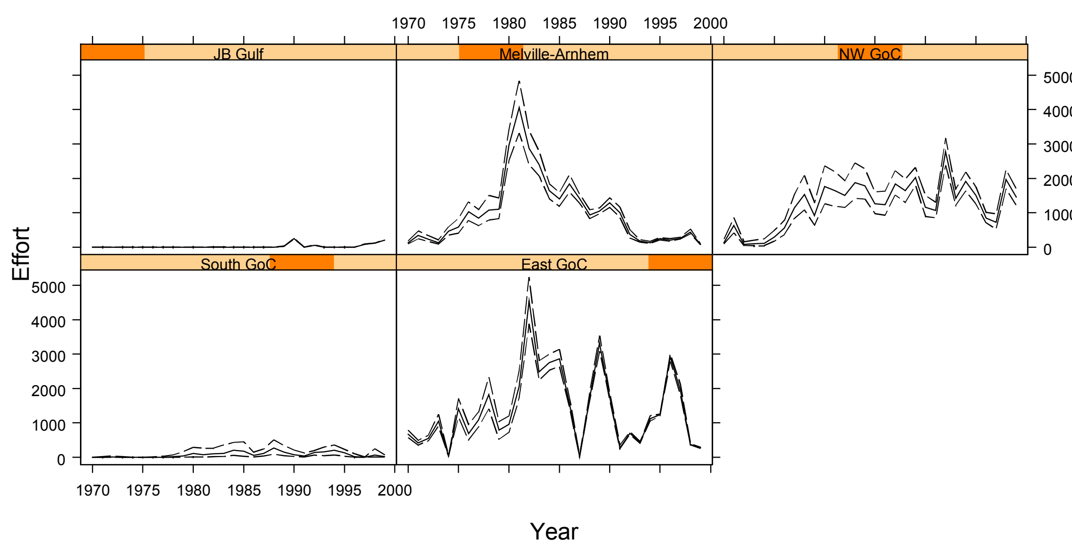


Figure 31: *Annual nominal effort given to M. ensis in 5 stocks*

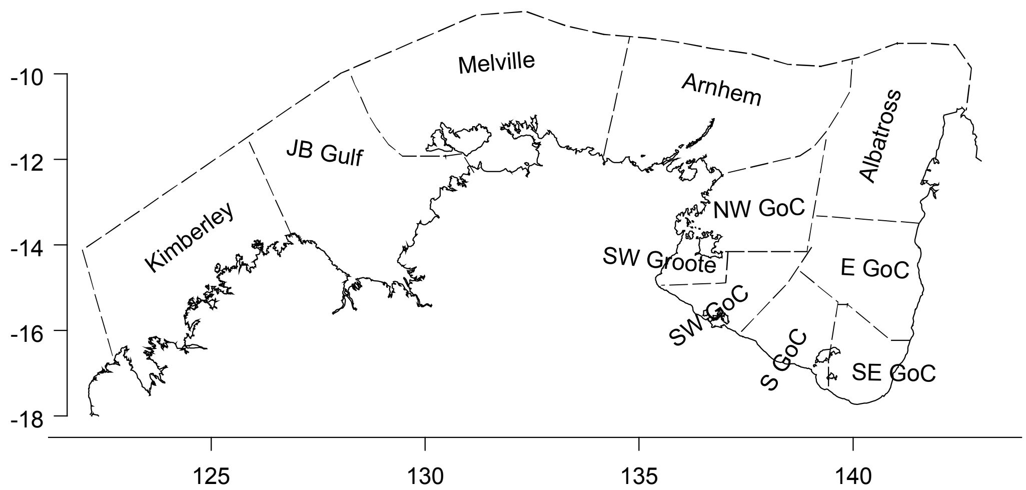


21.4. Banana prawn stock regions, catch and effort, 1970-1999

Unlike the Tiger prawn group which share stock regions, the Banana group have very different stock regions. For common bananas (*P. merguiensis*) a complex structure of 11 regions in the NPF is suggested and the boundaries are shown in Figure 32.

Again, the names shown here for these regions are not standard but only for mnemonic purposes.

Figure 32: *Stock regions for 11 Common Banana prawn stocks in the NPF*



The catch and effort histories are shown in Figure 33 and Figure 34. The situation is complex.

Figure 33: *Annual catch of P. merguiensis in 11 stocks*

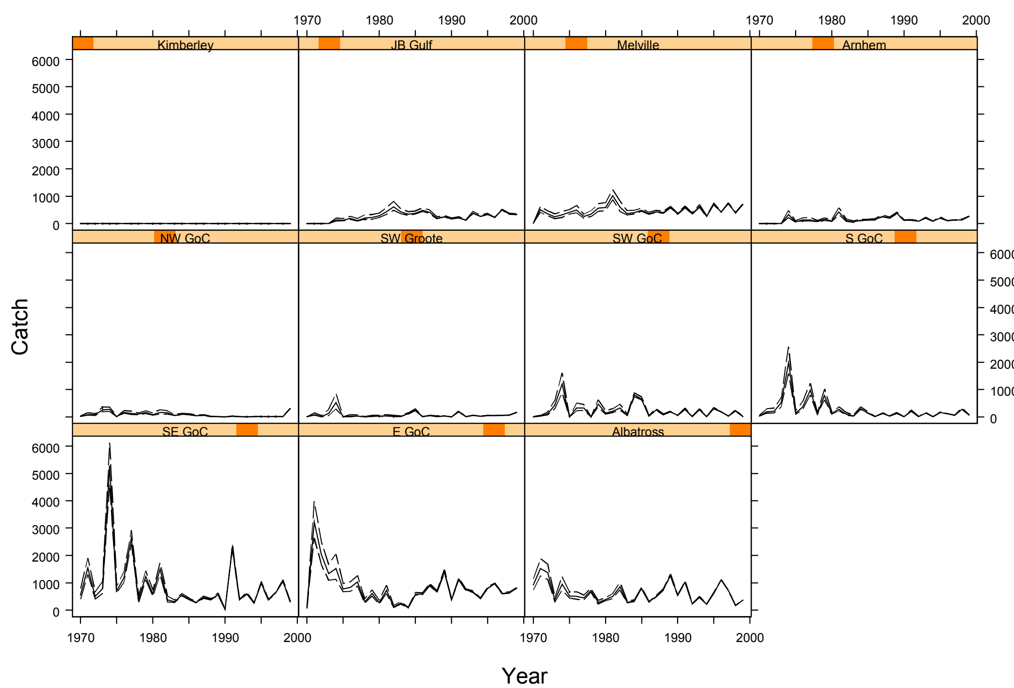
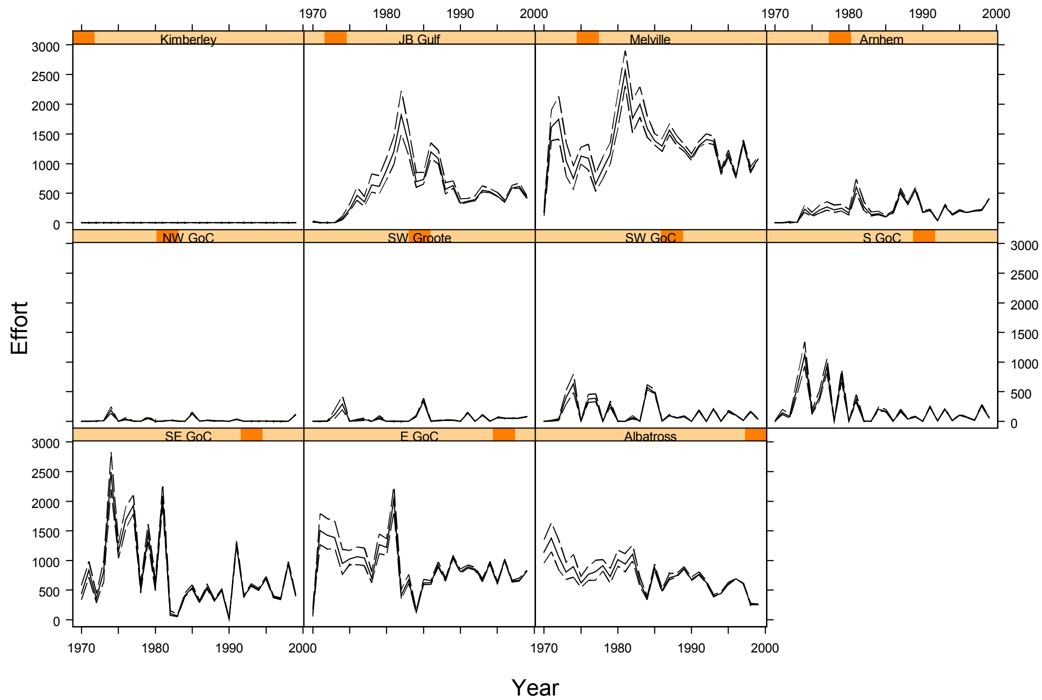


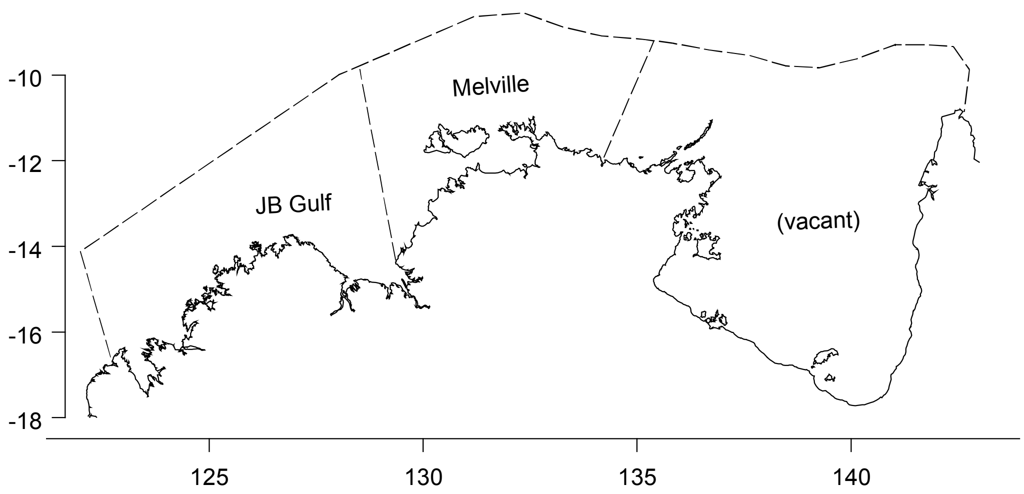
Figure 34: *Annual nominal effort given to P. merguiensis in 11 stocks*



Red-legged banana prawns do not appear in the survey data east of the Coburg Peninsula so we infer that the stock boundaries as well do not cover the entire NPF. There appears to be two distinct stocks, the major one in the Joseph Bonaparte Gulf beyond the 50 m depth contour and the other centred north of Melville Island but straying somewhat in both directions.

The regions are shown in Figure 35.

Figure 35: *Stock region boundaries for 2 red-legged Banana prawn stocks in the NPF*



The catch and effort histories are shown in **Figure** 36 and Figure 37. The major fishery is clearly the Joseph Bonaparte Gulf, which apparently started only in 1980. The region north of Melville Island and the Coburg Peninsula is a relatively minor catch and effort region. The species itself is only a small part of the full Banana prawn catch.

Figure 36: *Annual catch of P. indicus in 2 stocks*

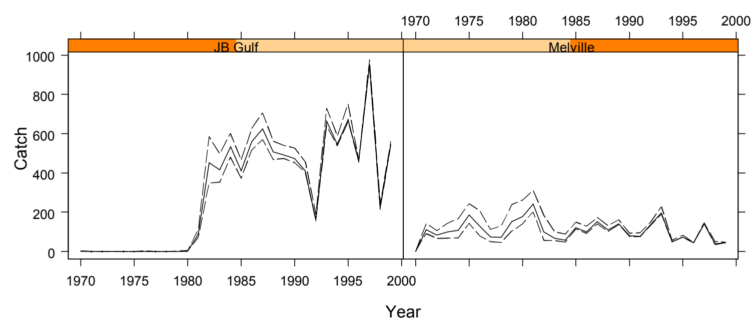
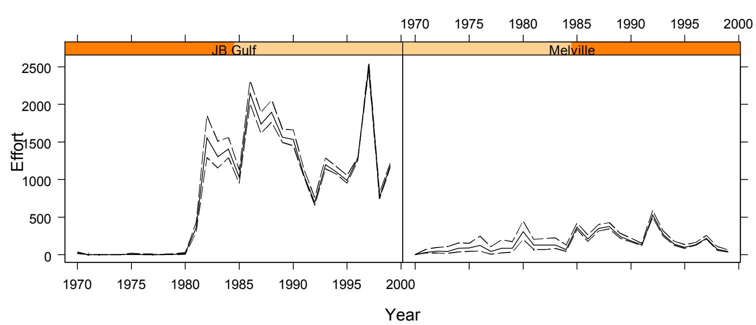


Figure 37: *Annual nominal effort given to P. indicus in 2 stocks.*



21.5. Aggregate catch and effort over stocks for all 6 species

Figure 38, Figure 39 and Figure 40 show the history of catch and effort for all 6 main commercial species aggregated over stocks within year. The scale of the response has been reduced to thousands of tonnes or thousands of boat days purely for presentation purposes. Note also that each horizontal pair of graphs share a vertical axis for comparability purposes. In some cases this obscures the temporal pattern in the data. For example in Banana prawns *P. merguiensis* has so much the greater catch the part of the common $y-$axis left for *P. indicus* is scarcely enough for it to show any vertical movement at all.

Figure 38: *Aggregate catch and effort histories for the Tiger prawn group, 1970-1999. Catch in 000's of tonnes, effort in 000's of days*

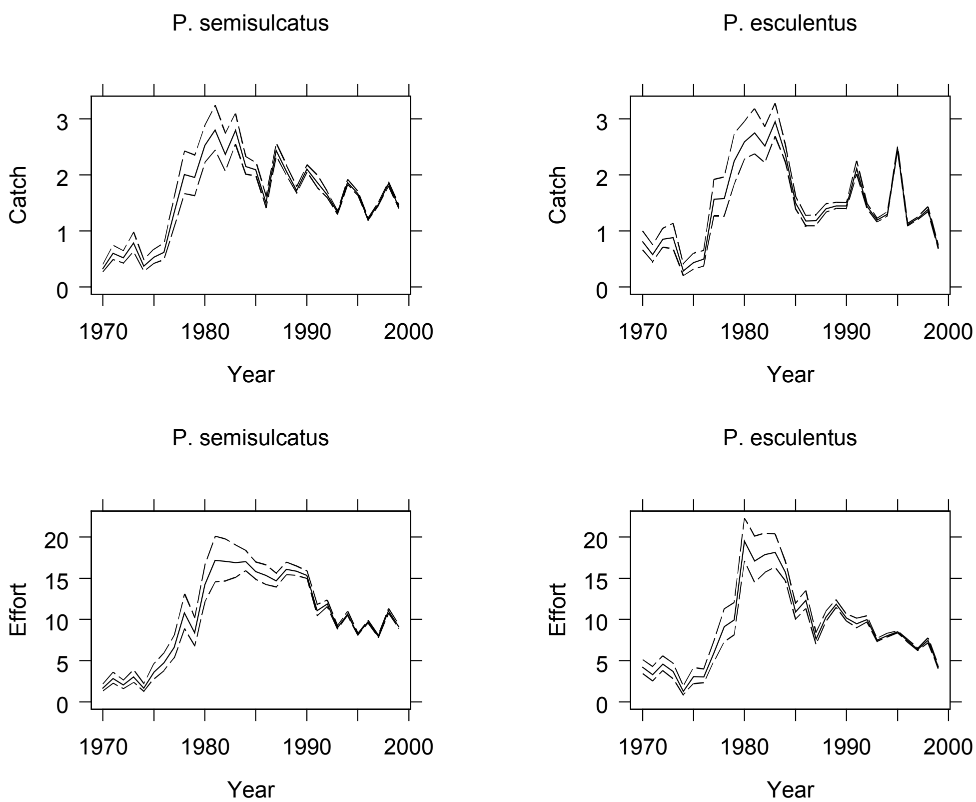


Figure 39: *Aggregate catch and effort histories for the Endeavour prawn group, 1970-1999. Catch in 000's of tones, effort in 000's of boat days*

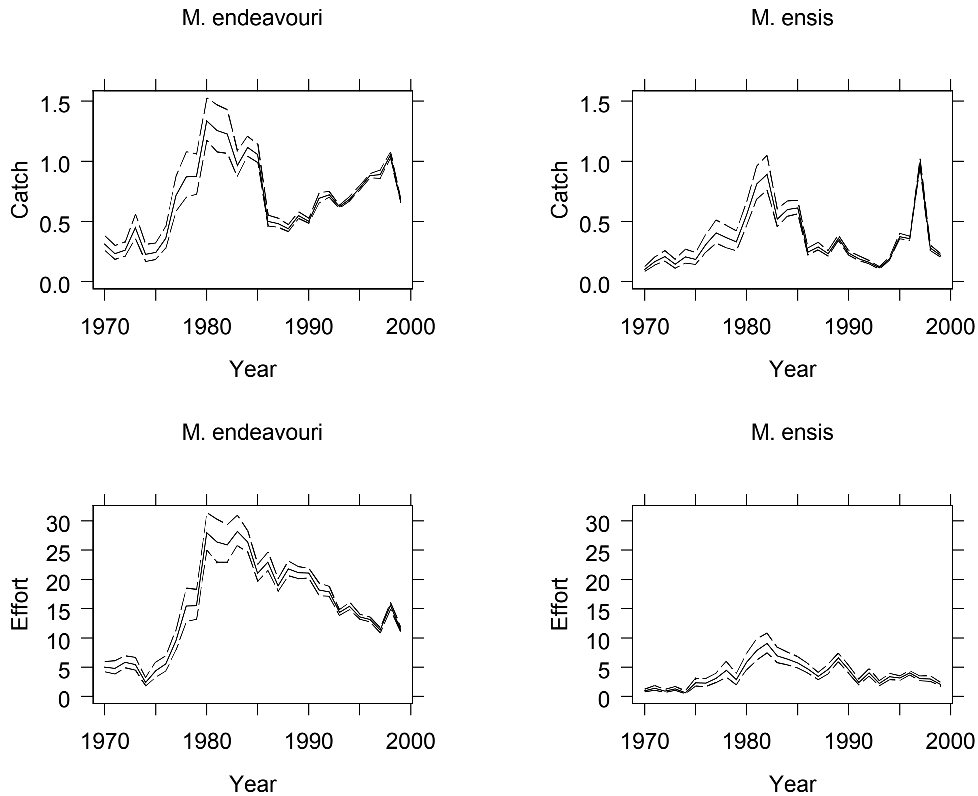
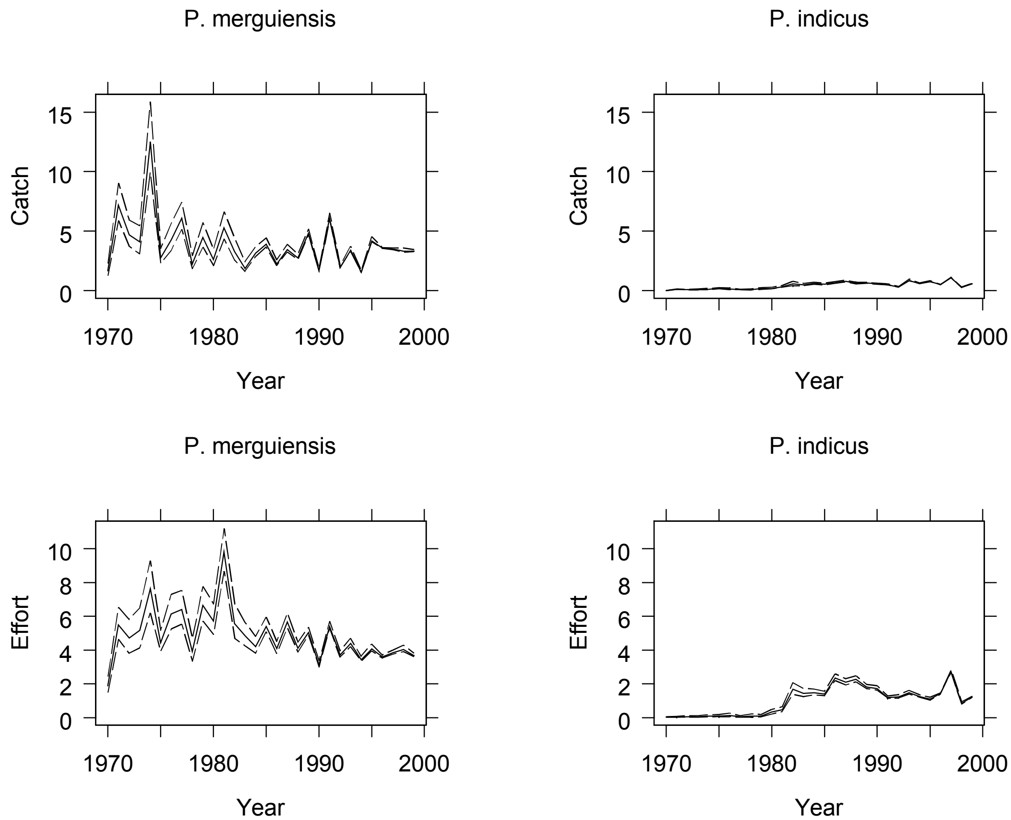


Figure 40: *Aggregate catch and effort histories for the Banana prawn group, 1970-1999. Catch is in 000's of tonnes and effort in 000's of boat days***.**



22. Comparison with the base case: Tiger prawn group

In **Figure 41** we see a comparison of the catch estimate of *P. semisulcatus* using the traditional methods of augmentation and species split as currently used in the stock assessment process and, overlaid upon it, an estimate of the same catch as the median of the 77 imputed data sets produced by the methods introduced in this report. The graphs show the weekly catch estimates, one calendar year per panel.

Clearly both methods are capturing the same strong signal, but in 1978 and 1979 when the reported catches were very low compared to landings figures, the current method produces estimates that spread the catch more evenly over the season and produce a result that is much closer to continuous from one calendar year to the next.

Figure 42 shows the corresponding comparison for *P. esculentus*. Again both series capture the same major signal but the new methods give a more continuous trace across the calendar years.

Figure 41: *Comparison of* P. semisulcatus *catch as estimated by standard augmentation and species split methods (solid line) and by the current method (dashed line).*

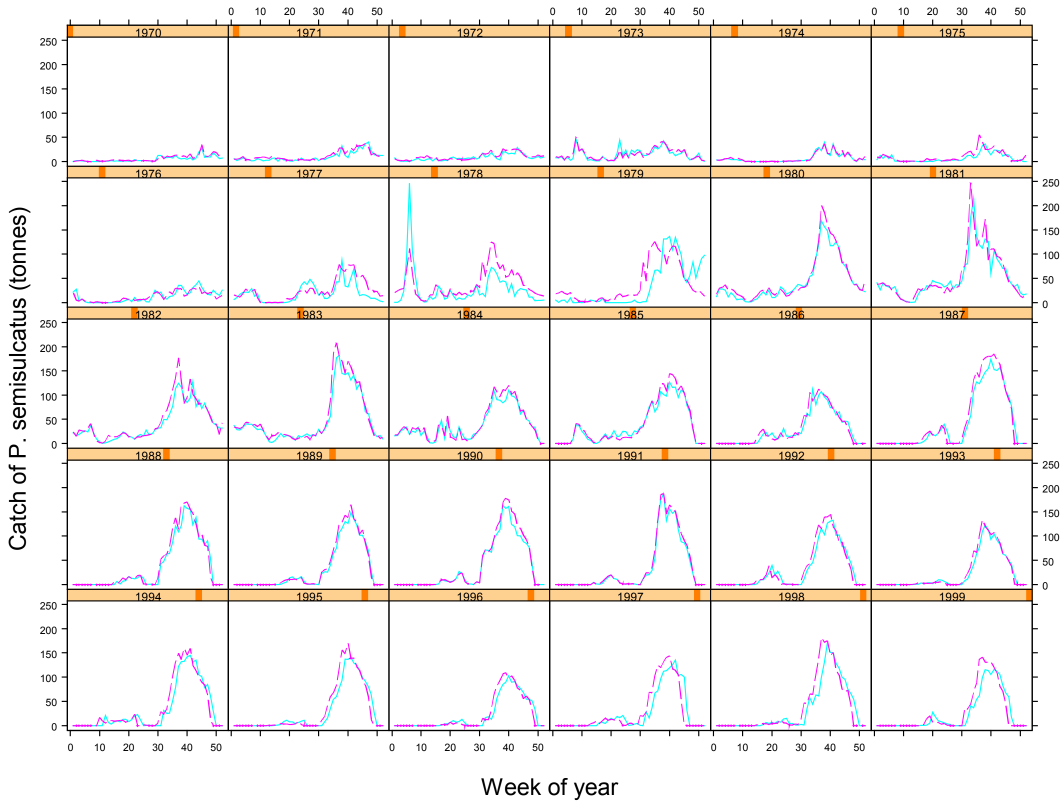


Figure 42: *A comparison of* P. esculentus *catch as estimated by standard augmentation and species split methods (solid line) and by the methods described in this report (dashed line).*

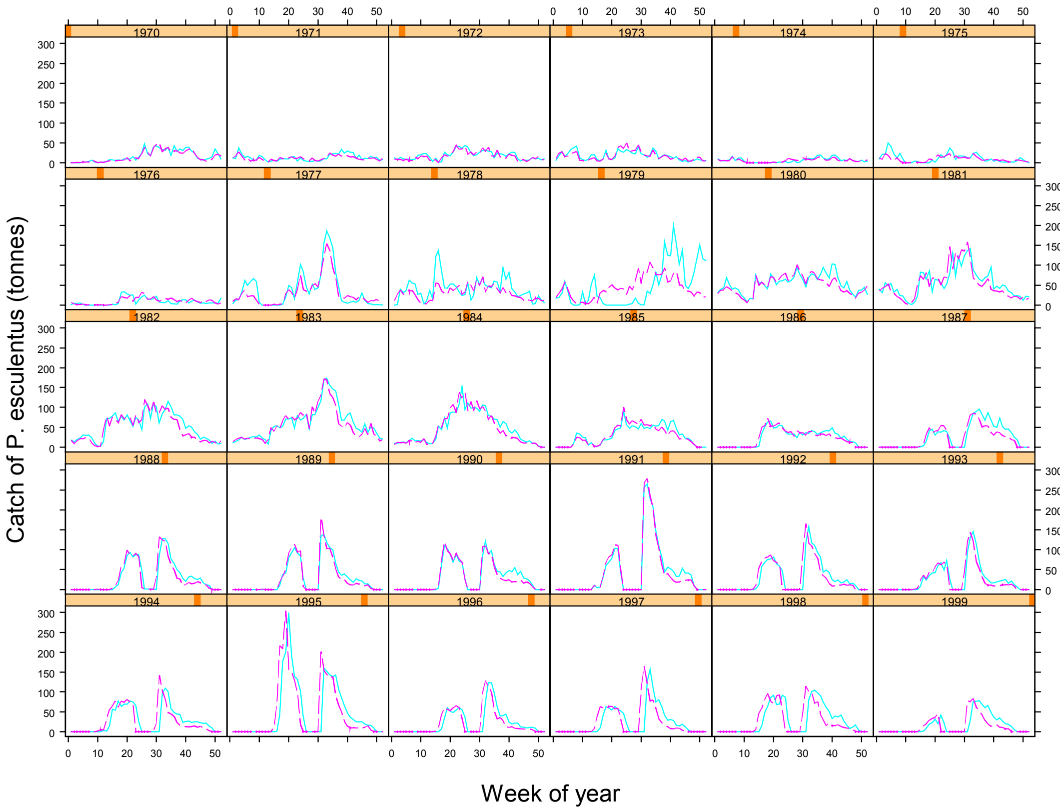


Figure 43: *Comparison of nominal effort expended on* P. semisulcatus *as estimated by traditional augmentation and species split methods (solid line) and by the methods described in this report (dashed line).*

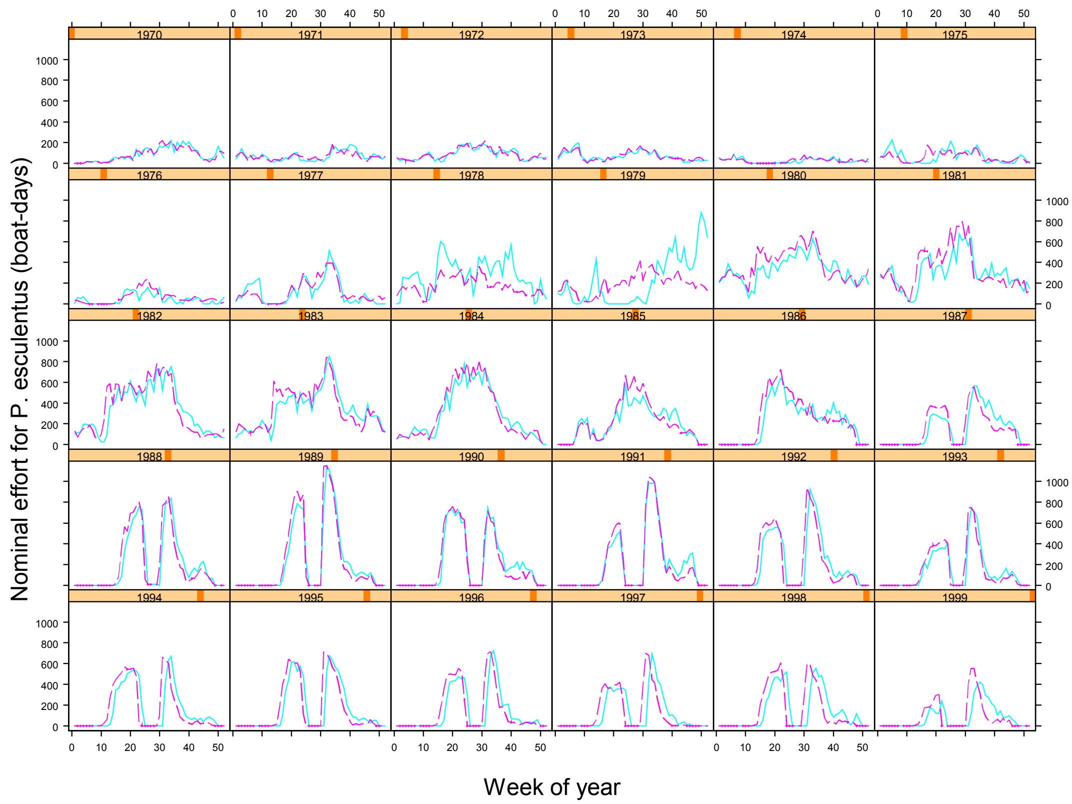
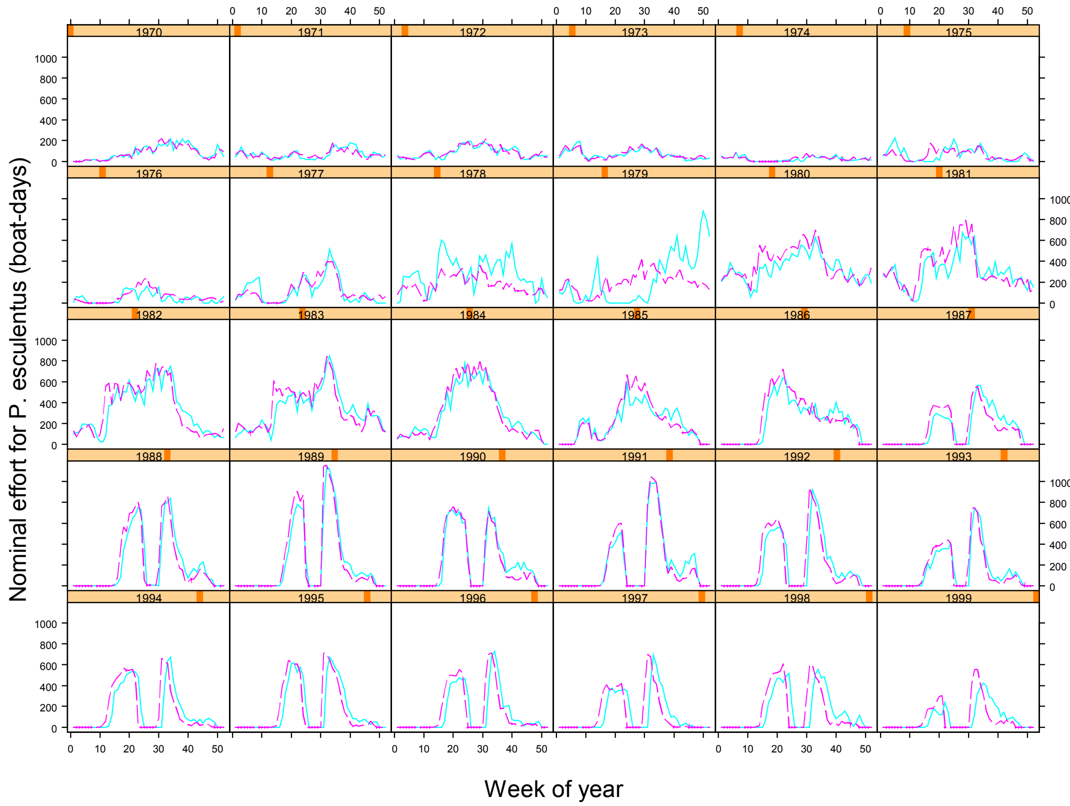


Figure 44: *Comparison of estimates of nominal effort expended on* P. esculentus *as estimated by the traditional method (solid line) and by the methods described in this report (dashed line).*



Similar comparisons of nominal effort estimates are shown in Figure 43 and Figure 44. Again the present methods capture the same strong signal as the traditional methods, but the more subtle augmentation and species split methods yield a more continuous series.

We can focus on the differences between the two results as given by the two methods in this case by plotting the differences between the outcomes for the two methods rather than the outcomes themselves. This loses the perspective that the plots of the outcomes above have but allows smaller patterns in the differences to be more easily perceived.

The results, shown in Figure 45 and Figure 46 show hints of patterns, particularly in recent years, which will be discussed in more detail later in this report. Briefly it appears that the new species split procedure, which has a dependence on the time within the year and is not static over the season suggests that the two species are to some extent caught at different times of the year from those suggested by the older method.

Figure 45: *Differences in catch estimates, (old method - new method), for* P semisulcatus *(solid line) and* P. esculentus *(dashed line).*

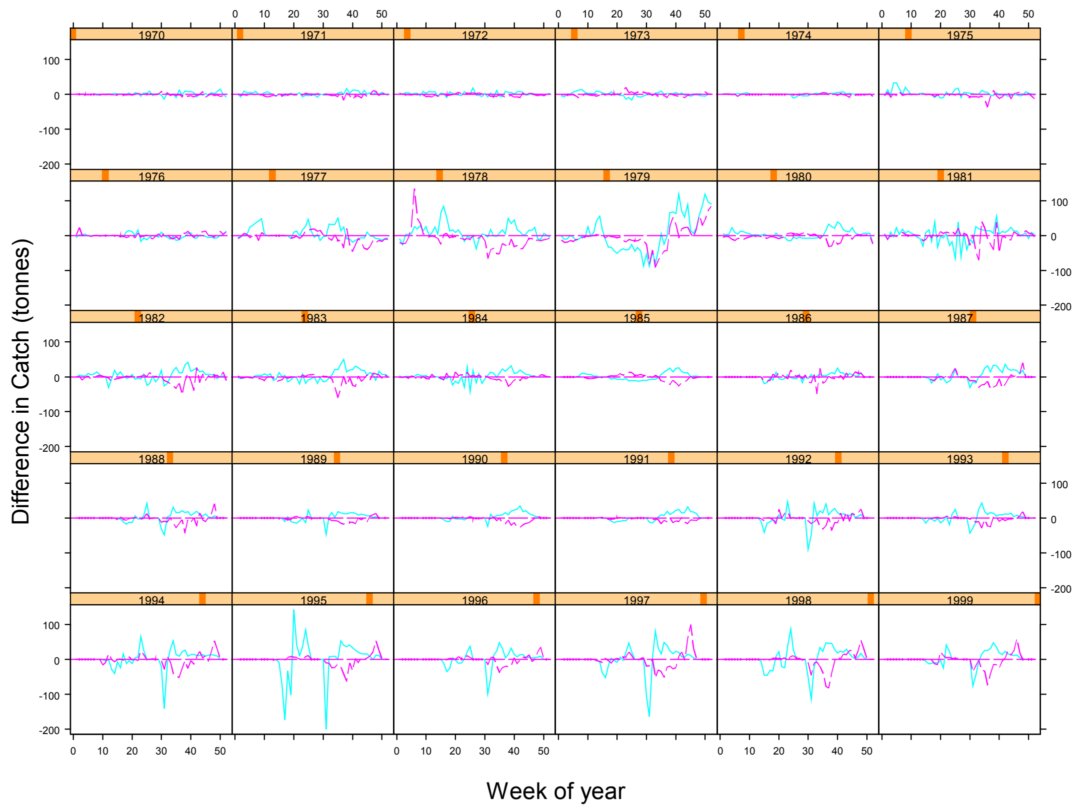
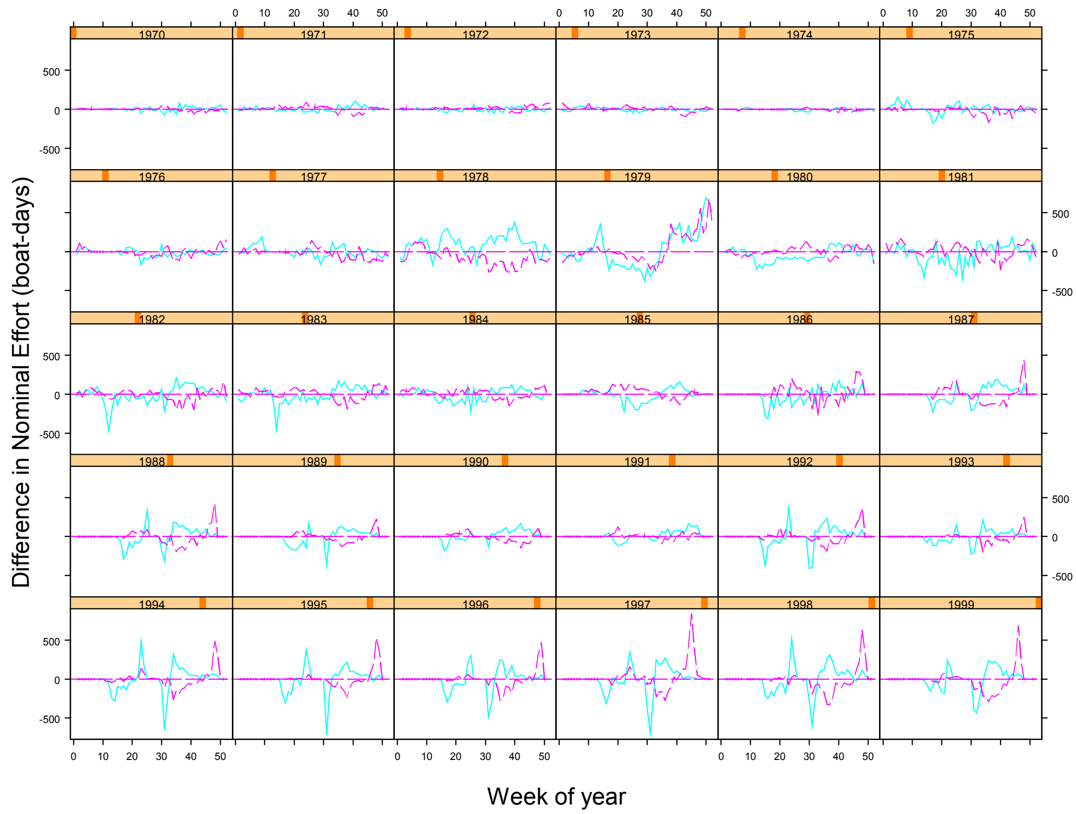


Figure 46: *Differences in estimates of nominal effort, (old method - new method), for* P semisulcatus *(solid line) and* P. esculentus *(dashed line).*



23. Discussion and further research

Any incompleteness or impreciseness in the record of catch and effort has to inject some additional uncertainty into the stock assessment process. Note that even if the input data were complete and fully accurate the stock assessment would still be subject to uncertainty because of the very nature of the biological processes involved.

The NPF records are, by most fishery standards, reasonably good but the earlier years are clearly incomplete, as shown by the difference between total recorded catch and landings records and by the fact that so many records present are geographically imprecise, that is, only located up to the area, region or province level. In a risk analysis we believe it is important to investigate the influence of these additional sources of uncertainty in the stock assessment process since they have hitherto been effectively ignored.

Our strategy has been not to reconstruct a complete and notionally accurate record in any unique way but rather to focus on *imputing* the missing and incomplete part, that is completing it in a non-deterministic way that will reasonably reflect the underlying additional uncertainties when the imputation process is repeated sufficiently often and the completed imputed records are used as input to a simulation process for the next stage. Our strategy strongly relies on an assumption that any missing or incomplete records are like a random sample of the ones that are present, that is, they are "missing at random". In all likelihood this is not true entirely, in which case our estimates of uncertainty are probably still too low, but any allowance for this known additional cause has to be an improvement on schemes that ignore it. Our imputation scheme is informal but borrows from other methods such as bootstrapping in a very obvious way. We always produce a data set where all *known* features of the data set are faithfully preserved and all *unknown* features are simulated in a way that credibly reflects that uncertainty.

The strategy itself can be summarised in a few steps:

1. For any single year, we divide the known records into two classes, which we describe as being primarily "Banana" or "Tiger" target records. This division is not based on the actual catch of the record itself but on a notional *à priori* appraisal of the chances of achieving a "reasonable catch" in each of the two groups based on location, time of year, depth of water and distance from land, only.
2. The records are then re-sampled using a guided form of random sampling with replacement aimed at simultaneously making the Tiger and Banana total catches equal to the landings records.
3. Records with an imprecise location are then randomly assigned to one of the grids from within the known set of grids from which they came with probabilities proportional to the known fishing frequencies for the grids within the set using all available logbook data.
4. Species split is then conducted, but in a stochastic way that incorporates the uncertainty inherent in the species split process itself.

5. Finally the imputed data sets are used as simulation inputs to the stock assessment process.

In this chapter we have worked with a single set of 77 imputed records mainly for demonstration purposes. This number is large enough to reflect the uncertainty usefully and has the slightly convenient property that for the case of normally distributed the average probability content between the second and second last sorted value is very close to the 95% of conventional confidence intervals. Our uncertainty intervals are then based on these two order statistics. Having one more extreme order statistic at either end usefully reduces the variance of this random probability content as well.

One useful output after step 4 in the process above is that we get an estimate of historical catch and effort levels together with an assessment, perhaps a low assessment, of the level of uncertainty due to incomplete or imprecise data. We have shown these historical estimates for annual catches and notional efforts, firstly by stock and then aggregated over stocks.

The boundaries of the discrete stock regions for any species of prawn in the NPF are not yet settled by research but expert knowledge can give us a workable first cut. Based on these we have shown catch and effort histories for the six major commercial species and the uncertainty levels appear to be reasonably low. This must be the case for recent years as the logbook record itself is assumed very nearly complete and accurate, but even for years when the record was palpably incomplete the fact that the landings totals are known and the assumption of missing at random together combine to give a result that suggests that even there the uncertainty level is not so large that the estimates are worthless.

23.1. Suggested further research

23.1.1. Stock structure in the NPF

Some formal work on establishing stock structure in the NPF is clearly overdue. Just how this would be best done is clearly an issue for biologists to decide, but genetic surveys and tagging experiments may be two complementary ways of attacking the problem. There may also be opportunities for attacking the stock structure and species split problems together as they are clearly related issues both of which could be addressed by similar survey methods.

23.1.2. Augmentation and imputation methods for incomplete data

The imputation methods presented here are tailored to fit this particular missing data situation in the NPF and their justification has been frankly heuristic. There are some ideas here that appear new and that may be more generally applicable. There is scope for purely statistical research to study the behaviour of the methods we use here in a more formal way and to generalize them to other settings.

23.1.3. Inferring target species

Our method here for inferring a *target species group* was initially used only to guide the re-sampling method in order to achieve simultaneous matching of Tiger and Banana prawn totals to the corresponding totals. Further refinement to a *target species* was used to assess effort and bycatch effort. This method appears new, but needs further development before it can be accepted as a fully serviceable method for stock assessment. The advance we see for it over the method presently used for the NPF is that it does not rely on the outcome of the particular catch explicitly but only on information pertaining to the time and place of fishing. We suggest that further research in this area is urgently needed.

24. Reference List

Sharp, A., Malcolm, J. and Bishop, J. Northern Prawn Fishery and Kimberley Prawn Fishery Data Summary 1999. Australian Fisheries Management Authority:

Wang, Y.-G. and Die, D. (1996) Stock-recruitment relationships of the tiger prawns (*Penaeus esculentus* and *Penaeus semisulcatus*) in the Australian Northern Prawn Fishery . *Marine and Freshwater Research* **47**, 87-95.

CHAPTER 4: FISHING INTENSITY AND DEPLETION STUDIES BASED ON VMS AND LOGBOOK DATA

25. Introduction

Satellite-based vessel monitoring systems (VMS) are being widely applied at the regional level for the implementation of mainly a monitoring, control and surveillance system for natural conservation, environmental protection and fisheries management.

In Australia’s Northern Prawn Fishery (NPF), VMS initially was introduced mainly to assist enforcement of fishery regulations. It recorded each vessel’s position at fairly regular intervals during the fishing seasons, therefore the trawl areas and tracks for each vessel can be interpolated using the VMS data by conducting trawling track analysis. Trawling track analysis is a useful tool for stock assessment. For example, these data make it possible to determine the distribution of fishing intensity on spatial and temporal scales, so that one could more accurately estimate and manage impacts of trawling on benthos. Another example is using the technique to analyse depletion events from aggregated and random fishing areas to investigate the relationship between biomass and catch per unit effort.

Previous trawl track analyses using simulated variable polling frequency VMS data from Global Positioning Systems (GPS) has been undertaken by Hall et al but is as yet unpublished. They concluded that the standard polling frequency was not suitable for fine-scale trawling track analysis without the help of GPS data. As a result, the project acquired high polling frequency VMS data from Australian Fishery Management Authorities (AFMA) for 3 specific fishing ground grids. These areas were chosen as they represent historically high catch and effort areas, but fishing patterns were either random or aggregated due to the degree of untrawlable grounds within them.

The research has two main aims: one of them is to derive the distribution of fishing intensity more precisely by trawling track analysis. An improved method has been devised to utilise series data-processing methods within the Geographical Information Systems package ARC/INFO.

The second aim is to conduct depletion analyses in the selected grids, comparing the random and aggregated fishing grounds (Figure 47).

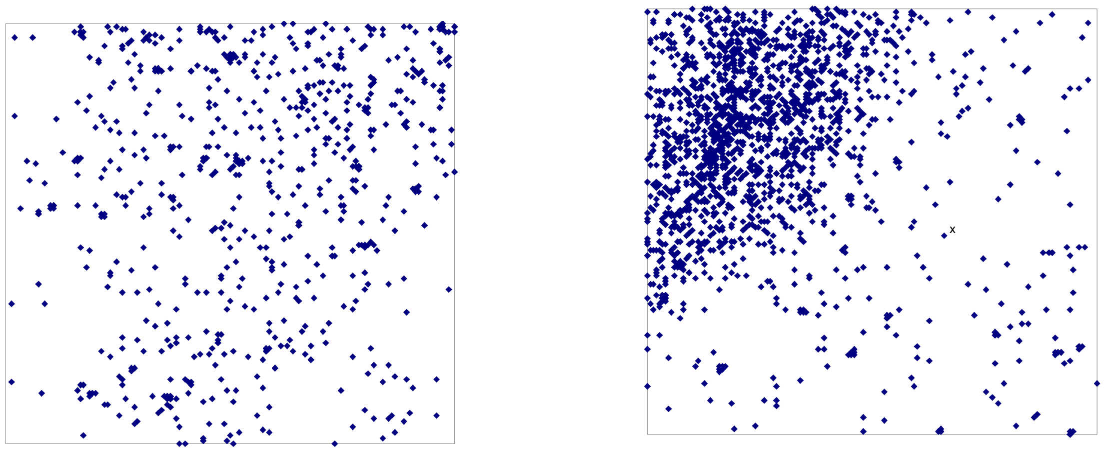


Figure 47: *1998 VMS point data for a random fishing grid (left hand side) and an aggregated fishing grid.*

Standard stock assessment techniques assume that the catch per unit effort is proportional to stock biomass, that is the catch per effort unit (CPUE) is an index proportional to stock abundance (Hilborn and Walters, 1992). In fact the catch or catch per unit effort could be affected by gear saturation through intensive fishing in a small area since much of the remaining area in the vicinity was untrawlable and not necessarily because of any aggregation of prawns. Therefore the hypothesis being tested in this project is that the rate of depletion in highly aggregated fishing areas would be artificially greater than that in randomly fished areas (Figure 48). The rate of decline in the biomass could be the same as elsewhere but not the rate of decline in CPUE. It would follow that the highly aggregated AND intensively fished areas may not conform to the assumption that CPUE is an index proportional to biomass.

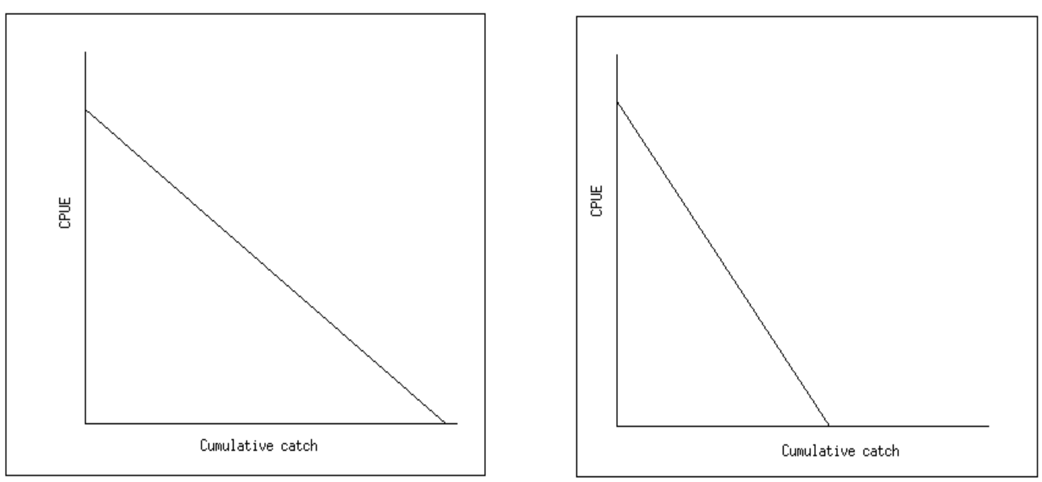


Figure 48: *Hypothesis of affect of random (left hand side) and aggregated (Right hand size) fishing areas on a depletion curve of CPUE versus cumulative catch.*

26. Method

26.1. Areas

It was the original intention that four areas be selected for this study, however one area was subsequently closed to fishing. The remaining 3 grids were each 6' by 6' geographical grid squares. These areas in the southern Gulf of Carpentaria represent the most intensively fished areas in the NPF, producing up to 88% of the tiger fishery catch between 1993 and 1997 (Table 10). For confidentiality reasons, the positions of these grids cannot be displayed. These areas represent two kinds of fishing grounds, namely random and aggregated.

Table 10: *Annual average catch and effort in the tiger prawn fishery taken from the selected grids during 1993 and 1997 (AFMA logbook data).*

Grid number	*Latitude*	*Longitude*	*Tiger Prawn Catch (Kg)*	*Total Tiger Prawn Fishery Catch (Kg)*	*Effort (Boat Day)*	*Boat Number*
A	Lat A	Lon A	19647.6	22312	90.4	25.8
B	Lat B	Lon B	35767.2	73044	189.6	41.2
C	Lat C	Lon C	29880.4	40483	100.6	27.8

However, current catch and effort data indicated a big decline in catch and effort taken within the areas (Table 11), which means that local depletion may not have occurred within these regions.

Table 11: Yearly catch and effort of the selected areas since 1998.

Grid number	*Year*	*Tiger Catch (kg)*	*Total Catch (kg)*	*Effort (Boat days)*	*Boat number*
A	1998	21993	24793	74	30
A	1999	10584	11150	47	25
B	1998	4253	23562	76	36
B	1999	*	*	<10	<10
C	1998	13045	20523	58	30
C	1999	1857	2754	12	8

*** Restrictions on the publication of low effort and catch results prevent us from giving detailed data for grid number B in 1999.**

26.2. Data set

The challenge of undertaking a depletion analysis is to combine the high precision VMS position data with the daily, relatively coarse spatial and temporal scale logbook data. However, the VMS data does not record whether the vessel is fishing or is in transit. The data format from the VMS system is presented in Table 12. This information can only be inferred from the vessel speed, calculated from the distance travelled between different polls and the time taken.

Table 12: *Original VMS data format*

Name	*Date*	*Time*	*Latitude*	*Longitude*	*Distance*	*Speed*	*Course*
Vessel A	Day x	Time1	Lat1	Lon1	0.87	12.98	317.94
Vessel A	Day x	Time2	Lat2	Lon2	0.56	16.77	321.61
Vessel B	Day y	Time3	Lat3	Lon3	0.81	3.47	270
Vessel B	Day y	Time4	Lat4	Lon4	0.12	0.5	270
Vessel B	Day y	Time5	Lat5	Lon5	0.75	3.22	90
Vessel B	Day y	Time6	Lat6	Lon6	0.75	2.83	87.26

The NPF logbook data are commercial fishery data recorded daily. The skipper records each fishing vessel's name, vcode (vessel ID), fishing day, daily catch of each species group and location (longitude, latitude) at which the largest catch was obtained. The date and the vcode were used as the key to link the logbook data with the VMS data (Table 13).

Table 13: *Logbook data format*

LGB_DAY	*LAT*	*LON*	*BANA*	*TIG*	*ENDE*	*KING*	*MIXED*	*F*	*HOURS*	*VCODE*	*NAME*
Day x	Lat X	Lon X	0	230	9	0	0	t	13	999	Vessel B
Day y	Lat Y	Lon Y	0	320	9	0	0	t	13	999	Vessel B
Day z	Lat Z	Lon Z	0	320	9	0	0	t	13	999	Vessel B
Day m	Lat M	Lon M	0	144	18	0	0	t	13	1000	Vessel C

At times, the high frequency polling data from the girds were not enough to link the Grid information and the logbook data correctly. This was mainly due to discrepancies between the location in the VMS and that given in the logbook record. In these cases the standard VMS data from a much larger area surrounding the grids were used as a supplement.

26.3. Linking the VMS and logbook data

It is essential to link the VMS and logbook data properly for accurate analyses. The depletion analysis required knowledge of the catch area. But the different spatial and temporal scales of the VMS and logbook data mean that the catch cannot be accurately linked to the grids, but rather can only be associated with a larger, more loosely defined area. When plotting the position from high polling frequency VMS data within the 6 x 6 minute grids and from the logbook data, the logbook position for highest catch of the day need not correspond to that obtained from the VMS grids, which we know the vessels had entered only for some of the nights.

This mismatch of grid square and recorded positions of maximal catch during the research time imply that the precise RESEARCH AREAS to which the effort pertains has to be carefully defined in some compromise fashion. We have adopted the following compromise method. For each area the convex hull of all points is first calculated. This is the smallest convex polygon containing all the points and can most easily be visualised by imagining pins being inserted at all observed points and a tightly fitting rubber band fitted to enclose all the points. There is a difficulty with this definition, though. A single outlying vagrant point can easily double the entire research area. For this reason we define the area more conservatively by using the one-peel convex hull. In the rubber-band interpretation this means conceptually removing the pins that the rubber band makes contact with and using the convex hull of the remaining set. This adequately allows for outlying points and defines the study area in a realistic way.

VMS records that did not represent fishing location i.e. anchored vessels, vessels in transit (cruise speed > 4 knots) and daytime records (8am ~ 6pm) during which tiger prawn fishing is prohibited were eliminated from raw VMS data. In order to create the link of VMS data and logbook data, a common field vessel code, or VCODE, which already appears in the logbook data, was introduced to the VMS data. We selected all logbook records that geographically fell in the grid and its 8 surrounding 6-minute grids. Both the VMS and logbook position records were placed into a GIS package (ARC/INFO) to display their geographical positions. Related standard VMS position records were also imported as references to adjust our *RESEARCH AREAS*.

26.4. Calculation of fishing intensity

Fishing intensity is the number of times an area is swept by a trawl net in some fixed time. It largely determines the level of impact of trawling on benthos (Hall *et al.*, unpubl.). High polling frequency VMS data recorded the vessel's detailed trace of fishing or trawling. Previous VMS simulation studies on GPS data provided good examples for this advanced research.

Before further study, several assumptions and definitions were made: the vessels travel in a straight line between polls; trawling width is 20 meters on both sides of vessels; one trawling track (40 metres wide) is the trace of one vessel for one fishing day.

The method for assessing fishing intensity is to calculate the overlap times for one individual track and then sum up the total overlap times for all tracks in the study areas for a specific fishing season. To achieve this aim, the individual track records have to be sorted and plotted respectively. For this purpose we imported the data into the GIS package ARC/INFO and used its features/operations of arc, buffer, polygon, region and grid to obtain the final results.

The original VMS data were in excel format. The field VCODE and Date in both VMS data and logbook data were used to produce the unique track ID for each track identity.

It is also necessary to make VMS day and logbook day consistent. There is a 12-hour advance of VMS date over logbook date, since the vessels tend to record the morning's date in their logbooks, but the VMS data would start on the date of the night before. So an adjustment was done to make them compatible.

To ensure the correct track patterns, correct time sequence values from all date and time fields in VMS data set were generated. The records for each TRACK_ID were sorted according to time-sequences-values and exported as an ASCII file for further processing.

To integrate the VMS data with ARC/INFO automatically, the exported ASCII file should be further sorted and filtered to meet the requirements for importing the data into ARC/INFO. The data were sorted and extracted according to the TRACK_ID in the same format as presented in Table 14.

Table 14: Data format applicable to import into arc (line) in ARCINFO

331432	
137.498	-15.39
137.498	-15.39
137.497	-15.39
137.504	-15.389
137.489	-15.387
137.475	-15.385
137.463	-15.385
End	
End	

The records of the same TRACK_ID were selected and extracted to compose the pre-importing track data file, one-track data file representing one track and being imported as one coverage in ARC/INFO. A PERL script and an AML script were produced to complete these tasks. Figure 49 shows the complete trawling tracks in Grid A from high polling frequency VMS data in the 1999 tiger prawn fishing season.

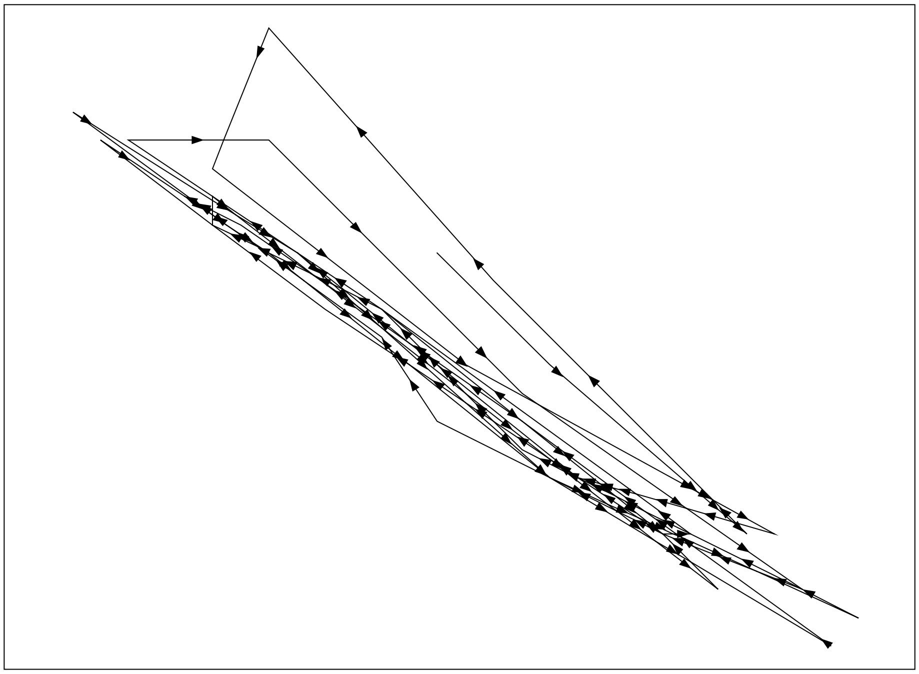


Figure 49: *NPF Trawling track from VMS data*

For further calculation of fishing intensity, special analysis was imposed on the trawling tracks individually. We select one section from one individual trawling track to give detailed explanation of the method.

To simulate the real trawling track we set the trawling width 40 meters. The buffer regions with 40 meters width along the track line were then created (Figure 50). The function REGIONBUFFER in ARC/INFO generated regions in a specified output region subclass around specified input coverage features. Since regions required supporting polygon topology, polygons were created as well. It was noticed there were many small polygons when tracks intersected (Figure 51). The region number over the polygons was derived by function REGIONPOLYCOUNT. In our case, the region number over the polygon represents the trawling times over that polygon, i.e. the fishing intensity. By rasterizing those polygons with the value of region numbers, we obtained the fishing intensity grid for individual trawling tracks (Figure 52). Another AML script was written to produce the grid sum from all individual trawling tracks and, therefore, the final distribution of fishing intensity in the areas in the specific fishing season.

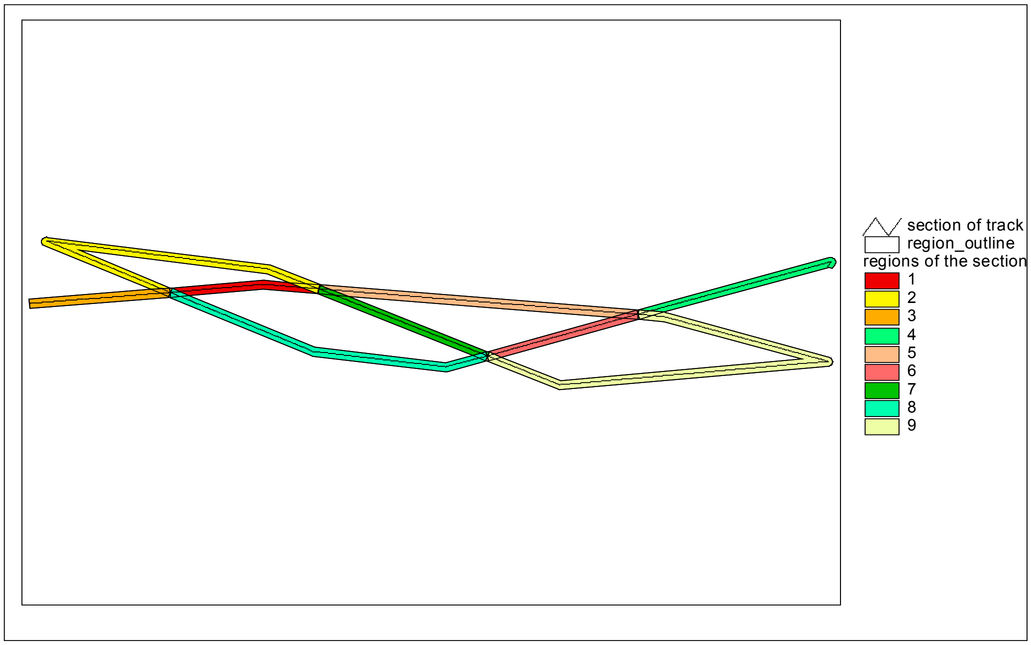


Figure 50: *Section of individual track and its regions*

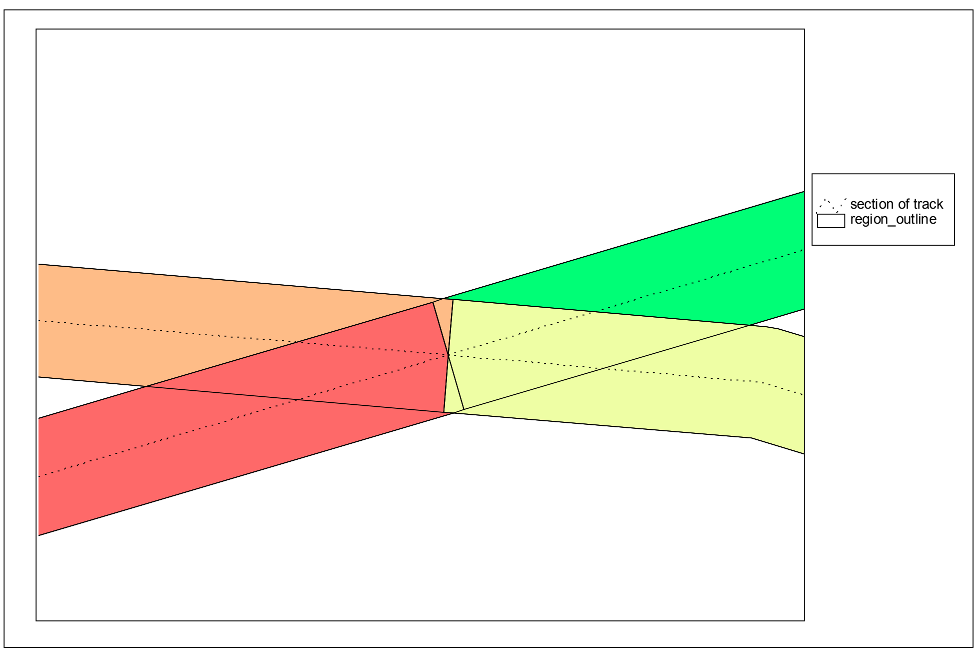


Figure 51: *Detailed regions-supported polygons in trawling track*

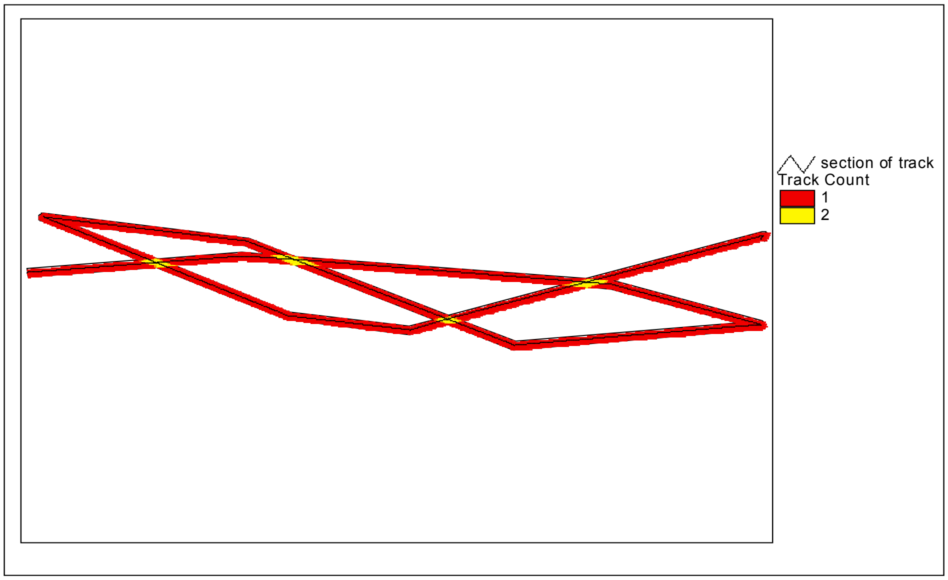


Figure 52: *Regions number over polygons in sample trawling track*

26.5. Depletion event analyses

As described earlier in this chapter, there are two types of fishing grounds to conduct the depletion experiments. In one type fishing is at random and in the other the fishing is aggregated. The careful definition of *RESEARCH AREAS* is a critical factor for this purpose. In the selected areas, VMS data are consistent spatially and temporally with logbook data. The information on which parts of the fishing grounds were untrawlable was supplied by Haywood et al (Unpublished).

Applying the depletion estimate method (Hilborn and Walters, 1992), we selected all logbook records that fell into the *RESEARCH AREAS* from an Oracle database and calculated the daily cumulative catch of tiger prawns and its CPUE. Then the tiger prawn depletion curves were plotted. The trends of the curves indicate the depletion situations in the *RESEARCH AREAS*.

27. Results

There are four kinds of main results from study.

1. Deliberately defined *RESEARCH AREAS* (Figure 53, Figure 54, Figure 55, Figure 56, Figure 57 and Figure 58) when the VMS data and Logbook data spatially and temporally consistent. The depletion analysis was based on these areas.

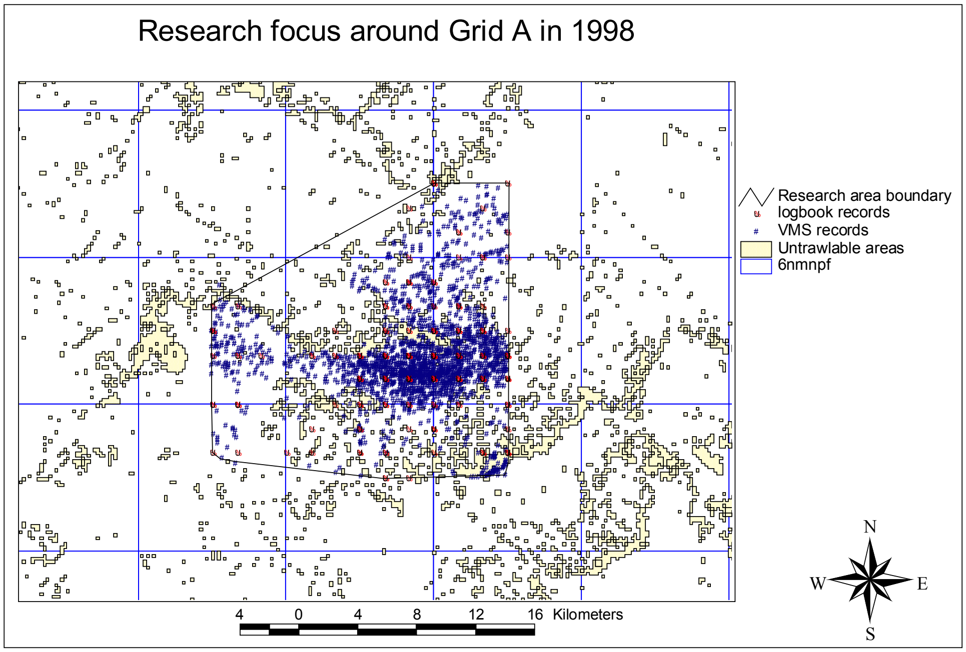


Figure 53: *Defined RESEARCH AREAS for Grid A in 1998 (Aggregated fishing ground)*

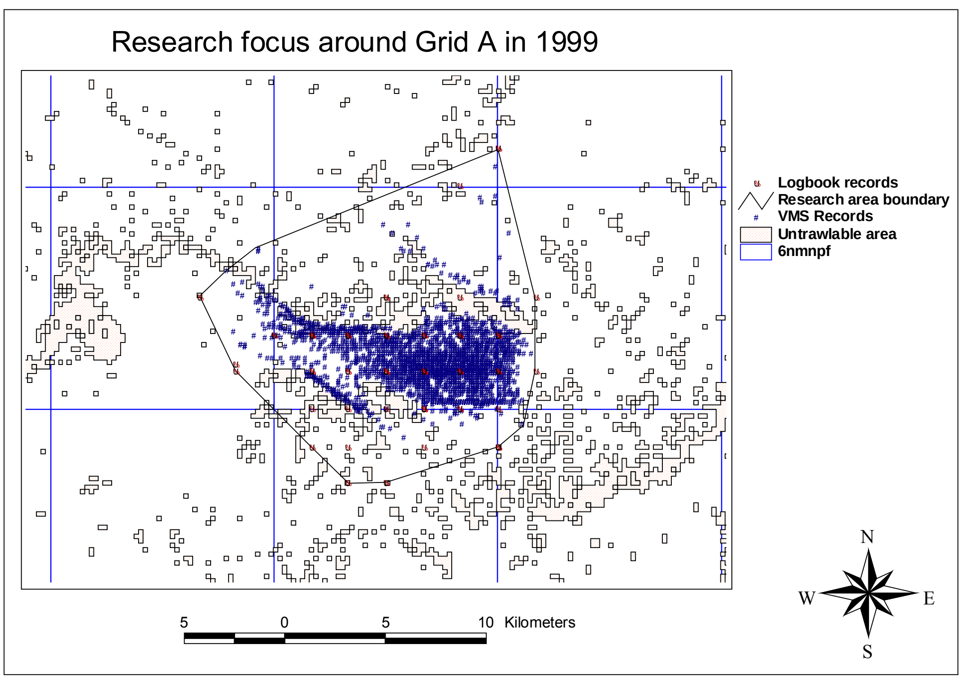


Figure 54 *Defined RESEARCH AREAS for Grid A in 1999 (Aggregated fishing ground)*

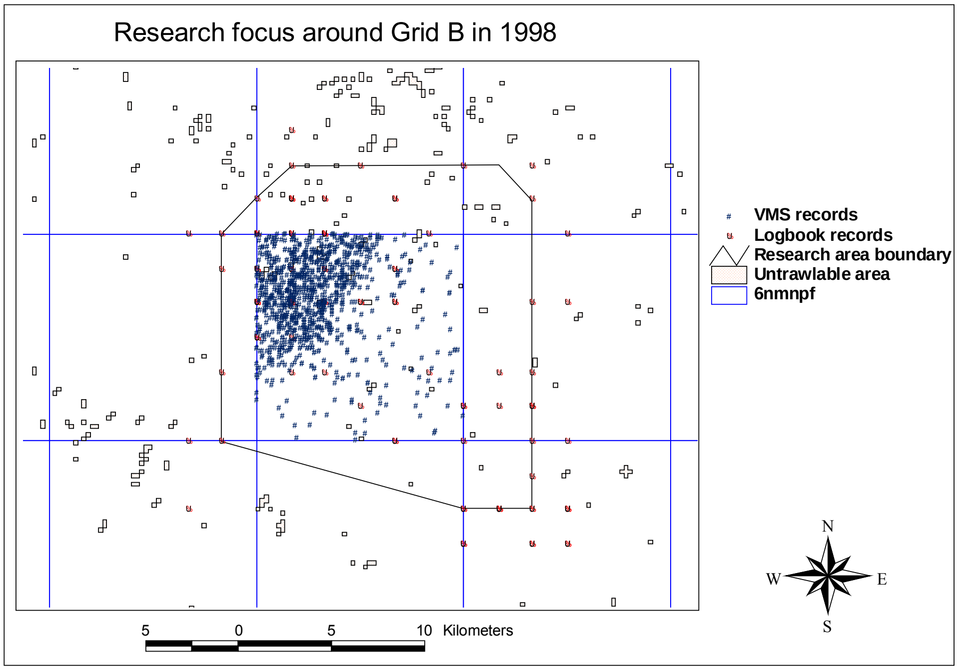


Figure 55 *Defined RESEARCH AREAS for Grid B in 1998 (Aggregated fishing ground)*

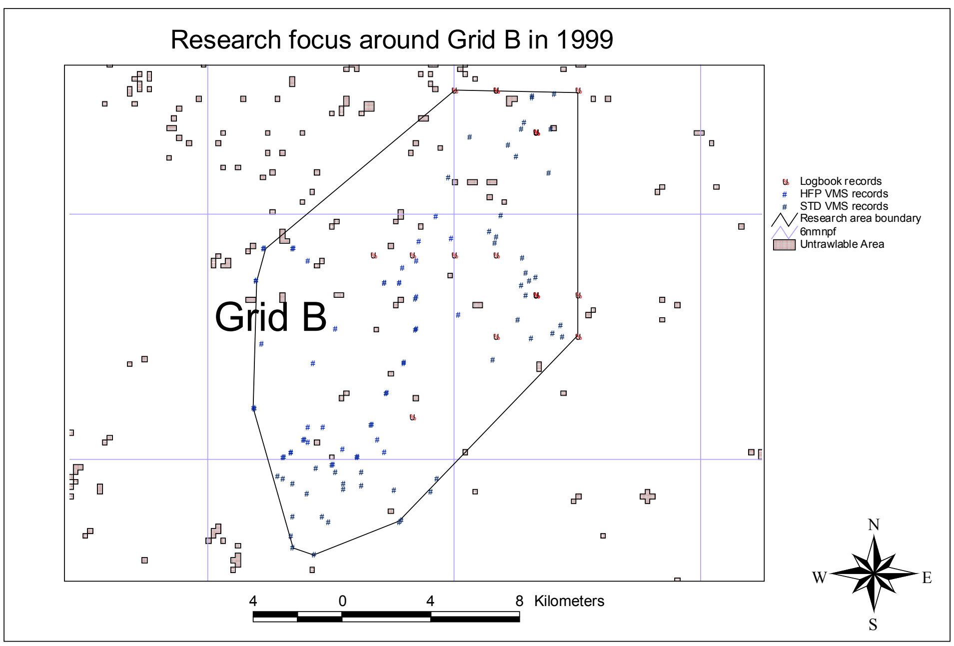


Figure 56 *Defined RESEARCH AREAS for Grid B in 1999 (Randomly fishing ground)*

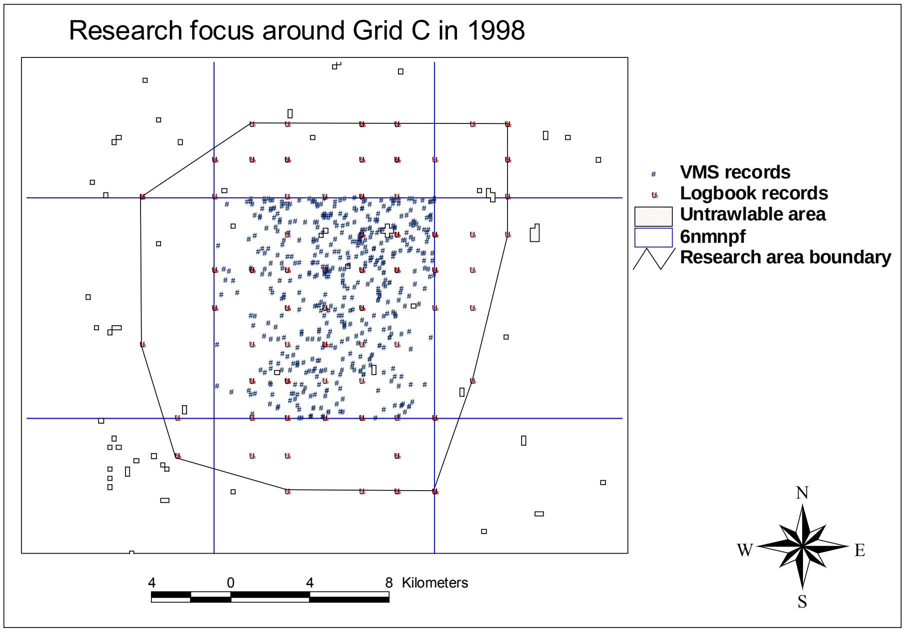


Figure 57: *Defined RESEARCH AREAS for Grid C in 1998 (Randomly fishing ground)*

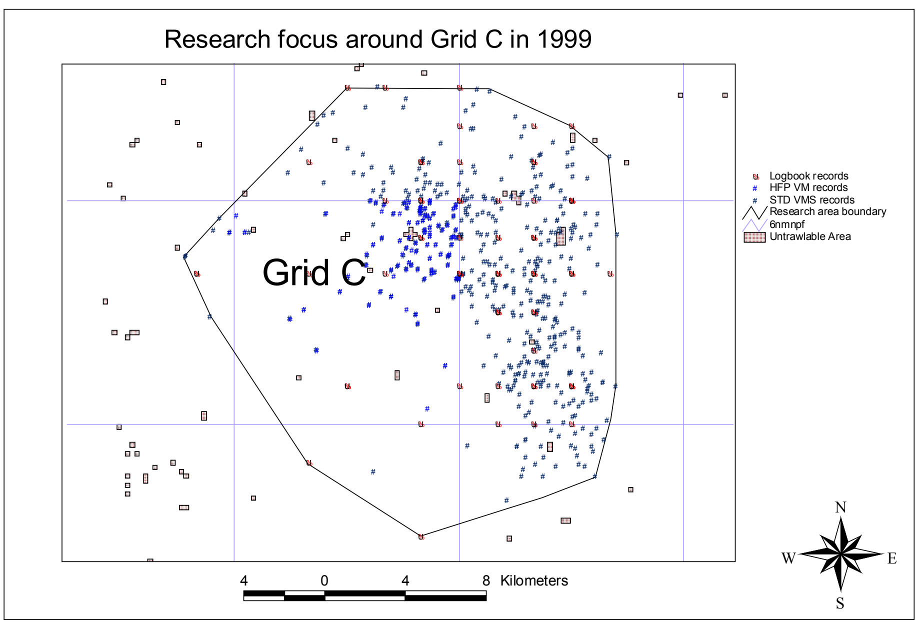


Figure 58 *Defined RESEARCH AREAS for Grid C in 1999 (Aggregated fishing ground)*

2. Pattern of the trawling tracks (Figure 59, Figure 60, Figure 61, Figure 62, Figure 63 and Figure 64)

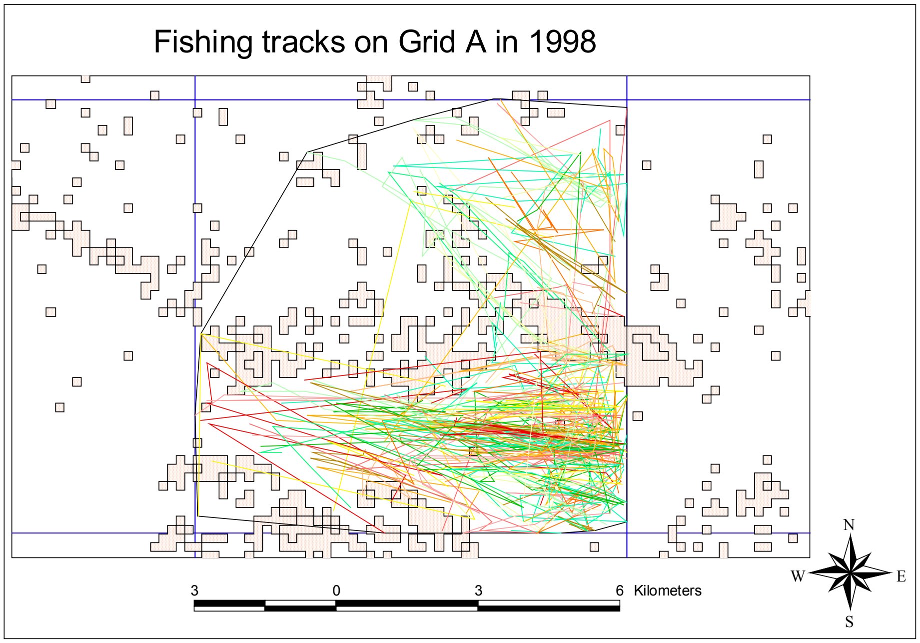


Figure 59: *NPF trawling tracks in Grid A for year 1998 tiger prawn fishing season (different shades of lines represent different trawling tracks, and the dot square areas represent untrawlable areas)*

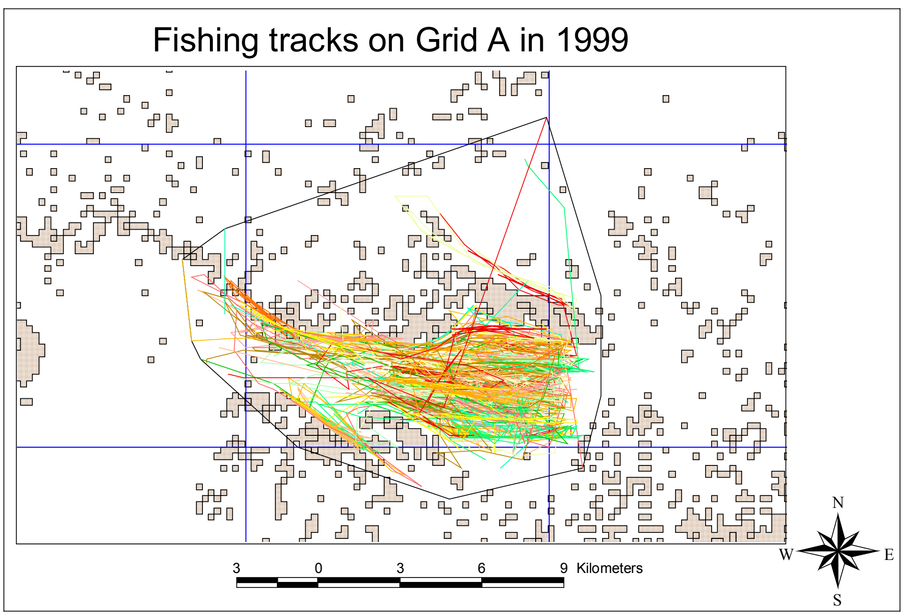


Figure 60: *NPF trawling tracks in Grid A for the 1999 tiger prawn fishing season (different shades of lines represent different trawling tracks, and the dot square areas represent untrawlable areas).*

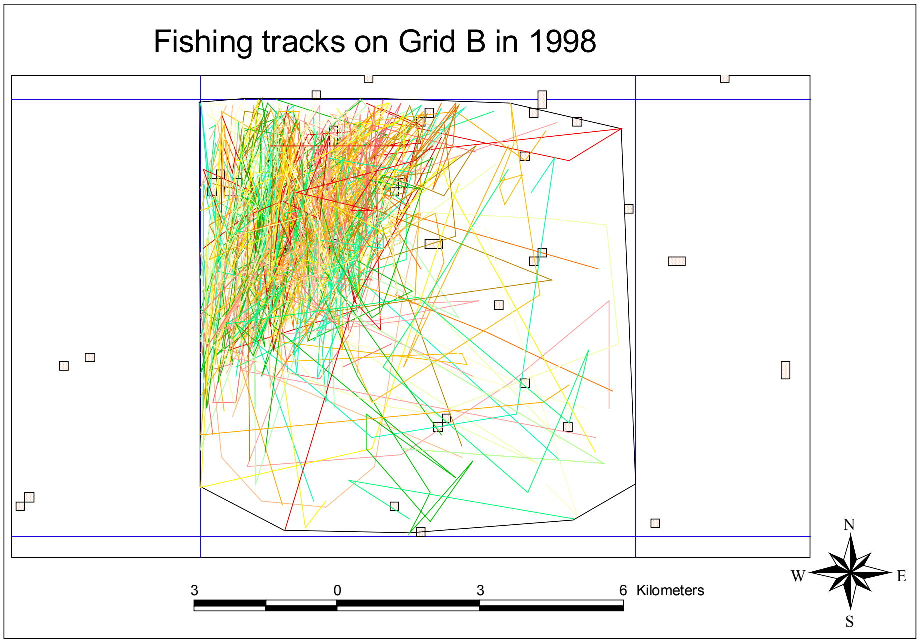


Figure 61: *NPF trawling tracks in Grid B for year 1998 tiger prawn fishing season (different shades of lines represent different trawling tracks, and the dot square areas represent untrawlable areas)*

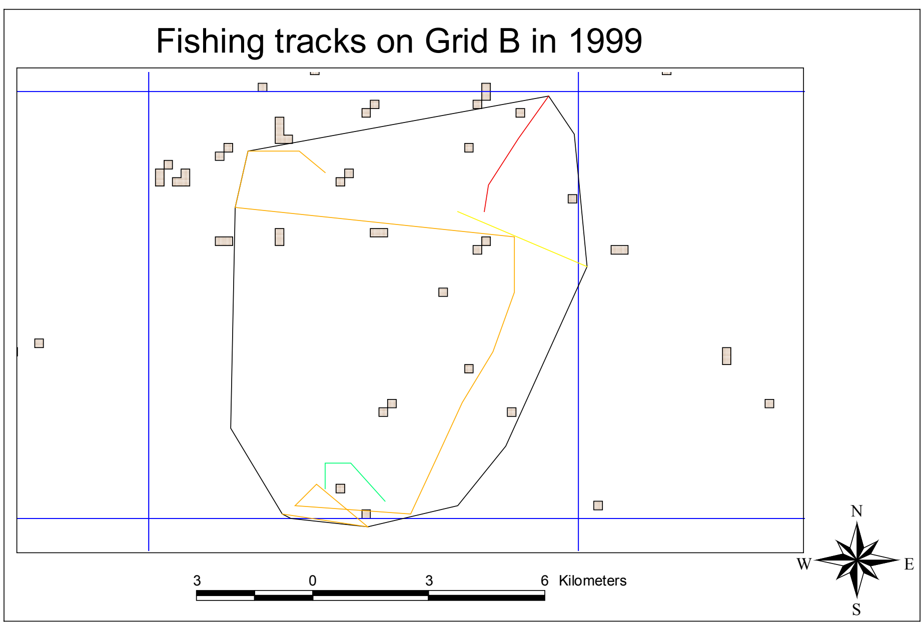


Figure 62: *NPF trawling tracks in Grid B for year 1999 tiger prawn fishing season (different shades of lines represent different trawling tracks, and the dot square areas represent untrawlable areas)*

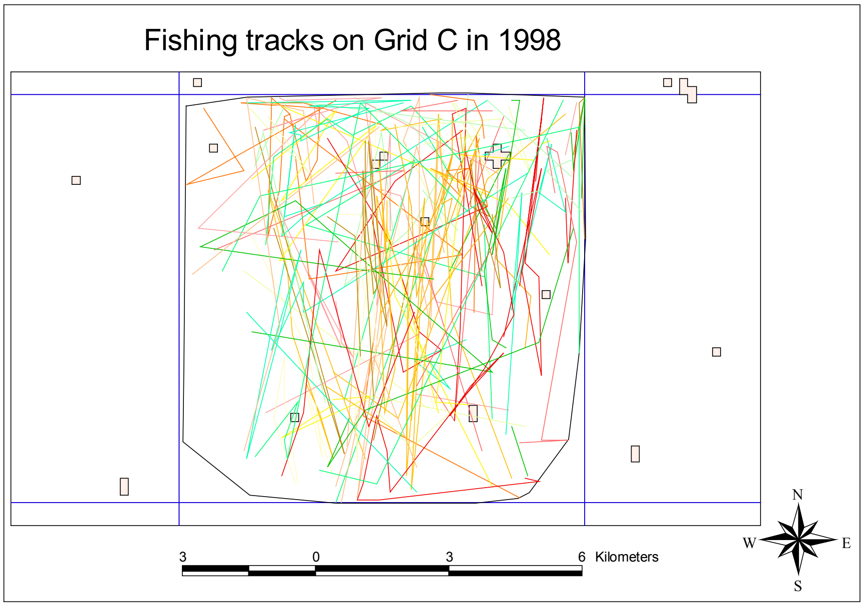


Figure 63: *NPF trawling tracks in Grid C for year 1998 tiger prawn fishing season (different shades of lines represent different trawling tracks, and the dot square areas represent untrawlable areas)*

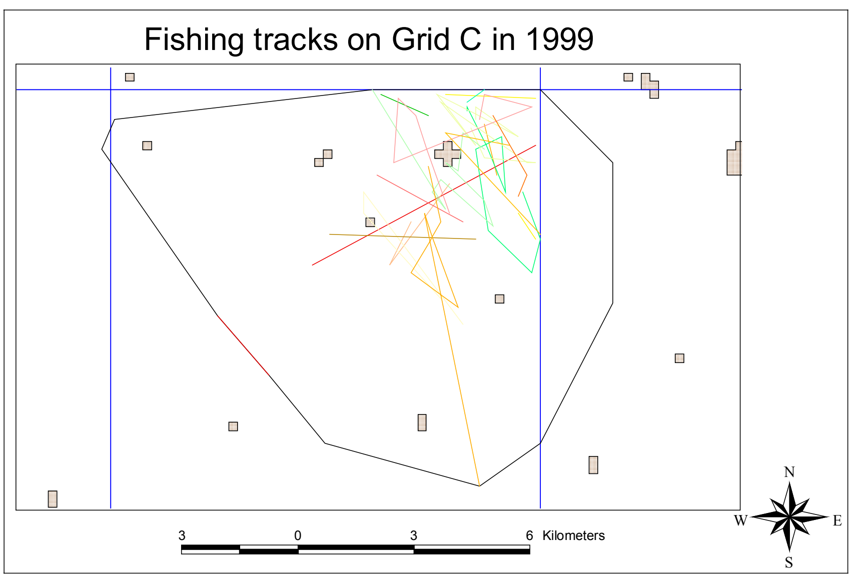


Figure 64: *NPF trawling tracks in Grid C for year 1999 tiger prawn fishing season (different shades of lines represent different trawling tracks, and the dot square areas represent untrawlable areas)*

3. Distribution of fishing intensity in the areas where high polling frequency data is available (Figure 65, Figure 66, Figure 67, Figure 68, Figure 69 and Figure 70)

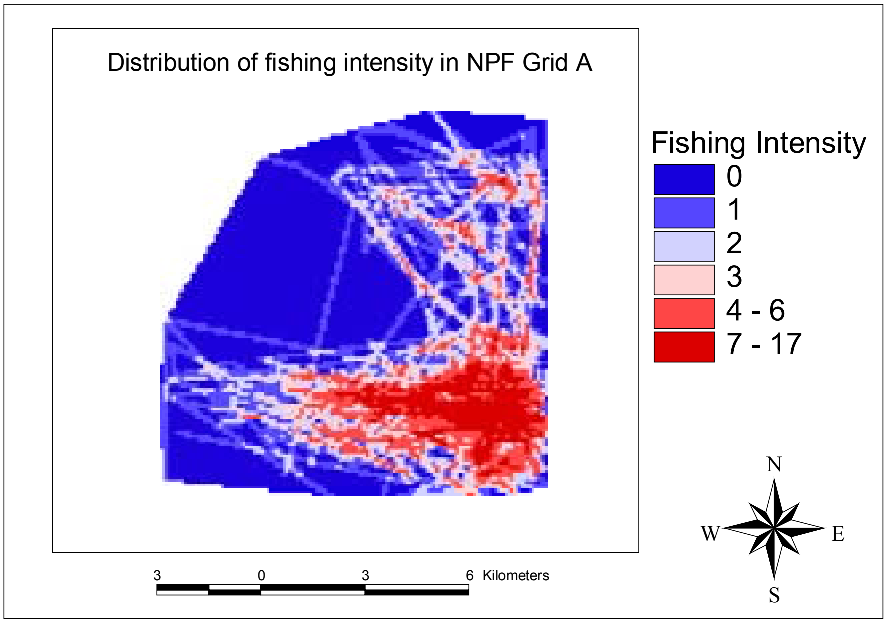


Figure 65: *Fishing intensity distribution around Grid A in 1998*

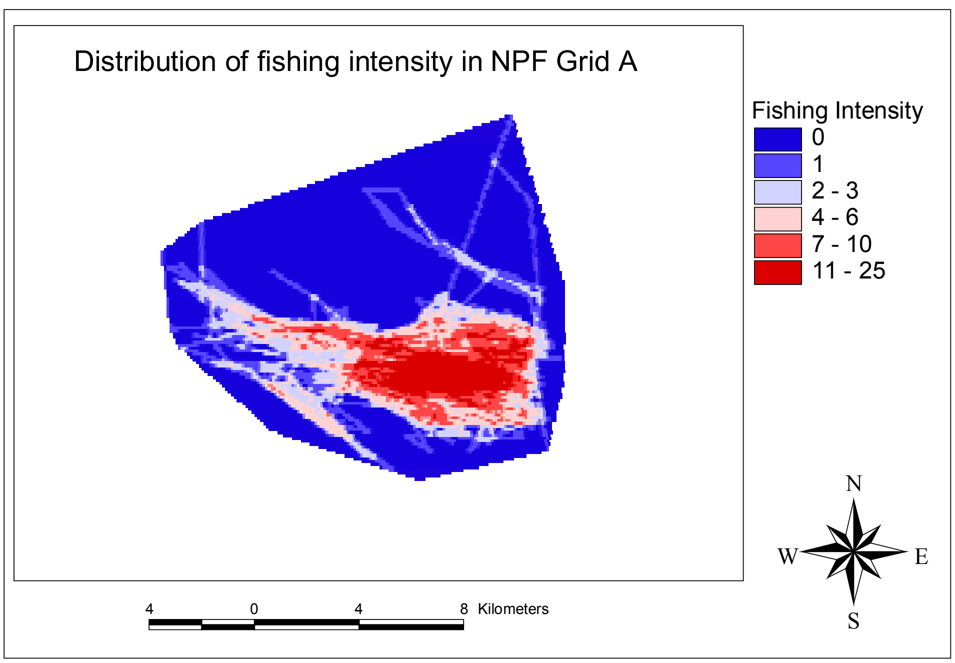


Figure 66: *Fishing intensity distribution around Grid A in 1999*

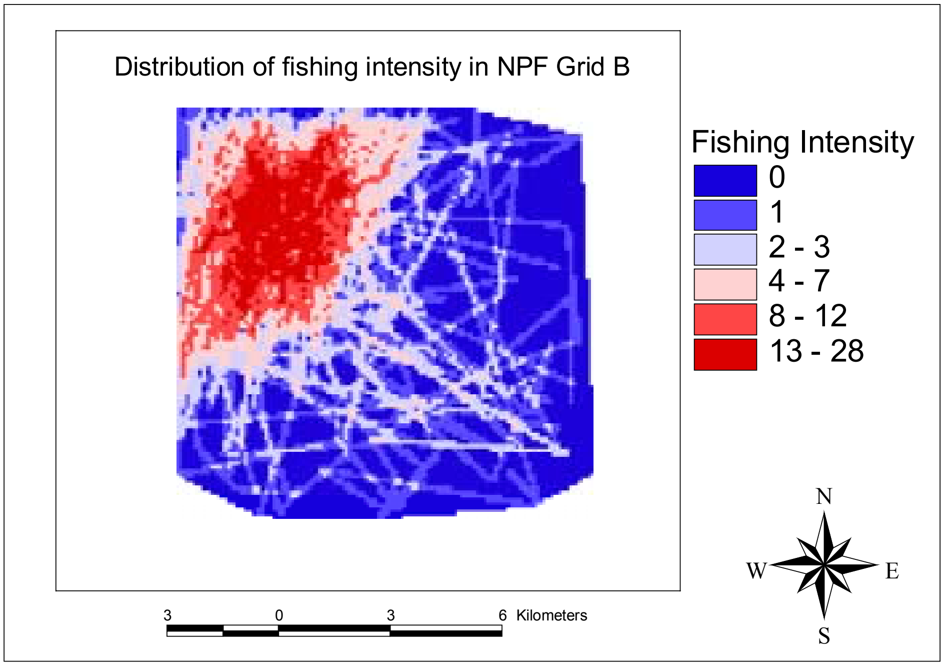


Figure 67: *Fishing intensity distribution around Grid B in 1998*

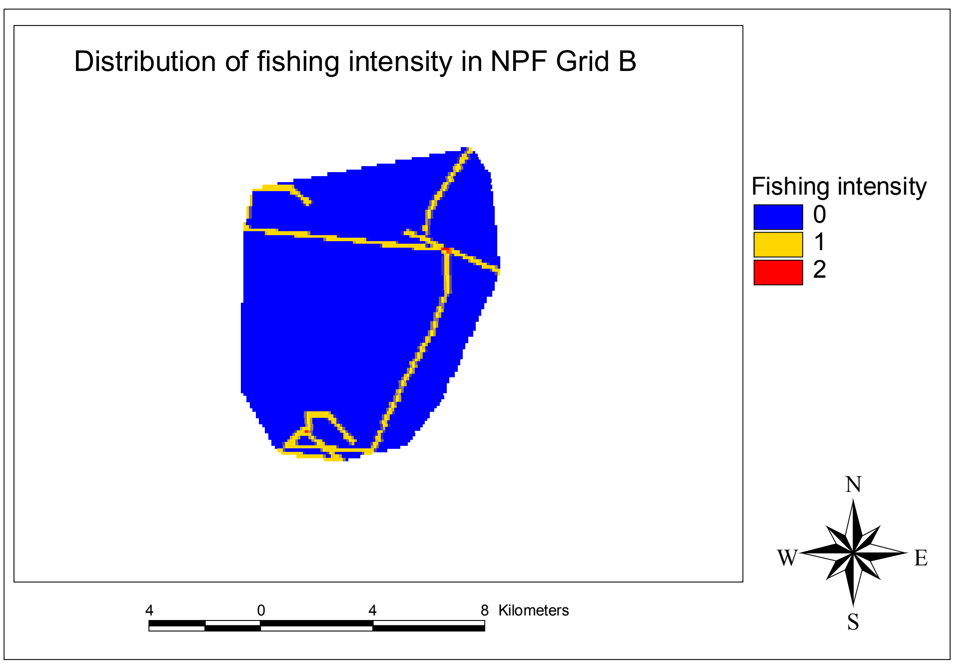


Figure 68: *Fishing intensity distribution around Grid B in 1999*

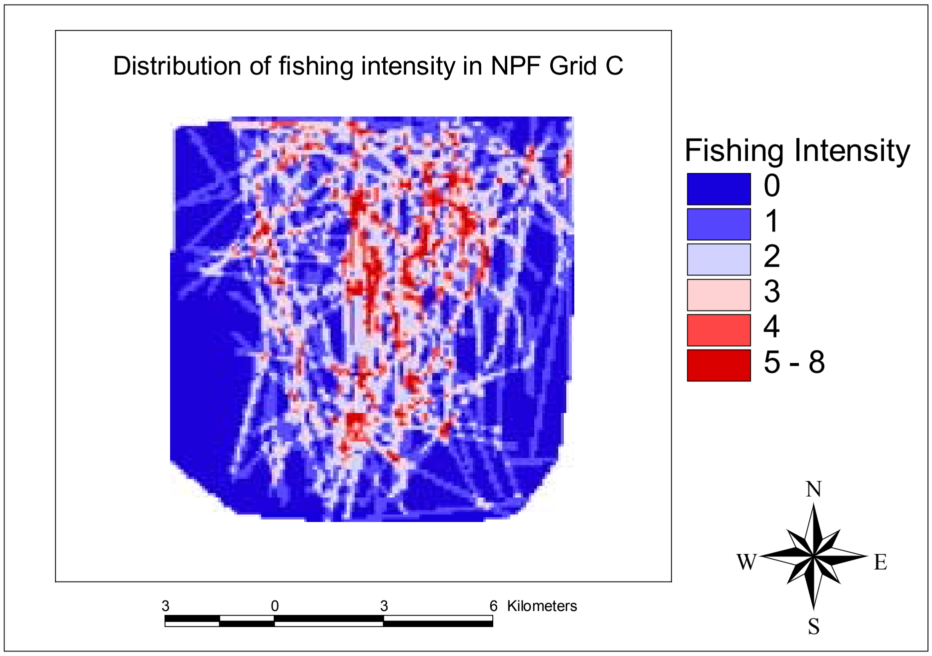


Figure 69: *Fishing intensity distribution around Grid C in 1998*

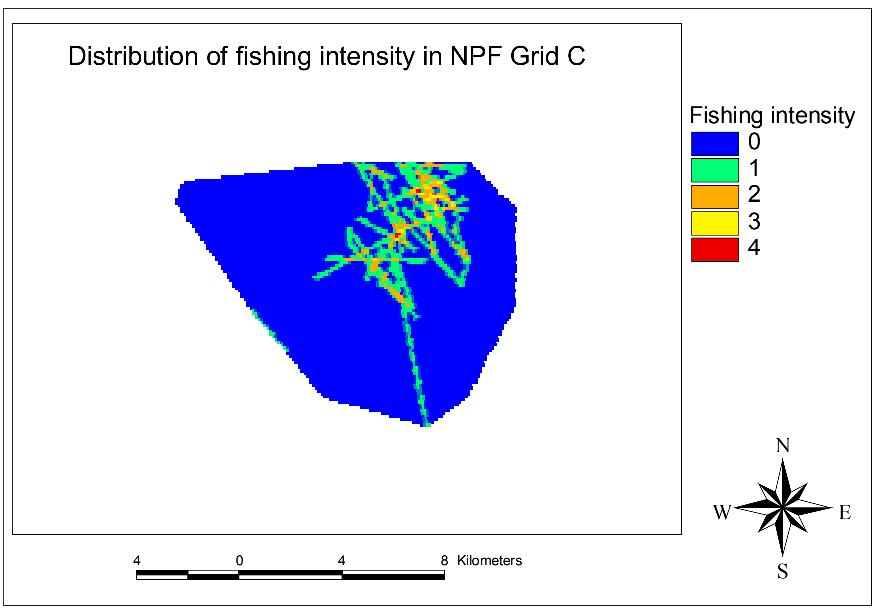


Figure 70: *Fishing intensity distribution around Grid C in 1999*

4. Depletion graphs (Figure 71, Figure 72, Figure 73, Figure 74, Figure 75 and Figure 76).

From current VMS data, several depletion analysis scenarios were conducted and resulted in the depletion graphs.

Scenario 1 (Figure 53 and Figure 71)

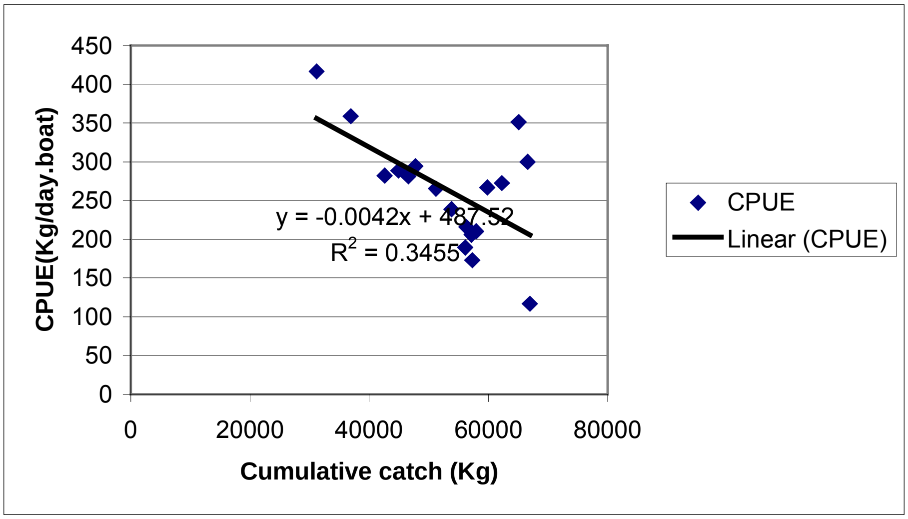


Figure 71: *Depletion curves around Grid A areas in 1998 (Aggregated fishing ground)*

The area around Grid A in 1998 represents an aggregated fishing ground area. The depletion curve trend line declines down gently when the cumulative catch increases. The slope is –0.0042.

Scenario 2 (Figure 55 and Figure 72)

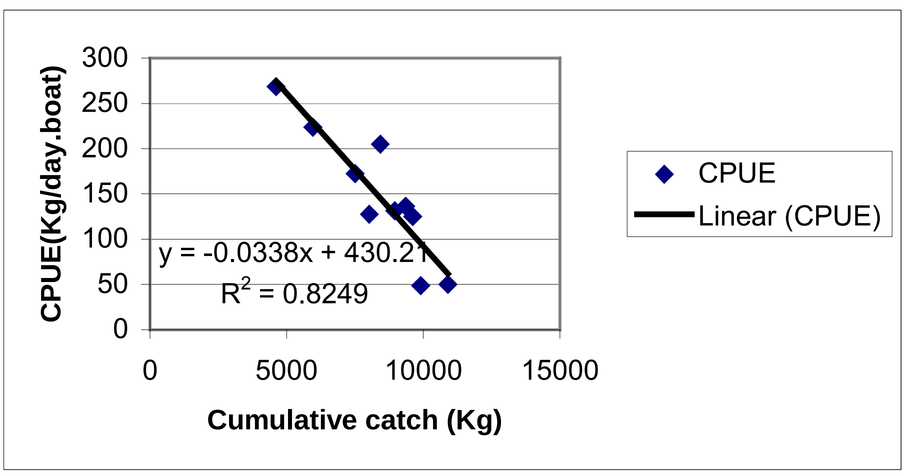


Figure 72: *Depletion curves around Grid B areas in 1998 (Aggregated fishing ground)*

Area around Grid B in 1998, the fishing pattern appeared aggregated fishing ground and more fishing effort inputs were imposed on the area. The depletion curve shows the steepest decline with a slope of –0.0338.

Scenario 3 (Figure 57 and Figure 73)

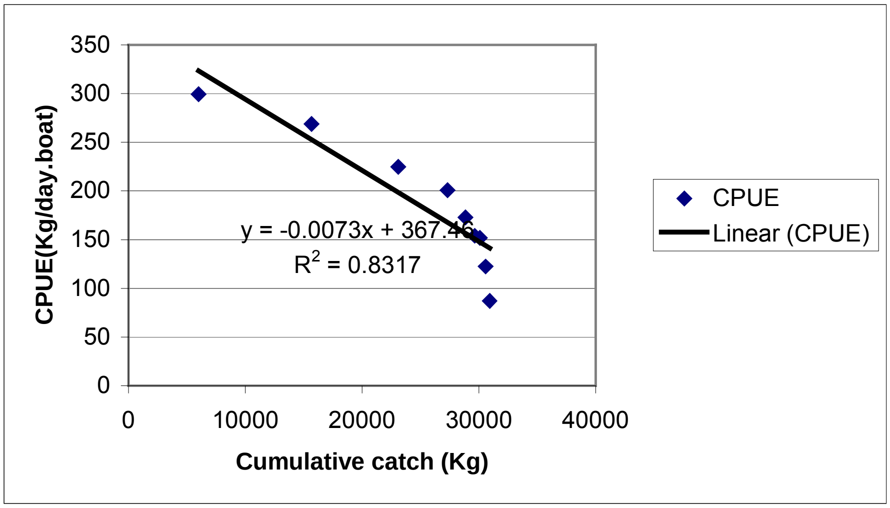


Figure 73: *Depletion curves around Grid C areas in 1998 (Randomly fishing ground)*

Area around Grid C in 1998, fishing pattern appeared more in random. Depletion curve declines moderately with the slope of –0.0073. Note that this result is not well summarised by a straight line model.

Scenario 4 (Figure 54 and Figure 74)

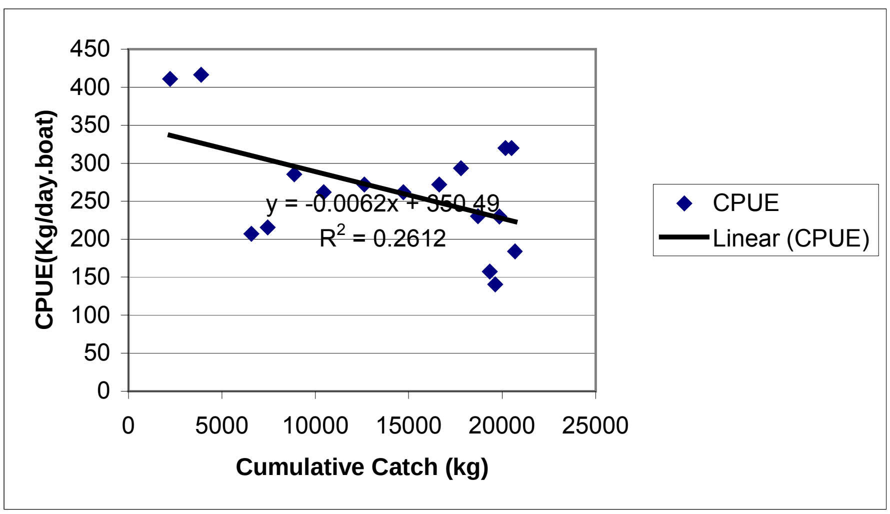


Figure 74: *Depletion curves around Grid A areas in 1999 (Aggressive fishing ground)*

Area around Grid A in 1999, there were many untrawlable locations in these areas. The fishing activities avoid those untrawlable grounds producing an aggregated fishing pattern. The depletion curve appeared gentle, declining with a slope of –0.0062.

Scenario 5 (Figure 56 and Figure 75)

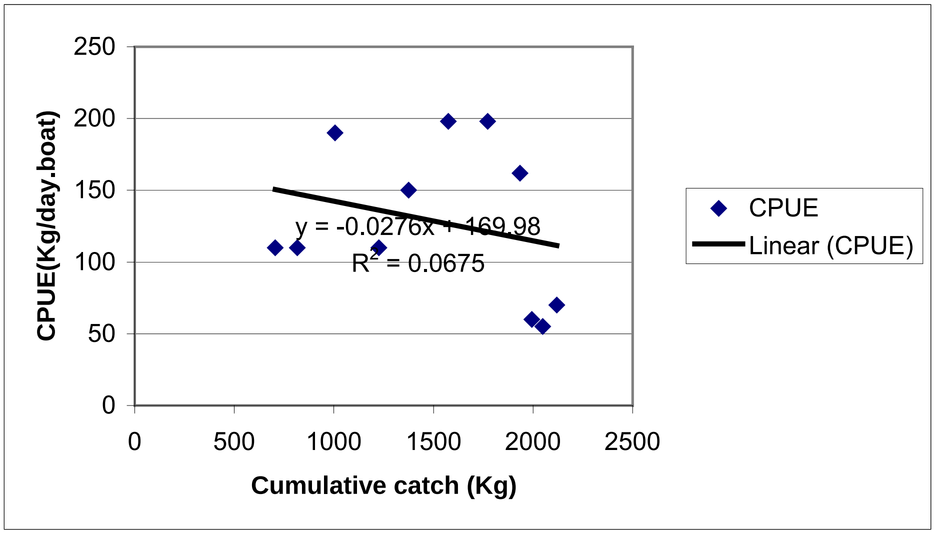


Figure 75: *Depletion curves around Grid B areas in 1999 (Randomly fishing ground)*

Area around Grid B in 1999, according to latest information from industry, the area was circled by untrawlable ground. This would usually lead to aggregated fishing activities in its northern west corner. However, the effort input in this year was very limited, and actually appeared as a randomly fishing ground. Though the depletion curve trend line is much steeper than others in this year, it is unreliable due to the sparse effort input in the area. The slope of the depletion curve is –0.0276.

Scenario 6 (Figure 58 and Figure 76)

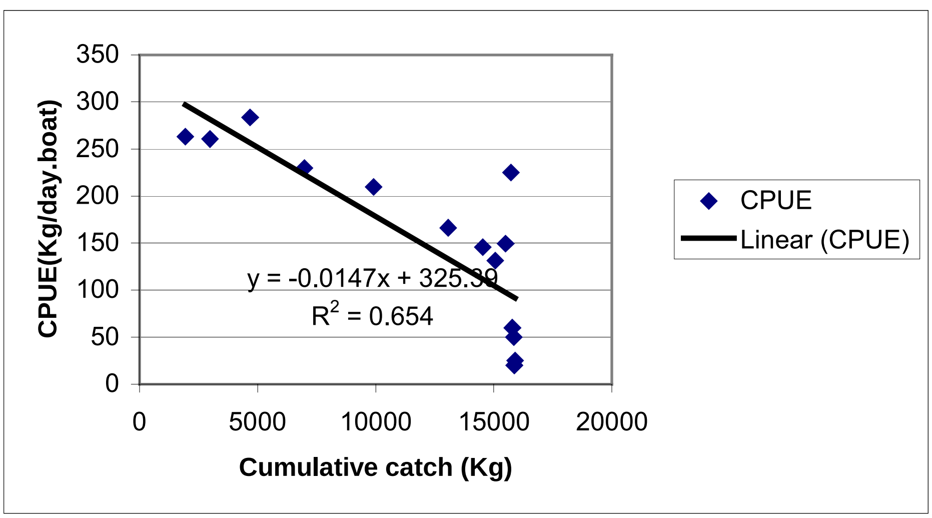


Figure 76: *Depletion curves around Grid C areas in 1999(Aggregated fishing ground)*

Areas around Grid C in 1999, is a region with less untrawlable areas, but due to aggregated fishing activities in the area, it appeared as more or less an aggregated fishing ground pattern. The depletion curve trend line declines more steeply with a slope of -0.0147.

28. Discussion

There are several concerns in this study, such as spatial and temporal consistency, distribution of fishing intensity, depletion experiment curves in relation to the hypothesis in the introduction and their effects on stock assessment.

28.1. Spatial and temporal scale consistency of different data sets

It was proposed to monitor vessel position intensively in 4 grids with high polling frequency VMS after recommendations from a previous VMS simulation study. Three grids of intensive VMS data were collected during the time of this study. It was a complex operation to establish reliable links between VMS data and logbook data, because they had different spatial and temporal scales. Logbook data represent the locations of the highest catch on the specific fishing day and VMS records represent vessel locations according to the preset polling times. Generally, there are 4 types of linking relationships between logbook and intensive VMS records for one vessel on one day in our current study.

Case 1: Compatible relationship. Logbook records were properly linked to VMS data in the area.

Case 2: Vicinity relationship. Logbook records distributed around the research area but no links with VMS data.

Case 3: Remote relationship. Logbook records distributed far away from the research area and do have links with VMS data

Case 4: Nil relationship. Logbook records fell into the research area, but there were no links with VMS data.

The number of records in each grid of each case is given in Table 15. Case 1 is the ideal situation and can be easily analysed. Case 2 might affect the accuracy of our research, because the logbook records were very close to *RESEARCH AREAS* and might represent partial input from the research area. Case 3 and Case 4 would lead to substantial problems for our research area boundaries and logbook data analysis. Case 3 indicates fishing happened in our research area, but the catch was reported in other areas. This means most of the catch reported for that night did not come from the study area. Case 4 implies that catch was reported in the study area, but there were no trawling activities recorded in the intensive VMS records.

Table 15: ***Categorised Logbook records***

Grid Number	1998					1999				
	Case1	Case2	Case3	Case4	Total	Case1	Case2	Case3	Case4	Total
Grid A	112	31	159	13	315	64	14	26	6	110
Grid B	37	54	117	45	253	4	12	8	1	25
Grid C	22	38	101	42	203	21	30	13	11	75

Introducing normal VMS records/untrawlable fishing ground information and applying **convex-hull/one-peeling** methods are key solutions to this complexity. Normal VMS records are a good reference to have the appropriate study area determined. The convex-hull method was used to produce the study boundary and the one peeling method was applied to adjust the boundary with the reference of Normal VMS data and untrawlable fishing ground information. In some cases, more peeling is necessary.

28.2. Fishing intensity

Fishing intensity results come from intensive VMS data of three grids in 1998 and 1999. This data is extremely useful and appropriate for the analysis of fishing intensity on the ground, which would assist benthic effects studies.

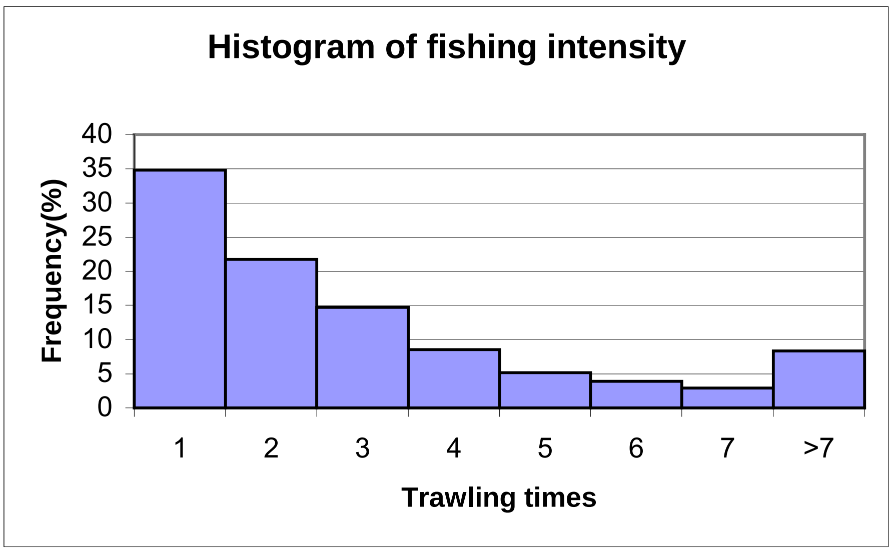


Figure 77 *Histogram of fishing intensity in Grid A in 1998(Result come from intensive and normal VMS data)*

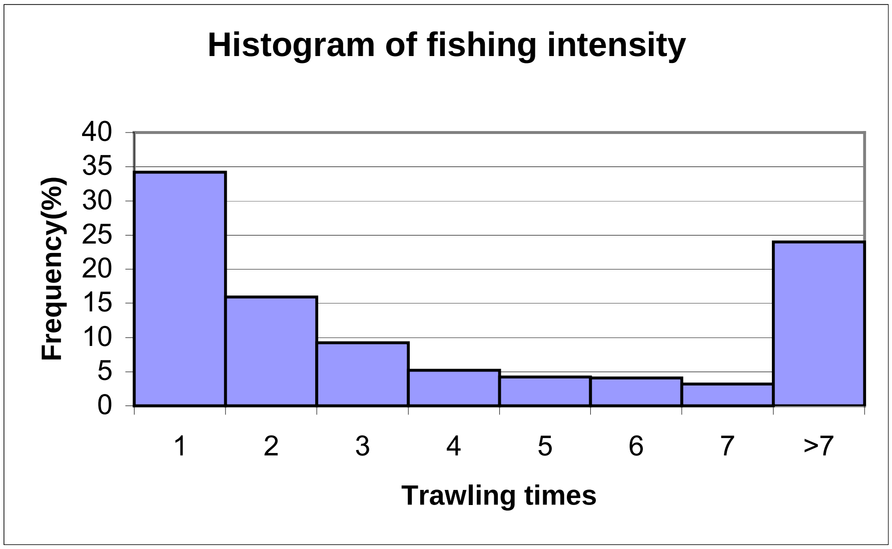


Figure 78: *Histogram of fishing intensity in Grid B in 1998(Result come from intensive and normal VMS data)*

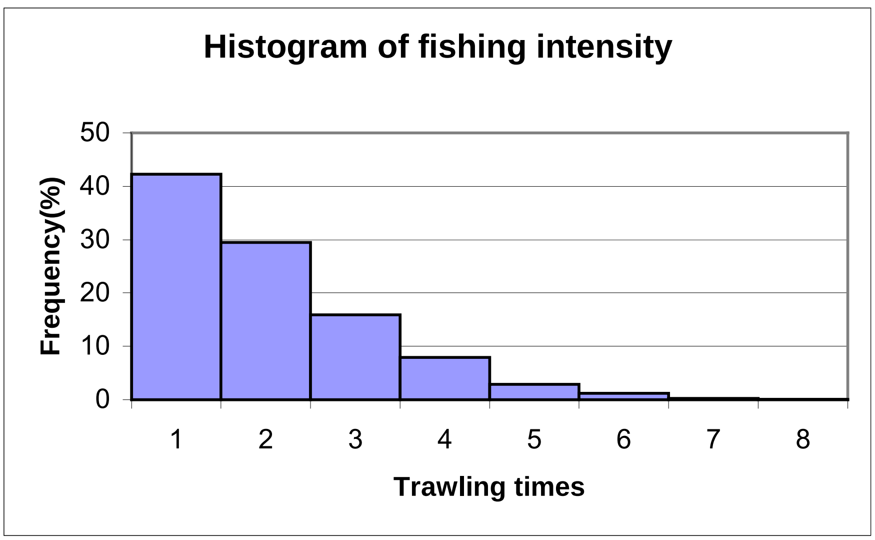


Figure 79 ***Histogram of fishing intensity in Grid C in 1998(Result come from intensive and normal VMS data)***

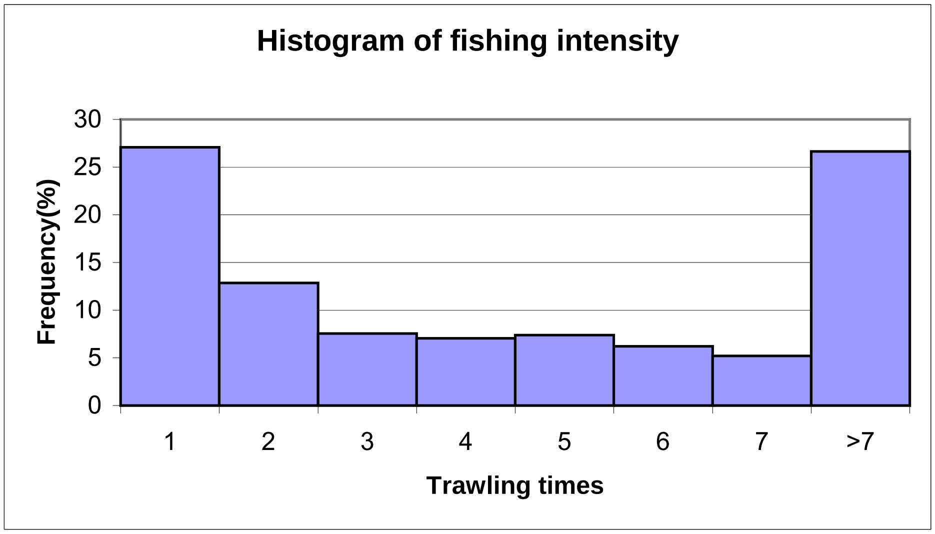


Figure 80: *Histogram of fishing intensity in Grid A in 1999(Result come from intensive VMS data only)*

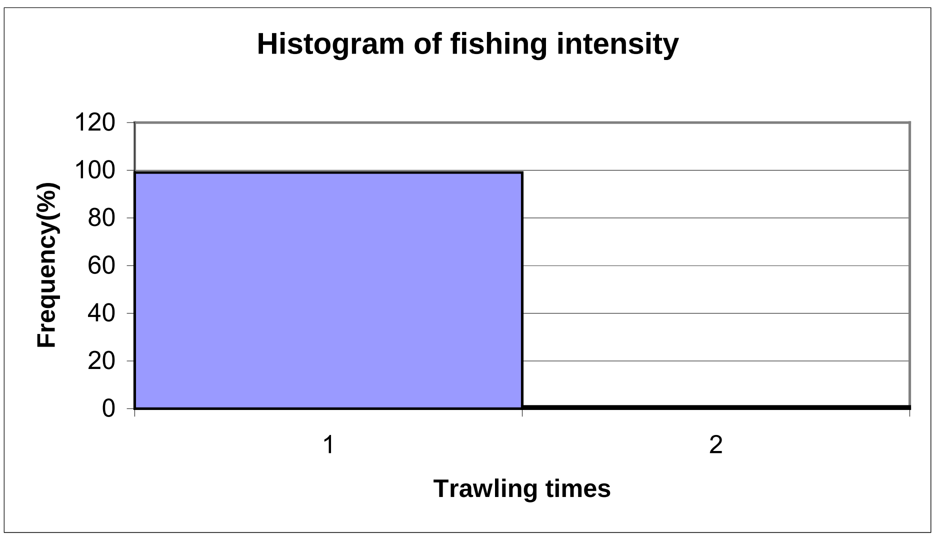


Figure 81 *Histogram of fishing intensity in Grid B in 1999(Result come from intensive VMS data only)*

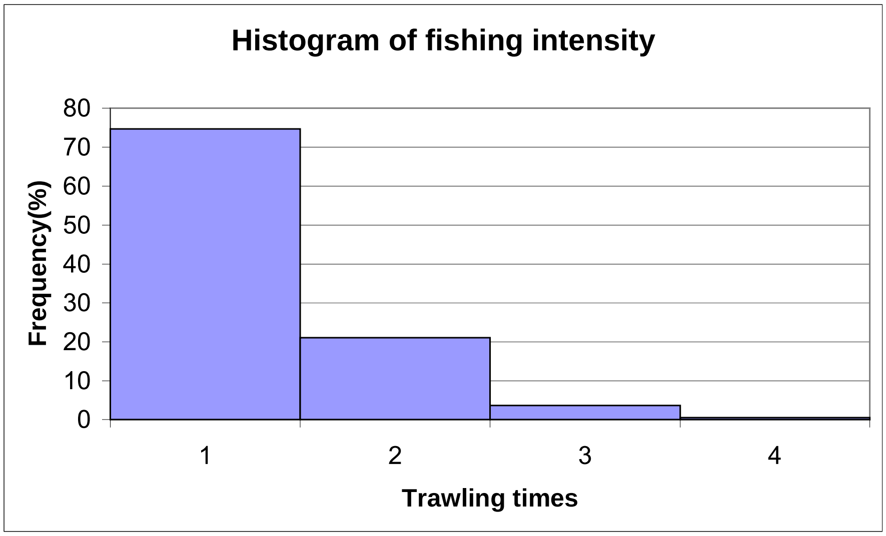


Figure 82: *Histogram of fishing intensity in Grid C in 1999(Result come from intensive VMS data only)*

In 1999 the catch and effort levels were not high enough, so the fishing intensity distribution was narrowed and reduced in Grid B and Grid C (Figure 68, Figure 70, Figure 81, Figure 82). The fishing intensity distribution around Grid A, however, still remained high. There was more than 25% of the trawled area in which there was trawling over 7 times in just one tiger prawn fishing season. The most intensively fished area was trawled up to 25 times (Figure 66 and Figure 80). According to previous repeat-trawl depletion studies (Poiner *et al.*, 1998), repeat prawn trawling significantly depletes benthic classes. The benthic classes (including algae) have been grouped into sessile and mobile organisms and have got a different depletion rate on their groups (Table 16).

Table 16 ***Average estimated percent depletion rate of benthic classes (Adapted from Poiner*** **et al.*****, 1998)***

Sessile benthic classes	Average depletion rate	Standard Error	Mobile benthic classes	Average depletion rate	Standard Error
All sessile	6.8	1.7	All mobile	8.8	1.8
Algae	4.8	4.4	Crustacea	9.6	2.0
Porifera	7.7	2.2	Bivalvia	10.5	3.6
Hydrozoa	4.9	2.5	Gastropoda	24.6	3.6
Gorgoniacea	24.0	2.8	Cephalopoda	7.3	3.3
Alcyonacea	10.6	2.3	Asteroidea	11.3	3.0
Zoantharia	5.3	2.5	Crinoidea	8.1	2.2
Bryozoa	6.1	2.0	Echinoidea	10.5	3.8
Ascidiacea	9.4	2.2	Holothurordea	10.6	2.6
			Ophiuroidea	11.8	3.8

In 1998, the effort inputs were much greater than in 1999. Fishing intensity remained at high levels in all grids, especially in the aggregated fishing grounds. In Grid A, the portions bearing trawling over 7 times approached almost 10% of the total trawling area (Figure 65 and Figure 77). In Grid B, which was treated as a random fishing ground initially and later was recognised as an aggregated fishing ground by the latest information from the fishing industry, the area trawled over 7 times was very close to 25% of the total trawling areas (Figure 61 and Figure 78). Because the fishing intensity largely determines the level of trawling impact on benthos, the more intensively trawled an area, the greater the depletion of benthic organisms (Hall *et al.*, unpubl.). Those intensively trawled areas would suffer depletion of benthic organisms. Moreover, if the areas have many untrawlable locations and the fishing activities are aggregated, according to our hypothesis, the depletion would happen earlier than that on the randomly fished ground.

28.3. Depletion analysis

The depletion curves described in the results section as Scenarios 5 and 6, which characterised an aggregated fishing ground and random fishing ground respectively in two neighbouring girds, would strongly reject any hypothesis that the depletion rates in different types of fishing grounds were the same, even approximately. In these two cases, fishing efforts were big enough to conduct the effective depletion experiment. Conversely, the curves in Scenarios 2 and 3 might not reflect the real relationship between these two scenarios. In 1999, the fishing effort invested in these two grids was limited. The effort levels were insufficient to establish useful results in the depletion analysis. As for Scenario 1 and Scenario 4, they represent one aggregated fishing ground grid for the years 1999 and 1998 separately. Due to the sparse fishing effort in other grids in 1999, it was not feasible to compare scenario 1 with scenario 2 and 3. Scenario 4 has a depletion curve with similar slope to scenario 6, which is not inconsistent with the hypothesis previously rejected. However, it could suggest some constraints to the hypothesis is needed e.g. comparing similar fishing environments (such as locations, sediments and current conditions), similar effort levels or similar extensions of the areas and vicinity of the target areas.

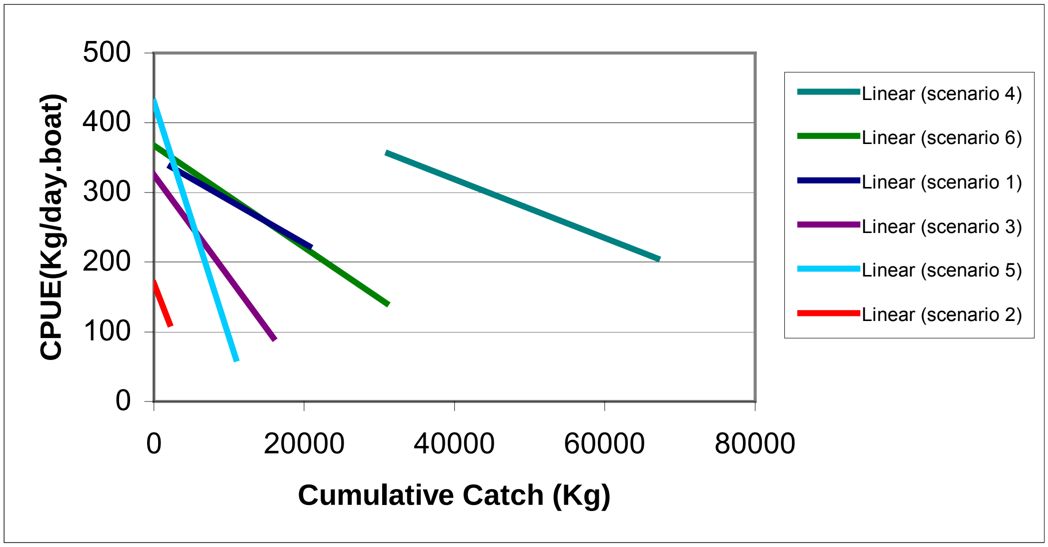


Figure 83: *Depletion curves for all scenarios*

29. CONCLUSION

By this research we conclude that high polling frequency VMS data are uniquely informative for fishing intensity studies. But they are more complex for depletion studies as it can be difficult to combine area specific VMS data with logbook data. Therefore further studies are recommended as follows:

1. Preliminary work needs to investigate further the linking of high polling frequency, normal polling frequency VMS data and linkage with logbook data for input into stock assessment.
2. Further monitoring and collecting VMS data is needed on an ongoing basis from the 3 grids examined in this study at high polling frequency to compare good fishing years with bad fishing years and to explore the differences between them in fishing pattern over time.

30. References

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CHAPTER 5: THE ASSESSMENT AND RISK ANALYSIS: TIGER PRAWNS

31. Introduction

A risk analysis is the evaluation of the consequences of alternative management actions in terms of the conservation and utilisation of the resource, taking account of all identifiable and quantifiable uncertainties. The benefits of a risk analysis are that it leads to an improved understanding of the extent of uncertainty, it allows decision makers to consider the consequences of uncertainty, and it allows funding bodies to target research at the perceived most critical uncertainties for the management of the fishery. As there is an existing tiger prawn assessment model being used annually to manage the resource, the risk analysis of tiger prawns concentrated on changes that could be made to the present model and data. This chapter also draws attention to those aspects of the input data, input parameters and model assumptions to which the model outputs are most sensitive.

31.1. Types of uncertainty

There are four main types of uncertainty:

- Model uncertainty. The main question here is whether the mathematical framework underlying the analysis is sufficient to capture the essential characteristics and behaviour of the resource under fishing pressure. Typical questions to consider might be:
    - Is it important to take account of spatial structure?
    - Does the assessment need to encapsulate the pattern of growth?
- "Conditioning" uncertainty. The question here is if we "fix" parameters in the assessment based on prior research data (and then assume them known when applying the stock assessment), have we done this correctly? Parameters that are currently assumed known include: growth rates, within-year recruitment patterns and natural mortality.
- "Statistical" uncertainty. The question here is, given a particular assessment model, how well do the data allow us to estimate the parameters not fixed from prior research data? e.g.,
    - "variances" of estimated quantities
    - "confidence intervals"
- "Process" uncertainty. The issue here is that the relationships in the assessment (e.g. the stock-recruitment relationship and natural mortality) pertain to "average" behaviour but the world does not act in an "average" way e.g.,
    - The stock-recruitment relationship, is this constant or changing with time?
    - There is variability about any average weekly recruitment and spawning patterns.

31.2. Confidence intervals

This project has calculated 90% confidence intervals for the quantities included in the present management advice. Note that a confidence interval may be interpreted as the set of possible values for an unknown parameter that are, in the statistical sense, *not contradicted* by the data. Conversely the values outside the confidence interval are regarded as deviating by too much from the best estimate to be considered, in a statistical sense, consistent with the data.

31.3. The base case

This project utilised two assessment models; a modified version of the (Wang and Die, 1996) model and a weekly Deriso-Schnute model (both described below). Both models were applied to different catch and effort datasets and input parameter assumptions for the tiger prawns *Penaeus esculentus* and *Penaeus semisulcatus*.

During the October 2000 Northern Prawn Fishery Advisory Group (NPFAG) meeting, the output from both assessments were presented and indicated that the Deriso-Schnute assessment produced results comparable to those from the application of the modified Wang and Die assessment. The Deriso-Schnute assessment is mathematically similar to the Wang and Die assessment, producing the same results with less procedural steps during the computer-processing phase. At the October NPFAG meeting it was determined that the base case assessment and projection models were therefore to be undertaken with the Deriso-Schnute assessment using the original tiger species split of catch and effort derived by (Lockwood, 1970). The input parameters of this base case assessment are given in Appendix B.

The Deriso-Schnute assessment was applied to a large suite of scenarios to assess the sensitivity of the assessment and subsequent condition of the tiger fishery to different model assumptions and input data. Additionally, a projection component was incorporated to simulate consequences of certain management scenarios and their effect when forecast twenty years into the future. The latter results are described in the next chapter.

32. Methods

32.1. Population dynamics

Two alternative assessments (the modified Wang and Die, and the Deriso-Schnute assessments) are considered. Both assessments operate on a weekly time-step (where week runs from w=1 to $n_w = 52$ weeks), and include weekly changes in availability, recruitment and spawning. The two assessments differ in that the Wang and Die model considers age-structure explicitly whereas the Deriso-Schnute model is a delay-difference model that considers only changes in the biomass of the resource. The following sections provide the equations that describe growth, changes in biomass and spawner stock size with time, the stock-recruitment assumptions, and the assessment estimates of the catches by week. The assessments in this project can include uncertainty about quantities previously considered known (e.g. growth) and examine assessment sensitivity to some of the key assumptions (e.g. the form of weekly catchability).

32.2. The basic dynamics

The Wang and Die assessment (Lockwood, 1970) defines the recruited biomass and recruited numbers using the equations:

$$\begin{aligned} B_{y,w} &= \sum_c w_{y,w,c}\, N_{y,w,c} \\ \tilde{N}_{y,w} &= \sum_c N_{y,w,c} \end{aligned} \tag{8}$$

where $N_{y,w,c}$ is the number of prawns (of both sexes) that recruited in week c alive at the start of week w of year y,

$$N_{y,w,c} = \begin{cases} 0 & \text{if } y\times 52+w \;<\; c \\ \alpha_{y,w}\, R_{y(y,w)} & \text{if } y\times 52+w = c \\ N_{y,w-1,c}\, e^{-Z_{y,w-1}} & \text{if } y\times 52+w > c \end{cases} \tag{9}$$

$Z_{y,w}$ is the total mortality during week w of year y,

$\alpha_{y,w}$ is the fraction of the recruitment during (calendar year) year y that occurs during week w:

$$\alpha_{y,w} = \alpha_w\, e^{\varepsilon^1_{y,w}} \Big/ \sum_{w'} \alpha_{w'}\, e^{\varepsilon^1_{y,w'}} \tag{10}$$

α_w is the expected fraction of the annual recruitment that occurs during week w,

$\varepsilon^1_{y,w}$ is the fluctuation about the fraction of the annual recruitment that occurs during week w,

σ_α is a measure of the extent of inter-annual variability in when recruitment occurs.

R_y is the recruitment during 'biological year' y, and

$y(y,w)$ if the 'biological year' corresponding to week w of year y:

$$y(y,w) = \begin{cases} y & w < 40 \\ y+1 & \text{otherwise} \end{cases} \tag{11}$$

Equation (4) implies that the 'biological year' ranges from week 40 (roughly the start of October) until week 39 (roughly the end of September). Equation (9) is modified to account for the case in which the week is the start of the year.

The Deriso-Schnute assessment ((Deriso, 1980); (Schnute, 1985)) defines the recruited biomass and recruited numbers using the equations:

$$B_{y,w+1} = (1+\rho)\,B_{y,w}\,e^{-Z_{y,w}} - \rho\,e^{-Z_{y,w}}\,(B_{y,w-1}\,e^{-Z_{y,w-1}} + w_{k-1}\,\alpha_{y,w-1}\,R_{y(y,w-1)}) + w_k\,\alpha_{y,w}\,R_{y(y,w)}$$
and (12)
$$\tilde{N}_{y,w+1} = \tilde{N}_{y,w}\,e^{-Z_{y,w}} + \alpha_{y,w}\,R_{y(y,w)}$$

where ρ is the Brody growth coefficient,

w_{k-1} is the average weight of a prawn the week before it recruits to the fishery, and

w_k is the average weight of a prawn when it recruits to the fishery.

Mortality

The total mortality during week *w* of year *y*, $Z_{y,w}$, is given by the equation:

$$Z_{y,w} = M\,e^{\varepsilon^2_{y,w} - \sigma^2_M/2} + F_{y,w} \tag{13}$$

where M is the average (over week) weekly instantaneous rate of natural mortality (assumed to be independent of sex and age),

$F_{y,w}$ is the fishing mortality during week *w* of year *y*:

$$F_{y,w} = \tilde{q}_w\,A_w\,q_{y,w}\,\left(B_{y,w}\,e^{\varepsilon^3_y - \sigma^2_w/2}\right)^{\chi}\left[\frac{(E^T_{y,w} + E^B_{y,w}/q_b)}{1+\gamma(E^T_{y,w} + E^B_{y,w}/q_b)}\right]^{\phi} e^{\varepsilon^4_{y,w} - \sigma^2_q/2} \tag{14}$$

$E^T_{y,w}$ is the effort during week *w* of year *y* 'targeted' towards the species under consideration,

$E^B_{y,w}$ is the 'by-catch' effort during week *w* of year *y*,

$\varepsilon^2_{y,w}$ is the fluctuation in natural mortality during week *w* of year *y*,

σ_M is a measure of how natural mortality varies over time,

ε^3_y is the (annual) fluctuation in weight,

σ_w is a measure of the extent of inter-annual variability in weight,

$\varepsilon^4_{y,w}$ is the fluctuation about the fishing effort – fishing mortality relationship during week *w* of year *y*,

σ_q is a measure of how catchability varies over time,

χ is the parameter that determines the extent of density-dependence in catchability,

ϕ is the parameter that determines the extent of non-linearity between effort and fishing mortality,

γ is the parameter that determines the extent of saturation in effort,

$\tilde{q}_w$ is the overall catchability coefficient for week *w*,

q_b is the by-catch catchability (the number of days of by-catch effort that is equivalent to a single 'targeted' effort day),

A_w is the relative availability during week *w*,

$q_{y,w}$ is the relative efficiency during week *w* of year *y*:

$$q_{y,w} = (\omega_y)^{(w-1)/52} \prod_{y'<y} \omega_{y'} / \prod_{y''<1993} \omega_{y''} \tag{15}$$

ω_y is the efficiency increase during year *y*.

Spawner stock size

The spawner stock size index for calendar year *y*, S_y, is computed using the equation:

$$S_y = \sum_w \beta_w \frac{1-e^{-Z_{y,w}}}{Z_{y,w}} \tilde{N}_{y,w} \tag{16}$$

where β_w is a relative measure of the amount of spawning during week *w*.

32.2.1. Predicted catch in weight

The model estimate of the catch (in weight) during week *w* of year *y*, $Y_{y,w}$, is given by:

$$Y_{y,w} = \tfrac{F_{y,w}}{Z_{y,w}} B_{y,w}\, e^{\varepsilon^3_y - \sigma^2_w/2} (1-e^{-Z_{y,w}}) \tag{17}$$

Growth

The expected weight of an animal is determined by the number of weeks after it recruits and is assumed to be the average of the weight for females and males:

$$w_{y,w,c} = \begin{cases} 0 & \text{if } 52\times y + w < c \\ 0.5\left[e^{\mathrm{f}}\,(L^{\mathrm{f}}_{52\times y+w-c})^{f^{\mathrm{f}}} + e^{\mathrm{m}}\,(L^{\mathrm{m}}_{52\times y+w-c})^{f^{\mathrm{m}}}\right] & \text{otherwise} \end{cases} \tag{18}$$

where L^s_z is the length of a prawn of sex s (where s=m denotes males and s=f denotes females), z weeks after recruitment:

$$L^s_z = \ell^s_r + (\ell^s_\infty - \ell^s_r)(1 - e^{-\kappa^s z}) \tag{19}$$

ℓ^s_∞, κ^s are the von Bertalanffy growth equation parameters for prawns of sex s,

ℓ^s_r is the length-at-recruitment for prawns of sex s, and

e^s, f^s are the length-weight parameters for prawns of sex s.

For computational convenience, all prawns that have been recruited for more than 52 weeks are assumed to weigh the same as prawns that have been recruited for 52 weeks.

32.2.2. Stock and recruitment

Recruitment is assumed to be related to spawner stock size according to a stock-recruitment relationship. Two alternative models for the relationship between the index of spawner stock size for calendar year y, S_y (see Equation 16), and the subsequent recruitment during biological year y+1, $\hat{R}_{y+1} = g(S_y)$, are considered:

$$g(S_y) = \begin{cases} \tilde{\alpha}\, S_y\, e^{-\tilde{\beta} S_y} & \text{Ricker stock-recruitment relationship} \\ S_y /(\tilde{\alpha} + \tilde{\beta}\, S_y) & \text{Beverton-Holt stock-recruitment relationship} \end{cases} \tag{20}$$

where $\hat{R}_y$ is the conditional mean for the recruitment during biological year y (i.e. the recruitment from October of year y-1 to September of year y) based on the stock-recruitment relationship, $g(S)$, and

$\tilde{\alpha}$, $\tilde{\beta}$ are the parameters of the stock-recruitment relationship.

The relationship between the actual recruitment and conditional mean based on the stock-recruitment is given by:

$$R_y = \hat{R}_y\, e^{\eta_y} \qquad \eta_{y+1} = \sqrt{1-\rho_r^2}\,\xi_{y+1} + \rho_r \eta_y \qquad \xi_{y+1} \sim N(0;\sigma_r^2) \tag{21}$$

where ρ_r is the environmentally-driven temporal correlation in recruitment, and

σ_r is the (environmental) variability in recruitment about the stock-recruitment relationship.

The parameters estimated in the model and displayed in the results, steepness and virgin spawning size, have more biological meaning and can be related to $\tilde{\alpha}$ and $\tilde{\beta}$ by:

$$\tilde{\alpha} = \frac{R^* e^{\tilde{\beta} S^*}}{S^*}$$

and

$$\tilde{\beta} = \frac{\ln(5 \text{ steepness})}{0.8 S^*} \tag{22}$$

for the Ricker stock-recruitment function and by:

$$\tilde{\alpha} = \frac{S^*}{R^*}\left(1 - \tilde{\beta} R^*\right)$$

and

$$\tilde{\beta} = \frac{(\text{steepness} - 0.2)}{0.8 \text{ steepness } R^*} \tag{23}$$

for the Beverton and Holt function.

Growth (in mass) after recruitment is assumed to be governed by the Brody growth curve:

$$w_{a+1} = (1+\rho) w_a - \rho w_{a-1} \tag{24}$$

where ρ is the Brody growth coefficient (Ricker, 1975), and

w_a is the average mass of an individual of age *a* time-steps (weeks).

The values for ρ and w_k, the average mass of an individual at recruitment, are obtained by fitting Equation (24) to the average over sex of the mass of individuals of age *a*.

32.2.3. Parameter estimation

The values for the bulk of the parameters of the model are assumed known (Table 17). Appendix A of this report outlines how the values assumed for availability, q_w, relative weekly spawning fraction, β_w, and relative weekly recruitment, α_w, were obtained. Rather than treating the values for the parameters of the stock-recruitment relationship,

$\tilde{\alpha}$, $\tilde{\beta}$, as estimable parameters, these parameters are instead derived from those for the virgin spawning index, S_0, and the 'steepness' of the stock-recruitment relationship, *h*. Steepness is the ratio of the recruitment expected at the 20% of S_0 to the recruitment expected at S_0 (Francis, 1992).

Two options are considered for overall catchability as a function of week, $\tilde{q}_w$:

a) constant catchability, i.e. $\tilde{q}_w = \tilde{q}$; and

b) a sine function of week, i.e. $\tilde{q}_w = \tilde{q}\exp(\sin(\frac{2\pi\alpha_w^1}{52}\{w-\beta_w^1\}) + \sin(\frac{2\pi\alpha_w^2}{52}\{w-\beta_w^2\})$ where $\alpha_w^1, \beta_w^1, \alpha_w^2, \text{and } \beta_w^2$ determine how catchability changes over the year.

In option (a) the constant catchability can be estimated or input (as in (Wang and Die, 1996)). In both these options, a weekly availability pattern would still be applied. This caters for behavioural changes of the prawn during the year. In option b), the combination of a constant catchability combined with an availability function is replaced with sinusoidal function which estimates the scale and shape of the relationship.

The recruitment in the first year (1969) is assumed to be same as that in the second year (1970) while the recruitment for the last year (2000) is fixed to be equal to 1999. The former assumption is made because there are no catches for 1969 so the 1969 recruitment is essentially non-estimable. The 2000 recruitment is not an estimable parameter of the model because the data for 1999 provide very little information about the magnitude of this recruitment as only a small fraction of the 1999 fishery occurred after October (when the 2000 year-class is first recruited).

The noise terms (ε_y^1, $\varepsilon_{y,m}^2$, $\varepsilon_{y,m}^3$, $\varepsilon_{y,m}^4$) are generated from normal distributions with means 0 and standard deviations σ_ε, σ_M, σ_w, and σ_q respectively)

Estimation of the parameters of this model involves a two-step process. The first step involves estimating the annual recruitments and the parameters that determine catchability, and the second step involves fitting the stock-recruitment relationship to the resultant estimates of spawner stock size and recruitment.

The first step in the estimation process involves selecting the values for the annual recruitments and the parameters that determine catchability to minimise an objective function based on the data on catch in weight. An extension (described later) is made to this objective function if the model is fitted simultaneously to multiple areas for single species. Assuming that some function of the observed catch is normally distributed, the contribution of the catch in weight data to the objective function is:

$$L = \sum_y \sum_w \{\log\sigma_c + \frac{1}{2\sigma_c^2}[k(Y_{y,w}^{obs}) - k(Y_{y,w})]^2\} \tag{25}$$

where σ_c is the residual standard deviation,

$Y_{y,w}^{\text{obs}}$ is the observed catch (in weight) during week *w* of year *y*, and

$k()$ is the transformation function (logarithm, square root, and identity).

The summations in Equation (25) are restricted to the weeks for which the catch is non-zero. Sensitivity to the choice of transformation function is examined because different transformation functions give different emphasis to small and large catches-in-weight. For example, assuming an identity transformation function gives considerable weight to fitting the data for weeks during which the catch is large whereas assuming a logarithm transformation function gives increased weight to weeks during which the catch is relatively small.

One of the outputs from the first step in the estimation process is the variance co-variance matrix for the estimates of the annual recruitments, *V*.

Estimation of the four parameters of the stock-recruitment relationship (steepness, the virgin spawning index, ρ_r and σ_r) involves minimising the following objective function:

$$L = \log\left(\sqrt{\det(\Omega + V)}\right) + \tfrac{1}{2}\sum_{y_1}\sum_{y_2}\left(\log R_{y_1} - \log\hat{R}_{y_1}\right)([V+\Omega]^{-1})_{y_1,y_2}\left(\log R_{y_2} - \log\hat{R}_{y_2}\right) \quad (26)$$

where Ω represents the temporal correlation among recruitments due to environmental fluctuations.

The entries in the matrix Ω are determined from the assumed autocorrelation structure in recruitment (see Equation 21) which implies that the correlation between the recruitments for years y_1 and y_2 is $\sigma_r^2\,\rho_r^{|y_1-y_2|}$. The estimation of the stock-recruitment relationship therefore takes account of the relative precision of the annual recruitments (through the matrix *V*) and the impact of (correlated) environmental variability in recruitment (through the matrix Ω).

32.3. Estimation of MSY *and* E$_{MSY}$

MSY is the Maximum Sustainable Yield and E_{MSY} is the fishing effort (standardized to 1993) at which *MSY* is achieved. The calculation of E_{MSY} and *MSY* is based on the assumption of deterministic dynamics (i.e. no variation in recruitment about the stock-recruitment relationship). The annual catch is equal to the long-term catch from an annual cohort under this assumption.

If $C(E)$ is the equilibrium catch from an annual cohort as a function of the total annual effort, then E_{MSY} is defined as the solution to the equation:

$$\left.\frac{dC(E)}{dE}\right|_{E=E_{MSY}} = 0 \quad (27)$$

Now, $C(E) = \tilde{C}(E)\,R(E)$ where $\tilde{C}(E)$ is the equilibrium catch as a function of effort when the annual recruitment is 1 and $R(E)$ is the equilibrium level of recruitment as a function of effort. The value for $\tilde{C}(E)$ is determined by projecting the population dynamics model (Equations 8 and 9 for the Wang and Die model and Equation 12 for the Deriso-Schnute model) forward for ten years under the assumption that recruitment is unity (i.e. $R_y = 1$) in the first year and then zero thereafter. The choice of ten years is to ensure that (essentially) all prawns are dead by the end of the projection period. The value of $\tilde{C}(E)$ is determined by summing the catch in mass (see Equation 17) over time and recruitment cohort. A by-product of ten-year projection is the spawning index (per recruit) as a function of effort, $\tilde{S}(E)$. The recruitment as a function of effort is computed from the stock-recruitment relationship (see Equation 20) replacing S_y and R_y by $R(E)\tilde{S}(E)$ and $R(E)$ respectively, and solving for $R(E)$. For the Ricker stock-recruitment relationship, for example, this leads to:

$$R(E) = \log(\tilde{\alpha}\, S(E)) / (\tilde{\beta}\, S(E)) \tag{28}$$

It is necessary to specify the relative amount of effort by week to estimate *MSY* and E_{MSY}. These calculations do not take into consideration bycatch of the other tiger prawn species.

32.4. Extensions to multiple areas

When the model is applied to multiple areas, the values for the parameters are estimated separately for each area and all of the above equations are generalised to be functions of area. The following term is added to the objective function to constrain the relative differences in catchability among areas:

$$L = \tfrac{1}{2\theta^2} \sum_w \sum_a \left(\log \tilde{q}_{w,a} - \log \overline{q}_w \right)^2 \tag{29}$$

where $\tilde{q}_{w,a}$ is the overall catchability coefficient for week *w* and area *a* (see Equation 14),

$\overline{q}_w$ is the geometric mean catchability for week *w* across areas, and

θ is the weight assigned to ensuring that the weekly pattern of catchability is similar among areas.

Table 17: *The parameters of the population dynamics model.*

(a) Recruitment and spawning

Parameter	Specification
Annual recruitment, R_y	Estimated
Relative weekly recruitment, α_w	Assumed known (see Appendix A)
Relative weekly spawning, β_w	Assumed known (see Appendix A)
Extent of variation in α_w, σ_α	Assumed known (b-c value 0)
Stock-recruitment parameters, $\tilde{\alpha}, \tilde{\beta}$	Derived from h and S_0
Virgin spawning stock index, S_0	Estimated
Steepness, h	Estimated
Extent of temporal variation in recruitment, σ_r	Estimated
Extent of temporal correlation in recruitment, ρ_r	Estimated

(b) Effort – fishing mortality-related

Parameter	Specification
Overall catchability by week, $\tilde{q}_w$	Estimated (three options)
Relative weekly availability, A_w	Assumed known (see Appendix A)
By-catch catchability, q_b	Estimated
Extent of density-dependent catchability, χ	Assumed known (b-c value 0)
Extent of effort saturation, γ	Assumed known (b-c value 0)
Extent of non-lineararity in F vs E relationship, ϕ	Assumed known (b-c value 1)
Extent of variation in catchability, σ_q	Assumed known (b-c value 0)
Annual efficiency increase, ω_y	Assumed known (see Appendix B)
Target effort, $E^T_{y,w}$	Data – pre-specified
By-catch effort, $E^B_{y,w}$	Data – pre-specified

Catches, $Y^{obs}_{y,w}$	Data – pre-specified
Sine catchability, $\alpha^1_w, \beta^1_w, \alpha^2_w, \beta^2_w,$	Estimated

(c) Growth

Parameter	Specification
Brody growth coefficient, ρ	Assumed known (see Appendix B for b-c)
Von Bertalanffy growth parameters, ℓ^s_∞, κ^s	Assumed known (see Appendix B for b-c)
Length-weight parameters, e^s, f^s	Assumed known (see Appendix B for b-c)
Length-at-recruitment, ℓ^s_r	Assumed known (see Appendix B for b-c)
Weight-at-recruitment, w_k	Assumed known (see Appendix B for b-c)
Weight the week prior to recruitment, w_{k-1}	$((1+\rho)w_k - w_{k+1})/\rho$
Extent of variability in weight, σ_w	Assumed known (b-c value 0)

(d) Other parameters

Parameter	Specification
Average rate of natural mortality, M	Assumed known (see Appendix B for b-c)
Extent of variation in natural mortality, σ_M	Assumed known (b-c value 0)
Catch in weight residual standard deviation, σ_c	Estimated
Catchability weight, θ	Assumed known

33. Results

The results in the section compare estimates of several management-related quantities (and their associated 90% confidence intervals) for *P. esculentus* and *P. semisulcatus.* The management quantities reported are:

a) Steepness - the expected recruitment at 20% of the virgin spawner biomass (Figure 84).

b) Depletion – the ratio (expressed as a percentage) of the spawner stock index for 1999 to that at which *MSY* is achieved (in the absence of fluctuations in recruitment), S_{MSY}.

c) *MSY* – the (deterministic) Maximum Sustainable Yield.

d) E_{MSY} – the effort level (expressed in terms of 1993 days) at which *MSY* is achieved.

e) S_{MSY} – the spawner index value at which (deterministic) *MSY* is achieved.

f) Likelihood (catch) – the value of Equation (25) corresponding to the parameter vector that maximises the likelihood function.

g) Likelihood (Stock-Recruit) – the value of Equation (26) corresponding to the parameter vector that maximises the likelihood function.

The steepness of the stock-recruitment relationship is reported as it indicates the relative productivity of the resource. Depletion and E_{MSY} are quantities that relate to the current management objectives for the fishery (values for depletion less than 100% indicate over-exploitation while employing a fishing effort equal to E_{MSY} is a current management objective for the fishery). The Base Case catchability coefficient was estimated using data for 1993 and this estimate would include fishing power (Wang, 1999). As a result, all the fishing power schedules are calculated relative to 1993 in which the creep value for the year is set as 1. This means that all E_{MSY} estimates are always reported in 1993 days.

The following sub-sections contrast the results of a variety of sensitivity tests to those from a base-case analysis. The base-case analysis (see Appendix B) is based on the Deriso-Schnute formulation and that: efficiency is increased at 5% per annum, recruitment is related to spawner stock size according to a Beverton-Holt stock-recruitment relationship. The values for *MSY* and E_{MSY} for the base-case analyses are computed under the assumption that effort is spread uniformly across the year.

The assessments reported in this Chapter are all based on fitting the models individually to the two species. The model allows for the implications of fishing for one species on another (see Equation 14). However, apart from this, the two models are independent. It is possible, in principle at least, to estimate the parameters for the two species simultaneously. However, this has not been done as it is computationally inefficient. The results for the two species are combined for the projections as the effort directed towards one species has an impact upon the harvest (and status) of the other.

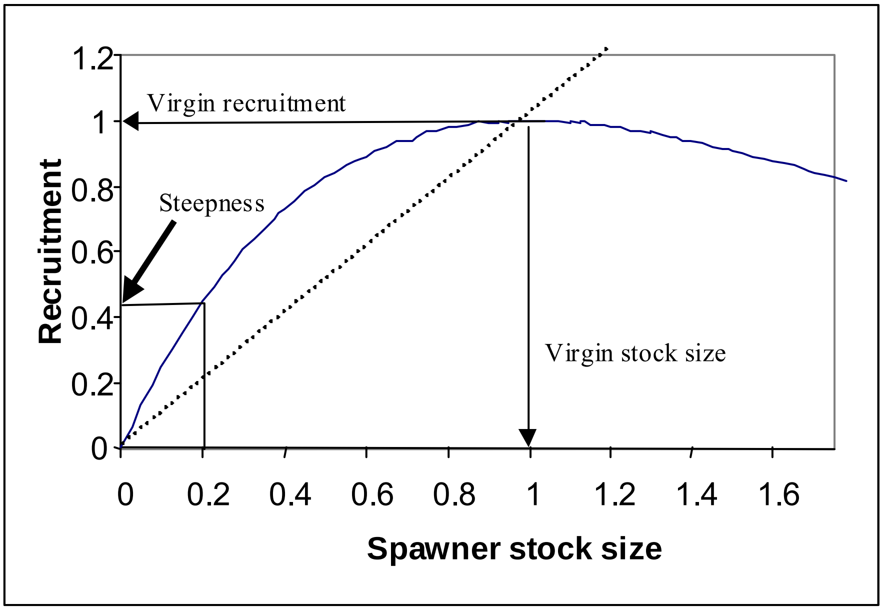

Figure 84: Illustrative stock and recruitment curve showing steepness, virgin recruitment and virgin stock size. The dotted line gives the replacement line which is the recruitment required to replace the spawning population.

Where possible, 90% confidence intervals are calculated. It should be noted that for both species, the intervals of all parameters are poorly estimated. The early recruitment periods are especially poorly known. These wide intervals are therefore reflected in intervals of the management advice.

33.1. Changes to input parameters and model assumptions

33.1.1. Comparison of the Wang and Die (modified) and Deriso-Schnute assessments

Table 18 and Figure 85 contrast the management-related quantities for the Modified Wang and Die and Deriso-Schnute models. The values for biological parameters were taken to be those in Table 6.1 and both models were applied to the same data set. The two assessment methods provide very similar point estimates and 90% confidence intervals (Table 18) and estimated stock-recruitment relationships are virtually identical. This result is to be expected, because apart from the way weight is treated in the two models (see Equations 18 and 24), the two models are identical.

The two assessment methods were applied to a series of alternative data sets (results not shown here). As expected, the results for each alternative data set were also virtually identical.

Table 18: *Results for the base-case Deriso-Schnute analysis and the modified Wang and Die model. The values in parenthesis are 90% confidence limits*

Parameter	Deriso-Schnute	Wang & Die	Deriso-Schnute	Wang & Die
	(*Penaeus semisulcatus*)		(*Penaeus esculentus*)	

Steepness	0.304	0.303	0.279	0.278
	(0.279 - 0.339)	(0.278 - 0.336)	(0.257 - 0.321)	(0.256 - 0.318)
Depletion (%)	67	66	71	70
	(55 – 85)	(54 - 84)	(53 - 100)	(51 - 101)
MSY (tonnes)	1685	1683	1419	1414
	(1405 – 2002)	(1400 - 2001)	(1061 - 1890)	(1059 - 1886)
E_{MSY} (1993 days)	7143	7073	6149	6059
	(5494 – 9281)	(5453 - 9166)	(4474 - 9182)	(4413 - 9030)
S_{MSY}	1.233	1.246	1.594	1.622
	(0.982 - 1.474)	(0.992 - 1.493)	(1.194 - 1.991)	(1.205 - 2.036)
Likelihood (Catch)	3898.2	3914.9	4154.3	4159.8
Likelihood (Stock-Recruit)	-31.17	-31.79	-19.65	-20.14

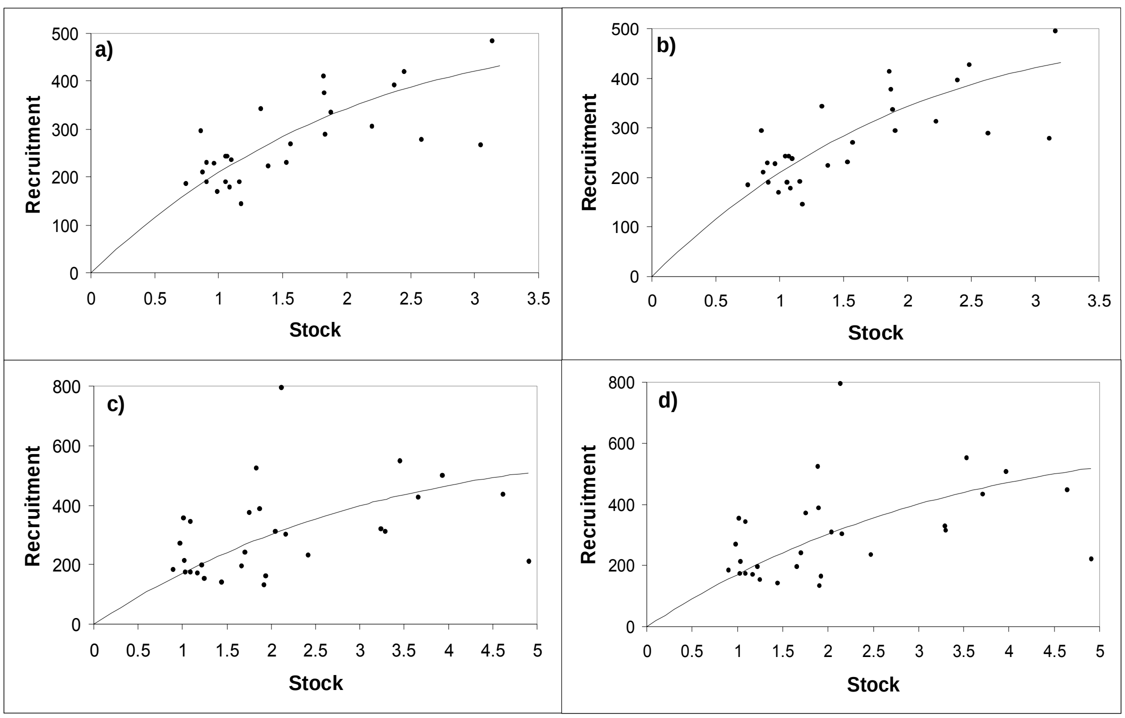

Figure 85: Ricker stock-recruitment relationships from the Deriso Schute model for a) P.semisulcatus, c) P.esculentus and from the modified Wang and Die model for b) P.semisulcatus and d) P.esculentus.

33.1.2. Ricker verses Beverton-Holt stock recruitment relationship

The base-case analyses are based on the assumption that recruitment is related to the size of the spawner-stock index by means of the Ricker stock-recruitment relationship. Table 19 compares the estimates of the management-related quantities for assessments based on the Ricker and Beverton-Holt (Beverton and Holt, 1957) relationships. The value of "likelihood (catch)" is the same for the two sets of results because the choice of stock-recruitment relationship does not have a serious impact on the fit to the catch-in-mass data. The fit of the Ricker model is better for both species although the qualitative results are similar. Basing the assessment on the Beverton-Holt stock-recruitment relationship leads to a slightly less depleted (but nevertheless still overexploited) resource although E_{MSY} is higher for the Beverton-Holt-based assessment.

Table 19: *Comparison of the best estimate model results using the Ricker and Beverton-Holt methods to describe the stock-recruitment relationship (90% confidence intervals are presented in the brackets)*

Parameter	Ricker	Beverton-Holt	Ricker	Beverton-Holt
	(Penaeus semisulcatus)		(Penaeus esculentus)	
Steepness	0.304	0.311	0.279	0.284
	(0.279 - 0.339)	(0.281 - 0.364)	(0257 - 0.321)	(0.261 - 0.339)
Depletion (%)	67	71	71	75
	(55 - 85)	(57 - 97)	(53 - 100)	(54 - 113)
MSY (tonnes)	1685	1662	1419	1386
	(1405 – 2002)	(1371 - 1991)	(1061 - 1890)	(1041 - 1853)
E_{MSY} (1993 days)	7143	7499	6149	6417
	(5494 – 9281)	(5622 - 10,738)	(4474 - 9182)	(4429 - 10,350)
S_{MSY}	1.233	1.161	1.594	1.489
	(0.982 - 1.474)	(0.871 - 1.443)	(1.194 - 1.991)	(1.013 - 2.018)
Likelihood (Catch)	3898.2	3898.2	4154.3	4154.3
Likelihood (Stock-Recruitment)	-31.17	-31.11	-19.65	-19.52

However, plots of the Ricker and Beverton-Holt curves (Figure 86) illustrate that the results are only similar in some of the range. The boxed area depicted on Figure 86a and b indicate the stock size relevant to the tiger fishery modelled for the historical period of 1970 to 1998. It is only where theoretical larger stock sizes occur that differences in the description of the stock recruitment relationship are of any effect.

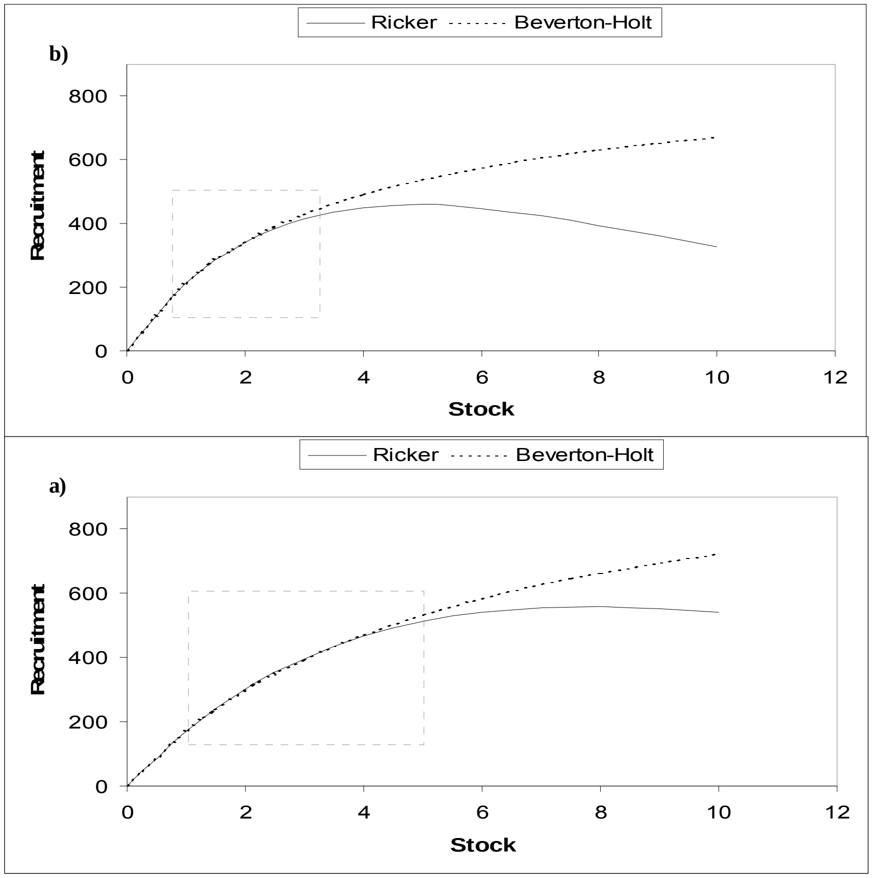

Figure 86: Stock recruitment relationships as described by the Ricker and Beverton-Holt methods for a) P. semisulcatus and b) P. esculentus.

33.1.3. Fishing power change scenarios

The base-case analyses are based on the assumption that efficiency (catchability) is increasing by 5% annually. Table 20 and Table 21 contrast the management-related quantities for different choices for the (constant) annual rate of increase in efficiency. They also contain results for assessments in which the change in efficiency is not constant but rather changes with time. The annual efficiency rates for these last two sensitivity tests were based on an attempt (NPFAG, 2000) to quantify the impact of changes over time in the structure of the fishery and the management controls.

The results are, as expected, very sensitive to assumptions about changes over time in efficiency. In general, the results become more alarming (steepness, depletion and *MSY* lower) as the constant rate of increase in efficiency is set at higher assumed values. The results for the two analyses based on time-varying efficiency rates are less alarming than even the constant 4% efficiency increase rate case (the net rate of efficiency for these two analysis is 4.4% and 4.5% per annum). The reason for this is that a major decline in fishing power in 1987 and subsequent low annual fishing power increases have resulted in greater resource recovery than the constant fishing power options would allow.

The spawner stock and recruitment values for these two analyses for 1975-85 are lower than those for any of the other analyses (Figure 87). The best fit to the catch-in-weight data occurs when the rate of change in efficiency is assumed to be 6% per annum. The fits to the catch-in-weight data for the two analyses with annually varying efficiencies are particularly poor in comparison (differences in log-likelihood from the constant 6% case between 82.7 and 157.1).

Table 20: C*omparison of the model results from different fishing power schedules for P. semisulcatus. A constant 4, 5 and 6% increase in effort per year were compared with the 'Table 1' and 'Table 2' fishing power schedules as defined in the (NPFAG, 2000) report*

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Parameter	**Fishing Power Schedule:**				
	4%	5%	6%	Table 1	Table 2
Steepness	0.325	0.304	0.290	0.350	0.371
	(0.294 - 0.368)	(0.279 - 0.339)	(0.269 - 0.318)	(0.318 - 0.400)	(0.334 - 0.415)
Depletion (%)	80	67	57	94	99
	(66 - 100)	(55 - 85)	(45 - 72)	(80 - 116)	(86 - 120)
MSY (tonnes)	1726	1685	1669	1870	1902
	(1447 - 2014)	(1405 - 2002)	(1366 - 2019)	(1576 - 2188)	(1601 - 2236)
E_{MSY} (1993 days)	8411	7143	6255	9936	11 190
	(6466 - 11 061)	(5494 - 9281)	(4878 - 8007)	(8029 - 12 903)	(8967 - 13787)
S_{MSY}	1.077	1.233	1.389	0.992	0.900
	(0.868 - 1.285)	(0.982 - 1.474)	(1.108 - 1.664)	(0.826 -1.167)	(0.768 - 1.024)
Likelihood (Catch)	3912.9	3898.2	3886.8	4000.4	4043.9
Likelihood (Stock-Recruit)	-31.59	-31.17	-30.72	-29.16	-28.83

Table 21: *Comparison of the model results from different fishing power schedules for P. esculentus. A constant 4, 5 and 6% increase in effort per year were simulated, along with the 'Table 1' and 'Table 2' fishing power schedules as defined in the (NPFAG, 2000).*

Parameter	**Fishing Power Schedule:**				
	4%	5%	6%	Table 1	Table 2
Steepness	0.293	0.279	0.269	0.307	0.318
	(0.265 - 0.342)	(0257 - 0.321)	(0.251 - 0.317)	(0.282 - 0.349)	(0.291 - 0.364)
Depletion (%)	83	71	61	95	96
	(63 - 119)	(53 - 100)	(44 - 84)	(75 - 128)	(76 - 128)
MSY (tonnes)	1471	1419	1375	1606	1621
	1128 - 1917)	(1061 - 1890)	(993 - 1883)	(1277 - 1993)	(1300 - 1989)
E_{MSY} (1993 days)	7128	6149	5381	8191	8995

	(5069 - 10 696)	(4474 - 9182)	(3919 - 8154)	(6384 - 11 137)	(7018 - 12 219)
S_{MSY}	1.430	1.594	1.750	1.366	1.261
	(1.065 - 1.813)	(1.194 - 1.991)	(1.316 - 2.204)	(1.094 - 1.636)	(1.009 - 1.512)
Likelihood (Catch)	4169.4	4154.3	4140.7	4223.4	4248.6
Likelihood (Stock-Recruit)	-19.74	-19.65	-19.50	-19.50	-19.04

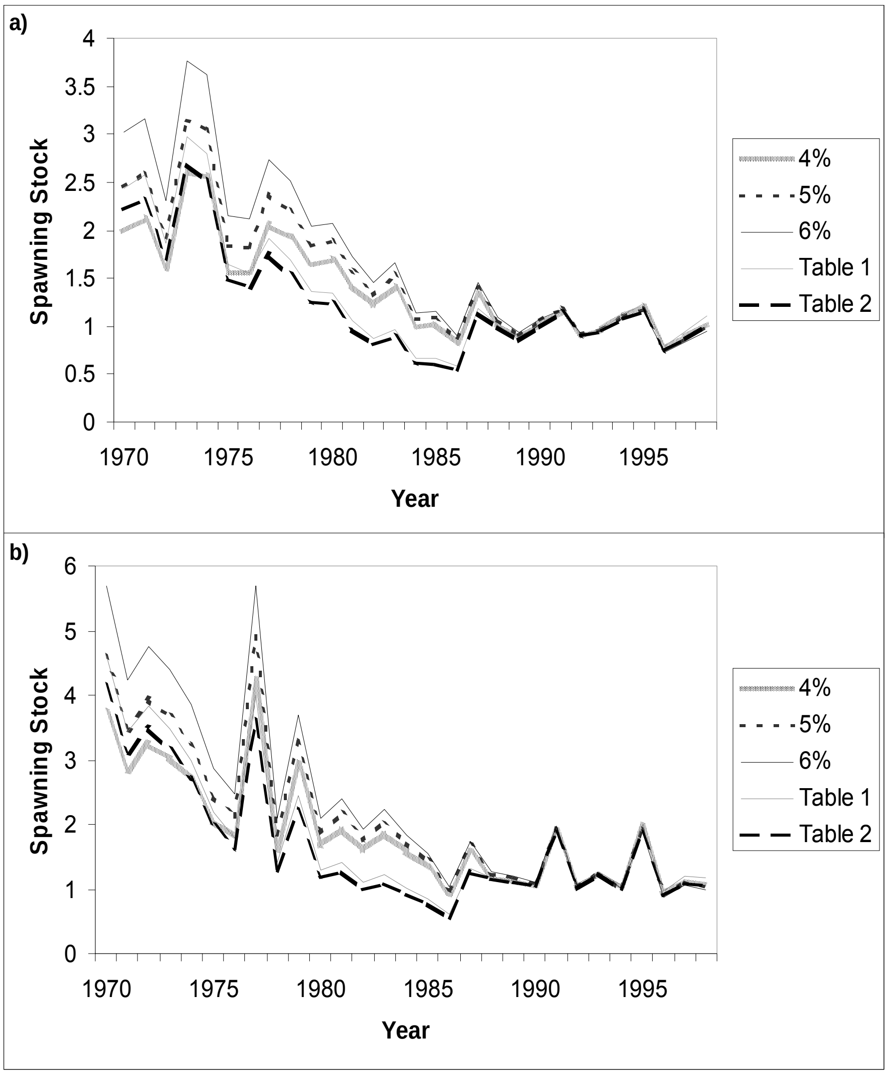

Figure 87: Spawning stock indexes over the historical period of the tiger fishery for the 5 fishing power scenarios for: a) *P. semisulcatus* and b) *P. esculentus*

33.1.4. Varying the reference year for MSY estimation

The estimation of *MSY* and E_{MSY} is based on a yield-per-recruit model with a weekly time-step. The estimates of *MSY* and E_{MSY} are therefore influenced by the proportion of the fishing effort that occurs each week. Fishing occurred almost throughout the year during the early 1980s. By 1993, the year in which there was a large-scale vessel buy-back scheme in force, a mid-year spawning closure was mandatory as well as a seasonal closure over the December/January period. The season was again shortened in 1998 to reduce effort. *MSY* (and hence those management quantities related to *MSY*) was estimated replacing the base-case assumption that effort is spread uniformly across the year by the assumption that the distribution of effort across the year is the same as that in some pre-specified year (Table 22 and Table 23).

Table 22: *Comparison of the impact on management-related quantities of changing the assumption regarding the distribution of effort across the year for P.semiculcatus. The Base Case scenario uses a uniform effort distribution.*

Parameter	Uniform Effort (BaseCase)	1980 Reference year	1993 Reference year	1998 Reference year
Depletion (%)	67	66	65	65
	(55 - 85)	(54 - 83)	(54 - 82)	(54 - 81)
MSY (tonnes)	1685	1825	1919	1961
	(1405 - 2002)	(1525 - 2164)	(1604 - 2273)	(1642 - 2321)
E_{MSY} (1993 days)	7143	9842	11411	12003
	(5494 - 9281)	(7477 - 12 989)	(8458 - 15 576)	(8913 - 16 327)
S_{MSY}	1.233	1.256	1.262	1.272
	(0.982 - 1.474)	(1.004 - 1.500)	(1.018 - 1.499)	(1.028 - 1.509)

Table 23: *Comparison of the impact on management-related quantities of changing the assumption regarding the distribution of effort across the year for P. esculentus. The base-case scenario uses a uniform effort distribution.*

Parameter	Uniform Effort (BaseCase)	1980 Reference year	1993 Reference year	1998 Reference year
Depletion (%)	71	70	70	70
	(53 - 100)	(54 - 97)	(52 – 96)	(46 – 172)
MSY (tonnes)	1419	1445	1506	1509
	(1061 - 1890)	(1399 – 2001)	(1116 – 2118)	(1118 – 2124)
E_{MSY} (1993 days)	6149	6632	7642	7444
	(4474 - 9182)	(4484 – 10 549)	(5500 – 13718)	(5335 – 13371)
S_{MSY}	1.594	1.592	1.592	1.59
	(1.194 - 1.991)	(1.207 – 2.000)	(1.210 – 2.003)	(1.209 – 2.002)

The estimates of some of the management-related quantities are sensitive to assumptions about the distribution of effort across the season. (Table 22 and Table 23, and Figure 88). The uniform fishing year led to the lowest values for *MSY* and E_{MSY} and a reference year of 1998 to the highest estimates for these quantities. Changing the distribution of effort across the year resulted in little change to the depletion values. It is noteworthy that the values for *MSY* and E_{MSY} are higher for years in which more seasonal closures were mandated and the season length shortened. This result highlights the benefits of reducing effort during key periods such as spawning and early ‘recruitment’.

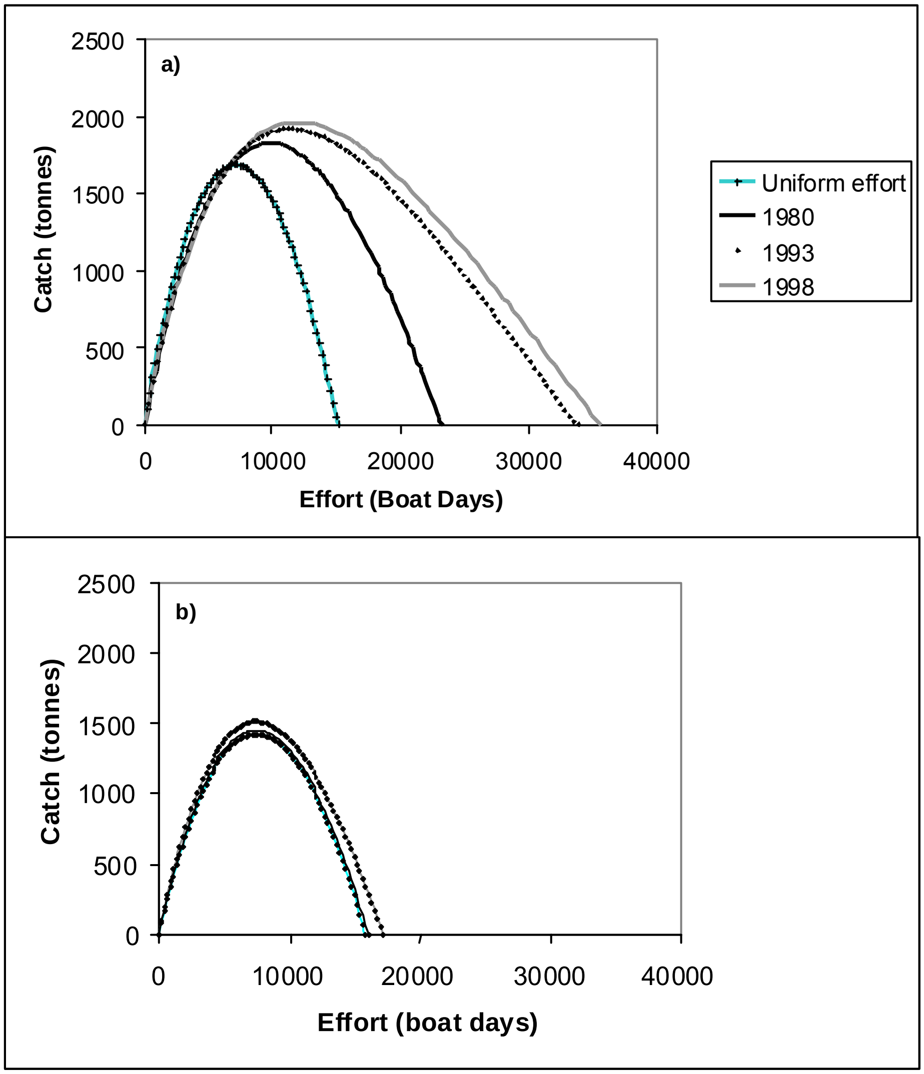

Figure 88: Catch and Effort curves comparing the results of using various reference year data to estimate MSY for a) *P.semisulcatus* and b) *P.esculentus*

33.1.5. Transformation of catch data

The likelihood function for the base-case analysis assumes that catch-in-mass is normally distributed. There is, however, little objective basis for this assumption so the sensitivity to assuming that the square root and logarithm of the catch-in-mass is normally distributed (see Equation 15) was examined. Changing the transformation function in Equation 15 has the effect of changing the emphasis placed on matching large and small catches when fitting the model – the base-case assumption implicitly gives greater emphasis to fitting large catches whereas the logarithm transformation gives equal emphasis to fitting small and large catches. The values of the negative log-likelihood for the catch data are omitted from Table 24 and Table 25 as they are not comparable.

Table 24: *The sensitivity of the management-related quantities for P. semisulcatus to changing the transformation function applied when fitting to the catch-in-mass data.*

Parameter	Untransformed (Base Case)	Square-root Transformation	Log transformation
Steepness	0.304	0.304	0.299
	(0.279 - 0.339)	(0.281 - 0.332)	(0.274 - 0.345)
Depletion (%)	67	69	62
	(55 - 85)	(58 - 87)	(45 - 81)
MSY (tonnes)	1685	1514	1190
	(1405 - 2002)	(1253 - 1782)	(913 - 1556)
E_{MSY} (1993 days)	7143	7097	6785
	(5494 - 9281)	(5644 - 8872)	(5190 - 9688)
S_{MSY}	1.233	1.114	0.915
	(0.982 - 1.474)	(0.918 - 1.287)	(0.719 - 1.116)
Likelihood (Stock-Recruitment)	-31.17	-33.37	-25.61

Table 25: *The sensitivity of the management-related quantities for P.esculentus to changing the transformation function applied when fitting to the catch-in-mass data.*

Parameter	Untransformed (Base Case)	Square-root Transformation	Log transformation
Steepness	0.279	0.279	0.281
	(0257 - 0.321)	(0.257 - 0.317)	(0.258 - 0.330)
Depletion (%)	71	64	54
	(53 - 100)	(48 - 86)	(38 - 72)
MSY (tonnes)	1419	1466	1428
	(1061 - 1890)	(1110 - 1881)	(1083 - 1979)
E_{MSY} (1993 days)	6149	6162	6257
	(4474 - 9182)	4465 - 8900)	(4545 - 9810)
S_{MSY}	1.594	1.637	1.574
	(1.194 - 1.991)	(1.288 - 1.992)	(1.207 - 1.962)
Likelihood (Stock-Recruitment)	-19.65	-23.79	-25.13

The estimates of the management-related quantities for *P. semisulcatus* are notably more sensitive to the choice of transformation function (a range for *MSY* across the three options of 495*t*) than those for *P. esculentus* (a range for *MSY* across the three options of only 47*t*). The reasons for this are unclear. However, there are more small catches in the data set for *P. semisulcatus* and the stock-recruitment relationship (Figure 89 and Figure 85) for *P. semisulcatus* indicative of a high virgin biomass if the data are untransformed.

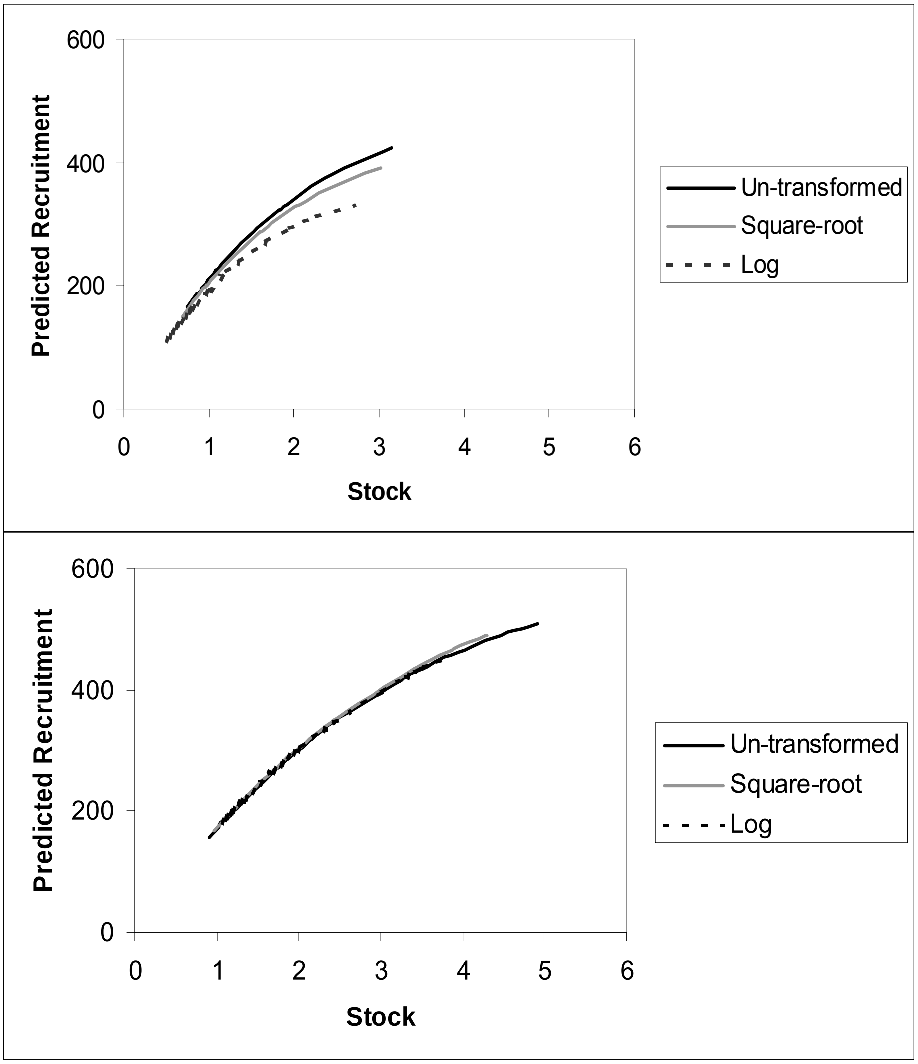

Figure 89: Stock verses modelled recruitment predicted by the model for a) *P. semisulcatus* and b) *P. esculentus*.

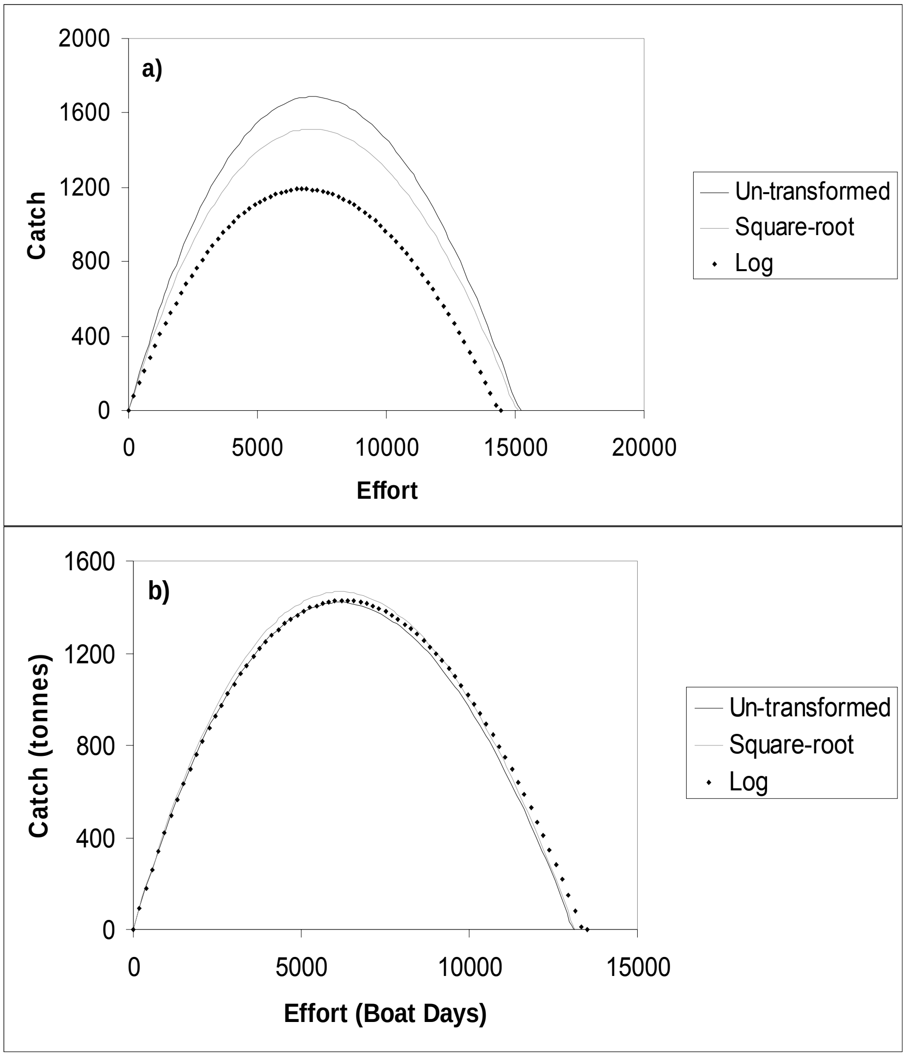

Figure 90: Catch – effort curves for a) *P. semisulcatus* and b) *P. esculentus*

33.1.6. Catchability assumptions

As described in Appendices A and B, the values for the overall catchability coefficient, the by-catchability coefficient, as well as the weekly availability pattern are pre-specified as part of the base-case analysis. Table 26 and Table 27 examine the sensitivity of the results to modifying these base-case assumptions by replacing the combination of the overall catchability coefficient and the weekly availability pattern by the assumption the availability is independent of week while catchability varies sinusoidally (see Section 1.3.3). The scale of the final sine function was an order of magnitude different from that of the input catchability values (Figure 91). An attempt at inputting the availability function and estimating catchability was made, but the model was extremely sensitivity and did not converge for *P. esculentus*. These results presented in this report are preliminary and more research needs to be undertaken on this topic.

Table 26: *Sensitivity to input or various forms of estimated catchability values for* P. semisulcatus.

Parameter	Base Case	Sine q
Steepness	0.304	0.252
Depletion (%)	67	76.14
MSY (tonnes)	1685	1139.44
EMSY (1993 days)	7143	8814.7
SMSY	1.233	1.532
Likelihood (Catch)	3898.3	3571.9
Likelihood (Stock-Recruit)	-31.17	-26.44

Table 27: S*ensitivity to input or various forms of estimated catchability values for* P. esculentus**.**

Parameter	Base Case	Sine q
Steepness	0.279	0.238
Depletion (%)	71	80
MSY (tonnes)	1419	893
EMSY (1993 days)	6149	5799
SMSY	1.594	1.900
Likelihood (Catch)	4154.3	3466.5
Likelihood (Stock-Recruit)	-19.65	-21.44

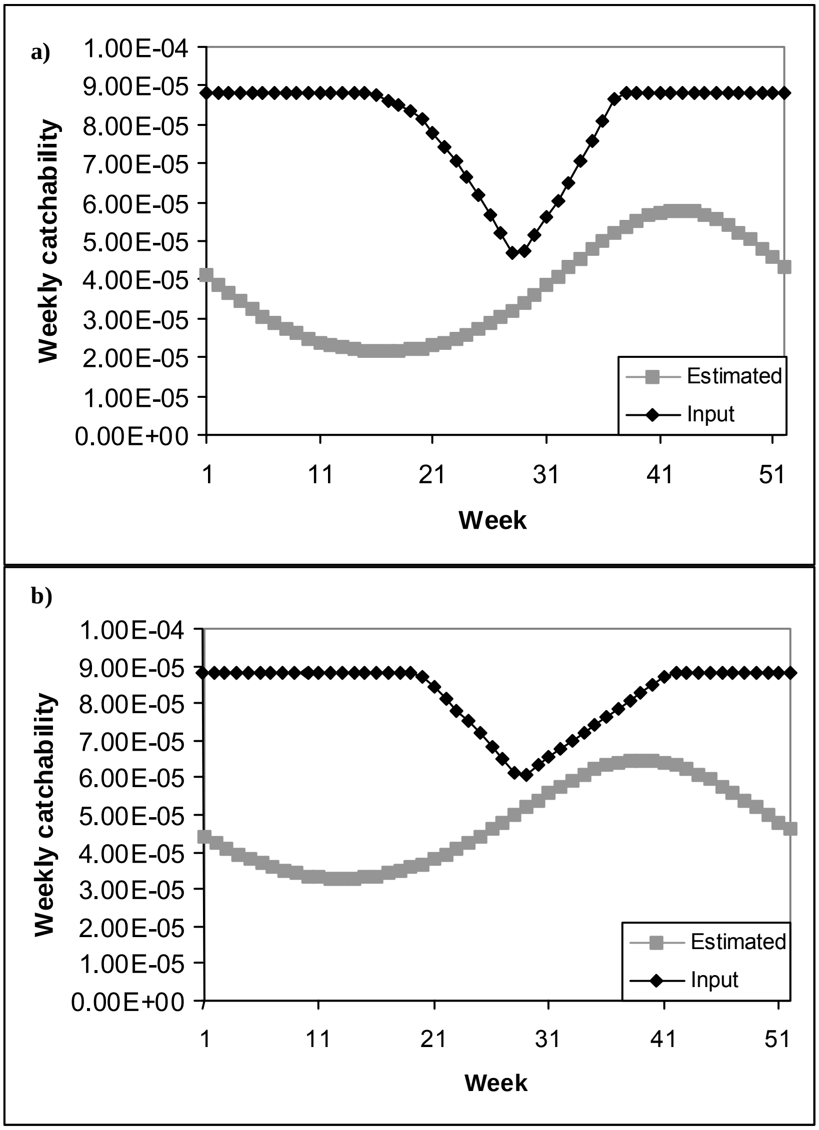

Figure 91: Weekly overall catchability in 1993 days as an input (combining the weekly availability and catchability) and estimated (as a sine function) for a) *P. semisulcatus* and b) *P. esculentus*.

33.1.7. Weekly recruitment

The weekly pattern of recruitment is based on data collected during research programme conducted in relatively small areas in the Gulf of Carpentaria (see Appendix A). The extent to which the result inferred from data for a relatively small area applies, at least approximately, to the whole Northern Prawn Fishery is not known, but such an assumption is considered reasonable. The base-case recruitment pattern is certainly not representative of the stock as a whole so to assess the influence of this unrealistic assumption a sensitivity analysis was done. . To do this, the phase of the weekly *pattern* was changed to be one month earlier and one month later even though the model still works with the recruitment year starting in week 40). Although the quantities of primary interest to management were largely insensitive to the choice of month when the recruitment for year *y* starts to enter the population (Table 28 and Table 29), the estimate time-sequence of recruitment (particularly for the early years) is sensitive to this assumption (Figure 92).

Table 28: *The sensitivity of the management-related quantities for P. semisulcatus to changing the weekly recruitment pattern one month earlier or one month later.*

Parameter	Base Case	Early recruitment	Late recruitment
Steepness	0.304	0.306	0.306
	(0.279 – 0.339)	(0.280 - 0.340)	(0.280 - 0.340)
Depletion (%)	67	69	64
	(55 – 85)	(56 - 88)	(53 - 80)
MSY (tonnes)	1685	1757	1654
	(1405 – 2002)	(1476 - 2069)	(1369 - 1972)
E_{MSY} (1993 days)	7143	7347	7556
	(5494 – 9281)	(5649 - 9544)	(5838 - 9719)
S_{MSY}	1.233	1.220	1.246
	(0.982 – 1.474)	(0.961 - 1.477)	(0.999 - 1.477)
Likelihood (Catch)	3898.3	4017.0	3839.2
Likelihood (Stock-Recruit)	-31.17	-32.91	-29.83

Table 29: *The sensitivity of the management-related quantities for P. esculentus to changing the weekly recruitment pattern one month earlier or one month later.*

Parameter	Base Case	Early recruitment	Late recruitment
Steepness	0.279	0.280	0.281
	(0257 - 0.321)	(0.256 - 0.328)	(0.259 - 0.320)
Depletion (%)	71	75	66
	(53 – 100)	(55 - 108)	(49 - 90)
MSY (tonnes)	1419	1400	1470
	(1061 – 1890)	(1035 - 1886)	(1100 - 1949)
E_{MSY} (1993 days)	6149	6154	6505
	(4474 – 9182)	(4381 - 9644)	(4798 - 9407)
S_{MSY}	1.594	1.530	1.634
	(1.194 – 1.991)	(1.144 - 1.929)	(1.243 - 2.032)
Likelihood (Catch)	4154.3	4215.1	4053.7
Likelihood (Stock-Recruit)	-19.65	-19.5402	-18.8850

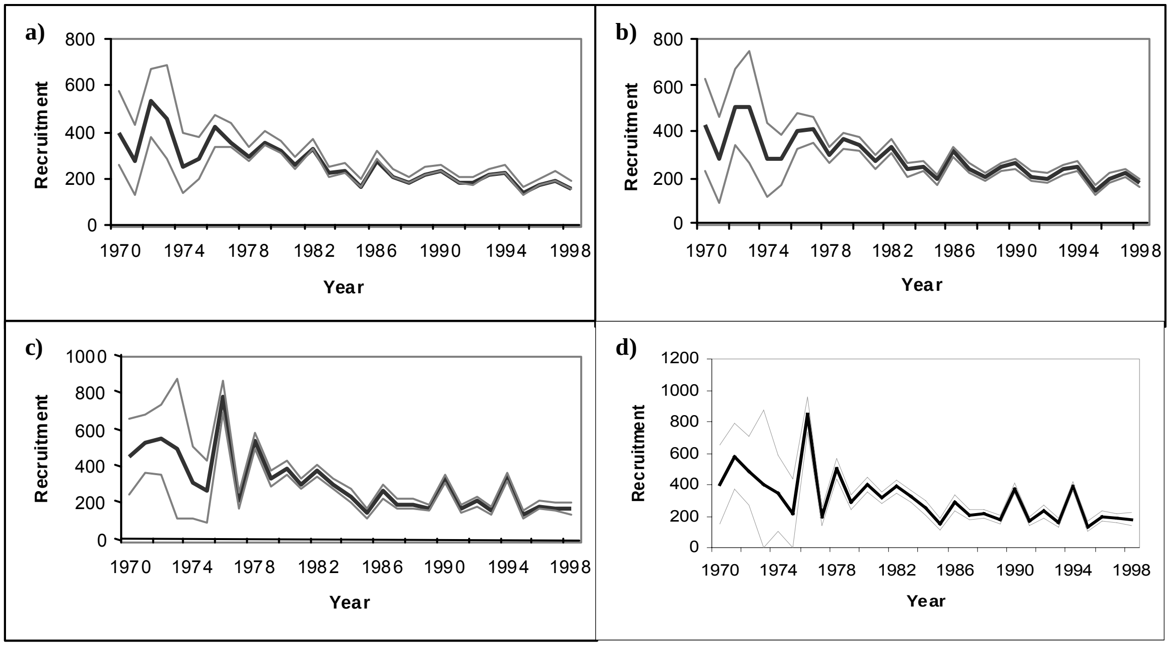

Figure 92: Modeled recruitment trends over the history of the NPF with 90% confidence intervals plotted for late and early recruitment scenarios of each tiger species. a) *P. semisulcatus* late recruitment, b) *P. semisulcatus* early recruitment, c) *P. esculentus* late recruitment and d) *P. esculentus* early recruitment.

33.1.8. Multiple stocks

Seven stocks have been identified for the tiger prawn stocks in the NPF (see Chapter 2). For each species, the catch and effort in some areas are not large enough to allow for an assessment in all seven stocks. Although the model has been developed to estimate all the parameters for each stock together, the model did not converge. Therefore, for this project, a single assessment for stocks with good data was undertaken. For *P. semisulcatus* the areas were "Melville", "NW Gulf of Carpentaria (GoC)", "SW GoC" and "NE GoC" (Table 30) and for *P. esculentus*, they were "Melville", "NW Gulf of Carpentaria (GoC)", "SW GoC" and "SE GoC" (Table 31). More than 90% of each species' catch comes from the relevant four regions.

For *P. semisulcatus* the range of estimated depletions range from 47 to 88%. The lowest corresponds to the NW GoC region, just north of Groote Eylandt, and the highest to NE GoC at Weipa. However, all the stocks are assessed to be overexploited. The equilibrium stock index, S_{MSY}, is small in Melville and NE GoC regions. In all stocks, the steepness is smaller than the Base Case. For *P. esculentus* the estimated depletions range from 67% to 147%. Only two of the three stocks are assessed as being overexploited. Interestingly, the *P. esculentus* stock in NW GoC is assessed as above SMSY even though that for *P. semisulcatus* is extremely low. The difference in the stock level steepness is below that of the Base Case, but this is not as marked as for *P. semisulcatus*.

Table 30: *The sensitivity of the management-related quantities for P.semisulcatus to estimating parameters at single stock level compared to the Base Case at NPF scale. See Chapter 2. GoC stands for Gulf of Carpentaria. The likelihoods are not comparable and have been removed.*

Parameter	Base Case	Melville	NW GoC	SW GoC	NE GoC
Steepness	0.304	0.21704	0.22133	0.23198	0.21952
Depletion(%)	67	79	47	72	88
MSY(tonnes)	1685	144.36	462.91	530.13	149.32
E_{MSY}(1993 days)	7143	1258.42	1568.23	2326.81	1438.11
S_{MSY}	1.233	0.58262	1.50193	1.16419	0.52790

Table 31: *The sensitivity of the management-related quantities for P.esculentus to estimating parameters at single stock level compared to the Base Case at NPF scale. See Chapter 2. GoC stands for Gulf of Carpentaria. The likelihoods are not comparable and have been removed.*

Parameter	Base Case	Melville	NW GoC	SW GoC	NE GoC
steepness	0.279	0.20708	0.22208	0.24208	0.22202
Depletion(%)	71	147	119	89	67
MSY(tonnes)	1419	47.74	234.57	628.23	233.27
E_{MSY}(1993 days)	6149	579.21	1784.02	3348.94	1778.93
SMSY	1.594	0.54424	0.87686	1.26618	0.87447

33.1.9. Overall summary of sensitivity tests

The results of the sensitivity tests are summarised in Figure 93 and Figure 94 by histograms of the 1999 depletion and E_{MSY}. These two variables were chosen for the summary as they are currently the two most important quantities from the viewpoint of management. To ease interpretation of the results, the base-case and the extreme sensitivity tests are highlighted.

Only two of the sensitivity tests (‘Table 1’ and ‘Table 2’ in the (NPFAG, 2000) report) led to point estimates for current depletion close to 100% - the remaining analyses all suggest that the stock is overexploited. It should be noted that these two analyses are outliers compared to the remaining analyses and they did not fit the data well (compared, for example, to the base-case analysis). The distribution of the point estimates of E_{MSY} are highly skewed with the values based on changing the reference year when calculating E_{MSY} and *MSY* leading to markedly higher values.

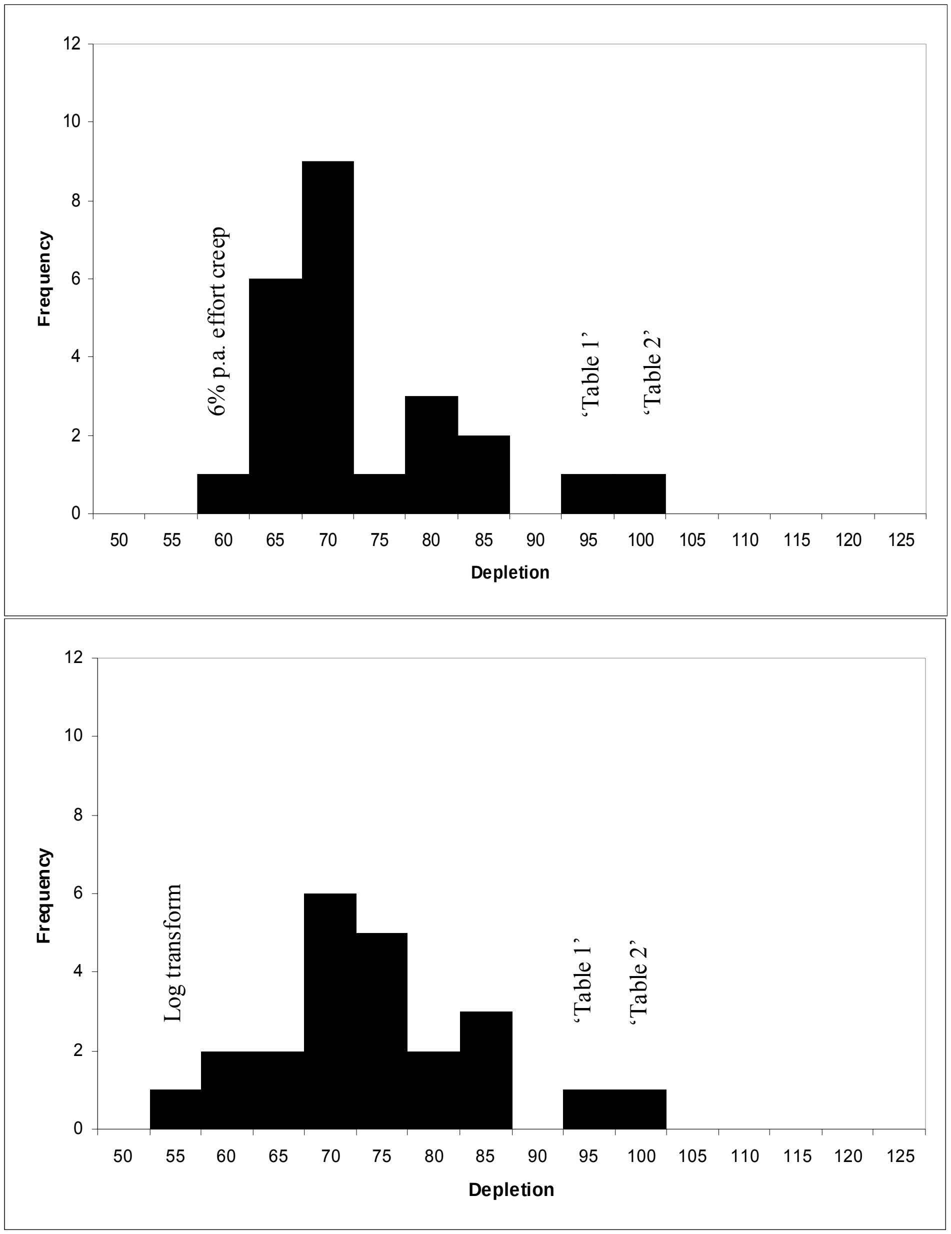

Figure 93: Frequency plot of depletion estimates for a) *P. semisulcatus* and b) *P. esculentus* of all above sensitivity tests undertaken. In both cases, the base case falls within the median.

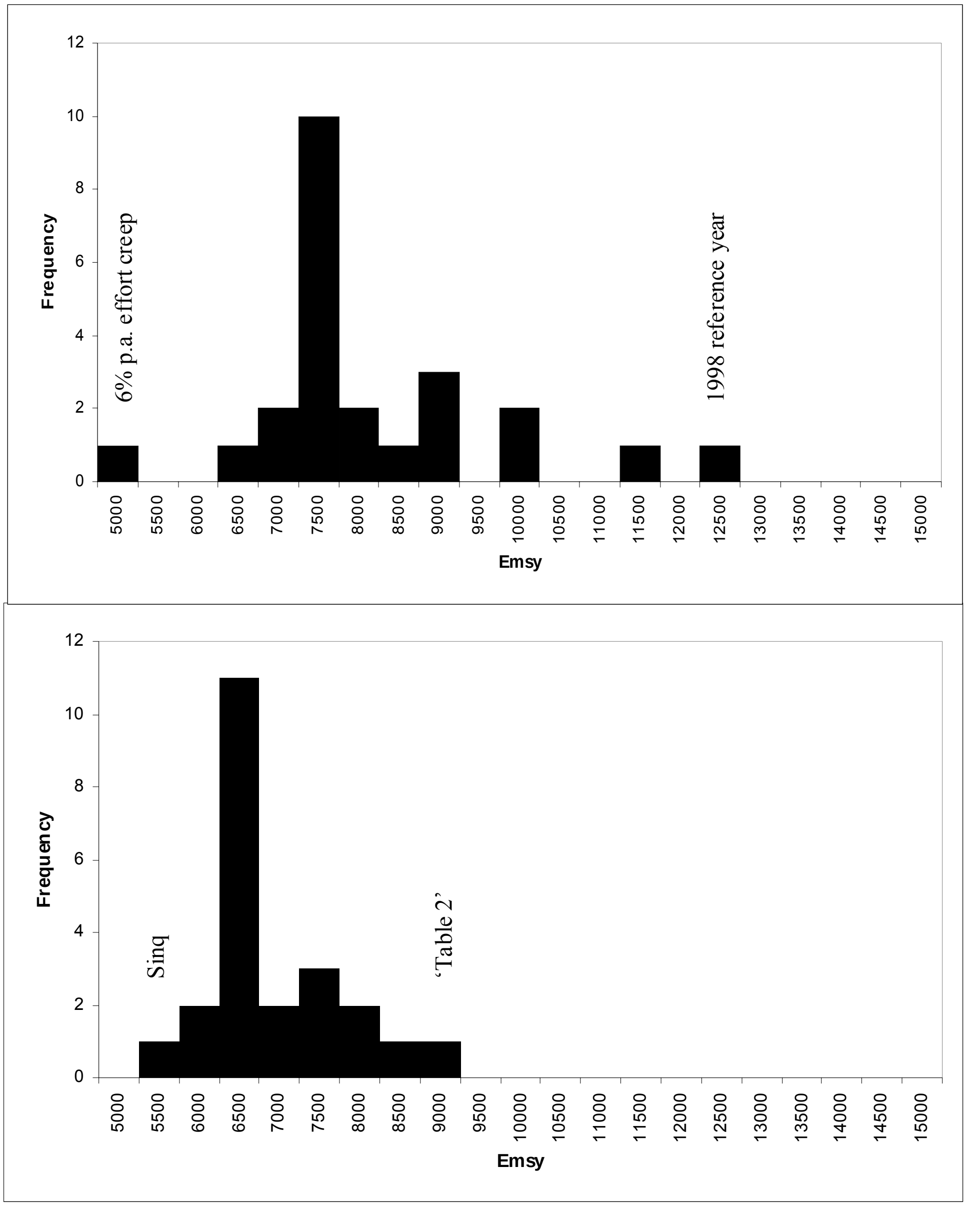

Figure 94: Frequency plot of E_{MSY} estimates for a) *P. semisulcatus* and b) *P. esculentus* of all above sensitivity tests undertaken. In both cases, the Base Case falls within the median.

33.2. Incorporating additional process error and variability in the catch and effort data

The base-case analyses and all of the sensitivity tests referred to in Section 33.1 only consider process error in recruitment and treat the catch and effort data as known. The impact of these simplifications is examined in the following sections. Although the results in this Section are again presented in the form of point estimates and 90% confidence intervals, the approach used to construct these is different from that used for the earlier Sections. In this Section, the model was fitted to about 70 alternative data sets and the point estimate reported is the mean of the estimates across these data sets while the 90% confidence intervals represent the 5th and 95th percentiles after the values are sorted (called 90% uncertainty intervals).

The alternative data sets, when examining the sensitivity to how the catch and effort data are defined, are constructed using the bootstrap procedure described in Chapter 2 and 3.

33.2.1. Error in the catch and effort data

Three sets of data are included in this sensitivity test:

(i) The first are a series of bootstrap data that uses the Base Case method of the logbook to landing augmentation, the species split and the definition of target. However, the data includes uncertainty in the estimation of total catch and in splitting the catch into different species. However, in this test as well as the Base Case, there is no uncertainty applied to the definition of target. Here known as "Base Method".

(ii) The second are a series of bootstrap data with the same definition of target as the Base Case, but a new method of interpolating total catch and dividing the catch into species. Uncertainty in only the latter two methods is also included. ("Partial Method")

(iii) The last is a series of bootstrap data with a new method for interpolating the catch, dividing the catch by species and defining the target. However, in this case uncertainty in all three methods is included. ("New Method")

These three methods are described in detail Chapters 2 and 3.

The results of these sensitivity tests with the 90% Uncertainty Intervals of the estimates of total bootstrap data sets are given in Table 32 and Table 33. There is little variation in the 90% Uncertainty intervals between the sensitivity test methods as they are based on the mean values from each of the bootstrap applications. The two alternative methods themselves differed marginally if at all in the averaged model output. A similar trend appeared in the stock recruitment relationships where all three methods are compared (Figure 95). However, there is a large change in the depletion between the Base Case with uncertainty and the alternative methods for *P. esculentus.*

Table 32: *Comparison of the Base Method with data uncertainty for P.semisulcatus species split and target definition derived by Wang and Die (1996), the new species split definition with Base Case target definition (Partial Method) and finally, new species split and new target definition input data (New Method). 90% Uncertainty Intervals of the estimates are given in the brackets.*

Parameter	Base Method	Partial Method	New Method
Steepness	0.304	0.303	0.303
	(0.279 - 0.339)	(0.302 - 0.304)	(0.301- 0.305
Depletion (%)	67	64	63
	(55 - 85)	(63 - 64)	(62- 64)
MSY (tonnes)	1685	1809	1823
	(1405 - 2002)	(1791 – 1825)	(1800 - 1838)
E_{MSY} (1993 days)	7143	7042	7162
	(5494 - 9281)	(6989 – 7089)	(6930 – 7036)

S_{MSY}	1.233	1.342	1.352
	(0.982 - 1.474)	(1.330 - 1.353)	(1.349 - 1.372)

Table 33: *Comparison of the Base Method with data uncertainty for P.esculentus species split and target definition derived by Wang and Die (1996), the new species split definition with Base Case target definition (Partial Method) and finally, new species split and new target definition input data (New Method). 90% Uncertainty Intervals of the estimates are given in the brackets.*

Parameter	Base Method	Partial Method	New Method
Steepness	0.279	0.281	0.271
	(0257 - 0.321)	(0.280 - 0.282)	(0.270 - 0.272)
Depletion (%)	71	58	60
	(53 - 100)	(56 - 58)	(59 - 61)
MSY (tonnes)	1419	1364	1346
	(1061 - 1890)	(1351 - 1376)	(1322 - 1361)
E_{MSY} (1993 days)	6149	6273	5522
	(4474 - 9182)	(6208 - 6337)	(5464 - 5577)
S_{MSY}	1.594	1.497	1.671
	(1.194 - 1.991)	(1.474 - 1.516)	(1.647 - 1.690)

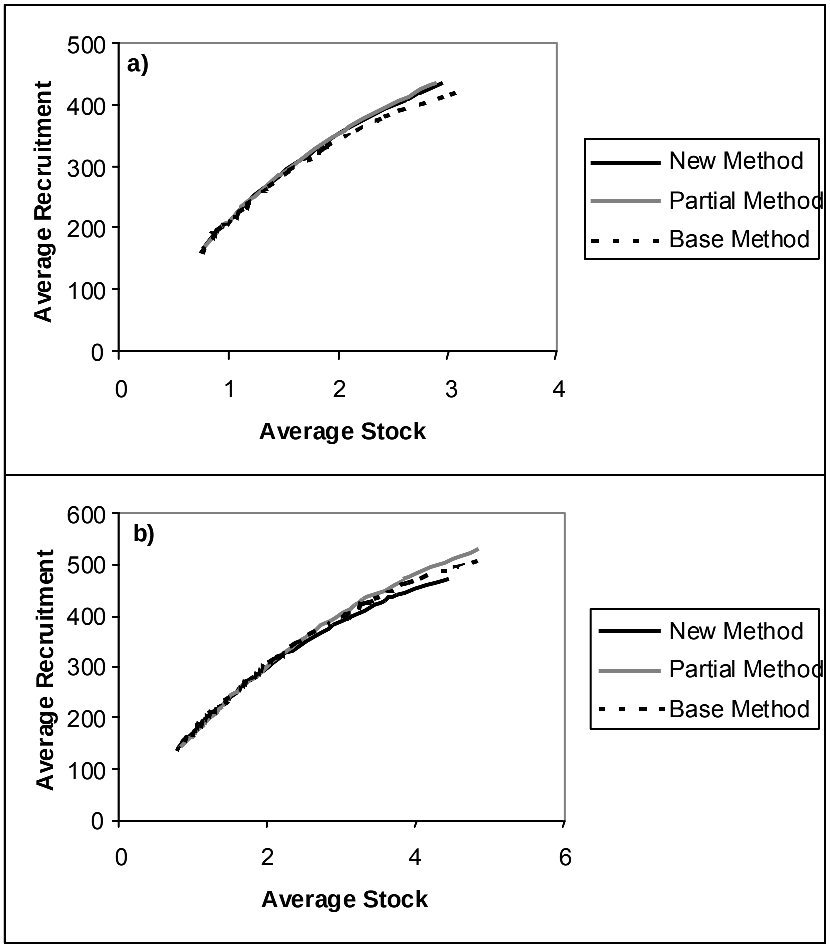

Figure 95: Comparison of stock-recruitment relationships for a) *P. semisulcatus* and b) *P. esculentus*. The "New Method" uses data based on a new method for the species split, interpolation of the catch and defining the target. The "Partial Method" uses data based on the method of augmenting the total catch and the species split, but using the base case method of defining the target. "Base case" here is using the base case method, but including data uncertainty.

33.2.2. Additional sources of process error

Table 34, Table 35, and Figure 96 contrast the results for the base-case analysis (which includes only process error in recruitment and computes 90% confidence intervals using an asymptotic method) with results for analyses that allow for process error (with a coefficient of variation of 0.3 in (a) catchability (σ_q), (b) weekly recruitment (σ_α), (c) natural mortality (σ_M), (d) mass-at-age (σ_w), and (e) all four of these sources of process error. In contrast to the situation when uncertainty regarding the catch and effort data was considered (Section 33.1), additional sources of process error can lead to increased 90% confidence intervals. Uncertainty about weight-at-age has the largest impact on the widths of the 90% intervals. This is probably a result of the implicit assumption that variations in weight-at-age are perfectly correlated across weeks (i.e. if the environment is such that prawns are larger than usual in week 1, it is assumed the prawns will also be larger than usual in week 50). In contrast, the process error related to other factors (catchability, weekly recruitment and natural mortality) is assumed to be independent between weeks.

Table 34: *Variation of 0.3 in sigma values for individual parameters and all parameters for P. semisulcatus. 90% Uncertainty Intervals of the Monte Carlo estimates are given in brackets.*

Parameter	Base Case	Alpha Sigma	Catchability	Natural Mortality	Weight at age	All combined
		σ=0.3	σ=0.3	σ=0.3	σ=0.3	σ=0.3
Steepness	0.304	0.305	0.307	0.306	0.332	0.334
	(0.279 –0.339)	(0.302 –0.307)	(0.300 –0.318)	(0.295 – 0.319)	(0.299 –0.377)	(0.295 – 0.392)
Depletion (%)	67	69	69	69	78	84
	(55 - 85)	(67 - 70)	(57 - 80)	(63 - 74)	(38 - 122)	(40 - 139)
MSY (tonnes)	1685	1688	1577	1694	1952	1822
	(1405 - 2002)	(1667 - 1709)	(1536 – 1612)	(1597 - 1783)	(1669 - 2206)	(1435 - 2252)
E_{MSY} (1993 days)	7143	7172	7309	7229	8817	8952
	(5494 - 9281)	(7022 - 7302)	(6885 – 8013)	(6539 - 8048)	(6814 – 11 598)	(6563 - 12 467)
S_{MSY}	1.233	1.230	1.129	1.227	1.188	1.084
	(0.982 - 1.474)	(1.216- 1.253)	(1.054 - 1.189)	(1.132 - 1.313)	(0.990 - 1.405)	(0.918 - 1.260)

Table 35: *Variation of 0.3 in sigma values for individual parameters and all parameters for P.esculentus. 90% Uncertainty Intervals of the Monte Carlo estimates are given in brackets.*

Parameter	Base Case	Alpha Sigma	Catchability	Natural Mortality	Weight at age	All combined
		σ=0.3	σ=0.3	Σ=0.3	σ=0.3	σ=0.3
Steepness	0.279	0.279	0.283	0.279	0.295	0.305
	(0.257 - 0.321)	(0.277 - 0.281)	(0.276 - 0.293)	(0.271 - 0.285)	(0.262 - 0.339)	(0.263 - 0.358)
Depletion (%)	71	73	76	72	82	85
	(53 - 100)	(71 - 74)	(64 - 88)	(64 - 77)	(37 - 136)	(37 - 145)
MSY (tonnes)	1419	1422	1352	1427	1568	1497
	(1061 - 1890)	(1395 - 1444)	(1294 – 1402)	(1312 -1515)	(1253 - 2029)	(1206 - 1832)
E_{MSY} (1993 days)	6149	6156	6394	6119	7310	7984
	(4474 - 9182)	(5985 - 6303)	(5895 – 7188)	(5516 - 6573)	(4836 - 10 452)	(4945 - 11 790)
S_{MSY}	1.594	1.590	1.461	1.606	1.543	1.407
	(1.194 - 1.991)	(1.557 - 1.620)	(1.334 - 1.600)	(1.493 - 1.750)	(1.244 - 1.855)	(1.057 - 1.763)

The results for the "combined" and "weight-at-age" sensitivity tests are surprising in that the mean values for some of the quantities (e.g. *MSY*) differ quite markedly from the point estimates that result from fitting assuming no additional process error. A similar but opposite effect is evident from the sensitivity test that examines the impact of additional process error in catchability. The reasons for this are unclear and should form a focus for future work.

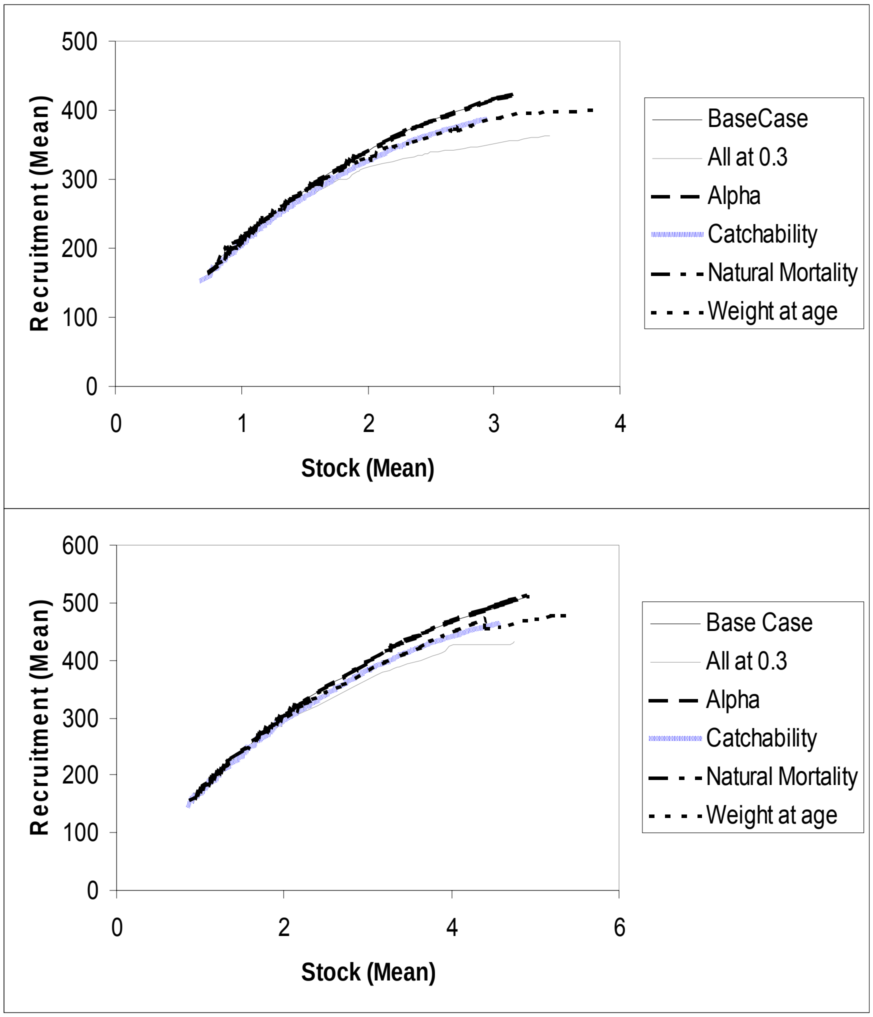

Figure 96: Comparison of stock recruitment relationships (Ricker), constructed from average values from the 100 runs of each sigma value varied for a) P. semisulcatus and b) P. esculentus. "Alpha" is variability in weekly recruitment and "All at 0.3" is variability in weekly recruitment, catchability, natural mortality and weight-et-age.

34. Discussion

34.1. Specific issues

34.1.1. The different models

Four approaches are presently available for conducting assessments of tiger prawns. Only two precede this project: the (Wang and Die, 1996) approach (used for the annual assessments) and that of (Haddon, 2000). The major differences between these two assessment approaches are:

- the (Wang and Die, 1996) model is age structured whereas (Haddon, 2000) uses a biomass dynamic model,

- the Wang and Die approach assesses the two tiger species separately whereas the Haddon approach treats them as a single homogenous population,
- the Wang and Die approach pre-specifies the extent of change in efficiency and the values for the overall and by-catch catchability coefficients whereas the Haddon approach treats these as estimable parameters, and
- the Wang and Die model is based on a weekly time-step whereas the biomass dynamics model is based on an annual time-step.

The Wang and Die approach was modified as part of this project and a new approach based on a delay-difference model with weekly time-steps formulated. The latter (henceforth referred to as the Deriso-Schnute approach) is biomass-based but nevertheless accounts for age-structure (subject to some simplifying assumptions). There is essentially no difference between the Modified Wang and Die and Deriso-Schnute approaches (Table 18). However, the Deriso-Schnute approach is based on a substantially simpler population dynamics equation so the bulk of the analyses in this Chapter were based on the Deriso-Schnute approach. The main differences between the Modified Wang and Die and the (Wang and Die, 1996) approaches are that the Modified Wang and Die approach:

- estimates the annual recruitments as free parameters rather than determining them using the recursive relationship derived by Wang (1999),
- allows for the uncertainty about each recruitment estimate when fitting the stock-recruitment relationship. The (Wang and Die, 1996) allows for the impact of correlated environmental variation about the stock-recruitment relationship but assumes that each stock-recruitment data point is equally precise.
- bases the estimate of *MSY* on the same (age-structured) population dynamics model that is used to estimate the stock and recruitment values. In contrast, the Wang and Die approach uses an empirically-derived surplus production curve to estimate *MSY*, E_{MSY}, and $S_{\mathrm{MSY.}}$
- can make allowance for temporal closures when estimating *MSY*, E_{MSY}, and $S_{\mathrm{MSY.}}$ In contrast in the (Wang and Die, 1996) approach the pattern of fishing effort used is essentially some average of that in the past.

The Modified Wang and Die and Deriso-Schnute approaches lead to less optimistic results than the (Wang and Die, 1996) approach for *P. semisulcatus* (67% compared to 81% for depletion and 7,143 compared to 10,428 days for E_{MSY}). The reasons for the differences are not completely understood. However, a key difference is the approach used to fit the stock-recruitment relationship. In contrast, to the situation for *P. semisulcatus*, the Modified Wang and Die and (Wang and Die, 1996) approaches led to very similar results for *P. esculentus* (71% versus 63% for depletion, 6149 compared to 7000 days for E_{MSY}).

The estimates of steepness are all surprisingly low, especially for a short-lived species – this is in stark contrast to the common belief that prawns are very resistant to exploitation (see (Francis, 1992)). The implied low productivity and associated high impact of recruitment variability indicate that recovery from overexploitation should not be expected to be rapid and that additional conservatism is needed to ensure a high probability that future recruitments are above average. We will have more to say of this in the next chapter.

The values for the overall and by-catch catchability coefficients and for weekly availability are assumed known exactly for the bulk of the analyses. However, although these quantities (and in particular catchability) are based on extensive research that is published (e.g. (Wang, 1999)), it is uncommon for assessments to pre-specify these quantities. This is primarily because of the potential circularity in using catch-effort data for a specific year to estimate catchability and then using the extended catch-effort data set (including 1993), to estimate the remaining model parameters. The estimation process generally had little difficulty estimating catchability when it was assumed to be related to week according to a sine curve (and the original weekly availability pattern ignored). However, the estimator did not perform adequately when the weekly availability pattern was pre-specified and the overall catchability coefficient estimated. This was most marked for *P. esculentus* – there was a tendency for the minimization method to converge to local minima and to switch from estimating an enormous unproductive stock to a small but productive stock. A reason for this may be that there appears to be less contrast in the recruitment series for *P. esculentus*.

34.1.2. Current stock status

Only two of the sensitivity tests led to point estimates for depletion at or near 100% ('Table 1' and 'Table 2'). This implies that the majority of the 25 model runs, including the lower annual rate of change in efficiency of 4%, led to the inference that the resources (both species) are currently overexploited.

Only three model runs (using the 1993 and 1998 effort distributions when computing *MSY* and 'Table 2') estimated the 1999 effort level (11129 standardised 1993 days) to be at or below E_{MSY} for *P. semisulcatus*. In contrast, the bulk of the model runs suggest that the current effort is 55-60% above E_{MSY}. The bulk of the model runs for *P. esculentus* suggested that the 1999 effort level (5753 standardised 1993 days) to be below $\mathrm{E}_{\mathrm{MSY}}$.

34.1.3. Key areas of sensitivity

The factors that had the greatest impact on the results from the assessment were the year chosen when defining *MSY* and the rate of change in efficiency. Somewhat surprisingly, the method used to define the catch and effort data (and its uncertainty) had relatively little impact of the key management-related quantities (Table 32 and Table 33,). Nevertheless, it seems appropriate that the 'New Method' for determining the species split, augmentation and target definition should be used in future assessments.

34.1.4. Multiple-species considerations

Although account is taken of the impact of fishing for one species on the dynamics of the other species when estimating the annual recruitments, the assessments are essentially single-species assessments. The current approach to estimating *MSY* is based on yield-per-recruit considerations but does not take the impact of by-catchability into account. In principle, it is possible to compute a joint *MSY* and this should be a focus for further work even though it may require substantial modifications to the current assessment software.

34.1.5. Multiple stock considerations

Seven possible stocks for both tiger species were identified from survey and catchment area information as described in Chapter 2 and 3. We were unable to develop, in the time available, a robust seven stock model as there is too little catch and effort in two to four (depending on the species) of the areas to fit such a model. An assessment was undertaken separately for the areas in which there was enough data. Results differ markedly for each stock to the Base Case. Where for *P. semisulcatus* the four stocks are overexploited only two of the four *P. esculentus* stocks were assessed as overexploited. For the multi-stock model, a better approach to inputing the catchability values for all the areas as being the same as the base case, would be to use some flexible family of functions, such as splines, to model variations in catchabilities over time and space.

It is recommended that more work be undertaken on a multi-stock, multi-species model, as there are indications, such as the VMS data in Chapter 4 and the conclusions of (Die et al. 2001), that there are major spatial changes in the fishing effort over time which would not be properly captured in a single stock model. Serial depletion may therefore not be prevented.

34.1.6. Ability to fit the data

The assessment has two main phases: fitting to the catch-in-mass information and to the stock and recruitment information. It is informative to investigate which of the sensitivity tests lead to the best fits to the data. The sensitivity tests with different transformations of the catch-in-mass data and those that consider data uncertainty and other sources of process error are ignored when conducting this comparison because the values of the likelihood function corresponding to the maximum likelihood estimates for these sensitivity tests are not comparable with those for the bulk of the analyses. Only the ability to fit the catch-in-mass data is considered because the fit to the stock and recruitment information depends on that to the catch-in-mass data.

The best fit to the observed catch series for *P. semisulcatus* and *P. esculentus* was achieved when catchability was assumed to be related sinusoidally to week while the worst fit occurred when the ‘Table 2’ efficiency increase scenario was assumed – the next worst fit was achieved the ‘Table 1’ efficiency increase scenario was assumed. Direct comparisons of the likelihoods for the different sensitivity tests is not totally valid as the number of estimable parameters differs among sensitivity tests. However, even after the difference in parameter number is accounted for, the same overall conclusions arise.

34.1.7. Implications for the stock assessment process

The output of this risk analysis process has been influential in changing the stock assessment output by NPFAG from a point estimate of stock status based on a single stock assessment method to:

1. results from several assessment methods (at present the (Wang and Die, 1996) approach, the Modified Wang and Die approach, The Deriso-Schnute approach and the (Haddon, 2000) approach are available) potentially being included in the management advice,
2. all important model outputs now routinely being accompanied by confidence intervals,
3. it being possible to examine the effect of alternative interpretations of key inputs and assumptions on the model output , and
4. it being possible to provide projections for specific management regimes.

These enhancements to the presentation of stock assessment advice has impacted the decision-making environment, simply because uncertainty is explicitly presented. Over the next year there will need to be increased communication between the NPFAG and NORMAC to capitalize on this and allow for better management decision-making under uncertainty. It may also be useful for NORMAC to consider the approach taken by other Commonwealth MACs that already work under this system.

The NPFAG, on the other hand, will need advice on what model outputs NORMAC would find most useful, what factors it would like to have investigated in the assessment, how the results should be presented as part of the standard assessment and what future management regimes (given the limitations of the models) it would like to have addressed.

35. Conclusions

- Most model runs estimate both species to be overexploited. The 1999 effort level for *P. esculentus* was generally estimated to be lower than E_{MSY} whereas the 1999 effort for *P. semisulcatus* is much higher than E_{MSY}.
- The impacts of variability in recruitment, uncertainty about the appropriate effort distribution and the time-sequence of rate of change in efficiency have the greatest impact of the model outcomes.
- The estimates of steepness are all surprisingly low – this is in stark contrast to the common belief that prawns are very resistant to exploitation (see (Francis, 1992)). The implied low productivity and associated high impact of recruitment variability indicate that recovery from overexploitation should not be expected to be rapid and that additional conservatism is needed to ensure a high probability that future recruitments are above average.
- The 90% confidence intervals of the parameter estimates are wide especially those for the early recruitment years.

36. Further research

- This model would benefit from additional data being incorporated into the analyses. Since age information is not available for crustaceans as yet, detailed analysis of commercial size grade data should be undertaken. This may reduce the large confidence intervals of the parameters although it is highly unlikely the grade information is available for the early years.

- The model is extremely sensitive to fishing power and it is imperative that these figures are as realistic and as accurate as possible. Although the concept of variable effort creep by year is good, the model fits to the developed schedules are poor and the reason for this needs further investigation.
- This project only commenced preliminary analyses of stock based assessment in the NPF. These model runs have indicated that there are large differences between stocks and that there are areas of higher and lower depletion than the single-stock, NPF-wide model indicates. However, a much more sophisticated attempt at incorporating possible stock-specific changes in stock-recruitment and catchability needs to be undertaken.
- The MSY, E_{MSY} and S_{MSY} values are estimated using a single species approach. Although a large change to the code would be required, it is essential that it be updated to mimic the assessment itself, which includes the catch and effort on the bycatch tiger prawn species.

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CHAPTER 6: FUTURE PROJECTIONS OF THE DERISO-SCHNUTE TIGER PRAWN ASSESSMENT

38. Introduction

The Wang and Die (1996) model has never been used as the basis for a formal risk assessment in the sense of future projections conducted for alternative management actions. The Modified Wang and Die and Deriso-Schnute models were therefore extended to allow future projections to be conducted. This Chapter only provides results based on the Deriso-Schnute model because extensive checking has shown that future projections based on the Modified Wang and Die model would have been virtual identical. Moreover the Deriso-Schnute model is substantially quicker to apply, thereby facilitating consideration of a broader range of alternative management actions.

This chapter investigates three issues:

1. The trade-off between risk and reward as a function of the level of (future) fishing effort and the pattern of fishing;
2. A comparison of projections that include or exclude variability in recruitment; and
3. The difference between *certainty equivalent* and *myopic Bayes* projections (see Section 39.1 below for a description of these techniques).

These three issues were chosen as they demonstrate at least three aspects, namely:

- The relationship between effort and risk;
- Which factor dominates risk (which relates to the question "can risk be reduced with more data?"); and
- How flexible the management of this resource needs to be to decrease risk and increase reward.

The performance statistics used to provide information about these issues are:

- the percentage of times the spawning stock at the end of a 20-year projection period (starting in 2000), S_{+20} fell below S_{MSY} (abbreviation "Risk")
- the average depletion at the end of the projection period (i.e. S_{+20}/S_{MSY}) (abbreviation "Average depletion").
- the average catch across years of the projection and simulations (abbreviation "Average catch"), and
- the average coefficient of variation across simulations of the annual (future) catch (abbreviation "Average CV").

The first two performance statistics quantify risk relative to the current target level of S_{MSY}. An ideal management regime will achieve 50% for the first statistic and 1 for the second statistic. The third and fourth performance statistics quantify performance relative to the fishing industry. The coefficient of variation of the annual (future) catches is provided because, ideally, a management regime should achieve high but stable average catches.

39. Methods

The Modified Wang and Die and the Deriso-Schnute models were extended to include projection components. Although this chapter examines only some specific questions, the model was implemented to deal with arbitrary future seasonal patterns of fishing and total effort levels, with and without future recruitment variability.

Taking account of recruitment variability when conducting projections is important because the assessment of NPF tiger prawns (Chapter 5) has shown that recruitment fluctuates considerably about the underlying relationship between stock and recruitment. Serial correlation between recruitments is also an important aspect of the model. Recruitment is unpredictable so even if the values for the population parameter were known exactly, there would still be still be uncertainty regarding the consequences of future management actions. Therefore, many alternative (yet plausible) sequences of future recruitment are considered to evaluate the expected (rather than exact) consequences of any specific harvest strategy.

39.1. Imperfect and perfect knowledge

In this report two cases are considered. Firstly, the risk and reward for a specific management action are calculated assuming that the current best estimates of all the model parameters are the true values (Bergh and Butterworth, 1987); termed as *certainty equivalent* (Ludwig and Walters, 1982). For example, the single estimated E_{MSY} value is used for all possible future recruitment series.

The second situation is one where the uncertainty of parameter estimates is taken into account, but with a restriction these estimates are not updated following fresh simulation information (i.e. no feedback loop). This means that the probability distributions for the parameter estimates remain unchanged over the projections. These strategies are known as *myopic Bayes*. In our present case it means that a different E_{MSY} value is used for each future recruitment series.

For both situations, risk and reward are evaluated using two options. In the first, risk and reward are evaluated allowing for variation in recruitment about the value expected from the stock-recruitment relationship. This case will be termed “noise”. In the second case no future recruitment variability is considered - this case will consequently be termed “no noise”.

39.2. Future projections

The future projections involve projecting the model forward for a pre-specified number of years. This requires pre-specifying the future time series of fishing effort (both target and by-catch effort, at the weekly level) from the final year of the assessment (1999). Specifically, each simulation involves the following steps:

a) Select a set of values for the model parameters.

b) Project the population from 1969 until the last year of the assessment (1999).

c) For each year, y, from the last year of the assessment until the final year of the projection:

i) If required, generate a recruitment residual for biological year y+1:

$$\eta_{y+1} = \sqrt{1-\rho_r^2}\,\xi_{y+1} + \rho_r\,\eta_y \qquad \xi_{y+1} \sim N(0;\sigma_r^2) \tag{30}$$

(ii) Project the model from the start to the end of year y for different choices of R_{y+1} until the relationship $R_{y+1} = g(S_y)e^{\eta_{y+1}}$ is satisfied.

Note that step c) overrides the fixed recruitment for 2000.

39.3. Monte Carlo

Calculating expected risk and reward under the certainty equivalent and myopic Bayes strategies involves the evaluation of a series of expectation integrals. The integrals have been calculated by the Monte Carlo method of generating a large number (500 for purposes of the analyses of this report) of realisations for the future (20-year) time sequence of yield and stock depletion level, and averaging. Each simulation is based on a parameter vector drawn at random from the estimated variance-covariance matrix. The process of generating from the variance-covariance matrix also provides the values for each simulation of the extent of environmental variation in recruitment and its temporal correlation.

The projections are conducted simultaneously for the two species so that by-catch effort has an impact on the results of the projections. In the constant effort cases, the split of future effort among the two species is 50%:50% (the ratio of E_{MSY} of *P. semisulcatus* : *P. esculentus* is about 54%:46% and we therefore assumed 50%:50%) For these simulations, it is assumed that management measures are put in place to account for changes in efficiency over time.

40. Results

40.1. Managing at different effort levels

The base-case assessment (see Appendix B) formed the basis for an examination of the implications of different levels of fishing effort (expressed in equivalent 1993 days) from 0 (closure) to 16,000 days. The fishing effort pattern for these projections is assumed to be uniform across the year although the sensitivity of this to alternative specifications is also considered (reference years of 1980, 1993 and 1998 – Figure 97). Figure 98 and Figure 99 show plots for *P. semisulcatus* and *P.esculentus* of the values for three of the four performance statistics for a range of future levels of fishing effort and a range of assumptions about how that effort will be distributed across the year.

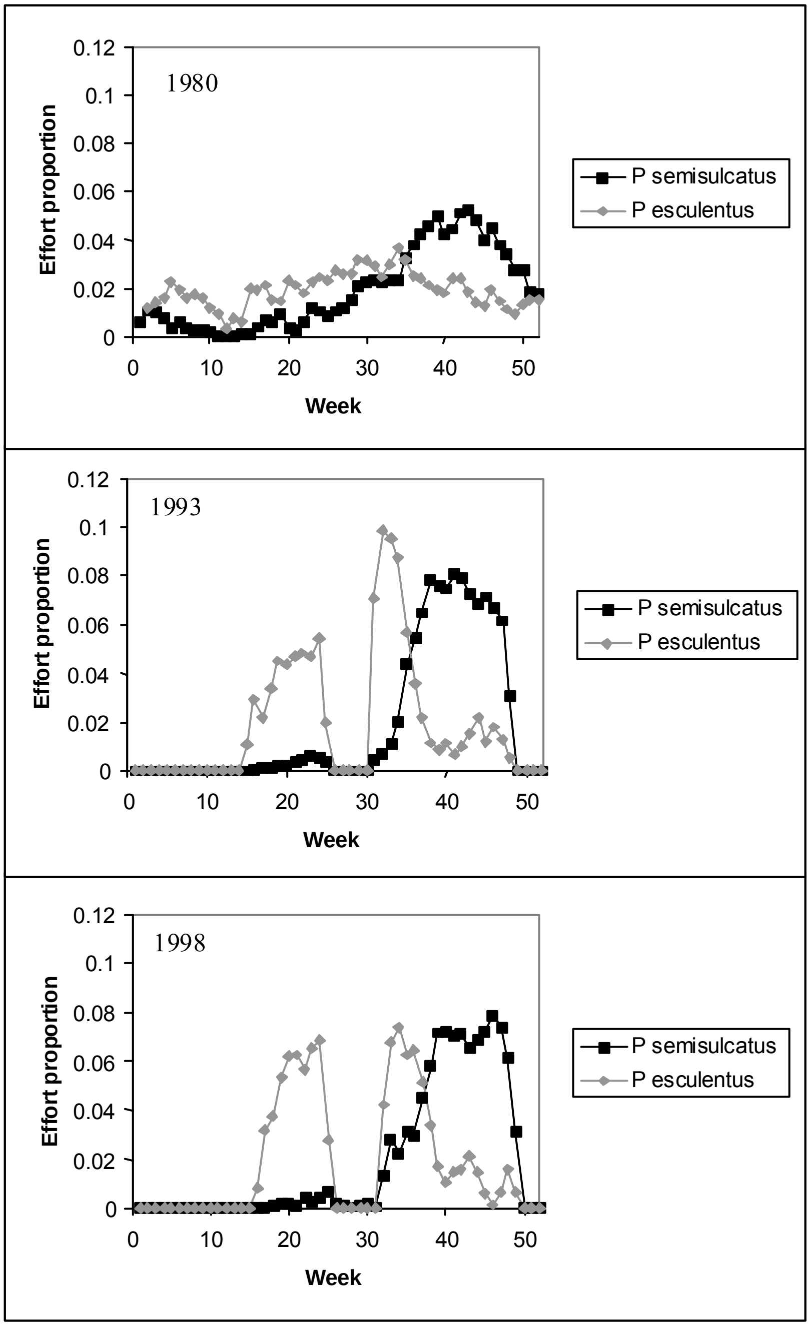


Figure 97: Proportion of effort in each week of different years (reference years) targeting *P. semisulcatus* and *P. esculentus*.

As expected, the risk (probability of being below S_{MSY} at the end of the simulation) increases as a function of effort. Note that this risk depends critically on when fishing is allowed to occur within the season. For example, if the pattern of fishing effort is equal to that for 1980, the risk is higher for a given level of effort. This is because fishing was allowed to extend across most of the year in 1980. This is very unlike the situation in 1993 and 1998 when spawning closures were implemented. The results for a uniform distribution of effort across the year (horizontal and vertical lines) indicate even greater risk than the 1980, 1993 and 1998 distributions of effort. Note that although there was less overall effort in 1998 than 1993, this is irrelevant as the amount of future effort is specified.

The average catch also increases as a function of effort. However, unlike risk, it reaches a maximum and then declines. This occurs because high levels of effort lead to the resource being driven to low levels. This is counter-balanced to some extent by removal of 'standing stock' but only partially. For higher effort levels, fishing patterns with a seasonal closure (1993 and 1998) achieve higher expected catches. For lower levels of effort, fishing patterns with a seasonal closure achieve lower expected catches, at least for *P. semisulcatus*. The extent of variability in catch is almost independent of the future effort level or how effort is distributed across the fishing year, except for cases where the catch is in decline in the later years of the projection as the population itself starts to decline. With the coefficient of variation more than 20% it must be acknowledged, though, that the level of variability in catch is relatively high.

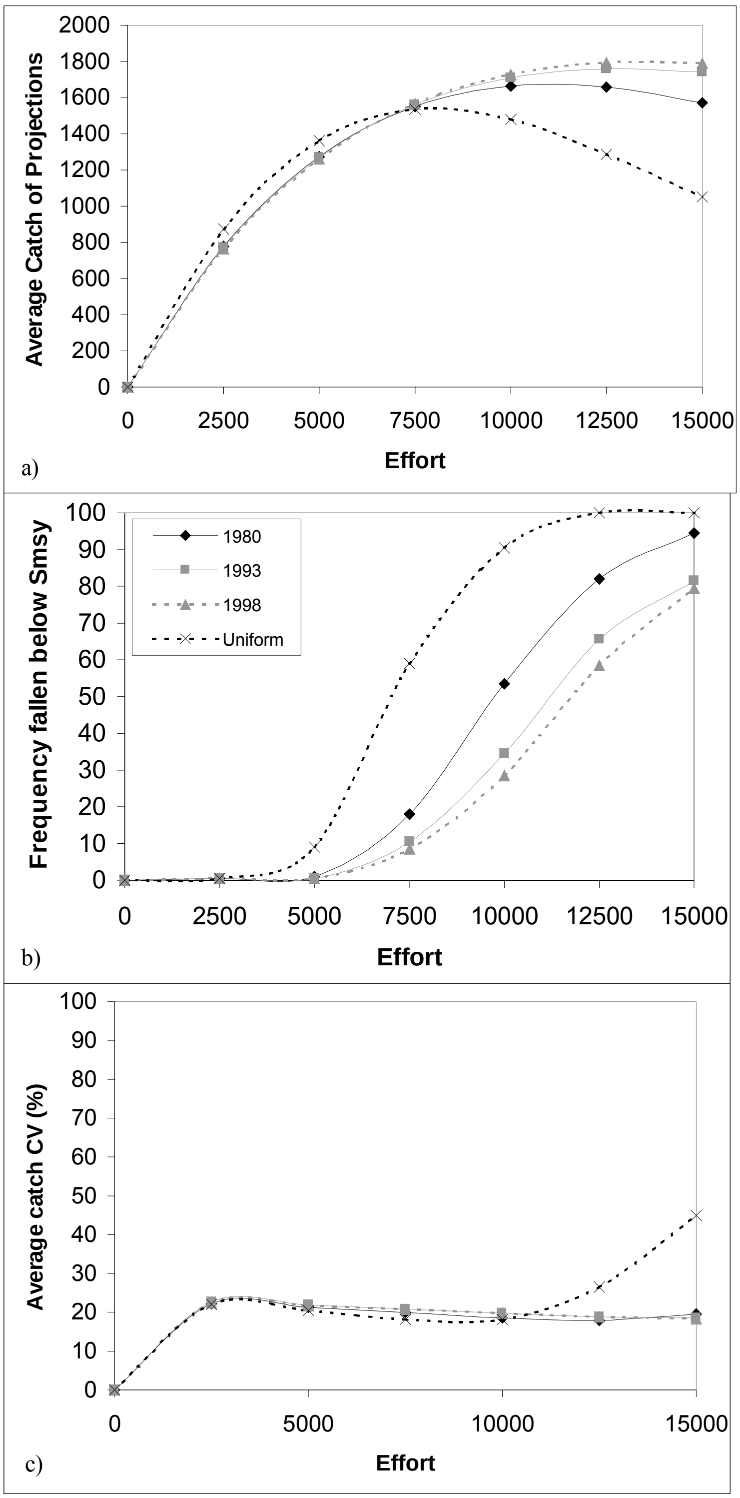


Figure 98: Implications for *P. semisulcatus* of different (future) effort levels in terms of: a) average catch over the projection period (tonnes), b), percentage of simulations for which S_{+20} is less than S_{MSY}, and c) coefficient of variation for the catch over the projection period (%). The result corresponding to setting the (future) effort level to the point estimate of E_{MSY} and fishing uniformly distributed over the year is indicated by the horizontal and vertical lines. The difference in effort between each successive point is 2500 days and zero risk corresponds to zero days.

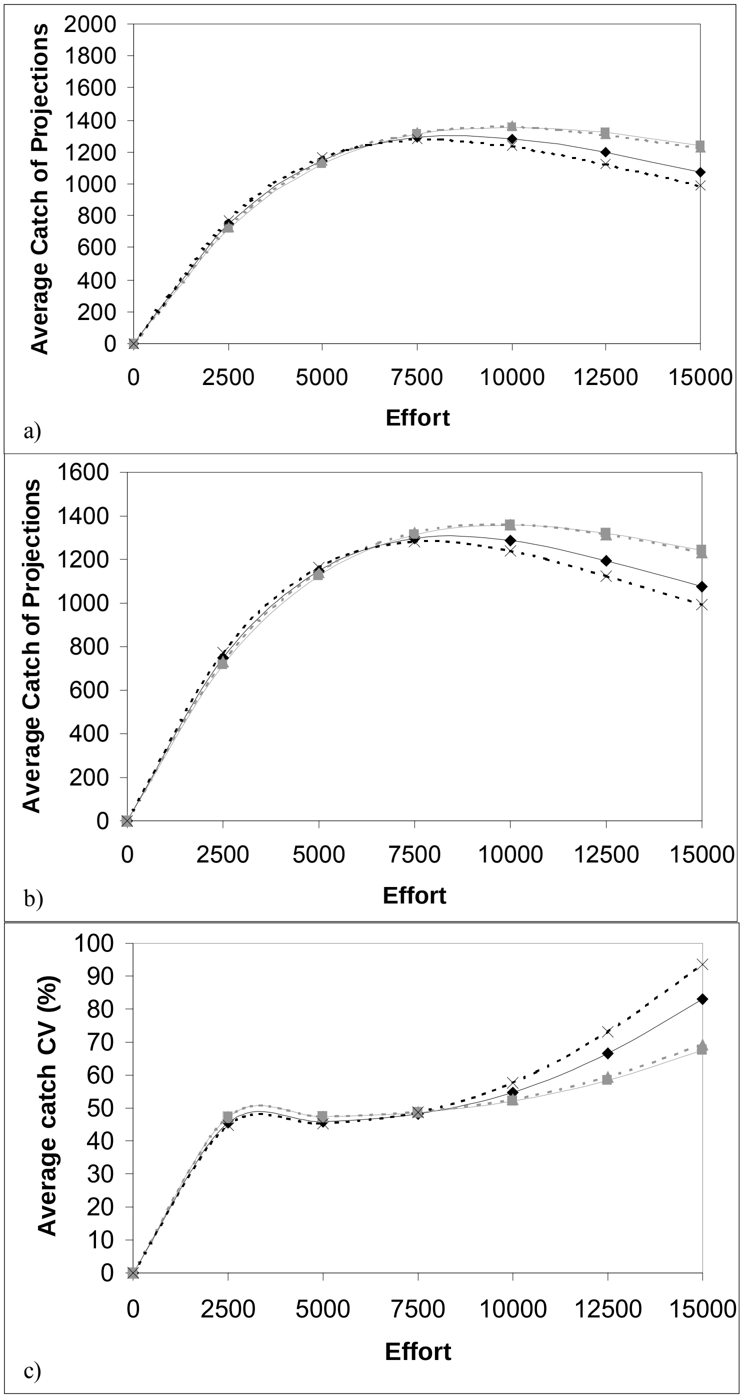


Figure 99: Implications for *P.esculentus* of different (future) effort levels in terms of: a) average catch over the projection period (tonnes), b), percentage of simulations for which S_{+20} is less than S_{MSY}, and c) coefficient of variance in catch over the projection period (%). The result corresponding to setting the (future) effort level to the point estimate of E_{MSY} and fishing uniformly distributed over the year is indicated by the horizontal and vertical lines. The difference in effort between each successive point is 2500 days and zero risk corresponds to zero days.

Another method of displaying this information, similar to that used in economic studies, is a risk versus reward plot. A subset of the information in Figure 98 and Figure 99 is given in Figure 100. This fishery is input control, therefore the effort is an input to the model and the resultant catch is an output. The results for the best estimate of E_{MSY} are highlighted in the graph, because the present constant effort policy applied to the NPF is based on E_{MSY}. The difference in the risk-reward curves between the uniform and 1998 reference years is much smaller for *P. esculentus* than for *P. semisulcatus*.

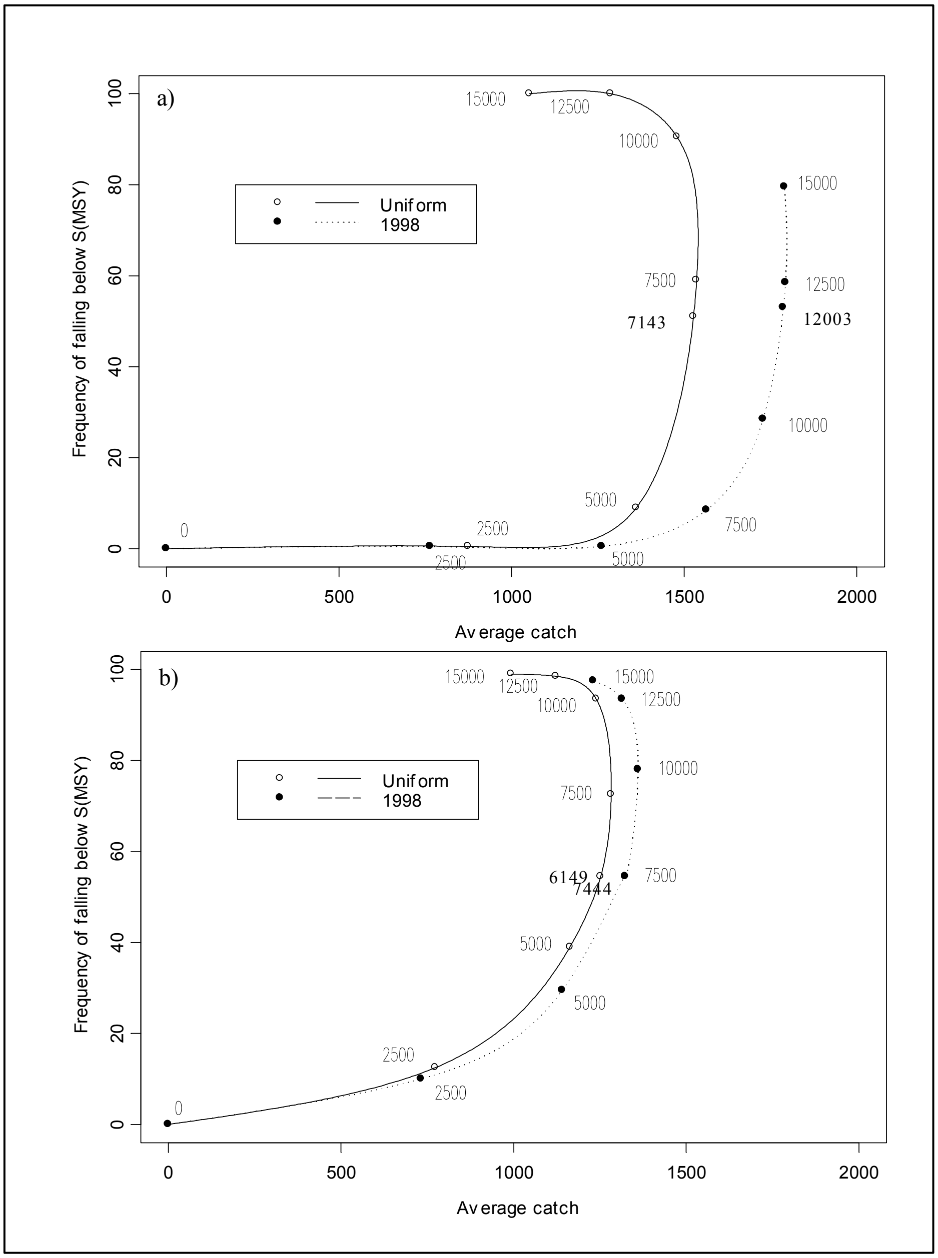


Figure 100: Risk versus reward (average catch versus the frequency of being below S_{MSY} after 20 years) curves for two different within-year effort distribution patterns for a) *P. semisulcatus* and b) *P. esculentus*. Input effort values (in standardised days) are entered at the markers. The larger bold font effort values indicate results for projections based on the best estimates for E_{MSY}.

40.2. Recruitment variability

The analyses presented in the previous chapter estimated the extent of recruitment variability and this was included in the projections upon which Figure 98 to Figure 100 were based. Although there is no chance that the extent of variability in prawn recruitment is subject to human control, it is illustrative to compare results with and without this source of uncertainty. For both species, recruitment variability greatly increases the risk for only a small increase in catch (Figure 101). It is clear therefore that at low levels of effort the dominant component of risk is variability in recruitment.

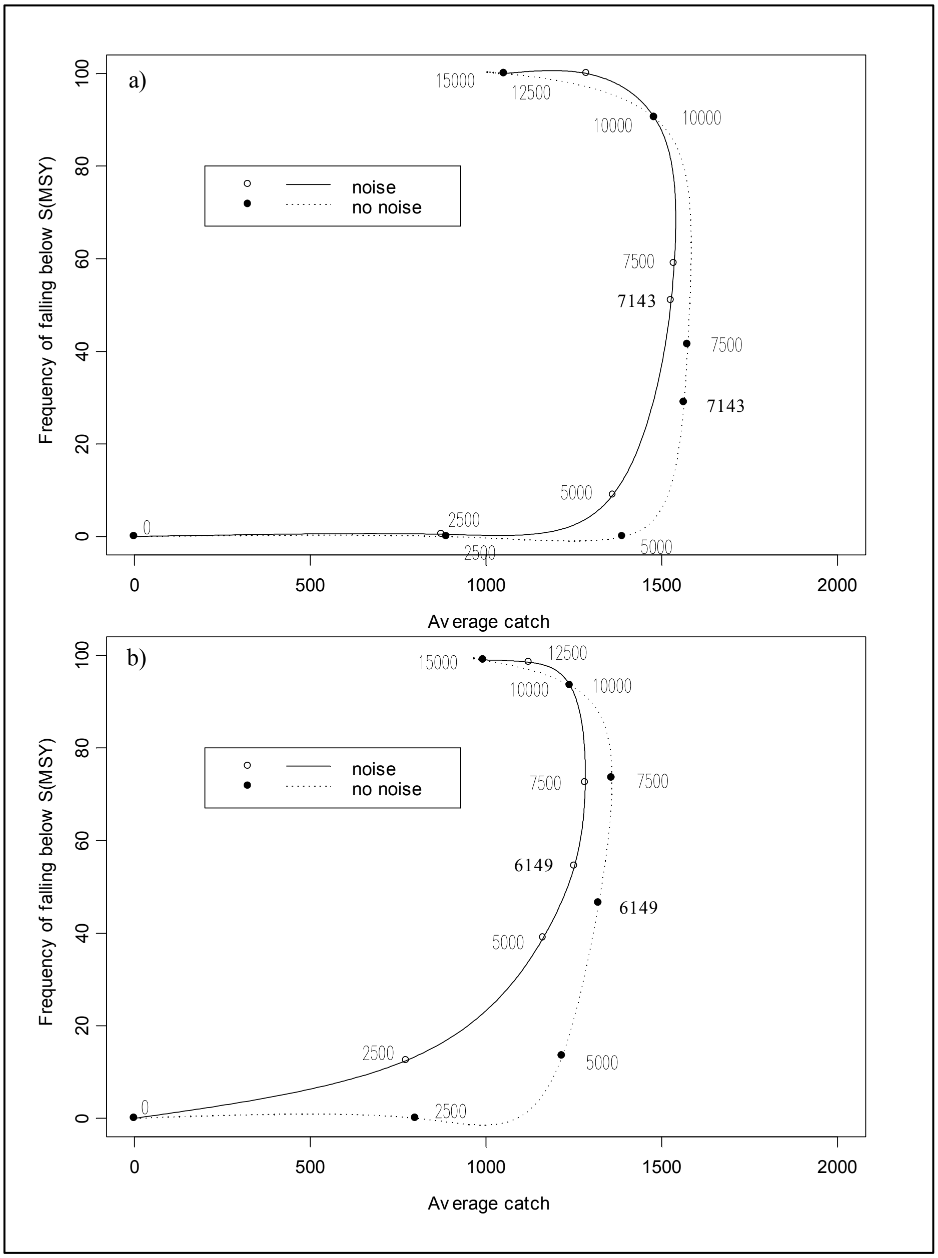


Figure 101: Risk versus reward (average catch versus the frequency of being below S_{MSY} after 20 years) curves for a) *P. semisulcatus* and b) *P. esculentus*. The clear markers indicate results for

projections based on the best estimates for E_{MSY}. Black lines are projections with recruitment variability and grey lines projections without recruitment variability. These projections are all based on the assumption that effort is uniformally distributed over the year. Input effort values (in standardised days) are entered at the markers. The larger bold font effort values indicate results for projections based on the best estimates for E_{MSY}.

40.3. Certainty equivalent versus myopic Bayes

Table 36 contrasts the values for the performance statistics for projections in which future effort equals the best estimate of E_{MSY} irrespective of the true value of E_{MSY} and in which effort is set equal to the true value of E_{MSY}. As expected, the 90% intervals for depletion are narrower when E_{MSY} is known perfectly. However, perhaps contrary to expectation, the risk is higher for the case in which E_{MSY} is known perfectly and this needs to be explained in future studies. The average catches for the 'myopic Bayes" cases are higher than for the "certainty equivalent" cases but this has to be traded off against the higher levels of risk for these cases. In many respects, there is surprisingly little practical difference in the outcomes between the two cases.

Table 36: Performance statistics for a management regime of setting fishing effort to E_{MSY} for projections in which future recruitment is variable and effort is distributed uniformally across the year. Sensitivity to whether future effort is set to the best estimate (certainty equivalent) or the actual value of EMSY for the parameter vector underlying the simulation (myopic Bayes).

	P.semisulcatus		*P.esculentus*	
	Certainty equivalent	Myopic Bayes	Certainty equivalent	Myopic Bayes
Risk	51.0	61.0	54.5	61.5
Average catch (t)	1527	1559	1252	1299
Average CV	18.4	18.4	38.1	29.0
Average depletion	99.7	95.5	96.4	93.8
90% CI for depletion	(63.2-142.6)	(67.0-131.4)	(34.6-165.7)	(42.4-167.3)

41. **Discussion**

At present, the fishery is managed using input controls. The standard assessment provides the information for management to change effort on a yearly basis so that it is maintained at E_{MSY} or less (after accounting for changes in fishing power). In theory, this effort level should allow the fishery to reach the target reference point, S_{MSY}, i.e. ideally there should be a risk of 50% and the expected long-term spawning size relative to that at *MSY* should be unity However, E_{MSY} is estimated under equilibrium conditions and there is considerable variability about the stock-recruitment relationship, recruitment is serially correlated, and an incoming recruitment constitutes a large fraction of the spawner biomass the year after it recruits.

There is a clear trade-off between risk and economic benefit – up to a point higher levels of effort correspond to higher catches but also to higher levels of risk. It will be necessary for NORMAC to make an explicit decision regarding the extent of the risk that it is willing to accept in order to utilise the results for management purposes. In principle, the impacts of risk and economic benefit can be combined through a utility function. However, at present, no such function has been proposed or even foreshadowed. Although, there will always be a trade-off between risk and economic benefit, the results suggest that it is possible to optimise catches given a pre-specified amount of risk.

There is a distinct difference between the results of *P. semisulcatus* and *P. esculentus* in terms of risk and reward. For the first of these two species, the risk rises sharply after an effort of 5000 standardised days. Conversely, for a small decrease in reward, the risk can be substantially reduced. This is not the case for *P. esculentus*. At 5000 days the risk is already substantially higher than for *P. semisulcatus*. A small reduction in risk results in a similar decrease in catch. This difference seems to reflect the lower productivity level for *P. esculentus*.

The target level of 50% is not achieved in many of the projections. The reasons for this are unclear but are probably related to the non-linearity of the population dynamic model and how recruitment is generated. This 'bias' can be removed by managing with a lower level of effort than E_{MSY}. For the base-case analyses, managing with about $0.98E_{MSY}$ and $0.94E_{MSY}$ for *P. esculentus* than *P. semisulcatus* respectively leads to a 50% value for the risk statistic.

There are substantial benefits to be gained by appropriately chosen seasonal closures, especially for *P. semisulcatus*. For this species there is a large difference between results for a 1980 fishing pattern and those for 1993 and 1998 fishing patterns. The major differences between the 1980 and 1993/98 fishing patterns lie in the mid- and end-season closures. The mid-year temporal closure and the fact that little effort is directed towards *P. semisulcatus* in the first season of the year implies that little effort is applied to *P. semisulcatus* prior to spawning. However, this is not the case for *P. esculentus* and therefore much of the effort on *P. esculentus* occurs prior to spawning even with the 1998 effort pattern.

42. Conclusions and further research

This section investigated the effects of managing with the following realities. The first reality is that recruitment is highly variable, serially correlated, and is the dominant factor determining the level of the risk of overexploitation for low effort levels. The second is that only a single E_{MSY} value (that estimated from a stock-recruitment relationship without variability and under uniform effort conditions) is used by management. The third is that since recruitment is serially correlated, it is possible for a series of recruitments to be above or below average for several successive years.

The steepness values estimated in the previous chapter indicate clearly that this resource is much less productive than previously thought, with relatively high variability in recruitment about the stock-recruitment curve. This may partially explain why, over a 20-year projection period, managing using a single E_{MSY} value without knowledge of future recruitment trends, does not, on average, reach S_{MSY}.

Although beyond the scope of the current study, the implications of different proposed closure schemes could be evaluated using a dynamic model structure such as that outlined in this project. This would extend the work of Somers and Wang (1996) who utilised a deterministic model to evaluate the impact of different seasonal closures.

If it were possible for management to know future recruitment (or at least the trend in future recruitment), it might be possible to modify the short-term target level of fishing effort to be better able to satisfy management objectives. The current study does not provide a framework within which the value of such knowledge can be determined. However, the techniques of Management Strategy Evaluation (Smith, 1994; Punt *et al*., in press) do provide such a framework. This permits the uncertainty associated with estimation of recruitment and the rules that would be used to interpret recruitment information to be evaluated formally. This is because, although intuitively additional data should lead to improved management, the impact of uncertainty in the data may negate any benefits. It is highly recommended that this research be undertaken as it would allow investigation of management methods and reference points to decrease risk without a major reduction of the economic benefit.

CHAPTER 7: FURTHER DEVELOPMENT

A list of all the recommendations of future research provided in each chapter is repeated below for convenience. Points in bold we recommend as a priority task.

43. Species split methodology

We recommend that further research is undertaken into species split methodology and additional data is systematically acquired to enable this. Specifically:

i) There should be a small, carefully planned and well-designed programme of acquisition of additional species split data. This should as far as possible come from skilled observers on commercial vessels taking low impact samples from specified commercial trawls. The sample design should cover all fished areas and should evenly cover the fishing season in time. We envisage a scheme in broad terms as follows:

a. Areas and times for sampling should be chosen in such a way as to optimise the information base for calibration and development of species split models.

b. Skippers visiting those areas at those times should be required, for a fee pre-negotiated with the industry, to supply a small, randomly selected sample of, say 5 kg of Tiger and of Endeavour prawns from the trawl catch of the specified night in the specified area.

c. The samples should be supplied as soon as possible to a skilled third party in the state they are when the logbook records are made. This third party should classify the sample into species and sexes and for each animal record carapace length *and* weight.

d. The data should be used to calibrate and develop refinements to species-split models as well as weight at length curves. Of particular interest would be to check for any long-term trend in the overall species proportions, so the programme has to run for several seasons at least.

ii) In parallel with 1 above there should be further statistical research into optimal species split models as a problem in its own right and not simply as a preliminary step to stock assessment. Changes in species split proportions have management implications directly, as well as through the influence they have on stock assessment. The kinds of developments suggested here would be primarily random-effects and Bayesian extensions to the generalized linear quasi-likelihood models of the type proposed in this report, but the problem should be open-ended and specified in terms of the desired outcomes rather than the methodology to be developed.

44. Stock structure in the NPF

(i) Some formal work on establishing stock structure in the NPF is clearly overdue. Just how this would be best done is clearly an issue for biologists to decide, but genetic surveys and tagging experiments may be two complementary ways of attacking the problem. There may also be opportunities for attacking the stock structure and species split problems together as they are clearly related issues both of which could be addressed by similar survey methods.

45. Augmentation and imputation methods for incomplete data

(i) The imputation methods presented here are tailored to fit this particular missing data situation in the NPF and their justification has been frankly heuristic. There are some ideas here that appear new and that may be more generally applicable. There is scope for purely statistical research to study the behaviour of the methods we use here in a more formal way and to generalise them to other settings.

46. Inferring target species

(i) Our method here for inferring a *target species group* was initially used only to guide the re-sampling method in order to achieve simultaneous matching of Tiger and Banana prawn totals to the corresponding totals. Further refinement to a *target species* was used to assess effort and bycatch effort. This method appears new, but needs further development before it can be accepted as a fully serviceable method for stock assessment. The advance we see for it over the method presently used for the NPF is that it does not rely on the outcome of the particular catch explicitly but only on information pertaining to the time and place of fishing. We suggest that further research in this area is urgently needed.

47. VMS Data

Therefore further studies are recommended as follows:

(i) Preliminary work needs to investigate further the linking of high polling frequency, normal polling frequency VMS data and linkage with logbook data for input into stock assessment.

(ii) Further monitoring and collecting VMS data is needed on an ongoing basis from the 3 grids examined in this study at high polling frequency to compare good fishing years with bad fishing years and to explore the differences between them in fishing pattern over time.

48. Stock assessment

(i) This model would benefit from additional data being incorporated into the analyses. Since age information is not available for crustaceans as yet, detailed analysis of commercial size grade data should be undertaken. This may reduce the large confidence intervals of the parameters although it is highly unlikely the grade information is available for the early years.

(ii) The model is extremely sensitive to fishing power and it is imperative that these figures are accurate. Although the concept of variable effort creep by year is good, the model fits to the developed schedules are poor and the reason for this needs further investigation.

(iii) This project only commenced preliminary analyses of stock based assessment in the NPF. These model runs have indicated that there are large differences

between stocks and that there are areas of higher and lower depletion than the NPF-wide model indicates. However, a much more sophisticated attempt at incorporating possible stock specific changes in stock-recruitment and catchability needs to be undertaken.

(iv) The MSY, E_{MSY} and S_{MSY} values are estimated using a single species approach. Although a large change to the code would be required, it is essential that it be updated to mimic the assessment itself, which includes the catch and effort on the bycatch tiger prawn species.

49. Future projections

(i) Although beyond the scope of the current study, the implications of different proposed closure schemes could be evaluated using a dynamic model structure such as that outlined in this project. This would extend previous research that utilised a deterministic model to evaluate the impact of different seasonal closures.

(ii) If it were possible for management to know future recruitment (or at least the trend in future recruitment), it might be possible to modify the short-term target level of fishing effort to be able to better satisfy the management objectives. The current study does not provide a framework within which the value of such knowledge can be determined. However, the techniques of Management Strategy Evaluation (Smith, 1994; Punt *et al.*, in press) do provide such a framework. This framework permits the uncertainty associated with estimation of recruitment and the rules that would be used to interpret recruitment information to be evaluated formally. This is because, although intuitively additional data should lead to improved management, this impact of uncertainty may negate any such benefits. It is highly recommended that this research be undertaken given the large rage of projected spawning biomass relative to SMSY. The research would allow investigation of management methods available and reference points available to decrease risk without a major reduction of the reward.

APPENDIX A: DESCRIPTION OF THE WANG AND DIE (1996) TIGER PRAWN MODEL AND SOME OF ITS ASSUMPTIONS

50. Introduction

Over the last few years since the development of the (Wang and Die, 1996) model, it has become clear that the model inputs and some of its assumptions are not described in a single text. For this reason, the Risk Analysis project team decided to document the input data, input parameters and this model used as the annual tiger assessment. A description of some of the assumptions behind the research is included and highlighted in bold.

Only two input data are needed for the (Wang and Die, 1996) model namely catch and unstandardised effort by week for each tiger species from 1970 to the present. However, the data recorded in the logbook are for tiger prawns as a group and do not distinguish between the two tiger species. (The same applies to categories “banana”, “endeavours” and “king” which each consists of at least two species.) Furthermore, not all the logbook records are complete in the early part of the series. Only some of the logbook data gives spatial information at a small enough scale to deduce a likely species composition and only the landing data give total catch for all the years. Thus while we have a complete catch series of total landings data, this matches with an incomplete series of logbook data. Unfortunately landings data do not record total effort nor spatial information.

50.1. Species split

The catch is made up of 8 prawn species recorded in 4 commercial prawn groups. Four species account for most of the catch: the common banana prawn *Penaeus merguiensis*, the red-leg banana prawn *P. indicus*, the brown tiger prawn *P. esculentus* and the grooved tiger prawn *P. semisulcatus*. The other less commonly caught species are the two endeavour prawn species, *Metapenaeus endeavouri* and *Metapenaeus ensis*. The king prawns, *P. latisulcatus* and *P. longistylus*, are caught incidentally and the black tiger prawn, *P. monodon*, is caught only occasionally.

The species composition data used in the analyses by (Somers, 1994) are reproduced in Table 37 (and are described in greater detail in the Somers’ paper). The method developed by Somers was limited to the Gulf of Carpentaria whereas that used in the (Wang and Die, 1996) model was applied to the whole NPF. Data for the remainder of the NPF is available and was used for the species split in the Wang and Die model, but a detailed description of the exact sources have not been published.

Each datum used in the amalgamation of the data was either collected by scientists on research vessels or on commercial vessels. This data usually recorded trawl position (with a precision within 3 nautical miles), date and proportion of each species in the sample. The time interval between the successive collection of samples within a grid ranged from a few days to several years. The proportion of each species was calculated for each grid for integration with the commercial fishery logbook data.

Logbooks have records of the catch in species groups. The vessels’ position is usually that for the largest catch of the night/day. The position scale could be from fishing ground (in the earlier years) or in a more precise location (recently, up to 1 minute of longitude and latitude). For each logbook record, the Wang and Die approach to the species split problem was as follows:

1. Use the survey data to give a relative split, by weight, for each species for all grid squares included in the surveys.
2. If a logbook record is ascribed to a grid square for which survey-based split proportion estimates are available, partition the record in the same ratio.
3. In other cases use the split proportions for the geographically nearest grid square for which survey-based estimates are available.

Note that the split is made essentially deterministically and from that point of the process the procedure is the same as if the actual catches of both species were separately, accurately recorded. **The method assumes no seasonal or yearly variation in the species split.**

The stability of the species composition within the species groups in each grid square was examined in (Somers, 1994) by calculating the standard deviation of these percentages for those grid squares with at least three samples of more than 20 individuals in a species group. Somers found the ratio of one species to another within a species group was relatively stable over the time for which he had data (Table 37)

Table 37: *Sources of data used by (Somers, 1994) to describe the species composition of the commercial penaeid prawn caught in the Gulf of Carpentaria.*

	Research surveys			*Commercial-catch sampling*		
Source	CSIRO[A]	CSIRO[B]	CSIRO[C]	NT Fisheries	Newfishin g Australia	CSIRO /Industry[D]
Period	1976-78	1983-85	1986-92	1979	1986-87	1988-90
Region	E.Gulf	N.-W Gulf	N.-E. Gulf	W. Gulf	Gulf-wide	Gulf-wide
Samples (n)	4284	1367	1443	115	196	1605
Prawns (n)	182211	67117	201099	26349	21386	197164

50.2. Logbook catch by species to landings augmentation

The ratio of logbook catches to processor returns varies from 50% in the early 1970's to over 95% in the 1990's (Sachse, 1994). However, the species split can only be obtained from the logbook data as they generally contain spatial information. Total catch by species is estimated by adjusting the logbook catch by species to match the processor's returns.

50.3. Logbook effort augmentation

Nominal fishing effort per species was calculated from the ratio between the total catch by species described above and catch per unit effort by species from the grid-specific logbook data. **This assumes that the catch per unit effort estimated from the logbook**

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

51. Input parameters

In Table 38 we have reproduced the input parameters described in Wang and Die (1996). A detailed description of the sources of data used to estimate these and other input parameters are described in the next few paragraphs. Due to the added complexity of the Risk analysis model, it was not always possible to use the same parameter names.

Table 38: *Updated table of input parameters used in the (Wang and Die, 1996) model. Sources of data are [A](Somers and Kirkwood, 1991), [B](Kirkwood and Somers, 1984), [C](Farmer, 1980), [D](Penn and Hall, 1974), [E](Wang, 1999) and [F]assumed.*

Wang and Die (1996) Parameter Names	*Risk analysis model parameter names*	P. semisulcatus *Female*	*Male*	*P.esculentus* *Female*	Male
k (week^{-1})	κ^s (week^{-1})	0.043[A]	0.062[A]	0.041[B]	0.034[B]
l_∞ (mm)	ℓ^s_∞ (mm)	51.6[A]	37.5[A]	44.8[B]	37.5[B]
a	e^s	0.00265[C]	0.00195[C]	0.00373[D]	0.0027[D]
b	f^s	2.648[C]	2.746[C]	2.574[D]	2.764[D]
lr (mm)	ℓ^s_r (mm)	28[A]	26[A]	28[A]	26[A]
M (week^{-1})	M (week^{-1})	0.045[F]	0.045[F]	0.045[F]	0.045[F]
$q \times 10^{-5}$	$\tilde{q} \times 10^{-5}$	8.8[E]	8.8[E]	8.8[E]	8.8[E]

51.1. Relative weekly recruitment pattern

Recruitment is defined as animals of a specific size (l_r in Table 38) entering the fishery. ***(Wang and Die, 1996) model assume a sex ratio for these recruits of 1:1 and that the biological year starts on the 1st of October.*** This date is different to that published in the Wang and Die paper, which is a typographical error.

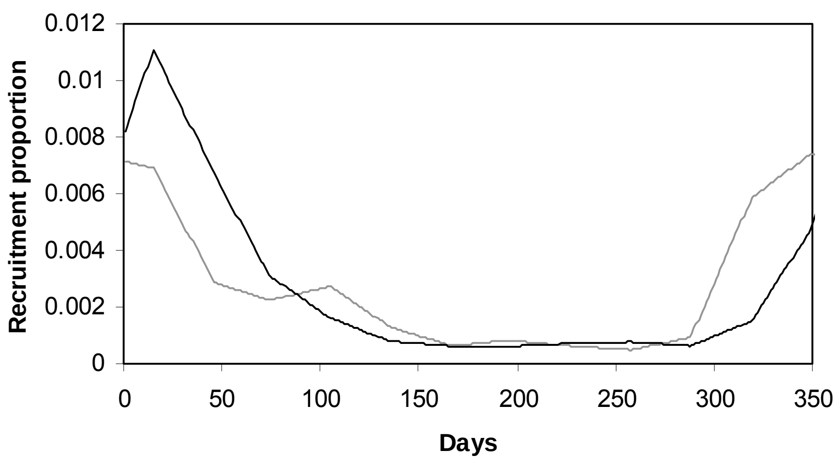
Recruitment patterns for an individual species may vary considerably from year to year and from region to region. **Regional variability is not considered in this model**, rather an index of the recruitment pattern within a year that would represent the recruitment pattern over the whole NPF was determined by investigating trawl survey data. No data exist that describe directly the pattern of prawn recruitment into the NPF. However, several studies carried out in the Gulf of Carpenteria have given an indication of the relative abundance of prawns by species and by size over time. These sources of data are;

1. A series of monthly research trawl surveys in the eastern Gulf of Carpenteria between August 1977 and July 1978 (Redfield et al. 1978),
2. Research trawls every 4 weeks in the western Gulf of Carpentaria, between Groote Eylandt and Cape Arnhem, from August 1983 to March 1985 (Somers et al. 1987),
3. Research trawls around Mornington island in the southern Gulf of Carpentaria every 4 weeks throughout 1983 (Robertson et al. 1987), and
4. A comprehensive research trawl survey between 1986 and 1992 in the north-eastern Gulf of Carpenteria, around Albatross Bay (Crocos and van der Velde, 1995).

(Somers et al. 1987) reported a good match between logbook CPUE and survey CPUE. The index of the recruitment pattern used by (Somers and Wang, 1997), was an index of the monthly mean CPUE of prawns with carapace lengths between 20 and 25 mm from the SE Gulf, S Gulf and NW Gulf studies above.

By contrast, (Wang and Die, 1996) used data from only two sources in their model. Data from source 2 was used mainly for *P. esculentus* and data from source 4 for *P. semisulcatus*. The number of recruits from the length-frequency data in each month was calculated as the sum of all prawns smaller than or equal to the size of recruitment (l_r) described in (Wang and Die, 1996)and below. Because monthly sampling effort was constant in the research surveys, ***each month's proportion of the annual recruits represent CPUE and can be considered as a direct index of abundance.*** In the (Wang and Die, 1996) model, the input data are daily recruitment (Figure 102) and is linearly interpolated from the monthly estimates. These are converted to a weekly proportions in the code.

Figure 102 Daily recruitment pattern for P. esculentus (grey) and P. semisulcatus (black) from monthly survey data used in (Wang and Die, 1996). Week 1 is the first week in January.



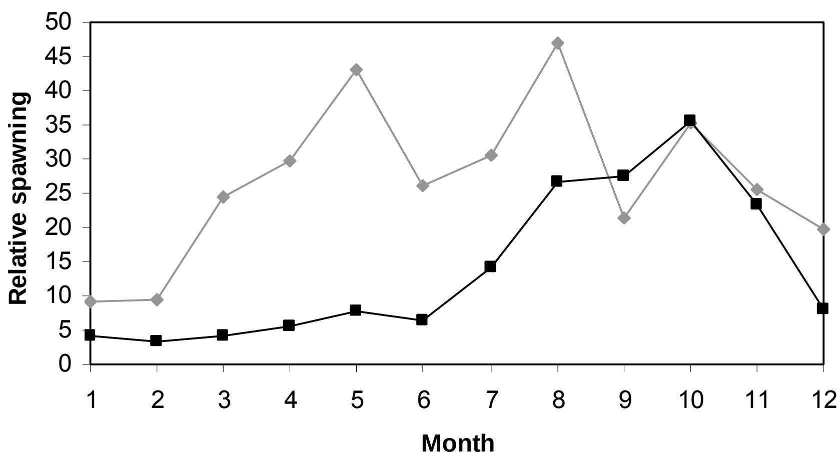
These seasonal recruitment patterns of brown and grooved tiger prawns in the western Gulf for the period 1979 to 1982 were also found by (Buckworth, 1985). His study showed that the main recruitment period of grooved tiger prawns was between November and February as shown by the presence of animals ≤25 mm CL in the commercial catch. Recruitment for grooved tiger prawns was from January to April.

51.2. Relative weekly spawning pattern, maturity and spawning size

(Buckworth, 1985) analysed commercial catch samples and CPUE patterns in the Western Gulf of Carpenteria tiger prawn fishery for the period 1979 to 1982. Minimum size at first maturity of brown tiger prawns was 26 mm carapace length (CL) and for grooved tiger prawns 30 mm CL (Buckworth, 1985). Brown tiger prawns had a protracted spawning period with between 34 and 69% of females having visible ovaries throughout the year. Spawning in grooved tiger prawns was limited to the period August to December.

However, (Crocos, 1987a) and (Crocos and van der Velde, 1995) describes that grooved tiger prawns spawn year-round, with a major spawning peak between August and October and, in most years, a secondary peak between January and February. Brown tiger prawns have a similar pattern, but with smaller peaks (Crocos, 1987b). The relative percentage of spawners by month that was used in the (Wang and Die, 1996) model is shown in Figure 103. Note that in the Wang and Die model, the values over the year do not add to unity, whereas they do in the Risk model. Therefore there is a scale difference between the two assessment's indices.

Figure 103: Relative proportion of spawning adults by month for P. esculentus (grey) and P. semisulcatus (black) used in the (Wang and Die, 1996) model



51.3. Growth

Growth data were obtained for the two tiger prawn species from a tagging experiment carried out in February 1981 in waters adjacent to Groote Eylandt in the Western Gulf of Carpentaria (Kirkwood and Somers, 1984). A von Bertalanffy growth function was fitted to these data and least squares estimates of the parameters, L_∞ and K, and joint 95% confidence regions were calculated for males and females of both species under the **assumption of identically distributed errors**. For females, especially for *P. semisulcatus*, the fit of the model was not satisfactory due to the available data.

Concurrent trawl and tag-recapture studies were subsequently conducted in the north-western Gulf of Carpentaria near Groote Eylandt between August 1983 and March 1985

(Somers and Kirkwood, 1991). A von Bertalanffy growth model similar to (Kirkwood and Somers, 1984) was fitted to the tag-recapture data. This study showed that high individual variability in L_∞ for length-frequency data for *P. semisulcatus*. The maximum length for each prawn released was an observation from a truncated normal distribution, which was assumed to have a mean, μ and a variance of σ^2 and was truncated below at the release length, L_R (and therefore assumes no shrinkage). Model error, E, assumed to be normally distributed with a mean of 0 and a variance of ε^2, was also incorporated into the model thereby the final model becomes:

$$I = \left(L_\infty - L_R\right)\left(1 - e^{-KT}\right) + E \tag{31}$$

where L_∞ is the asymptotic maximum growth, with a distribution TN(μ, σ2, L_R),

L_R is the release length,

K is the intrinsic growth rate,

T is time, and

E has an independent N(0, ε^2) distribution.

Parameter estimates and their standard errors were obtained by maximising the likelihood function described in (Somers and Kirkwood, 1991).

51.4. Allometry

A variety of morphometric relationships were established for *Penaeus semisulcatus* in samples of different size, gender, origin and species in the Arabian Gulf (Farmer, 1980). (Wang and Die, 1996) used data collected in the Bahrain industrial fishery between 1974 and 1975 for the length-weight regression in their model.

Similar relationships for *P. esculentus* by sex were provided by (Penn and Hall, 1974) from commercial trawl catches taken in Shark Bay, Australia during the prawn seasons of 1962 to 1973 inclusive (Table 39).

Table 39. *Carapace length versus weight relationships for two tiger prawn species separated by gender. The relationship is* $\text{Weight} = a\,(\text{Carapce length})^b$.

	P. semisulatus		*P. esculentus*	
	Female	Male	Female	Male
a	0.00265	0.00195	0.00373	0.00207
b	2.648	2.746	2.574	2.764

51.5. Length-at-recruitment, l_r, and mesh selectivity (Somers and Kirkwood, 1991)

Different recruitment lengths for each species and sex were determined from length-frequency data obtained in the surveys listed in Section 51.1 above: for *P. semisulcatus* from the data set described in point 4 and for *P. esculentus* from the data described in point 3. Larger than the length-at-recruitment, animals were assumed to be fully selected by the fishing gear. However, (Somers et al. 1987) report on a catchability experiment which showed that 100% retention is only achieved in the high twenties (mm carapace length).

51.6. Natural mortality

The (Wang and Die, 1996) model proposed that the life history characteristics of tiger prawns suggest their natural mortality is lower than that of banana prawns (Dall et al. 1990). **Therefore the instantaneous natural mortality coefficient, *M*, was assumed to be 0.045 week^{-1} for tiger prawns,** which is slightly smaller than the value of 0.2 month^{-1} used in previous assessments (Somers, 1990).

51.7. Catchability

Two types of catchability are utilised within the model: the target tiger prawn species and non-target tiger prawn species catchability. These are respectively called catchability and bycatchability. Bycatch here is defined as the catch of one species of tiger prawn when the other tiger prawn species was the target. Furthermore, the overall catchability is moderated by a daily availability proportion factor and relative fishing power. Unusually for an assessment model, the catchability and bycatchability values are input parameters and not estimated.

51.7.1. Catchability and bycatchability

Overall catchability coefficients for grooved tiger prawns were estimated from commercial catch and effort data for a given natural mortality using the method of (Wang, 1999) and natural mortality estimates described in (Somers and Wang, 1997). ***The data were too fragmented for estimating brown tiger prawn catchability and it was therefore assumed to be the same as for grooved tiger prawns.***

(Wang, 1999) described in detail a stochastic model based on Markov chains that uses a maximum likelihood approach for estimating natural mortality and the catchability coefficient simultaneously from catch and effort data. When applied to grooved tiger prawn data in the NPF, the catchability from year 1989 to 1993 was calculated for a given natural mortality. As can be seen from Table 40, the catchability has remained almost constant since 1991. Prior to that year, catchability increased significantly. This can be explained by reference to studies by (Robins et al. 1998) which suggest that GPS may have had a significant effect on catchability, especially for the first three years from 1989.

Table 40: *Number of vessels and proportion of vessels with GPS for 1989-1993, and the maximum likelihood estimates of catchability ($q*10^{-5}$) of the tiger prawn P. semisulcatus for different values of natural mortality. Source: (Wang, 1999).*

Year	*Number of vessels*	*%GPS*	*Natural mortality (week^{-1})*		
			0.030	0.045	0.065
1989	223	20	5.5	4.1	2.8
1990	200	55	7.0	5.3	3.6
1991	172	97	10.6	8.6	6.6
1992	170	99	10.3	8.4	6.6
1993	127	100	11.1	8.8	6.6

(Wang and Die, 1996) assumed a natural mortality of 0.045 week^{-1} in their model and the catchability estimated for 1993 was used. This is the year that the fishery had a major restructure.

Targeting one species in a multi-species fishery does not always result in monospecific catches. To accommodate this, (Somers and Wang, 1997) describes the calculation of bycatchability coefficients. These estimates were based on the ratio of bycatch and catch from commercial data for all months.

In a multi-species fishery in which fishing for one species may result in the catch of another species, the catch ($C_{ij}(k)$) of species i, when fishing is targeting for species j during period k in days is:

$$C_{ij}(k) = \frac{q_{ij}E_j(k)}{Z_i(k)}\left(1 - e^{-Z_i(k)}\right)N_i(k), \tag{32}$$

where $Z_i(k) = q_{ij}E_j(k) + q_{ii}E_i(k) + M$ and M is the total mortality of species i over period k, $N_i(k)$ is the population at the beginning of period k. From these equations, q_{ii} is the catchability and q_{ij} is the bycatchability of species j when fishing is for species i ($i \neq j$).

In order to estimate bycatchability, the dynamic abundance $N_i(k)$ needs to be known. Since in the tiger model recruitment is assumed to be continuous, the assumption that the dynamic abundance depletes exponentially over time is violated. In this case, recruitment is accounted for on a daily basis and it is possible to obtain the following expression using the catch equation above:

$$\frac{q_{ij}}{q_{ii}} = \frac{C_{ij}(k)E_i(k)}{C_{ii}(k)E_j(k)} \tag{33}$$

which is independent of the dynamic abundance.

Note that unbiased estimates of the ratio of $\frac{q_{ij}}{q_{ii}}$ were obtained from the preceding equation because the equation requires no knowledge of recruitment and dynamic abundance. If the catchability q_{ii} is known, the bycatchability q_{ij} can thus be easily obtained from the ratio and the catchability q_{ii}.

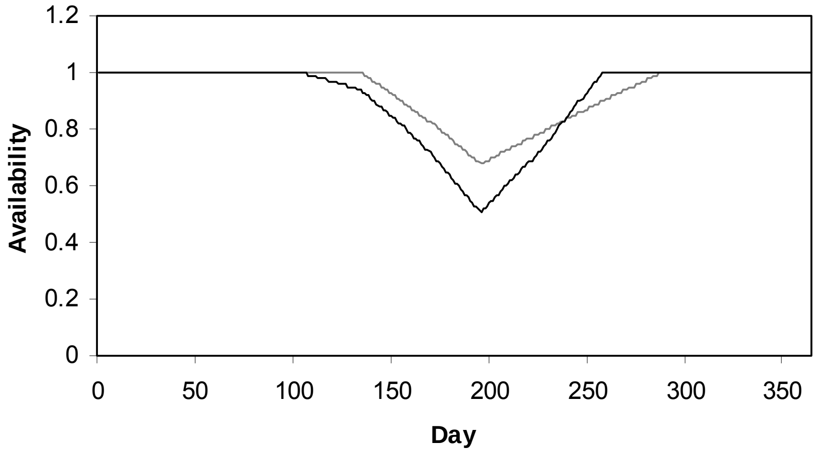
51.7.2. Availability to capture

The presence of seasonal changes in catchability is illustrated from monthly survey data in which winter catch per unit effort values declined dramatically and cannot be described by fishing pressure alone (Somers et al. 1987). (Hill, 1985) found that brown tiger prawns had reduced activity at water temperatures below 27°C, at which times they remained buried (and therefore by implication not susceptible to capture by trawlers) for longer periods. Below 15°C, they did not emerge from the substrate at all overnight

Hill's (1985) research was based on continuous time-lapse video recordings of the brown tiger prawn in 2m and 6m diameter tanks under controlled conditions. The mean duration of nocturnal emergence of prawns exposed an annual cycle of temperature and night was directly related to temperature and can be described by a regression model: $Emergence = 34.7t - 488$ where t is the temperature, this accounted for 40% of the variation in emergence. A similar temperature effect was described for brown tiger prawns in Exmouth Gulf, Western Australia by (White, 1975). In (Somers and Wang, 1997) and (Wang and Die, 1996) this equation was used to calculate the proportion of brown tigers available to fishing in a month from monthly water temperatures in the Gulf of Carpenteria, T, by:

$Emergence = (34.7T - 488)/480$. For temperatures above 27°C, the availability was assumed to be 1. Daily availability values were obtained from linear extrapolation of the monthly values (Figure 104).

Figure 104: Daily availability of *P. esculentus* (grey) and *P. semisulcatus* (black) in a standard year.



However, this temperature effect has not been demonstrated for grooved tiger prawns (Somers et al. 1987). (Somers and Kirkwood, 1991) offered an alternative explanation for the decline in grooved tiger prawn survey catch per unit effort in winter namely that grooved tiger prawns in the Gulf of Carpenteria disperse into deeper water in the winter months. CPUE data from their study showed that in spring (September to November), tiger prawns appeared to aggregate in shallower waters and they become the focus of the commercial fishery. By using the April to September CPUE indices of (Somers and Kirkwood, 1991) to calculate the natural rate of decline in the population (0.03/week), (Somers et al. 1987) compared the CPUE's from intervening months with those from an exponential decay model to the define seasonal adjustment for grooved tiger prawn catchability coefficient. These figures were extrapolated to daily values (Figure 104).

51.7.3. Fishing power

To be consistent with the choice of natural mortality and corresponding 1993 estimated catchability value (Wang, 1999), the fishing power values used in the Wang and Die model are set at unity in 1993. The annual percentage increase in fishing power was input as 5%. Studies on fishing power in the NPF (e.g. (Robins et al. 1998) and (Bishop et al. 2000)) have demonstrated fishing power increases from 1989 of an average of 2.5% per year. Since not all the factors that affect fishing power were included in the models, NORMAC recommended using a precautionary level of 5% per annum in the assessment.

51.7.4. Overall catchability

For each species, the overall catchability for each tiger prawn species, *i*, in boat-days when species *i* is the target, q_{ii}, is 8.8E-5 ((Wang, 1999), (Wang and Die, 1996)). Final daily catchability for a tiger species as the target (Q*y,d*) is calculated from the overall catchability coefficient for day d (q*ii* as above or $\tilde{q}_d$ used in subsequent chapters), the relative availability (q_d). Average weekly catchability values are then multiplied by fishing power ($q_{y,w}$):

$$Q_{y,d} = \tilde{q}_d \, q_d \tag{34}$$

and $q_{y,w} = (\omega_y)^{(w-1)/52} \prod_{y'<y} \omega_{y'} \,/\, \prod_{y''<1993} \omega_{y''}$ (35)

and ω_y is the efficiency increase during year y.

Overall bycatchability, is calculated as above but in the (Wang and Die, 1996) model, no fishing power is applied to bycatchability.

Values of about 7.92E-6 and 1.065E-5 per day for brown and grooved tiger bycatchability respectively were estimated in (Somers and Wang, 1997).

Overall catchability and bycatchability is assumed to be constant from year to year.

52. Basic model dynamics

The basic dynamics of the Wang and Die model as used by the Risk analysis project is described in detail in Chapter 5 along with the Delay-Difference model which is a simplified model and runs quicker. This section will therefore concentrate on the slight differences between the age-based model developed by the Risk project and that published in (Wang and Die, 1996).

The first small difference is that the Risk model does not take mortality of animals during the week into consideration whereas the Wang and Die model does. The basic dynamic equation of the Risk model is :

$$N_{y,w,c} = \begin{cases} 0 & \text{if } y \times 52 + w \; < \; c \\ \alpha_{y,w} \, R_{y(y,w)} & \text{if } y \times 52 + w = c \\ N_{y,w-1,c} \, e^{-Z_{y,w-1}} & \text{if } y \times 52 + w > c \end{cases} \tag{36}$$

for the case where y*52+w=c would in the Wang and Die model be:

$$N_{y,w,c} = \alpha_{y,w} \, R_{y(y,w)} P_w \tag{37}$$

where

$$P_w = \left(1 - e^{-Z_w}\right) / \, Z_w \tag{38}$$

The additional term assumes that a recruit can appear at any time during the week, and therefore describes the probability that a recruit that was recruited in week c will survive to the end of the week w. Whereas the Risk age model would simply use the Baranov catch equation, the Wang and Die model uses:

$$C_{y,w} = N_{y,w} P_w F_{y,w} + \left\{ \alpha_w \, (1 - P_w) F_{y,w} \, / \, Z_{y,w} \right\} R_y \tag{39}$$

Note that the catch ($C_{y,w}$ in numbers) is made up of two components, corresponding to the catch of prawns recruited before and during week w respectively.

A small detail that does not affect the model outputs, is that the Risk model codes the age structure explicitly (i.e. always scales in numbers) whereas the Wang and Die code uses transition matrices. In the latter model, the 1969 initial condition matrices are 0.6 for brown tiger prawns and 0.52 for grooved tiger prawns.

52.1.1. Stock-recruitment relationship

The spawning stock-recruitment relationship (SRR), recruitment-spawning stock relationship (RSR) and catch-effort relationship in the Risk model is a per recruit approach, whereas the age structure in the Wang and Die model is not considered. These equations are therefore yearly. The yearly SRR Ricker equation would be:

$$R_y = \alpha_1 S_{y-1} e^{\left(-b_1 S_{y-1}\right)} \tag{40}$$

and the RSR:

$$S_y = \alpha_2 \, \mathrm{R}_y \mathrm{e}^{-b_2 F_y} \tag{41}$$

with catch in tonnes-effort relationship approximated as:

$$C_y = \alpha_3 R_y \left\{1 - e^{\left(-b_3 F_y\right)}\right\} \tag{42}$$

The parameters of each of these three equations are estimated separately. To account for correlation in the error terms over the years, a log-linear, first-order autoregressive time-series model was developed.

53. Maximum sustainable yield and related management outputs

Equations (40) and (41) can be solved assuming equilibrium spawning stock and recruitment (i.e. the year subscript is removed) for a given fishing mortality and the Maximum Sustainable Yield (MSY) with these modified equations and the equilibrium form of equation (42) can be calculated. The resultant fishing mortality at MSY (F_{MSY}) for a give effort at the MSY (E_{MSY}), recruitment at MSY (R_{MSY}), spawning stock size at MSY (S_{MSY}) and MSY equations are:

$$F_{MSY} = \tilde{q} E_{MSY} \tag{43}$$

$$R_{MSY} = \alpha_1 S_{MSY} e^{-b_1 S_{MSY}} \tag{44}$$

$$S_{MSY} = -\left\{b_2 F_{MSY} - \ln\left(a_1 a_2\right)\right\} / b_1 \tag{45}$$

$$MSY = \alpha_3 R_{MSY} \left(1 - e^{-b_3 F_{MSY}}\right) \tag{46}$$

These equations are solved iteratively. The catchability value used here assumes a fishing power of unity and is therefore in 1993 days i.e. standardised days and assumes pulse fishing.

54. Sequence of Wang and Die program

In the Wang and Die assessment, these recruitment parameters and then the parameter sets of the spawning stock-recruitment relationship (SRR), the recruitment-spawning stock relationship (RSR) and the catch-effort relationship are estimated sequentially. The above sections are coded into SAS whereas all the MSY-related management outputs are calculated separately in Excel with the a_{1-3} and b_{1-3} parameters updated after the new assessment.

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APPENDIX B: BASE CASE

This Appendix gives details of input data and parameters of the Base Case in the Risk analysis and Futuring Chapters, being the Deriso-Schnute assessment. The Base Case assesses the resource as a single species (with some consideration to bycatchability) and a single stock.

56. Input data

The input data, weekly catch and effort per species since 1970, is calculated as per the Wang and Die method described in Appendix A.

57. Input parameters

Table 41: *Input parameters of the Base Case Deriso-Schnute assessment used in the Risk analysis and futuring chapters.*

(a) Recruitment and spawning

Parameter	Base Case Specification (*Penaeus esculentus)*	Base Case Specification (*Penaeus semisulcatus)*
Annual recruitment, R_y	Estimated	Same
Relative weekly recruitment, α_w	Assumed known (see Figure 102 in Appendix A)	Same
Relative weekly spawning, β_w	Assumed known (see Figure 103 in Appendix A)	Same
Extent of variation in α_w, σ_α	0	0
Stock-recruitment parameters, $\tilde{\alpha}, \tilde{\beta}$	Derived from h and S_0. Ricker model	Same
Virgin spawning stock index, S_0	Estimated	Same
Steepness, h	Estimated	Same
Extent of temporal variation in recruitment, σ_r	Estimated	Same
Extent of temporal correlation in recruitment, ρ_r	Estimated	Same

(b) Effort – fishing mortality-related

Parameter	Base Case Specification (*Penaeus esculentus)*	Base Case Specification (*Penaeus semisulcatus)*
Overall catchability by week,	Calculated with all	Same

$\tilde{q}_w$	relevant parameter values known	
Relative weekly availability, A_w	Assumed known (see Figure 104 in Appendix A)	Same
By-catch catchability, q_b	0.09	0.121
Extent of density-dependent catchability, χ	0	0
Extent of effort saturation, γ	0	0
Extent of non-lineararity in F vs E relationship, ϕ	1	1
Extent of variation in catchability, σ_q	0	0
Annual efficiency increase, ω_y	5% per annum	Same
Target effort, $E^T_{y,w}$	Data – pre-specified using Wang and Die (1996) method	Same
By-catch effort, $E^B_{y,w}$	Data – pre-specified using Wang and Die (1996) method	Same
Catches, $Y^{obs}_{y,w}$	Data – pre-specified using Wang and Die (1996) method	Same
Sine catchability, $\alpha^1_w, \beta^1_w, \alpha^2_w, \beta^2_w,$	N/A	N/A

(c) Growth

Parameter	Base Case Specification (*Penaeus esculentus)*	Base Case Specification (*Penaeus semisulcatus)*
Brody growth coefficient, ρ	0.982	0.979
Von Bertalanffy growth parameters, ℓ^s_∞, κ^s	N/A	N/A
Length-weight parameters, e^s, f^s	Males: 0.003739, 2.574 Females: 0.0027, 2.764	Males: 0.00265, 2.648 Females : 0.00195, 2.746
Length-at-recruitment, ℓ^s_r	Males: 26 Females: 28	Males: 26 Females: 28
Weight-at-recruitment, w_k	Assumed known	Same

Weight the week prior to recruitment, w_{k-1}	$((1+\rho)w_k - w_{k+1})/\rho$	Same
Extent of variability in weight, σ_w	0	Same

(d) Other parameters

Parameter	Base Case Specification (*Penaeus esculentus)*	Base Case Specification (*Penaeus semisulcatus)*
Average rate of natural mortality, *M*	0.045 week^{-1}	0.045 week^{-1}
Extent of variation in natural mortality, σ_M	0	Same
Catch in weight residual standard deviation, σ_c	Estimated	Same

The catch likelihood is untransformed and the effort pattern to calculate the management measures assumes uniform fishing throughout the year. The Base Case uses the Ricker stock-recruitment relationship. The reason for this choice is that the Ricker relationship was used by Wang and Die (1996) and in the most recent tiger stock assessments (NPFAG 2000).

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