
Management strategies for an input controlled fishery based on the capture of short-lived tropical species: the example of Australia's Northern Prawn Fishery

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14 June 2006

Statement of Originality

I declare that this thesis is my own work except where duly acknowledged. It contains no material that has been accepted in any form for another degree or diploma by the University of Tasmania or any other institution. To the best of my knowledge and belief, no material within this thesis has been published or written by another person except where due acknowledgement is made in this declaration or in the text of the thesis.

C.M. Dichmont

Declaration

This work originates mainly from a paper submitted to the Northern Prawn Fisheries Advisory Committee (NORMAC), an invited chapter to a book, and two collaborative projects. It is therefore necessary to declare my contribution and those of my co-workers in this thesis.

Chapter 1 is the product of a multi-authored paper to be published as a chapter in a book edited by T.R. McLanahan and J.C. Castilla. I am the first author of the book chapter and initiated, co-ordinated and led the development of this chapter. However, each author has been the first author of certain sections. In addition to leading the development of this Chapter, I wrote the abstract, the historical perspective of the fishery, the sustainability of target species and the summary. Neil Loneragan wrote the section entitled ‘A complex ecosystem in time and space’, and Dave Brewer wrote the section ‘Prawns are not the only catch’. Everyone has contributed to edits.

I am the sole author of Chapter 2 which started as a document I submitted to NORMAC and then developed further for this thesis.

Chapter 3 onwards are the results from Dichmont *et al.* 2001 and Dichmont *et al.* 2005. For both these projects I was the Principal Investigator; I therefore obtained the funding (in the case of Dichmont *et al.* 2005), managed the project, determined the contents of the research, developed or supervised the methodology, undertook most of the write-up and edits, and undertook the communication. Some of the chapters refer to Dichmont *et al.*

(2003a), which is one of the published outputs of the FRDC project Dichmont *et al.* (2001). I am the first author of this paper and I have included this publication as Appendix 1 rather than simply copy the equations of the assessment model and its description from the publication into this thesis. Chapter 4, 5 and 6 are the product of a collaborative 3 year project entitled “A new approach to assessment in the NPF: spatial models in a management strategy environments that includes uncertainty” by Dichmont, C.M., Deng, A.R., Venables, W.N., Punt, A.E., Haddon, M. and Tattersall, K. and referred to as Dichmont *et al.* (2005). These chapters have been written up as 3 consecutive papers. I am the first author of each of the three papers to be submitted to Fisheries Research. Additional scenarios not in the papers are in Section 6.8. Appendix 2 is written by my supervisor Bill Venables and is added for interest only.

C.M. Dichmont

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INTRODUCTION AND SUMMARY

Rationale and Thesis Structure

Input controlled fisheries for short-lived species are common but the management options available are rarely examined in great detail. The Northern Prawn Fishery (NPF) of Australia is a very valuable industry and has a relatively long history. The extent of previous research and the value of the fishery mean the NPF provides an excellent opportunity for exploring alternative management strategies for a fishery on input controlled short-lived species.

I start this thesis with a description of the fishery and its management (Chapter 1). It is not a complete analysis of all the aspects of the partnership approach. An equally fascinating story on the personalities within the partnership approach and how they shaped the history of this fishery is not included. Included is a discussion of the achievements in the Northern Prawn Fishery (NPF) partnership approach that has relied on co-management by managers, scientists and the industry. These achievements include:

- (a) the scientific discovery of the prawn life cycle and its reliance on coastal habitat produced a series of protected areas formulated and supported by all these parties,
- (b) assessment of the sustainability of tiger prawns has resulted in very controversial and large effort reductions over several decades, and
- (c) research on bycatch in this fishery is more advanced than many others in the world mainly due to the proactive nature and support from the industry.

The next section (Chapter 2) broadens the scope beyond the NPF by describing the management and assessment process of some key short-lived species, with many from Australia. Here, I define a short-lived species as being animals that grow to a maximum of 3-4 years in age. A further criterion for choosing these examples is that they undertake at least some basic management such as limited entry and total effort/catch control. Interestingly, an array of management systems are applied across the range from using mostly input controls to mostly output controls, including mixtures of the two. Excluded are the vast bulk of fisheries that rely on short-lived species with little or no management. This is

not intended as an exhaustive list. I have chosen examples that have direct relevance to the NPF as comparisons or contrasts. In these cases many of the methods and conclusions from this study are applicable to these fisheries and vice versa.

Chapter 3 details the Management Strategy Evaluation (MSE) process itself (in the context of the NPF) and the most well known examples of its use. A key graph (Figure 3.1) should help the reader keep track of the remaining method sections that follow. Since this field is rich in terminology but also does not have consistency, a description of the terminology used in this study is provided in Section 3.1.

Historically, the official assessments of tiger prawns in the NPF did not forward project the assessment beyond a simple process to investigate different management options. In Dichmont *et al.* 2001 and Dichmont *et al.* 2003a (Appendix 1) simple harvest strategies and a risk analysis are undertaken. As a major upgrade to the methodology, this thesis uses a much more sophisticated approach; Management Strategy Evaluation (MSE). This has never been applied to this fishery before and, for prawns, has not been applied using a fully stock structured operating model. Indeed the only other prawn application that has been reported (O'Neill *et al.* 2004) is applied to Queensland and Torres Strait Island prawn fisheries, and developed an operating model at very much the same spatial and temporal scale as the Base Case management strategy. In this PhD we use one of the major strengths of the MSE methodology which is that it permits comparisons of alternative assessment assumptions. We used MSE to test the simplification assumptions in the NPF assessment (e.g. single versus multi-stock) and to determine the effect of incorrectly parameterising the assessment relative to the operating model (e.g. high fishing power in one with low fishing power in the other).

The operating model, which represents a virtual resource being managed, is described in detail in Chapter 4. The particular operating model in this MSE is new and mathematically describes a multi-stock and multi-species tiger prawn resource, but also includes effort directed at banana prawns. These are key aspects of the fishery and are a major change from past analyses in the NPF. In most instances, stocks are assumed to be biologically independent of each other. This is the worst case scenario i.e. if one stock is over-fished, it can not be supplemented or replenished by neighbouring stock regions. However, an option to include environmental influences that affect more than one stock is also included in some

scenarios. This required an analysis of the between stock covariance structure of the recruitment estimates and is new for the NPF.

As part of the MSE process (Chapter 5), one needs to describe the whole management system and include all known sources of uncertainty; from data collection, to assessment, setting the effort levels, and implementation of management decisions (see Chapter 5). The determination of the implementation errors entailed a detailed analysis of past decisions made by the managers of the fishery and highlights a key source of uncertainty within the management process. This is a new way of looking at management successes and failures in the NPF and has shown that a good management procedure can be thwarted by implementation error.

Three different stock “assessment” methods are included in the MSE (Chapter 5). These are a simple linear regression of annual catch rate against time, a biomass dynamic model and the delay-difference model (called the Deriso model in this thesis, described in detail in a paper published in Fisheries Research, and included as Appendix 1). The spatial and temporal scale (as well as complexity) is markedly different among these three approaches. A weekly delay-difference stock assessment was first formulated by Dr Andre Punt and applied to the Northern Prawn Fishery (Punt 1996), but is further refined and tested in Appendix 1. Until this application to the NPF, delay-difference models were applied with a time step of one year (e.g. Schnute 1985). However some changes were made to the original Deriso model of Punt as described below.

An interesting aspect of this application of a delay-difference model to a short-lived species is that an individual recruiting into the fishery may also be contributing to the spawning population at the same time. This means that the “delay” in the delay-difference equation of the model takes on a specialized meaning, another unusual aspect of the method. Why then use a delay-difference model? The underlying reason is that we are trying to keep track of some aspects of the age structure within the population; mainly because there has, in the past, been some dispute as to whether prawns have a defined stock and recruitment relationship and also that many reference points rely on knowing the parameters of the stock-recruitment relationship. As is common for a crustacean, age structure data is not available. Sadly, any long term size structure data is also not available which makes it impossible to directly estimate a full age/size structure tuned to data. Although there is a fully age structured assessment developed for the tiger prawn species in

the NPF by using the von Bertalanffy growth equation (see Wang and Die 1996 and Dichmont *et al.* (2001)), the delay-difference model described in Appendix 1 provides very similar results (to within 4 decimal places) to this age structured model, but is much quicker to run (something that is essential in a Management Strategy Evaluation framework). The main reason for this similarity is mathematically obvious, since both methods as applied to this fishery assume knife edged selectivity and use the same data source.

This fishery can be classified as relatively data poor, because no long-term fishery-independent monitoring data is available. This means that many parameters are being estimated from the same data sources, which complicates the analyses and causes serious confounding. Much of the discussion on this confounding occurs within the estimates of fishing power, which does not form part of this thesis (“effort creep” constitutes a major management problem in this fishery). Most of this debate and methodology is described in Dichmont *et al.* (2003b) and is used here as an input. Since the model suffers from data paucity, the process of assessment is unusual:

- (a) firstly, annual recruitment parameters and spawning indices are estimated using catch and effort data together with estimates of catchability and fishing power input to the model, and
- (b) given these parameter estimates, the stock-recruitment parameters are estimated. Since prawn recruitment success can be strongly affected by the physical environment, there is also an underlying set of temporal autocorrelation parameters about the estimated stock-recruitment relationship. In (a), no underlying stock-recruitment structure is assumed; each year’s recruitment is assumed to be independent of the next. Only in stage (b) is there an investigation of whether these estimates follow a stock-recruitment pattern. Given that the recruitment values are estimated in a separate process, the precision of these variables needs to be carried into the stock-recruitment estimation process. This is done through modifying the likelihood to include an asymptotic variance–covariance matrix obtained by fitting the population dynamics model in part (a). The estimation of the stock–recruitment relationship therefore takes account of the relative precision of the annual recruitments and the impact of (correlated) environmental variability in recruitment; this was a novel modification to the NPF assessment first presented in Dichmont *et al.* (2003a).

Wang and Die (1996) applied an innovative twist to their age structured model, which directly acknowledges the technical interactions between the two tiger prawn species that are caught i.e. there are almost no occasions where only one species is caught. The single species approach, if not modified, would grossly overestimate possible sustainable effort on a species if the “bycatch” of another species is not considered. In the Wang and Die (1996) model, they address this through calculating fishing mortality as the sum of effort applied to the target species and effort applied to the ‘bycatch’ tiger prawn species. Of course, this requires using two forms of catchability; a target and a “bycatch” (they use the phrase “bycatchability”) parameter. However, they did not extend this concept beyond this fishing mortality equation, which means that their calculation of the effort levels required to reach the Maximum Sustainable Yield (E_{MSY}) for each of the two species can not be simply added together as an estimate of the total E_{MSY} . As a result, in the delay-difference model described in this thesis the concept is extended to be included in future projections and in the calculation of the reference points (this complicates the mathematics of the model somewhat and is described in Appendix 1).

The successes (and failures) of the different Management Strategies are analysed in Chapter 5. It should be borne in mind that each Management Strategy includes the assessment process as well as the set of decision rules used to determine effort levels. Here the key issue was the appropriate spatial and temporal scale of the Management Strategies as well as their mathematical complexity. Options include annual versus weekly time steps, single versus multi-stock assessments and/or decision rules, different assessments, inclusion of age structure.

Designing an experiment to determine the key factors to which the MSE performance measures are sensitive is not new, but is rarely applied in fisheries simulation modelling. I suggest that the two stage process undertaken in Chapter 6 has been an excellent compromise between undertaking a comprehensive sensitivity test and minimising computer time. The first stage involved undertaking a statistically unbalanced experiment (thereby reducing the number of scenario runs to something more feasible in terms of computer time). The results from the unbalanced design were used to identify the key factors, which were fully tested using a statistically balanced design process. Chapter 6 therefore investigates the factors that are most influential to the Performance Measures and uses a range of different operating model arrangements and management strategies. In many cases, the

mismatching of assumptions between the operating model and management strategy was the most revealing of relationships and interactions. A few extra scenarios are described in Section 6.8 as an Appendix for completeness. They were excluded from the main part of the chapter purely to keep it to a reasonable length.

Finally, the study recommends future directions of management and research (Chapter 7). References occur after each chapter. The overall summary is in fact next.

Summary

The NPF is one of the Australian Commonwealth's most valuable fisheries. The species groups targeted include tiger, banana and endeavour prawns. The fishery is managed using input controls and, from 2001 until 2004 (the period which spans this study), the agreed target was for the level of fishing effort expended to lead to a 70% chance (or greater) that the spawning stock size of tiger prawns was at or above that corresponding to Maximum Sustainable Yield, S_{MSY} . A key issue in the management of this fishery is that the efficiency of fishing effort is continually increasing so that past effort reductions have been fully offset by improved efficiencies. In fact, some past effort reductions did not actually lead to a real reduction in effective effort. As a consequence of this, there was no recovery in the size of the tiger prawn resource but rather, in some years, a decline, until a major effort reduction program was implemented in 2001.

Early stock assessment methods for tiger prawns were limited to simple models (e.g. equilibrium surplus production models - Somers (1990)) with limited goals. More recent assessments were based on the population dynamics model developed by Wang and Die (1996). This model operates at a much finer (weekly) time-step, specifically includes growth and recruitment, and separates the two tiger prawn species. The assessment technique based on this model was evaluated and improved by a FRDC-funded project (Dichmont *et al.* 2001) which produced two assessment techniques: a) a modified version of the Wang and Die method, and b) a new method based on a Deriso-Schnute model (Dichmont *et al.* 2003a). A non-equilibrium, non-linear, biomass dynamic model with an annual time-step using tiger prawn data only was developed by another FRDC-funded project (Haddon and Hodgson 2000). The biomass dynamic and Deriso-Schnute models produce somewhat different outputs, but both suggested in 2001 that the tiger prawn resource was depleted and well below the biomass that could produce MSY. Both models

assume a single homogenous stock of tiger prawns in the NPF, although when fitting the biomass dynamic model, the catch and effort data used are standardized with respect to geographical location and week in the season to make some allowance for spatial heterogeneity.

Spatial stock assessments would appear to be essential for a resource that tends to aggregate, or that has distinct geographical trends in abundance or availability. Die *et al.* (2001) suggested that there are several distinct stocks of tiger prawns in the NPF and that assessment methods should be applied at a finer spatial scale than had been the case in the past. Dichmont *et al.* (2001) attempted to conduct stock assessments for tiger prawns in the NPF by “stock area”, but the calculations took a long time and were highly uncertain. The preliminary results of these spatial assessments suggested that some stock areas were highly depleted with spawning stock sizes much lower than suggested by the single-stock models.

Dichmont *et al.* (2001) and this study also assessed the magnitude of error in the estimate of the effort corresponding to MSY (E_{MSY}), and other parameters on which management advice is based. This error was caused by uncertainty in the data and in the values for some of parameters of the assessment model that are specified using auxiliary information rather than being estimated from the catch and effort data. In brief, the error bounds on the estimate of E_{MSY} were very large, implying that E_{MSY} was unlikely to be the best guide to good management in the NPF.

The findings from Dichmont *et al.* (2001) and Die *et al.* (2001), coupled with the transition in August 2000 of the fishery from management based on A-units to management based on gear-units, made it important that more realistic fishery sustainability targets needed to be identified. Specifically, there are indications that the present management targets, coupled with stock assessments applied at large spatial scales, may not be sufficiently precautionary and that serial or local depletion may not be prevented.

It is unknown whether the apparent failure of the NPF tiger prawn stocks to recover during the 1990's was related to limited management options, serial depletion of stocks (Die *et al.* 2001), overexploitation (Dichmont *et al.* 2003a), continued increases in fishing power (Dichmont *et al.* 2003b), or to the continued use of the now somewhat discredited MSY and E_{MSY} management targets (Larkin 1977; Punt *et al.* 2001).

Dichmont *et al.* (2001) undertook preliminary stock assessments of tiger prawns in the NPF at fine spatial scales. These assessments showed that some stock areas were much more depleted than the single-stock assessment would suggest. There was a need to clarify which stock areas are most affected, and why these stock areas were performing so poorly. There was also a need to develop a multi-stock operating model to open a new direction for modelling in the NPF. This technically complex model would have the potential to benefit the management of benthic crustacean species worldwide.

Given the Australian Fisheries Management Authority's (AFMA's) requirement to satisfy its ESD objective, there was therefore a need to consider uncertainty explicitly and to identify assessment methods and harvest strategies for short-lived species that are as robust as possible to incorrect structural assumptions and errors caused by limited data. Most importantly, these assessment methods and harvest strategies needed to be developed in the context of spatially-explicit considerations and a management system based on input controls.

A Management Strategy Evaluation framework is developed to examine the effects of the spatial scale, the temporal scale, and the overall complexity of tiger prawn assessment models on the ability to provide appropriate management advice. In addition, the framework is used to compare several alternative Management Strategies. A multi-species and multi-stock model is constructed and used to represent the "true" resource (this model forms the main part of what is known as the operating model). An operating model based on a 5-stock, two-species, tiger prawn resource forms the basis for the evaluations. The structure of the tiger prawn resource is based on expert opinion of stock number and boundaries (Dichmont *et al.* 2001) and by estimating the values of model parameters using historical stock and species-group level logbook data (analysed separately to species level). Banana prawns are represented in the operating model by assuming that historical catch levels reflect the best appraisal of future catches. No stock-recruitment relationship is assumed for banana prawns, although preliminary studies suggest that one may exist (Vance *et al.* 2003).

The annual steps in the operating model are an automated representation of the present management system:

1. a tiger prawn assessment is undertaken every year;

2. the optimal effort and season length for achieving the target reference points for the fishery are recommended by the Northern Prawn Fishery Assessment Group based on this assessment; and
3. AFMA (on the advice of NORMAC) set the season dates and total effort level.

Historically, management action has been heavily biased towards the *status quo*; when fishing effort has been reduced, this has been implemented through changing the length of the season, reducing the number of fishing vessels, or reducing the amount of gear available for fishing.

Sources of uncertainty and error are explicitly included in the evaluations of this study, again based on past experience. These sources include:

1. errors or biases in the effort data used in stock assessments, caused by uncertainties in the process of splitting species-aggregated effort into effort by species;
2. biases or error in the results of assessments caused by inaccuracies in the key assumptions required, for example, assuming a single stock or incorrect values for model parameters (e.g. fishing power, catchability, etc.);
3. high levels of inertia on the part of management; and
4. implementation error when imposing management decisions - in this study, this source of uncertainty is assumed to relate only to the total level of fishing effort rather than the dates for the fishing season (VMS is good at detecting deviations from the latter). In the past, “implementation errors” led to the effect of a reduction in effort being much more *or* less than that intended.

Modelling the management system involved specifying formal decision rules to mimic the way management decisions are made, even though this fishery does not currently use decision rules.

Management strategies consist of an assessment procedure combined with a set of decision rules to determine the total tiger prawn effort levels each year. Three alternative assessment procedures are examined and compared:

1. a running 5-year linear regression of recent catch rates;
2. a biomass dynamic model that assumes a single-stock and operates on a annual time-step; and

3. a species-specific Deriso model with a weekly time-step (this model can be applied to the entire resource or in a multi-stock model).

Performance measures are developed to compare the risk to the resource and the economic performance of the fishery when different combinations of assessment procedure, decision rules and specifications for the operating model are considered. Furthermore, the ability to estimate key output quantities (estimates of parameters and management-related quantities) are quantified and presented.

Several performance measures are used. Many of the risk-related performance measures are defined relative to the spawning stock size corresponding to Maximum Sustainable Yield (S_{MSY}) because the NPF currently uses S_{MSY} as a Limit Reference Point (LRP); in fact, the LRP for the NPF is that there is a probability of more than 70% that the resource is above S_{MSY} . For ease of calculation, this project used the median of the S_{MSY} estimates as the LRP (i.e. 50%). Fishery stability is quantified through economic performance measures such as catch variability, long term catch (discounted at 5% per annum as suggested by economists, Kompas *pers comm*), the lowest catch during the projection period, and the probability of total tiger prawn catches falling below 2000t (seen as a very poor year).

Factors affecting Management Performance

An exploratory set of simulations is undertaken to evaluate the management system and to identify the key factors impacting performance. A statistically unbalanced design had to be used in this exploratory phase because a fully balanced design would have been computationally prohibitive. The key factors affecting performance were identified to be:

1. fishing power;
2. catchability; and
3. fishing power and catchability combined.

Factors found to be of lesser importance were:

1. the amount of implementation error;
2. whether recruitment is spatially correlated among stocks or not;
3. the method of capturing parameter uncertainty; and
4. error when compiling and summarizing the data used for assessment purposes.

These seven factors formed the basis for a subsequent balanced design of scenario runs.

Many of the management strategies based on the Deriso assessment procedure tend to leave the spawning stock size of *P. esculentus* below the target level of S_{MSY} in median terms. A case therefore could be made for choosing one of the more conservative management strategies; at least until a management strategy is developed that is better able to leave the spawning stock size of *P. esculentus* above S_{MSY} . There were two time series of fishing power termed the Base Case High and the Base Case Low, which bounded the range of possibilities that came from a detailed investigation of fishing power changes through time (Dichmont *et al.* 2003). Setting the fishing power series to Base Case High leads to more conservative management advice than setting the fishing power series to Base Case Low. The catchability is a parameter whose value is specified and not estimated. Two alternative values were used, the first as "q" (Wang 1999) and the second as twice "q", that is "2q". Of the management strategies based on the Base Case High fishing power series, that based on setting catchability to "2q" in the assessment is more conservative than that based on setting catchability to "q", although the difference is slight, at least compared to the impact of the choice of the fishing power series.

Care should be taken that the data have enough information to estimate stock size *and* catchability (if catchability is estimated within the assessment, as is the case for the biomass dynamic model). At present, only logbook data are available for assessment purposes and it seems unlikely that there is enough contrast in stock size and exploitation rate to estimate both stock size and catchability without serious bias and model instability. The new recruitment surveys in this fishery have the potential to provide the data required to estimate the values for parameters such as catchability, in contrast to the present situation where these values are either assumed and pre-specified (as is the case for the Deriso model) or estimated with low accuracy (as is the case for the biomass dynamic model).

Given the possibility of pre-specifying catchability at an incorrect value, it was necessary that performance indicators from stock assessments should focus on the ratio of the spawning stock size in a given year relative to, say, S_{MSY} or the spawning stock size that would achieve Maximum Economic Yield, S_{MEY} , rather than on effort, catch or spawning stock size in absolute terms.

The economic performance of the fishery can be severely compromised by implementation error. Hence reducing the degree of implementation error as much as possible should become a high management priority; historically it has been of the order of 18%.

Model complexity and scale

The influence of the temporal scale, the spatial scale, and the overall complexity of the assessment procedure on the performance measures is investigated. The ideal is to be able to use a simple assessment procedure and set of decision rules that is nevertheless able to achieve the management objectives for the fishery.

The difference between a target reference point (TRP) and a limit reference point (LRP) is important. The TRP is assumed to be the ideal state for the fishery (where the balance between long-term productivity and sustainability is optimized; see Caddy and Mahon 1995). On the other hand, the LRP is an agreed upon threshold state beyond which a fishery requires immediate and strong management measures to move the stock and fishery back towards the TRP. In the case of the NPF, the fishery moved in 2004 to using the Maximum Economic Yield (fixed to economic values determined in Rose and Kompas (2004)) as its TRP. However, this TRP is not considered in this thesis because it is not defined at the species level and because economic data were unavailable to the current project. It will, however, be used in a newly funded project where the Management Strategy Evaluation framework developed here will be expanded to include economic and ecosystem considerations.

Increasing the target spawning stock size used in the management strategy to define effort levels leads to higher spawning stock sizes (less risk) but lower catches (less reward). However, there is some non-linearity in the relationship between decreasing risk and decreasing reward. If the target spawning stock size used in the management strategy to define effort levels is increased from S_{MSY} to $1.2 S_{MSY}$ there is only a relatively minor loss in catch. However, as this target spawning stock size is increased above $1.2 S_{MSY}$ the reduction in catch grows disproportionately. When the target spawning stock size used in the management strategy is $1.6 S_{MSY}$ the lowest catch during the projection period is close to 1000t per annum and the median discounted catch is only about 70% of that when the target spawning stock size in the management strategy is S_{MSY} . The non-linearity of these effects implies that the benefits of increasing the target spawning stock size used in the

management strategy to slightly above S_{MSY} seem to exceed the costs. Catch rates would be higher if the stock size is higher, and this would be expected to offset the economic costs of reduced catches to some extent. However, in the absence of detailed information about costs available to this study, the size of the offset cannot be quantified precisely.

None of the management strategies are able to stabilize the spawning stock size of *P. esculentus* (particularly that in Karumba stock area) at S_{MSY} if they set the target spawning stock size used in the management strategy to S_{MSY} even when the assessment model is based on the most of the same assumptions as the operating model. Trying to account for stock structure by applying the assessment procedure to parts of the NPF (i.e. by conducting a spatially-structured assessment) did not resolve this problem, probably because, even if assessments are conducted spatially, there remain no restrictions on where in the NPF fishing is to occur. Since some stock areas have much higher abundances in absolute terms, and are consequently almost always fished, effort remains in those stock areas irrespective of their stock status and much higher effort moves to those stock areas than is required to leave the spawning stock size at (or above) S_{MSY} . Even reducing the total effort (by increasing the target level of spawning stock size in the decision rule) does not achieve the desired goal of reducing effort in stock areas such as Karumba and Mornington.

The estimates of S_Y/S_{MSY} from the Deriso model-based assessment are fairly accurate for *P. esculentus* when the assumptions about catchability and fishing power series made when conducting the assessment are similar to those on which the operating model is based. This implies that the inability to leave the spawning stock size of *P. esculentus* at (or above) S_{MSY} is not related primarily to inadequate assessments. Rather, this poor performance is probably due to inadequacies in the decision rules, either because the wrong season length is set or because the spatial allocation of fishing effort is unrestricted. In contrast to the case of *P. esculentus*, the estimates of spawning stock size for *P. semisulcatus* (and hence S_Y/S_{MSY}) provided by the Deriso model-based assessment procedure are biased. This bias does not, however, prevent management strategies based on this assessment procedure from leaving the spawning stock size of *P. semisulcatus* at S_{MSY} on average.

Changing the algorithm that specifies season length in the management strategy was examined, but, unless the method used to specify the total effort is also changed, modifying this algorithm to avoid catching *P. esculentus* simply leads to a reduction in size of the *P.*

semisulcatus spawning stock. Increasing management's responsiveness to scientific management advice by changing the season length *and* total effort when this is recommended by the management strategy did not improve performance. This result further demonstrates that it is the inability of management to influence the spatial distribution of effort that is the main reason for the poor performance.

It seems clear therefore that some form of spatial management will eventually be required to ensure that all stocks for both species are at or above S_{MSY} . This in turn may necessitate spatially-structured stock assessments. If it becomes necessary to undertake such assessments, it seems appropriate to select a spatial structure that allows results for the Weipa and Karumba stock areas to be obtained separately. However, although spatially-structured assessments may reduce the bias caused by applying an assessment procedure to data for several stocks simultaneously, it should be understood that a spatially-structured assessment could have higher levels of uncertainty attached to the outcomes, (a) because it needs to estimate more parameters from the same amount of data and (b) because stock boundaries, if they exist objectively at all, are poorly known with those presently used for this study based only on expert opinion. Other concerns associated with moving to a spatially-structured stock assessment relate to the true number of stocks and the implications of movement among putative stocks. If spatial management is impossible to implement the only way to ensure that the spawning stock size is at or above S_{MSY} for both species is to undertake a mixture of a short first season (or no tiger prawn fishing) and a conservative target spawning stock size for brown tiger prawns in the decision rule.

Despite moving to MEY as the TRP, it seems likely that management will continue to want estimates of management-related quantities such as spawning stock size relative to S_{MSY} . Therefore, any future management recommendations would have to be based, to some extent, on an approach which involves stock assessment of some sort. Of the two stock assessment procedures considered in this study, there seems little reason not to continue using the Deriso model-based assessment technique. Being the *status quo* is one advantage, but it has also become clear that without imposing additional constraints, the alternative stock assessment procedure (the biomass dynamic model) could become very unstable.

In principle, a reduction in the resources needed to conduct the assessment could be achieved without seriously compromising the management objectives if formal assess-

ments are conducted every few (2-3) years and the cpue regression approach used to provide management advice for the intervening years. This option has yet to be fully evaluated using the MSE framework and the benefits of going this route may be minor because assembling the data tends to be the most time consuming task when conducting an assessment.

In conclusion therefore it would seem that movement towards spatially-structured assessments and management is appropriate. This entails a judicious compromise between model scale and complexity yet to be determined. However changing the *ad hoc* way the fishery is currently managed to one in which the approaches used to determine effort levels and season length are clear to all is an essential ingredient of this process.

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CHAPTER 1 INDUSTRY, MANAGERS, AND SCIENTISTS AS PARTNERS IN AUSTRALIA'S NORTHERN PRAWN FISHERY

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1.1 Abstract

The Northern Prawn Fishery in Australia has a 6000 km coastline and a total area of some 250,000 km². The fishery catches nine species of prawns (shrimp). From its discovery in the mid-1960s, the management of the fishery has included scientists and fishers in the management decisions. We describe how the partnership approach has functioned and developed. This approach has allowed the research to be proactive, making the results timely and relevant. The manager of the fishery – the Australian Fisheries Management Authority (AFMA) – has empowered fishers with a structure of property rights. It has also established committees on which all stakeholders (scientists, government departments, fishers, and conservationists) can be represented. As fishers have helped direct the research, they are mostly amenable to accepting and acting on scientific advice. However, negotiations have not always been easy and some decisions have been delayed far too long. Nonetheless, over the history of the fishery, the system has successfully overcome many problems. We give some examples of these problems and how they were resolved:

- Research surveys identified the nursery habitats (seagrass and mangroves) of the prawns the fishery targets. Extensive areas were closed to trawling to protect the juveniles and their habitats. This research acquired valuable information on seagrass and mangrove biology; estuaries; fish biology and predation; stock assessment; impacts of trawling; oceanography; larval transport and conservation.
- In the mid-1980s, science-based assessments indicated that tiger prawn species (*Penaeus semisulcatus* and *P. esculentus*) were overexploited. After several major restructures and effort reductions, agreed to by industry and implemented by managers, the resource seems to have recovered by 2005.
- The NPF was the first fishery controlled by the Australian Government to produce a Bycatch Action Plan. It was a partnership initiative, rather than a legislative directive. The Plan covers both direct (e.g. turtle catches) and indirect impacts (e.g. effects of trawling on benthos). Before Turtle Excluder Devices (TEDs) were introduced in 2000, about 5500 turtles were captured by this fishery each year. In 2001 the entire fleet caught less than 100 turtles and of these, fewer than 10 are likely to have drowned. These devices have also resulted in many potentially vulnerable species of sharks and rays now being caught only rarely.

The NPF plans to move from managing the prawn fishery separately via efforts to quantify and reduce the impacts of trawling to managing the whole of the ecosystem (as discussed by Sainsbury *et al.* 2000). This means combining objectives on economics and the sustainability of target species with that of understanding and managing the impact of trawling on the ecosystem's structure and function. The new management focus will be developed in a partnership of managers, researchers, industry and other stakeholders, including representatives of the community. The NPF is contributing its extensive knowledge base to the development of a Northern Regional Marine Plan as part of the implementation of Australia's Oceans Policy (1998), which will be designating a representative system of Marine Protected Areas for biodiversity conservation (Australian and New Zealand Environment and Conservation Council 1999).

1.2 An Historical Perspective

1.2.a Discovering the fishery

The Gulf [of Carpentaria] had scarcely been explored since Matthew Flinders charted it in 1802–1803, but as its total area exceeds 250,000 square kilometres, it was decided to confine operations to the southeast corner . . . We knew that tiger, blue-leg king, endeavour and banana prawns were to be expected in the Gulf But the abundance of juvenile banana prawns in the environs of the river mouths suggested that . . . large school of banana prawns concentrated in tight balls might be present [In] late May 1964 we found the first ball of 600 lb.

Ian S. R. Munro, project leader of the Gulf of Carpentaria Prawn Survey 1963–65

Exploratory fishers had found banana prawns in the Gulf in the 1950s, but at densities too low to justify a fishery (Pownall 1994). The Gulf of Carpentaria Prawn Survey of 1963–65 created history as the first properly conducted scientific investigation in Australia to lead directly to the development of a major fishery. The survey was a joint operation of Commonwealth and State government departments, Craig Mostyn and Co. (a private fishing company) and the Commonwealth Scientific and Research Organisation (CSIRO) Division of Fisheries and Oceanography. The fishery that developed in the late 1960s as a result of the survey's success is known as the Northern Prawn Fishery or NPF (Figure 1.1).

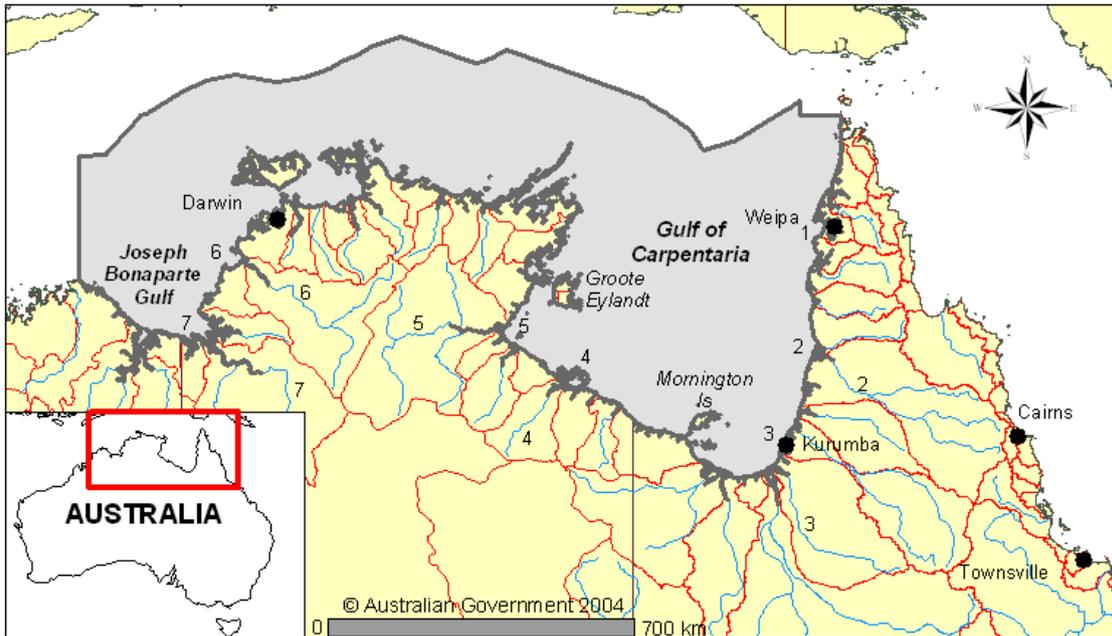


Figure 1.1: Map showing the extent of the Northern Prawn Fishery. Insert shows its position in the northern tropics of Australia. Source: AFMA, 2000. Also shown are catchments and some of the main river systems adjacent to the Northern Prawn Fishery shaded in grey. 1 = Embley River, 2 = Mitchell River, 3 = Norman River, 4 = McArthur River, 5 = Roper River, 6 = Daly River, 7 = Victoria River.

When commercial prawn fishing began in the Gulf of Carpentaria, it initially targeted only the banana prawn *Penaeus merguensis*, a species that formed dense aggregations that stir the sediment, making mud ‘boils’ visible on the surface. Catches of *P. merguensis* peaked at more than 12,000 t in 1974 (Figure 1.2) and have remained high, although they fluctuate from year to year. These large catches, together with the open access to the fishery (which attracted large foreign vessels in the 1960s and 70s) and government boat-building subsidies, resulted in the fishing fleet growing to about 280 vessels in the early 1980s. Furthermore, because *P. merguensis* is short-lived and aggregates, the fishery made substantial investments in processing and targeting equipment. The increased efficiencies led to the number of fishing days being reduced from year-round in the 1960s, to a few months in the 1970s, and to just over a month in the 1990s and thereafter (Somers and Wang 1997).

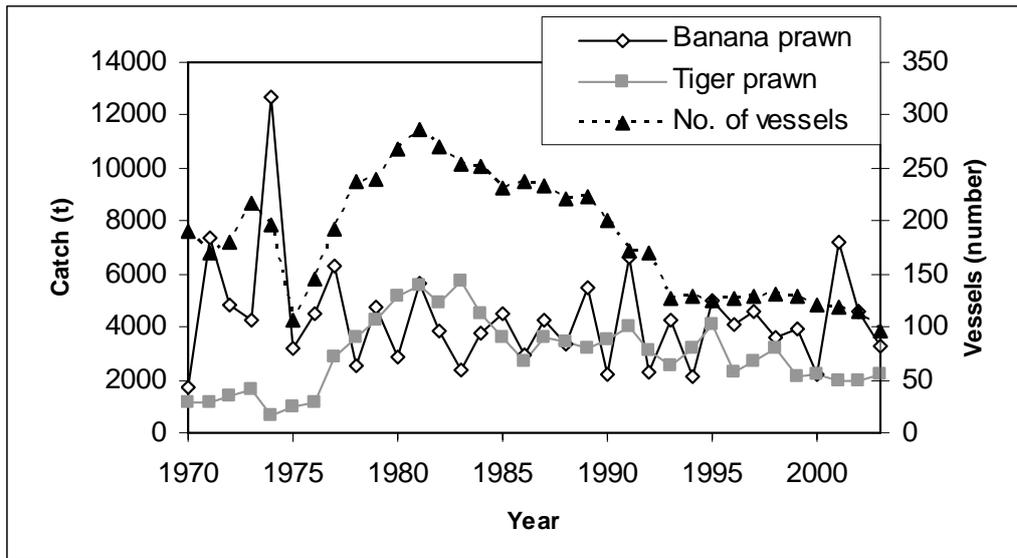


Figure 1.2: Annual banana and tiger prawn landings (tonnes) and the number of vessels fishing in the Northern Prawn Fishery.

The area fished in the NPF increased greatly during the late 1970s and early 1980s when a different suite of prawn species was captured: two valuable tiger prawn species (*Penaeus esculentus* the brown tiger and *P. semisulcatus* the grooved tiger), the less valuable endeavour prawns (*Metapenaeus endeavouri* and *M. ensis*), and a minor fishery for blue-legged king prawns (*P. latisulcatus*). (Note that the subgenera of *Penaeus* were elevated to genera by Pérez-Farfante and Kensley (1997). However, there is some controversy over the revised nomenclature; this present paper follows Baldwin *et al.* (1998) and Lavery *et al.* (2004). This tiger prawn fishery expanded rapidly, until it, too, began to suffer from excessive capacity and declining catches in the mid-1980s.

During the early 1980s, a fishery that targets a different banana prawn species (*P. indicus*) started in the Joseph Bonaparte Gulf, two to three days steaming west of the Gulf of Carpentaria (Figure 1.1). As a result, from the 1990s, the Northern Prawn Fishery covered the full range of commercial prawn species available in the northern region.

1.2.b Management

The original vessels in the fishery were mostly small (length mode of about 16 m) wooden otter trawlers towing four nets and using brine storage tanks (Figure 1.3). In contrast, the vessels in use today are predominantly large (length mode of about 22 m) steel prawn trawlers towing two large nets (Figure 1.3). They are equipped with colour sounders, satellite-based tracking systems and large freezers. They reduce down time by offloading their

product to barges. Spotter planes are used during the banana prawn season for finding concentrations of prawns. A considerable effort to improve quality has led to the introduction of snap freezers as well as grading and packing at sea. The fishery now lands between 6,000 and 8,000 tonnes of prawns annually. The fleet was reduced from more than 280 vessels in the 1980s to the present fleet of 85 vessels after many changes to management arrangements (Figure 1.2). From 1992-93 to 2001-02, the real revenue for operators in the NPF fluctuated between AUD115.8 and AUD185.7 million, with an average of AU\$146.8 million (in 2002-2003 dollars) (Galeano *et al.* 2004), making the NPF one of Australia's most valuable fisheries.



Figure 1.3: Typical vessels built in the 1970s (top) and in the 1980s or 1990s (bottom). Both vessels are still active in the fishery today, although the top vessel type is now uncommon. Source: Bob Pendrey, CSIRO (top) and David Vance, CSIRO (bottom).

Input controls (e.g. size of gear, number of fishing days) rather than output controls (e.g. catch quotas) are the basis for management of the NPF. Initially, the fishery was managed by the two States and the Territory whose waters include the NPF; unfortunately there was rarely a unified management response for resources that occurred within more than one jurisdiction (Taylor and Die 1999).

An Offshore Constitutional Settlement (OCS) between the Governments of the States of Queensland and Western Australia, and the Northern Territory, and the Australian Federal (or “Commonwealth”) Government was signed for the NPF in 1988. The Australian Federal Government became responsible for many of the resources in the NPF that straddle State or International boundaries. The Australian Fisheries Service (restructured in 1992 to form the present-day Australian Fisheries Management Authority (AFMA)) became responsible for the management of the NPF.

AFMA is responsible for the day-to-day management of fisheries that fall under the jurisdiction of the Australian Federal Government. The *Fisheries Management Act 1991* includes five specific legislative objectives:

1. Implementing efficient and cost-effective management on behalf of the Commonwealth (Australian Federal Governments).
2. Ensuring that the exploitation of fisheries resources and the carrying on of any related activities are conducted in a manner consistent with the principles of ecologically sustainable development, in particular the need to have regard to the impact of fishing activities on non-target species and the marine environment.
3. Maximizing economic efficiency in the exploitation of fisheries resources.
4. Ensuring accountability to the fishing industry and to the Australian community in the Authority’s management of fisheries resources.
5. Achieving government targets in relation to the recovery of the costs of the Authority.

AFMA is a Statutory Authority with a Board consisting of a Chairperson, Government Director, Managing Director, and five nominated directors. No more than two directors can be currently engaged in fishing or fish processing (see Smith *et al.* 1999 for further details).

1.2.c The partnership approach

The *Fisheries Management Act 1991* emphasises a ‘partnership approach’ among fishery managers, scientists, the different sectors of industry such as processors and owners, members of conservation groups, and other relevant stakeholders. This partnership involves close consultation, but also direct input into, and responsibility for, providing advice to the AFMA Board.

Two of the committees established to facilitate this process are fundamental to the successful management of the NPF: the Northern Prawn Management Advisory Committee (NORMAC), and the Northern Prawn Fishery Assessment Group (NPFAG)¹. Although these committees interact and provide advice to each other, they report directly and independently to the Board of AFMA, thereby maintaining the independence of scientific and management advice. NORMAC has an independent chairperson and eight members (five from industry, one from a conservation group, a scientist, and an AFMA representative). There are also two permanent observers: one representing the Northern Territory and the States of Queensland and Western Australia and, recently, one from the Commonwealth Department of Environment and Heritage; the Department responsible for independently auditing Australia’s export fisheries. The NPFAG has about 10 members; mostly stock assessment, biological and economic scientists; fisheries managers; and industry members. It is the technical committee that provides scientific advice on the status of stocks, bycatch and the ecosystem.

The second major piece of legislation affecting the operation of fishers in the NPF is the *Environment Protection and Biodiversity Conservation (EPBC) Act 1999*. Under this act, every export fishery in Australia must be certified every five years as being ecologically sustainable to obtain a licence to export product from Australia. The two main principles against which the sustainability of a fishery is assessed are:

1. A fishery must be conducted in a manner that does not lead to over-fishing, or for those stocks that are over-fished, the fishery must be conducted such that there is a high degree of probability the stock(s) will recover.

¹ recently renamed to the Northern Prawn Resource Assessment Group

- Fishing operations should be managed to minimise their impact on the structure, productivity, function and biological diversity of the ecosystem.

In its first attempt, the NPF was successfully certified under the EPBC Act in 2004.

1.3 A complex ecosystem in time and space

Prawns grow rapidly and most reach commercial size and reproductive maturity at the age of 6 months, although they take 9 to 12 months to reach the larger, more valuable, sizes. In the life-cycle of many of the commercial penaeids in northern Australia the sub-adults and adults live in offshore waters. The post-larvae and juveniles are found in the intertidal and shallow subtidal waters of estuaries and coastal waters (Figure 1.4; see Dall *et al.* 1990 for a full explanation). The combination of tidal currents and the behaviour of the larvae and post-larvae provides the mechanism for the larvae to move to the inshore/estuarine nursery habitats (termed 'larval advection' e.g. Rothlisberg *et al.* 1995, 1996; Condie *et al.* 1999), while the juvenile emigration from these habitats is size-related in some species, but in banana prawns is stimulated by the amount of rainfall and reduction of salinity in estuaries (Staples and Vance 1986).

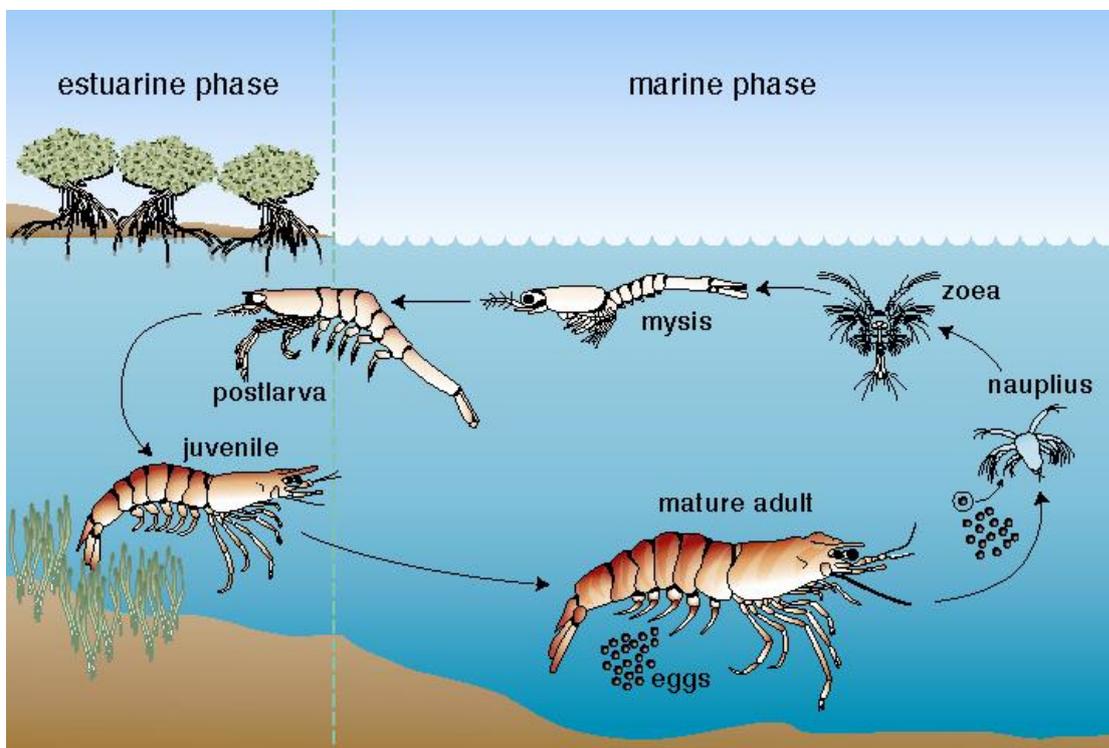


Figure 1.4: The life-cycle of the prawns caught commercially in the Northern Prawn Fishery showing inshore nursery habitats and offshore spawning grounds and larval habitat (drawing by Louise Bell, CSIRO Marine Research).

Rainfall in northern Australia is dominated by the summer monsoons, with about 90% of rainfall between December and April and effectively no rainfall between June and September (Figure 1.5, Vance *et al.* 1985, Gillanders and Kingsford 2002). The influence of rainfall on the estuaries and coastal waters is moderated by the size of the catchments, which vary greatly around the Northern Prawn Fishery (Figure 1.1). For example, rivers in the north-eastern Gulf of Carpentaria are relatively short, with small catchments. The size of both the river systems and catchments increases towards the south-east. Consequently, in high rainfall years, the effects of rainfall on salinity in the estuaries and coastal waters of the Gulf of Carpentaria are greater and last longer in the south-east (Vance *et al.* 1998). The distribution of seagrass, the critical settlement and juvenile habitat for tiger prawns, may also be affected by the interaction of catchment size and rainfall. Thus seagrasses have a very limited distribution along the eastern Gulf of Carpentaria and increase in coverage and diversity in the western Gulf, where rainfall is low and catchments are smaller (Figure 1.6) (Poiner *et al.* 1987, 1989, Poiner and Peterken 1995). There is a link between high rainfall and banana prawn catch, although this connection is moderated by the interaction between rainfall and catchment size (Vance *et al.* 1998).

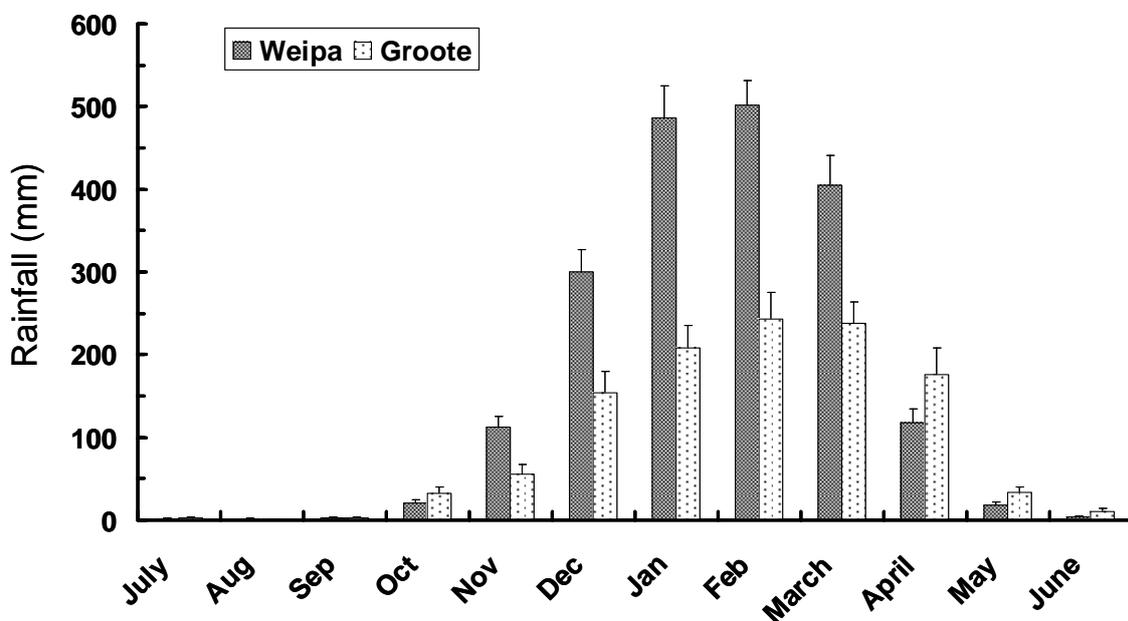


Figure 1.5: Mean annual rainfall (+ 1 SE) for Weipa in the north-eastern Gulf of Carpentaria and for Groote Eylandt in the western Gulf of Carpentaria for the period between 1970 and 2000. Data provided by the Bureau of Meteorology.

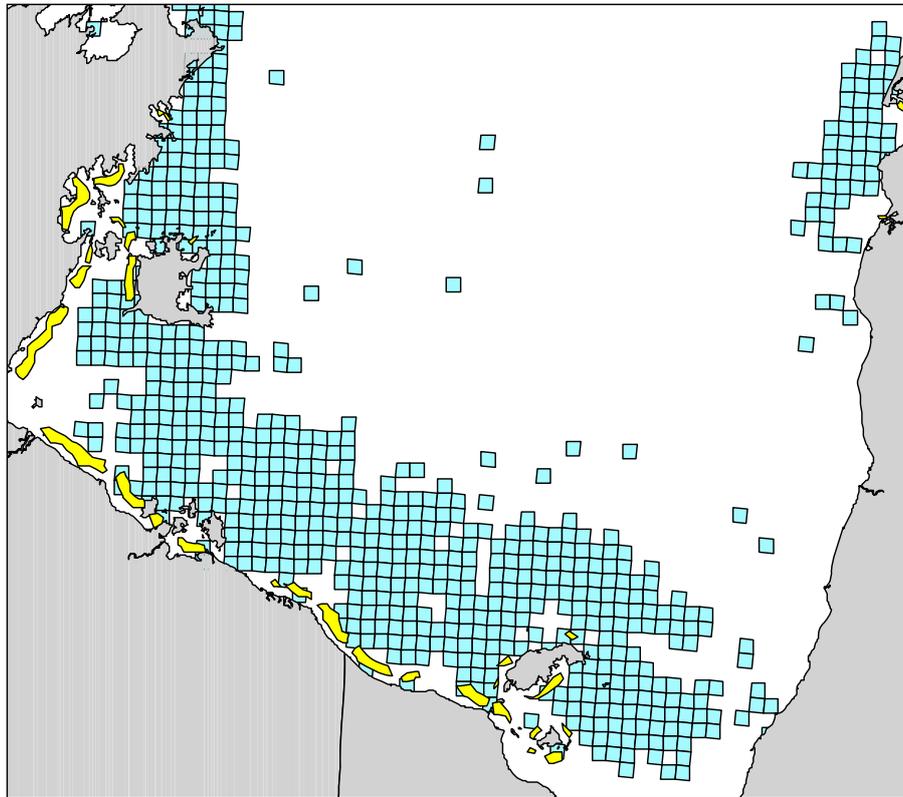


Figure 1.6: Distribution of seagrass in the Gulf of Carpentaria (yellow line close to the coast, from Poiner *et al.* 1987) and the 6 nm grids where the average annual catch of tiger prawns is reported to exceed 150 kg.

1.3.a Coastal habitats and prawn production

In the NPF region aquatic vegetation (seagrass and algae) provides the critical nursery habitat for tiger prawns *Penaeus esculentus* and *P. semisulcatus* (Loneragan *et al.* 1998), whereas juvenile banana prawns, *P. merguensis* and *P. indicus*, are found along mangrove-lined mudbanks (Staples *et al.* 1985, Vance *et al.* 1998, Kenyon *et al.* 2004a). Western king prawns *P. latisulcatus* are associated with sandy substrates (Potter *et al.* 1991). In general, most post-larvae and juveniles recruit to inshore waters between October and December, and February and April. The juveniles recruit into the fishery over many months fairly continuously except during the winter months from June to September (e.g. Dall *et al.*, 1990; Vance *et al.*, 1996; 1998).

The significance of coastal habitats to the productivity of the Northern Prawn Fishery was recognised very early in the fishery by researchers, managers and fishers. As a result, trawling has been banned in the rivers of Queensland since the 1960s and over seagrass

beds in the inshore waters since the early 1970s (Taylor 1994). Research on understanding the relationship between coastal habitats and prawn populations has been supported and encouraged by industry and managers since the 1970s and is continuing. The managers of the fishery now have valuable information on the distribution of juvenile prawns in relation to different coastal habitats (e.g. Staples *et al.* 1985), the impact of the loss of coastal habitats on juvenile prawn populations and the fishery (Rothlisberg *et al.* 1988; Poiner *et al.* 1992) and the processes that affect juvenile prawns in their coastal nursery habitats (Loneragan *et al.* 1996). The partnership approach and the appreciation of the significance of coastal habitats to fishery production led to closure of seagrass beds and inshore waters to trawling from the early 1970s (Kenyon *et al.* 2004b).

1.3.b The environment of the fishery

Depth and sediment type influence the distribution and abundance of commercial-sized penaeids (Dall *et al.* 1990). In general, most catches of *P. merguensis*, *P. esculentus* and *M. endeavouri* are taken in depths from 20 to 40 m, those of *P. semisulcatus* and *M. ensis* in 30 to 50 m, while *P. indicus* is fished at 50 to 80 m in the Joseph Bonaparte Gulf (Somers 1994a, b). The proportion of mud in the sediments influences distribution: *Penaeus indicus*, *P. merguensis* and *P. semisulcatus* are found in areas with a higher proportion of mud (65 to 100%) than *P. esculentus* and *M. endeavouri* (20 to 80% mud); *Metapenaeus ensis* spans a range of sediment types (30 to 95% mud); *P. latisulcatus* is found on sandier substrates (< 50% mud) (Somers 1994a, b).

The inshore waters of the Gulf of Carpentaria are mainly a turbid, muddy marine environment. The offshore waters are generally clear over soft sediments with patches of rich, hard-bottom communities such as sponges and corals. The hard substrates prevent these patches in the Gulf and other regions of the NPF from being trawled (Hill *et al.* 2002). A survey of the Gulf of Carpentaria in May 2004 located several of these patches in the south-eastern Gulf and found extensive epibenthic communities of sponges, corals and other species living at depths of about 20 m. The plotters fishers use to record information on trawls show that the distribution of these untrawlable grounds varies greatly throughout the Gulf, ranging from about 2% of the total area in the Weipa region up to about 40% in the north of Mornington Island and the Vanderlin Islands in the southern Gulf (Die *et al.* 2001). The geological history of these hard-bottom areas is still to be determined. Apart

from these areas of untrawlable ground, trawlers target areas of high prawn abundance. As a result, only about 25% of the NPF is trawled and a much smaller area is trawled heavily (> 100 days of trawling each year) (Die *et al.* 2001).

Demonstrating the sustainability of the fishery requires knowledge of the impacts of trawling on the prawns, the environment and other species caught in trawl nets (see later the section on impacts on other species). The NPF covers about 6,000 km of coastline and 15 marine bioregions identified in the Interim Marine Comprehensive Representative Area process (IMCRA 1998). Little is known of the benthic flora and fauna, particularly outside the Gulf of Carpentaria. Of 16 research surveys carried out in the NPF (reviewed in Hill *et al.* 2002), all except two were targeted at prawns and not the general biology of marine communities. NORMAC has encouraged research to increase knowledge of the 15 bioregions and to assess the areas potentially designated as Marine Protected Areas, particularly their effect on the fishery. This support resulted in the design and completion of a major survey to collect simultaneous data on the benthic habitats and fauna they support, and on the hydrographic environment, in the Gulf of Carpentaria. The survey was completed on the 66 m research vessel Southern Surveyor in March 2005.

1.4 Sustainability of target species

1.4.a Assessment advice

Simulation modelling techniques based on biological information and fishery-dependent field data were used from the 1970s to determine the opening dates of the banana prawn fishing season in order to maximise the value-per recruit (e.g. Lucas *et al.* 1979, Somers 1985, 1990, Somers and Wang 1997). Much of this research was based on extensive pre-season sampling over many years in several stock areas of the NPF. This work would not have been possible without cooperation of industry, which provided vessels at no charge (Somers and Taylor 1990). Stock assessments of the tiger prawn resource during the 1990s and 2000s showed that both prawn species were overexploited, and the relevant committees were informed (see

Table 1.1 for references and management details). Assessments of the tiger prawn resource changed from being simplistic to very complex and computer intensive: from an equilibrium surplus production model (Somers 1992) to an age-based (Wang and Die 1996) or biomass dynamic model (Haddon 1997, 2000, 2001), and ultimately to a delay-difference model within a Management Strategy Evaluation framework (Dichmont *et al.* 2001, 2003a, 2005). The later models consistently found that the tiger prawn resource was overexploited.

Perhaps the most influential scientific discovery for management of the fishery was that a strong stock-recruitment effect for tiger prawns became apparent: the expected level of recruitment declines with declining spawning-stock size (Wang and Die 1996). This was unexpected, because the prevailing scientific view was that prawn fishing, no matter how intense, would not affect the future productivity of the resource. However, the possibility of there being a stock-recruitment effect was seen as more likely by the scientific community (if not industry) when this finding in the NPF was combined with the collapse of the tiger prawn resource in Exmouth Gulf in 1982–83 (Penn and Caputi 1986, Anon 2003). A recent meta-analysis of published data on tiger prawn populations throughout the world found that prawn recruitment was in fact related to the abundance of spawners. It concluded that prawn populations should be managed to maintain sufficient mature adults to yield high recruitment (Ye 2000).

1.4.b History of effort reductions

Management of the NPF since the 1980s has been characterised by attempts to restructure the fishery and reduce effort. This was driven by the substantial increases in effort when new technologies were adopted as well as by declining catches. Several approaches to reducing the size of the fleet (

Table 1.1) led to a marked drop in the number of vessels in the fishery (Figure 1.2). However, this did not necessarily equate to a reduction in fishing mortality (Bishop *et al.* 2000, Cartwright 2005), because all vessels are not equally efficient and the fishing power of individual vessels increases over time (Dichmont *et al.* 2003b). As early as 1987, Buckworth (1987) quantified substantial increases in vessel fishing power, which continued through the 1990s, particularly with the advent of colour sounders and Global Positioning Systems (Robins *et al.* 1998, Bishop *et al.* 2000, Dichmont *et al.* 2003b). In the early years, total effort did not decline when vessels left the fishery as those remaining simply increased the number of hours they fished. Later, the introduction of new technologies increased fishing effort. Certain sections of the industry were reluctant to accept these findings. Considerable research was done to quantify the extent of the change.

In 1985, each vessel was assigned a number of “A-units” (a transferable Statutory Fishing Right based on vessel volume and engine horse power) and effort reductions were based on these units. However, this system was inflexible (because even small A-unit reduction could result in boats being unable to fish) and actually impeded restructuring the fleet. Eventually, both industry and management agreed that the A-unit management system had to be changed. Consequently, NORMAC formed a working group in 1992 to investigate alternative management systems, and AFMA and NORMAC embarked on extensive consultations in 1993 to determine the form of a new management system.

Scientists expressed concern about the status of the tiger prawn stocks in the NPF throughout the late 1990s, declaring the tiger prawn resource biologically overexploited every year from 1997 (e.g. Die *et al.* 1997), and noting that fishing power was increasing rapidly (Dichmont *et al.* 2001). For example, the use of GPS and plotters to target prawns was shown to increase fishing power by 12% over three years (Robins *et al.* 1998). Scientists expressed their concerns at NORMAC meetings from 1995 (

Table 1.1). However, the reductions in fishing effort implemented in the 1990s were less than those advised by the NPFAG and were often partly offset by increases in vessel fishing power. Advice, based on stock assessments included the effort reductions required to reach NORMAC's 1990s management target of setting the effort at a level that would achieve the Maximum Sustainable Yield (MSY). However, decisions on major effort reductions were delayed pending the change from one management system to another. For example, the NPFAG advised in 1998 that effort on tiger prawns should be reduced immediately by 35%, but the management action (a three-week closure) is estimated to have reduced fishing effort by only 15% (NORMAC 45).

There was general agreement in the industry – and unanimous agreement at NORMAC in November 1996 – that management should change to a system based on tradeable gear units (the number of gear units a vessel has defines the amount of headrope it can use). However, the industry's consensus disappeared once the formula for converting A-units to gear units was determined; operators who considered that they would be disadvantaged by the formula opposed the change (Cartwright 2005, Stone 2005). These operators, who were composed of smaller Statutory Fishing Right holders, also disputed the results of the stock assessment, especially that fishing power was increasing. Instead they argued that changes in the catch-rates were largely attributable to environmental factors, predation, or the reduced fleet being too small to work all the prawn grounds effectively (Cartwright 2005). The dispute within the industry led to a Senate Inquiry, which ultimately supported the shift to gear units and the simultaneous reduction in effort. An International review of the stock assessment methods supported the conclusion based on the stock-assessment advice that the resource was overexploited (Deriso 2001).

In the early 2000s, three major changes were made to the management of the fishery:

- The gear unit system, based on head-rope length, was implemented – and immediately reduced effort by 25%.
- Scientific advice on the need for a further substantial reduction in fishing mortality was accepted – the effort on *P. esculentus* was cut by 40% and of *P. semisulcatus* by 25% (Dichmont *et al.* 2001).
- An annual independent monitoring program (financed mainly by the industry) aimed at creating a recruitment and spawning index of abundance was implemented (Dichmont *et al.* 2002, Dichmont *et al.* 2003c, Ye *et al.* 2004).

The reductions were implemented in 2001 by shortening the total headrope length by 25%. In addition, changes were made in the length of fishing seasons to reduce fishing effort on brown tiger prawns (*P. esculentus*). The indications today are that there has been some recovery of the tiger prawn stock (NPFAG 2004). Management also changed its objectives from setting the level of fishing effort to achieve MSY to managing so that there is at least a 70% probability that the size of the spawning stock is above that to achieve MSY. Furthermore, the fishery invested heavily in a large-scale annual independent monitoring program (Dichmont *et al.* 2003c). In 2005, management again changed its objectives to achieving Maximum Economic Yield.

1.5 Prawns are not the only catch

The impact of fisheries on their incidental and unwanted catch, or bycatch, has become a growing and major issue in the last 15 or so years (e.g. Andrew and Pepperell 1992, Alverson 1994, Kennelly 1995). Trawl nets used to catch prawns have small mesh throughout and are towed along the sea bed where many other species live. Consequently, this relatively unselective fishing gear often catches a large and diverse suite of non-target species. Alverson (1994) estimated that around one third of the world's discards come from prawn trawl fisheries. The bycatch consists mostly of small fish with no commercial value in an industrial fishery. The resulting large quantities of discards and the impact of trawls on endangered or vulnerable and often charismatic species (such as turtles, sharks, rays, sawfish and seahorses) have given prawn-trawl fisheries a poor reputation.

The NPF catches a variety of bycatch species, usually making up more than 90% of the catch (Brewer *et al.* 1998, Stobutzki *et al.* 2001b). These species include:

- large quantities of small teleost fish (between 87.5% and 95.2% of the catch by weight and >300 species; Pender *et al.* 1992, Blaber *et al.* 1997);
- six species of marine turtles;
- >50 species of elasmobranchs (sharks, rays, sawfish etc; Stobutzki *et al.* 2001b);
- 13 species of seasnakes (Milton 2001);
- 230 benthic invertebrate taxa (Stobutzki *et al.* 2000).

Many of these species are dead when discarded, or have a poor chance of survival (Hill and Wassenberg 1990, 2000). Some are endangered (e.g. five of the six marine turtles) or protected by Australian law (e.g. sea snakes, sea horses and pipefishes). Others (e.g. most

elasmobranchs) have life histories that make them highly vulnerable to population declines with any increases in mortality rates (Last and Stevens 1994).

The high volume and diversity of the bycatch of this fishery continue to present fishery operators, managers and researchers with significant challenges. The *Australian Fisheries Management Act 1991* and the *Environmental Protection and Biodiversity Conservation Act 1999* require that negative impacts on endangered species are prevented, catches of non-target species are reduced and the long-term sustainability of bycatch and byproduct populations is demonstrated.

1.5.a Staying ahead of the game

Since the emergence of bycatch issues in fisheries, the NPF has actively sought knowledge and implemented bycatch avoidance initiatives. This has been directly due to the partnership approach to decision-making in this fishery. The balance of views from the different NPF committees has provided a well-considered, logical and forward-thinking approach to bycatch and other ecological issues.

The success of this partnership approach to decision making has been well demonstrated by the early recognition by the industry that the fishery had significant bycatch issues. Furthermore, its demonstrated intention was to understand and manage them in order to reduce criticism of the fishery and ensure its longer-term economic and political viability. Had industry adopted a ‘head in the sand’ approach to these issues, a more detrimental outcome for the fishery may well have resulted, as seen elsewhere (e.g. the expensive legal battles with conservation groups or Government, as experienced by United States shrimp fishery organisations over the compulsory introduction of Turtle Excluder Devices).

The NPF’s determination to tackle bycatch issues has resulted in a variety of initiatives that have set a platform for effective management into the future and a benchmark for other fisheries. These initiatives include establishing a broadly representative NORMAC subcommittee to advise specifically on bycatch issues (previously known as the ‘TED and BRD subcommittee’, now the ‘Fishing Impacts and Solutions Working Group’); supporting and funding a range of programs to improve knowledge of bycatch and related issues (

Table 1.2), and instigating a new blueprint – the NPF’s Bycatch Action Plans (NORMAC 1998, 2003) – to guide the direction of bycatch issues into the future. The use of Bycatch Action Plans is now widespread in Australian fisheries, with another nine Commonwealth-managed fisheries adopting similar plans.

1.5.b Bycatch research and management

Some initiatives aimed at managing prawn stocks have indirectly, but significantly, reduced the impacts on bycatch. For example, a series of effort reductions since the mid-1980s has reduced the annual number of boat days in the industry from 34,000 to the current level of 12,500. There has been a concurrent reduction in area fished from 1240 6-minute grids in 1984 to 804 in 2000. Although not quantified, this greatly reduced effort is likely to have improved the sustainability of bycatch populations in the Gulf of Carpentaria and other regions in the NPF.

Perhaps the most significant management initiative relating directly to bycatch was the mandatory introduction of Turtle Excluder Devices (TEDs) and Bycatch Reduction Devices (BRDs) in 2000 (Figure 1.7). TEDs are, in their most common form, inclined hard grids (Figure 1.8) that guide any large object or organism out of the trawl before it reached the codend and is not retained in the catch. Their introduction has resulted in a 99% reduction in catches of marine turtles (from $5,730 \pm 1,907$ p.a. in 1979 to 1988 (Poiner *et al.* 1990) to less than 100 in 2001) and of turtle drownings (from 344 ± 125 p.a. to less than 10 (Brewer *et al.* 2004)). The catch of large elasmobranchs (sharks >1 m long or rays >1 m wide) has also been reduced by 91% since the introduction of TEDs (Brewer *et al.* 2004).

The implementation of this change to the fishing operations followed two large research projects: to investigate the most effective TEDs and BRDs for this fishery (Brewer *et al.* 1998), and to help with the installation and effective use of TEDs in particular (Robins *et al.* 2000) (

Table 1.2). Both projects were funded as a result of NORMACs support. These projects also ensure that the prawn catch was reduced by only 3 to 6% when TEDs and BRDs became mandatory in 2000. Undoubtedly this result ensured the high TED compliance of NPF fishers.

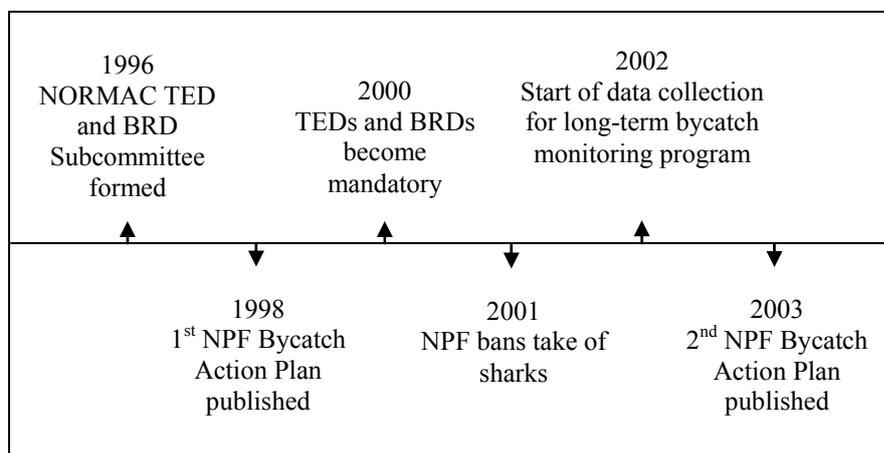


Figure 1.7: Time series of management actions to reduce the NPF’s impact on bycatch species.

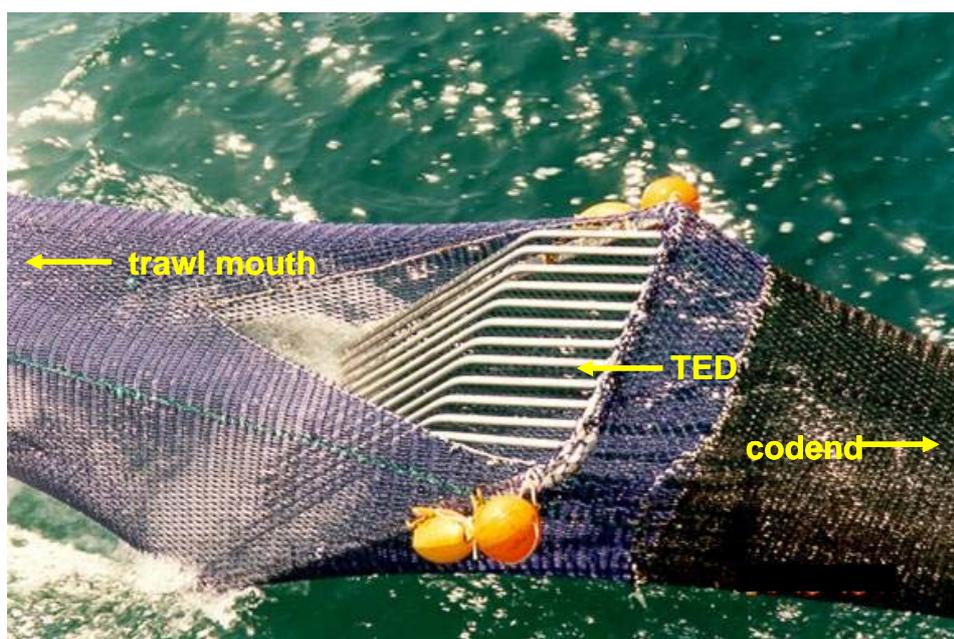


Figure 1.8: Turtle Excluder Devices (TEDs) have been mandatory in trawls in Australia’s Northern Prawn Fishery since 2000. They have dramatically reduced catches of endangered marine turtles and vulnerable species of sharks, rays and sawfish. The exit opening is normally covered by an open flap of netting.

Other projects supported by NORMAC, and subsequently funded, have increased our understanding of the interaction between the fishery and populations of species impacted incidentally. For example, the effects of trawling on the seabed biota of the NPF between 2002 and 2005 were quantified; a study was made of the sustainability of the bycatch and

biodiversity in prawn trawl fisheries between 1996 and 1999; and baseline descriptions were made of the composition of bycatch taken by the tiger prawn fishery (Stobutzki *et al.* 2001b) and the banana prawn fisheries (see Table 1.2 for details of these and other projects). Research such as this enables the NPF to make informed decisions about how to manage its environmental impact. The research has also led to the development of new methods to assess the risk that bycatch species populations will not be sustainable (Stobutzki *et al.* 2001a and 2002). These risk-assessment techniques have subsequently been adopted by other fisheries (Hobday *et al.* 2004).

Some of the key decisions made by the NPF have been based on information from other fisheries and other sources of scientific data. For example, in 2001 NORMAC banned the retention of any elasmobranchs (sharks, rays and sawfish). This decision was based mainly on the growing body of evidence that these species are highly vulnerable to many forms of fishing pressure (e.g. Last and Stevens 1994) and that thriving trade in their fins was seriously depleting shark populations around the world (e.g. NOAA News Release 2002).

The NPF's decisions and actions to reduce bycatch have allayed the criticism of the industry and paved the way for positive assessments of the NPF's impact on species and communities by the Australian government's primary environmental auditing agency (achieved in 2004), and the United States of America's team charged with placing import embargos on countries not using TEDs effectively (achieved for the NPF in 2001).

1.5.c Cooperation, participation and compliance

The partnership approach to fisheries management with fishing company managers and fishers on the committees has given industry an active role in research and monitoring programs. Participating in programs with an ecological focus has helped NPF fishers to understand the requirements of modern fisheries management and has overcome barriers to their participation in sampling and monitoring programs. As an example, many of the research projects listed in Table 1.2 have depended on the investment and voluntary participation of fishers, which has often included attending training programs to learn how to identify bycatch species and collect high-quality monitoring data.

The value of industry participating in management is also demonstrated in the fishery's high rates of compliance with management changes to their fishing operation. For exam-

ple, the introduction of TEDs in 2000 was not widely welcomed at first by NPF fishers. However, despite relatively little enforcement, industry has almost unanimously and effectively implemented these devices (Robins *et al.* 2004).

1.5.d Future challenges

The NPF's management processes and responsible attitude towards ecological issues has helped develop an unusual culture amongst its fishers. Perhaps the most impressive feature of this fishery's progress in dealing with these issues has been its willingness to look for solutions and to fund programs that are clearly breaking new ground. It has accepted the challenges of managing its impacts on the complex and varied bycatch species by taking a step-by-step approach to understanding and resolving these issues. The subsequent knowledge, and the innovative techniques adopted by the NPF, have led to strategies that set the benchmark for best practice in many areas of bycatch management.

Current initiatives aim to establish new, more accurate, risk assessments for bycatch species and a long-term program that will monitor the status of bycatch populations. Fishers are currently working in a program of continuous improvement of BRDs to maximise their effectiveness and reduce the quantity of small fish and invertebrates taken incidentally in catches. The challenges are likely to include devising processes to establish marine protected areas, better understanding of the unseen effects on sessile benthic communities, and management of the fishery's interaction with species at significant risk from this industry, including sawfish and sea snakes. The NPF's record in dealing with difficult issues such as these is noteworthy and the management processes it has developed should smooth the way for its continuation and success in the future.

1.6 Summary

1.6.a An analysis of the performance of the MAC, science and AFMA

The partnership approach of AFMA has been a great success, but it has been hard, challenging, work. It has helped produce excellent science that is relevant to industry and management and is also extensively referenced internationally. It has responded effectively to environmental issues, such as protecting major nursery areas, protecting recruits and spawning prawns, and also reducing the bycatch of many vulnerable species. In addi-

tion, the partnership approach has produced clearly defined objectives for the fishery (NPF Strategic Plan and the Bycatch Action Plan) and strategic directions for research (Five-year Strategic Research Plan), which have resulted a good balance between tactical and strategic research and management.

There can be a downside to the partnership approach. When management decisions will affect the economic viability and the tenure of individual fisher's in the industry, debate can become heated and decisions can be delayed or stalled altogether. For example, there was about 7 years between the time when concerns about tiger prawn stocks were first raised to the time when decisive management action was taken. Even so, while there was still no consensus on the status of the stocks, the decision to reduce effort was implemented. The delay in the implementation of effort reductions had the unfortunate consequence of large effort reductions, which was disruptive to the industry. Should similar cases occur, AFMA should not expect consensus, but should either give NORMAC a clear ultimatum or take decisive action itself.

1.6.b Vision for the future

The future will be strongly linked to the partnership approach. Long-term prawn and bycatch monitoring programs have been established and our understanding of ecosystem functionality is steadily improving. Ecosystem-based fisheries management is difficult for scientists, managers and industry to implement, but is more likely to be implemented successfully within the partnership approach. The reality is that the ultimate goals of fishers, managers and industry are not always very different. For example, achieving independent international certification of ecological sustainability requires that management be ecosystem based, backed by excellent science and proactive decision-making. Management by a partnership approach of all stakeholders is most likely to achieve a viable industry with a strong future.

Table 1.1: Scientific advice and management development (with intended target reduction if stated) in the Northern Prawn Fishery, 1980–2004.

Year	Scientific advice and management development	Target reduction, if any	Reference
1980	<ul style="list-style-type: none"> • Introduction of limited entry 		<ul style="list-style-type: none"> • Taylor and Die 1999
1985	<ul style="list-style-type: none"> • CSIRO presents data showing a decline of the brown tiger stocks and recommends a 25% reduction in effort. • Statutory Fishery Rights are granted in the form of A-units (a combination of hull dimensions and engine horse power). • Voluntary buyback scheme introduced (tends to reduce only latent effort). 		<ul style="list-style-type: none"> • Taylor and Die 1999 • Pownall 1994
1987	<ul style="list-style-type: none"> • Reduction from quad to twin gear, mid-year closure, ban on daylight trawling during the tiger prawn season. 	30% reduction of effort	<ul style="list-style-type: none"> • Pownall 1994
1988	<ul style="list-style-type: none"> • Restriction on headrope-length of nets 		<ul style="list-style-type: none"> • Pownall 1994
1990	<ul style="list-style-type: none"> • Voluntary industry-funded buy-back scheme with loans from the government (failed to reduce the fleet to the target; actual reduction by target date was 72,000 units (a reduction of 172 trawlers). 	50,000 A-units (i.e. fewer than 130 vessels) by 1 April 1993	<ul style="list-style-type: none"> • Pownall 1994
1993	<ul style="list-style-type: none"> • Compulsory, industry-funded, buy-back scheme (reduces the fleet to 137 (128 active) vessels). • Removal of net-size restrictions (but use of double gear only remains). 	Across-the-board reduction of 30% of the remaining A-units	<ul style="list-style-type: none"> • Pownall 1994
1995	<ul style="list-style-type: none"> • Start of annual assessments with an age-based model developed by CSIRO for consideration by the NPFAGs. • NPFAG declares effective effort to be too high. 		<ul style="list-style-type: none"> • e.g. Wang and Die 1996, Die 1996, Die <i>et al.</i> 1997, Die and Wang 1998
1996	<ul style="list-style-type: none"> • Fishing power estimated to be increasing at 2–5% p.a. (the 		<ul style="list-style-type: none"> • Robins <i>et al.</i> 1998

Year	Scientific advice and management development	Target reduction, if any	Reference
	<p>stock assessment used 5% p.a. as agreed by NORMAC).</p> <ul style="list-style-type: none"> • A Gear Units Workshop (attended by industry, scientists and managers) considers the idea of gear units as a management tool. • First attempt by NPFAG to introduce biological reference points; deferred by NORMAC 39 to 1997 for further discussion. 		<ul style="list-style-type: none"> • NORMAC 39 Agenda Item 5
1997	<ul style="list-style-type: none"> • NPFAG advises that both tiger prawn stocks are overexploited and recommends immediate reducing effort by at least 10%. • Independent tiger prawn stock assessment confirms NPFAG advice. • NORMAC recommends closing that the fishery be closed 3 weeks earlier at the end of the year and during the mid-season closure for 1998; also recommends issuing 15% fewer gear units when they are introduced in 1999. • AFMA Board accepts advice (although gear units are introduced in 2000). 	<p>Season change intended to decrease effort by 10% (i.e. a nett of 5% after the 5% increase in fishing power) and similarly for 1998</p>	<ul style="list-style-type: none"> • Die <i>et al.</i> 1997 • Haddon 1997 • NORMAC 41 and Die and Bishop in NORMAC 42
1998	<ul style="list-style-type: none"> • Mandatory introduction of satellite-based Vessel Monitoring System across the fleet. • NPFAG advises that spawning stocks are well below target levels and that rebuilding of stocks “requires significant and urgent efforts”. • Some sectors of industry dispute the advice. • The end-of-season closure reverts to the end of November and a large area closure is implemented on 1 November. • E_{MSY} becomes the target reference point when gear units are introduced. 		<ul style="list-style-type: none"> • NORMAC 43 • Die and Wang 1998

Year	Scientific advice and management development	Target reduction, if any	Reference
1999	<ul style="list-style-type: none"> • NPFAG advises that effort in 1998 was 35% greater than E_{MSY}, that both tiger prawn species remain overexploited, and that effort needs to be reduced by 35%. • NORMAC recommends replacing the spatial closure implemented in 1998 by larger mid-year and end-of-year closures. • Allocation Advisory Panel investigates the translation formula used in the gear unit system. • Bycatch Action Plan is released. 	15% reduction	<ul style="list-style-type: none"> • Die and Bishop 1999 • NORMAC 45
2000	<ul style="list-style-type: none"> • Australian Senate Inquiry endorses gear-based management. • Gear-based management starts in July and gear is reduced by 15%. • NPFAG reports that seasonal closures have reduced effort, but that stocks are still over-exploited and declining. • AFMA Board and Minister write to NORMAC insisting on reductions in effort • TEDs become compulsory in the tiger prawn fishery. 	10% reduction in effort	
2001	<ul style="list-style-type: none"> • CSIRO develops a new model for tiger prawns stocks. • Technical review of stock assessment models. • NPFAG considers tiger prawn stocks are over-exploited (brown tiger prawns are below 50% of their target level). • Minister calls meeting of fishers and local politicians to demand action. • NORMAC sets a target to rebuild tiger prawns stocks by 2006. • NORMAC agrees to reduce gear units by 25% and institute seasonal changes in July 2002. • TEDs made compulsory in ba- 	40% effort reduction on brown tiger prawns and 25% on grooved tiger prawns	<ul style="list-style-type: none"> • Dichmont <i>et al.</i> 2001, Dichmont <i>et al.</i> 2003a • Deriso 2001 • NORMAC 51

Year	Scientific advice and management development	Target reduction, if any	Reference
	nana prawn fishery.		
2003	<ul style="list-style-type: none"> • Stocks of both grooved and brown tiger prawn show signs of recovery. • Effort-neutral trade-offs between gear, season and spatial closures are investigated but do not result in management changes. 		<ul style="list-style-type: none"> • Deng and Dichmont 2003 • Venables <i>et al.</i> 2003 • Dichmont <i>et al.</i> 2003d in NORMAC 54
2004	<ul style="list-style-type: none"> • NPFAG declares that both grooved and brown tiger are recovered, although with caution, as survey results do not clearly support this. 		<ul style="list-style-type: none"> • Deng <i>et al.</i> 2004 • NPFAG 2004
2004, 5	<ul style="list-style-type: none"> • NORMAC changes the target to Maximum Economic Yield; a lower effort level than the recovery target set in 2001 and further reduces gear units by 25%. 		<ul style="list-style-type: none"> • NORMAC 56 • Rose and Kompas 2004

Table 1.2: Recently completed or current projects focused on bycatch and other non-target species that have been supported by the NPF's Management Advisory Committee, and the involvement of the NPF industry.

Project title	Industry involvement	Reference
1. Monitoring the catch of turtles in the Northern Prawn Fishery, 1998–2002.	Data collected by voluntary industry observers	Robins <i>et al.</i> 2003
2. Effects of trawl design on bycatch and benthos in prawn and finfish fisheries; 1993–96.		Blaber <i>et al.</i> 1997
3. An assessment of the TED performance in the NPF banana prawn fishery – Final report.	Data collected by scientific observers and industry crews on industry vessels	Eayrs and Bose 2001
4. Quantifying the effects of trawling on the seabed biota of the NPF; 2002-2005.		Haywood <i>et al.</i> in progress
5. Surrogates I – Predictors, impacts, management and conservation of the benthic biodiversity of the Northern Prawn Fishery; 2000-2002.	GPS data from industry volunteers to define untrawlable ground	Hill <i>et al.</i> 2002
6. Commercialisation of bycatch reduction strategies and devices within northern Australian prawn trawl fisheries; 1996-1999.	Gear technologist providing assistance on TED and BRD operation on NPF vessels	Robins <i>et al.</i> 2000
7. Ecological Sustainability of Bycatch and Biodiversity in Prawn Trawl Fisheries; 1996-1999.	Data collected by scientific observers on industry vessels	Stobutzki <i>et al.</i> 2000
8. Assessment and improvement of BRDs and TEDs in the NPF; a co-operative approach by fishers, scientists, fisheries technologists, economists and conservationists; 2000-2002.	Data collected by scientific observers on industry vessels	Brewer <i>et al.</i> 2004
9. Design, trial and implementation of an integrated, long-term bycatch monitoring program, road tested in the NPF. 2002-2005	Data collected by voluntary industry observers	Brewer <i>et al.</i> , in progress

CHAPTER 2 MANAGEMENT AND ASSESSMENT PROCESSES FOR SOME SELECTED SHORT-LIVED SPECIES

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2.1 Abstract

This chapter examines a number of examples of fisheries for short-lived species, which, like the NPF, have a fairly long-standing management system. ‘Short-lived’ is defined here to mean living up to three or four years. These fisheries considered are:

1. South African anchovy and pilchards (Output controls),
2. Falkland Island squid (Input controls),
3. Moçambique prawn (Input and Output controls),
4. Gulf Saint Vincent prawn, Australia (Input controls),
5. Spencer Gulf prawn, Australia (Input controls) ,
6. Exmouth Gulf prawn, Australia (Input controls),
7. Queensland prawn and scallop trawl fishery, Australia (Input controls), and
8. Torres Strait prawn trawl fishery, Australia (Input controls).

This chapter arose as an attempt to describe and analyse a few fisheries that have some common elements to the NPF. As criteria, they should target short-lived species, and apply limited entry in addition to several other management mechanisms. It is interesting that, on investigating several short-lived fisheries, that the vast bulk of fisheries for short-lived species (at the scale of prawns) are generally not actively managed; many do not have a basic season or even a limited entry mechanism (e.g. FAO 2005; Vasconcellos and Cochrane 2005 and references therein). This chapter is not meant to be an exhaustive study of each fishery, but rather provides a brief overview of the resource involved and the management system in each case, mainly for comparative purposes.

The eight examples shown exhibit a scale of control mechanisms that varies from using predominantly input controls, to combined input and output, to predominantly output controls (Table 2.1). Several have interactive, within season management (examples 1-5). Only two have decision rules that are used to set Total Allowable Catches (examples 1 and 6).

Table 2.1: Table summarising the properties of the eight fisheries contrasted with the same data from the NPF. LRP is the limit reference point and TRP is the target reference point. The TRP is assumed to be the ideal state for the fishery (where the balance between long-term productivity and sustainability is optimized; see Caddy and Mahon 1995). The LRP is an agreed upon threshold state beyond which a fishery requires immediate and strong management measures to move the stock and fishery back towards the TRP.

Fishery	Dominant Control	In Season Management	Decision Rules for TAC	LRP	TRP	Comment including issues
South African anchovy and pilchards	Output	Yes	Yes	Yes through the Management Strategy Evaluation (MSE)	Yes through the MSE	<ol style="list-style-type: none"> 1. Multi-species fishery 2. Two directed fisheries at pilchard adults and anchovy juveniles (with a pilchard bycatch) 3. Evaluation considers “bycatch” of other target species 4. affected by the switch of dominance between anchovy and pilchard due to El Niña or La Niña events 5. Extensive management strategy evaluation process has taken place. 6. Data rich with long-term independent monitoring data
Falkland Island squid	Input	Yes	No	No	Yes	<ol style="list-style-type: none"> 1. Remote area in low human population region 2. Assessment of recruitment strength is not available prior to the season 3. Some recent signs of stock issues
Mozambique prawn	Input and Output	No	Yes	No	No	<ol style="list-style-type: none"> 1. Industrial, semi-industrial and artisanal sectors 2. TAC and input control, but TAC hardly ever reached
Gulf Saint Vincent prawn, Australia	Input	Yes	Yes	Yes	Yes	<ol style="list-style-type: none"> 1. Lacks independent data for a good assessment 2. Single species fishery
Spencer Gulf prawn, Australia	Input	Yes	Yes	Yes	Yes	<ol style="list-style-type: none"> 1. Very good links with industry 2. Independent data to assess the status of the resource
Exmouth Gulf prawn, Australia	Input	Yes	No	Yes	No	<ol style="list-style-type: none"> 1. Fishery collapsed due to overfishing but was recovered 2. Second recruitment failure due to loss of seagrass after a cyclone 3. Few vessels
Queensland trawl, Australia	Input	No	No	Yes indirectly through a cap on effort	No	<ol style="list-style-type: none"> 1. Latent Effort 2. Multi-species fishery 3. Major restructure and change in management in last 5-10 years
Torres Strait trawl, Australia	Input	No	No	Yes indirectly through a cap on effort	No	<ol style="list-style-type: none"> 1. Small fishery in remote area 2. Recent discussions of restructuring

Fishery	Dominant Control	In Season Management	Decision Rules for TAC	LRP	TRP	Comment including issues
Northern Prawn, Australia	Input	No (but investigating this option for 2006)	No (but investigating this option for 2006)	Yes	Yes	<ol style="list-style-type: none"> 1. Multi-species fishery 2. Large levels of effort creep and uncertainty in estimates 3. History of effort and fleet reductions due to overfishing of tiger prawn resource

2.2 South African anchovy and pilchard (Individual quotas)

This is essentially a fishery targeting two or three species (anchovy (*Engraulis encrasicolus*), pilchards (*Sardinops sagax*) and round herring (*Etrumeus whiteheadi*)) that is managed by Individual (Non-transferable) Quotas. TACs (Total Allowable Catch) and TABs (Total Allowable Bycatch) are set for both the anchovy and pilchard resource in a complex staged approach. This fishery provides an example of setting TACs for:

1. short-lived species with highly variable annual recruitment and therefore catches,
2. a fishery in which the bycatch of another species is explicitly considered, and
3. a management system that is adaptive within the year.

The complex nature of the TAC setting process in this fishery is due to two factors:

1. there are two sectors in the fishery (canning and fish meal) which target slightly different species assemblages and age classes, and
2. anchovy biomass are highly variable annually (e.g. from 150,000t to >600,000t), a feature which necessitates attempts to adapt the TAC as information on recruitment becomes available during the fishing season.

2.2.a History of the fishery

Anchovy and pilchard are the main targets of the South African pelagic fishery (De Oliveira and Butterworth 2004). The fishery started as mainly a pilchard fishery in the 1940s and was aimed at adults for canning. After the pilchard catch collapsed in the mid-1960s there was a move to capturing anchovies using smaller mesh nets. The latter fishery is mainly aimed at juveniles for fishmeal and other similar products. In recent years the combined catches have been the highest annual yields in several decades in terms of landed mass (in the order of 250,000 to 450,000t per year) (De Oliveira and Butterworth 2004).

The spawning of both species is confined to the spring and summer months i.e. the period in which upwelling occurs. Both species have a strong migration pattern; from the Agulhas Bank where spawning takes place to the west coast of South Africa where upwelling (and therefore food) occurs (Shelton and Hutchings 1982). The migration on the west coast is initially northwards but, as the season progresses the fish migrate southward and inshore through the rich food resources and then ultimately back to the Agulhas Bank. The

directed anchovy fishery on the west coast captures juvenile pilchards as a bycatch as they migrate southwards.

In the 1950s and onwards, various management controls were put in place such as control on vessel capacity, a closed season, gear restrictions and a combined pilchard and horse mackerel (*Trachurus trachurus*) TAC (De Oliveira *et al.* 1998). This global TAC was changed to include most of the major species caught in the pelagic fishery (pilchard, anchovy, horse mackerel, club mackerel (*Scomber japonicus*), round herring (*Etrmeus whiteheadi*) and lanternfish (*Lampanyctodes hectoris*)) from 1971 onwards. In 1983 the TAC was restricted to pilchard and anchovy and one year later to a species specific TAC (De Oliveira *et al.* 1998). Initially, the TAC was based on little scientific opinion but that changed over time so that, by the late 1980s, scientific advice was showing the need for rebuilding the pilchard resource and avoiding the capture of pilchard juveniles by the anchovy fishery. One of the reasons for this increase in use of formal stock assessments to set the TAC was the introduction of annual acoustic surveys in 1984 which matured into being useful for TAC setting by 1987 (Hampton 1992). At this time, stock assessment techniques such as VPA or the ADAPT modification was applied to the resource (e.g. Punt 1989). In the 1980s and 1990s, several reference points and harvest strategies were selected to set the TACs e.g. $F_{status\ quo}$ (sets the fishing mortality to the average over a predefined period), constant proportion (aims to harvest the same proportion of the resource biomass from one year to the next), constant escapement (aims to permit sufficient spawning biomass to survive to generate the recruitment needed in the following year). The issues of setting appropriate TACs and controlling bycatch of juvenile pilchard led to the development of a Management Strategy Evaluation (MSE) for the pelagic fishery. Use of this method to set the TAC was applied from 1994 onwards and has been refined several times since then (e.g. Butterworth *et al.* 1993, Cochrane *et al.* 1998, De Oliveira *et al.* 1998, De Oliveira 2003).

In the 1990s, after the first post-apartheid election, new entrants were allowed into the fishery. A first attempt to re-allocate fishing rights was made in 1999 following the adoption of a new Marine Living Resources Act (Anon 1998), but this led to litigation opposing some of the changes, for example, the criteria used to score applicants were challenged as being too subjective to be used as a basis for excluding applicants from the rights allocation process. A second allocation system was put in place in December 2002.

2.2.b The Management System

Pilchard and anchovies are managed together under a joint Management Procedure (MP) (roughly equivalent to a Management Plan in Australia) aimed at accommodating the operational interaction between the fisheries for the two main species. Management Procedures have been in place for this fishery since 1991 (De Oliveira and Butterworth 2004), because pilchard and anchovy shoal together as juveniles of a similar size any targeting of juvenile anchovy is accompanied by a bycatch of juvenile pilchard and vice versa. This juvenile capture has implications for the directed fishery of pilchard in future years, which is based on adults.

Since a trade-off decision between these species is explicitly required, a joint MP provides this framework and takes into account the stock-dynamics (assessment) for each species. This is a data rich fishery, where long data series are available from both logbook and independent surveys.

The system of setting the total allowable catches is very complex (see Butterworth *et al.* 1993; De Oliveira 2003; De Oliveira and Butterworth 2004 for more details) and relies on within season management for the anchovy directed fishery. The pilchard TAC remains in force without alteration as this fishery targets adult pilchards. Crucial to the process are two acoustic surveys in a cycle; a spawning survey and a recruit survey. In brief, anchovy TACs and pilchard TABs are set at 3 stages during the year:

1. Prior to the season, the first anchovy (and the only pilchard) TACs are set based on how abundance estimated from a spawning biomass survey relates to past average values. The year's anchovy recruitment is predicted from the stock-recruitment relationship, assuming average recruitment. Only a proportion of this anchovy TAC can be caught. The pilchard TABs are based on two components; one that considers the anchovy fishery which catches juvenile pilchards and the other that catches round herring fishery with adult pilchards.
2. The second stage occurs after a recruit survey during the fishing season, which attempts to assess whether the assumption of average recruitment, taken in (1), was correct. Depending on this survey, the TACs and TABs are either maintained or adjusted (both upward and downward adjustments have been made). The full 2nd TAC can be caught.

3. The final stage relies on the separation of pilchard and anchovy schools later in the year. As a result, an additional sub-season TAC on anchovies can be introduced. Only a small pilchard TAB is set.

This system relies very heavily on two acoustic surveys a year, good assessment and an adaptive management framework. A full Management Strategy Evaluation has been undertaken for this fishery (Cochrane *et al.* 1998; De Oliveira 2003), providing a detailed analysis of the risk and reward trade-offs. Furthermore, the management procedures developed over the last few decades or so have been successfully applied to the fishery, even though they have been updated several times (De Oliveira and Butterworth 2004). The current system is well able to address the key issues of the pelagic fishery, those being its multi-species nature, two separate targets (with bycatch) and the variability of recruitment. The complexity of the management system has been shown to benefit the fishery in that the in-season management means that a more conservative TAC to cater for years of poor recruitment is not necessary (Butterworth *et al.* 1993).

2.3 Falkland Island squid (Input control)

2.3.a History of the fishery

The Falkland fishery catches, on average, about 260,000 tonnes per annum of which two squid species are the most important components in terms of volume and value (Barton 2002). These are the large ommastrephid squid; *Illex argentinus*, and the much smaller loliginid squid; *Loligo gahi*.

Until 1986, the fishery was largely unregulated. In 1986, the first Fisheries Conservation Zone around the Falkland Islands was introduced (Barton 2002). At that time, there was concern that their resources could not withstand the increasing levels of fishing effort being experienced at that time. The main objective in introducing a licensing system had been to curb the high levels of largely unregulated fishing. The Falklands Island Fishery Management regime was established in 1987 and the fishing year was divided into two six-month seasons (Agnew *et al.* 1998). This fisheries management regime is still in place, and whilst there have been some changes since 1987, the basic system remains much the same. One important change is that the two seasons have been shortened for the *L. gahi* fishery (Agnew *et al.* 1998).

Illex argentinus is the highest volume and value species in the Falkland fishery and is predominantly caught offshore in deep water. Its abundance and distribution make it a major component of the Southwest Atlantic ecosystem. FAO statistics (FAO 1999) indicate that in 1997 the catch of *I. argentinus* reached about 950,000 tonnes, which placed it in 13th position in terms of catch for all marine capture fisheries that year. The two highest catches of *I. argentinus* in the Falkland Conservation Zones during the last decade occurred in 1999 and 2000 (Barton 2002). *I. argentinus* are primarily caught by specialized squid jigging vessels, for example in the 1999 season, of a total catch of 266,169 tonnes, 95% was caught by jigging vessels (Barton 2002). In the 2000 season there were some 110 jigging vessels (most of which come from Far Eastern countries) and 16 trawlers involved in the Falkland's *I. argentinus* fishery.

Loligo gahi is the second most important fishery in terms of volume and value. The development of the Falklands fishing industry was based mostly on *L. gahi* (Barton 2002). *L. gahi* has a primarily neritic distribution with a significant amount of fishing occurring inside the 12 mile territorial sea. There are 15 stern trawlers involved in the *L. gahi* fishery (Barton 2002).

2.3.b Description of the resource

The characteristic of many squid species, including the main Falkland species, is that they have:

1. an annual or bi-ennial life span,
2. have highly variable levels of recruitment e.g. annual catches of *I. argentinus* in the Falkland's fishery have ranged from 64,000 tonnes in 1995 to 266,000 tonnes in 1999 (Agnew *et al.* 1998; Barton 2002), and
3. the animals tend to be captured either pre- or during spawning.

L. gahi spawn in shallow water, migrate to deeper waters where they feed and then move back to shallower waters to spawn (Hatfield *et al.*, 1990; Hatfield and Rodhouse, 1994). This life cycle appears to be very similar to that exhibited by the major target prawn species in the NPF. The squid fishery targets the immature feeding populations offshore in depths of about 100 m or more.

The life cycle of *I. argentinus* is different and more complex than *L. gahi* and they are found over a larger area. Fishing around the Falkland Islands targets spawning individuals (see Brunetti and Ivanovic 1992; Clarke *et al.* 1994).

It is clear in both fisheries, that next year's recruits, and hence the fishery, depend on the number of animals that survive the fishery to spawn (Barton 2002).

2.3.c Management System

This limited entry, input controlled fishery uses in-season management (through changing the season length) as its major annual effort control mechanism. There are two fishing seasons in each year (Agnew *et al.* 1998; Barton 2002).

Pre-recruit surveys are not feasible, which means that no clear assessment of stock size based on new data is available prior to fishing. The season is shortened or lengthened based on reference points for both *I. argentinus* and *L. gahi* (Barton 2002). The initial target reference point was that proportional escapement should not fall below 40% (Basson *et al.* 1996; Agnew *et al.* 1998; Barton 2002), where proportional escapement is defined as the ratio between the number of spawners surviving under a given level of fishing mortality, and the number of spawners under no fishing mortality (Basson *et al.*, 1996). This reference point is based on experience with what constitutes an acceptable level of effort directed at the *I. argentinus* fishery (Beddington *et al.* 1990). Subsequently, the target was changed to absolute escapement levels e.g. 40,000 tonnes of spawning stock biomass in the case of *I. argentinus* (Barton 2002). In years that the spawning stock levels fall below threshold levels, the season is closed early.

Fishing for *I. argentinus* takes place during February–June of the first season only, whereas the *L. gahi* fishery operates for 4 and 3 months, respectively, in the first and second seasons. Throughout each year, there are two or three *L. gahi* recruitment cohorts entering the fishery; with the second cohort caught in both the first and second season (Agnew *et al.* 1998). Interestingly, the different cohorts have different dynamics and can be treated as separate stocks (Agnew *et al.* 1998). In recent years the second *L. gahi* season has been closed early in both 1997 and 1999. In order to reduce the probability of early season closures, a reduction in fishing effort was implemented in the second *L. gahi* season for 2000. Licence numbers were reduced from 21 to 15 (Barton 2002).

Before the start of the season, when the recruitment size is unknown, fishing effort levels are based on historical average recruitment and past escapement levels (Basson *et al.* 1996). Once the fishing starts, daily reporting from fishing vessels allows almost real time stock assessments using modified Delury depletion models (e.g. Agnew *et al.*, 1998; Basson *et al.*, 1996). Once the season is closed, post season assessment is undertaken with the full data set (Basson *et al.* 1996).

In the case of *L. gahi*, there are occasions where catch rates increase at the end of a fishing season, which is contrary to the assumptions behind the Delury methodology of a closed population (Rosenberg *et al.* 1990). Modifications of this closed population assumption have been developed and tested, but a solution using this methodology was not easily found for *L. gahi* (Agnew *et al.* 1998). In years where the depletion method does not work, an extension is used that uses annual trends in catchability coefficients together with individual vessel CPUE data to estimate stock size (Agnew *et al.* 1998). Fishing effort is adjusted at six monthly intervals to reflect recommendations from revised stock assessments. This Delury method has now been adapted in a Bayesian framework and therefore uses priors for, amongst others, catchability (McAllister *et al.* 2004).

In recent years (e.g. 2002, 2004 and 2005), the *Illex* season has been closed early due to very poor recruitment. The early signs are that this may be due to a combination of unfavourable oceanography for *Illex* with warmer water temperatures (this link was demonstrated in, for example, Agnew *et al.* 2000, Arkhipkin *et al.* 2004) but also excess catches and excess fishing effort operating in some years (interview of Barton, Director of Fisheries in 2005).

2.4 Moçambican Prawn (Input and output control)

2.4.a History of the fishery

The shallow water shrimp fishery started in 1964 on the Sofala Bank located in the central part of Moçambique (Sousa 2004). It consists of three sectors: industrial, semi-industrial and artisanal. The industrial sector is characterised by having on-board freezers that enables the vessels to fish for long periods away from port (Palha de Sousa *et al.* in prep.) and by the vessels being greater than 20 m in length (Bomba 2004). This contrasts with the semi-industrial sector that stores the prawn on ice and therefore must return to port

each day. Most of the industrial fleet is made of joint ventures between Moçambican companies and Japanese or Spanish partners (Palha de Sousa *et al.* in prep.).

In 2001, the catch of the industrial fishery (including the freezer semi-industrial vessels) was 8 751 tonnes and for the ice semi-industrial fishery was 218 tonnes (Palha de Sousa *et al.* 2002). The main species are red-legged banana prawn (*Penaeus indicus*) and *Metapenaeus monoceros* with average catches of 4600 and 2500 tonnes, respectively between 2001 and 2003 (Palha de Sousa *et al.* in prep.). Until the early 1990's, fishing was focused during the day on the two main target species. The three other main species (*P. japonicus*, *P. latisulcatus* and *P. monodon*) have increased from about 10% of the catch in the 1980's to about 20% since 1992 as a result of increased fishing at night (Palha de Sousa 2002). In 2002 the semi-industrial catch represented about 3% of the industrial catch whereas the industrial fleet consisted of 59 vessels (reduced from the 67 vessels operating in 1999).

2.4.b Management

The industrial fishery is managed by limited entry, seasonal closures and catch quotas per vessel (Bomba 2004; Palha de Sousa *et al.* in prep.). Closed seasons were first introduced in 1991 and the fishing industry responded by fishing at night as well as during the day and moving from twin trawls to quad gear (Palha de Sousa *et al.* in prep.). A closed season for small prawns extends from December to March (Sousa 2004).

A fishery-independent survey is conducted annually to estimate recruitment of prawns to the fishery. In addition, data routinely collected are total monthly catch from the industry catch statistics and voluntary logbook data that includes size grade and species data. The annual quota is set before the survey starts and is used as the basis for collecting licence revenue. It is set taking into account the previous year's catch (Caputi, Department of Fisheries, Western Australia *pers commn*). Often the annual quota is not achieved or in years of very good recruitment, the level of quota is increased during the season (Bomba 2004; Palha de Sousa *et al.* in prep.) which in reality means that the major control mechanisms are the input controls listed below :

1. temporary or permanent inshore closures (e.g. no industrial trawlers are allowed to trawl in water less than 10 m deep and less than one mile offshore) and a total closed season for 3 month per year, and

2. limitations on the growth of fishing power by controlling vessel size or gear sizes and through restrictions on mesh size of the nets (55 mm) (Bomba 2004).

The fishery is declared fully or heavily fished based on an assessment that requires an understanding of the factors affecting the catch rate and mean size of each species such as location, seasonal trends, depth, time of day, vessel type, and an understanding of the biological characteristics of the species such as spatial and temporal trends in recruitment, spawning and migration.

2.5 Gulf St Vincent Prawn, South Australia (Input control)

2.5.a History of the fishery

The fishery started in 1968, but was only exploratory in nature for the first few years. Like many fisheries, including the NPF, the fishery expanded rapidly and, by the early to mid 1970's, the number of participants had increased (Svane 2003). Unlike the NPF, fishers initially used single rigged otter trawl gear. Very few management restrictions were in place at that time, until 1972, when a permanent spatial closure was established that prohibited fishing in areas less than 10 m in depth. A separate fishery in the Investigator Strait was opened in 1975, which added more vessels. By 1978, a total of about 22 permits had been issued for the Investigator Strait and Gulf St Vincent fisheries combined. Furthermore, before the Offshore Constitutional Settlement in 1988, Commonwealth endorsed vessels were also allowed to fish in the Investigator Strait. In February 1983, management of the fisheries in these waters were transferred to the South Australian State government and only two of the Commonwealth endorsed vessels remained.

From 1982 to 1983, management changed the gear type from single to triple gear, which resulted in major increases to fishing efficiency, and changes to targeting practices and the pattern of fishing. Subsequently, concerns about stock depletion led to effort reductions in 1984 and, following an economic review (Copes 1986), a buy-back scheme was introduced in 1987; Five vessels were removed from the fishery. Despite this reduction, after a parliamentary review (Quirk *et al.* 1991), the fishery was closed in 1991 for a review of management during which a single vessel surrendered its fishing licence. The fishery reopened in December 1993 with the present fleet size of 10 vessels.

A change of cod-end mesh type from diamond mesh to square mesh was implemented from 1996, because it was generally believed to allow the smaller prawns to remain unselected by the gear (but this contention was not statistically supported in several sea trials) (Svane 2003).

2.5.b Description of the resource

Unlike the NPF, the fishery targets a single species of western king prawn (*Penaeus latisulcatus*, presently reclassified as *Melicertus latisulcatus* (Perez-Farfante and Kensley 1997)). This animal has broadly similar behaviour to the NPF tiger prawns, in that it is active at night and is not highly variable in biomass from one year to the next (which contrasts with the NPF's banana prawn resource). Females spawn during October to March, with two peak periods occurring in mid-December and late January/early February. Individuals may spawn more than once in a year (Kangas and Jackson 1997). Larger female prawns release proportionately more eggs than smaller female prawns. Key nursery areas are characterised by the presence of muddy-sand, mangroves and tidal flats (Kangas and Jackson 1997).

Recruits in this fishery are defined as either males with a carapace length of 33 mm or less, or females with a carapace length of 35 mm or less. Recruitment takes place between February and June each year.

As has been shown for several prawn resources world-wide (see for example an overview of tiger prawns in Ye 2000), Carrick (1996) demonstrated a clear stock-recruitment relationship for the Spencer Gulf prawn resource using survey data and Morgan (1995) found a similar relationship using catch and effort data. However, Kangas and Jackson (1997) conclude that the time-series of data is too short to produce a valid spawner-recruit relationship for Gulf St Vincent prawns. The maximum life span of Gulf St Vincent prawns is estimated as 3-4 years from tagging studies (Kangas and Jackson 1997, Carrick 1982).

The fishing pattern is different to that for the tiger prawn resource within the NPF. In recent years, a typical fishing night in the Gulf St Vincent prawn fishery starts with one or more trawls shots of only about 20 minutes in duration using all three nets at a time, but with only one of the codends tied. If the catch rate is good or large prawns are caught then the shot duration increases and all codends are tied. This trial of the catch rate by closing only one codend seems superficially similar to the use of try gear by the NPF.

2.5.c Management System

General management relies on several input controls (after the basic input control of limited entry):

- i) season closures,
- ii) area closures,
- iii) a ban on daylight trawling,
- iv) a maximum vessel length of 22m,
- v) a max engine hp of 365 bhp,
- vi) max headline length of 27.43m, and
- vii) minimum mesh size of 4.5 cm (Svane 2003).

The primary management objectives are (Zacharin 1997, Svane 2003):

1. rebuilding the stock to historical levels and eliminate risk of recruitment decline due to over-fishing,
2. ensuring catching procedures are directed towards optimising size at capture,
3. maintaining and enhancing profitability of the fishery by optimising prawn size, improving the economic efficiency of fishing units and reducing the costs of fishing, and
4. minimising by-catch and trawl impact on the benthic environment by the development of more efficient gear and harvest strategies.

There is strong within season management, and decisions controlling the fishery throughout the season are made in accordance with the fleet's ability to fish within the reference points described in Table 2.2. These are applied spatially, so areas are opened and closed in sets of 4 days, depending on their indicators.

Three skippers, making up the Committee-at-Sea, are responsible for providing much of the data. Every 4-day fishing period, the fisheries agency processes the data supplied by the Committee-at-Sea plus any of their own and translates this information into maps of open and closed areas for the next 4 fishing days (Svane 2003). As a result, the following occurs each day:

1. modelling and evaluation of prawn size and catch rate depletion
2. evaluation of spawning status and reproductive depletion over the main spawning period
3. assessment of potential of closure line problems
4. developing and enhancing harvest strategies and closures including buffer lines
5. mapping closures and sending this to fishers.

Table 2.2: Target and limit reference points with the performance of the 2002/3 year (Svane 2003).

Indicator	2002/3	Target Reference Point	Limit Reference Point
Nights fished	47	36 fishing nights (11-14 nights in November)	34 and 38 fishing nights (9-14 nights in November)
Exploitation rate	NA	20% of exploitable biomass	30% of exploitable biomass
Recruitment index	4.24-64.5	25 pre-recruits per trawl hour in Industry survey	20 pre-recruits per trawl hour in Industry survey
Size at first capture	24.5 prawns per kg	Less than 24 prawns per kilo	More than 27 prawns per kilo

This system does not seem to have protected the resource as many of the reference points have been exceeded. The catch had declined to a level similar to that prior to the closure of the fishery in 1991. A reason for this may be that the observer data is highly variable and not statistically sound (Svane 2003). They also do not have precise stock assessment, as this needs pre- and post-season survey data. Fishery independent surveys were regularly undertaken up to 1994, but a survey undertaken in April 2003 showed catch rates were statistically lower than past surveys (Svane 2003).

2.6 Spencer Gulf Prawn, South Australia (Input control)

2.6.a History of the fishery

Western king prawns in the Spencer Gulf was first trawled in 1909, with the first serious attempt at commercial trawling in 1948 being unsuccessful (Carrick 2003). In 1967, an extensive resource survey by a fisherman was undertaken and successfully caught commercial quantities of prawns. The early fleet were diverse in vessel and gear characteristics as operators from other fisheries, such as the tuna and rock lobster participated using vessels more suited to their main targets. Since 1975, 39 vessels using double rig have been actively participating in the fishery (Carrick 2003) under a limited entry management system. A permanent spatial closure for prawn juveniles was introduced in 1974, with a further spatial closure added in 1981, primarily to protect juvenile King George Whiting (Carrick 2003).

2.6.b Description of the resource

As in the Gulf St Vincent fishery, the target resource is again *Penaeus* (or *Melicertus*) *latisulcatus*. Most of the trawling in this fishery takes place in waters less than 15 m and covers less than 10% of the area of the Gulf (Carrick and Williams 2001, Carrick 2003). King prawns have an offshore adult life and an inshore juvenile phase. Spawning occurs between October and April with two maturation periods, one late in November/December and another in late January (Carrick 1996). More larvae were found in surveys in the north of the Gulf than the South, corresponding to the location of the main prawn nursery areas (Carrick 1996).

2.6.c Management system

Much of what is described for the management of the Gulf St Vincent fishery is directly applicable to the Spencer Gulf prawn fishery. This fishery is spatially managed using an adaptive framework in real time. This means that the areas available for fishing can change throughout the fishing period. The Fishery objectives (MacDonald 1998) are exactly the same as the Spencer St Gulf fishery other than the first objectives which is to maintain (rather than rebuild) the stock at historical levels and eliminate risk of recruitment decline due to over-fishing.

An important difference from the Gulf Saint Vincent Prawn Fishery is that in this fishery the assessment and harvest strategies use both fishery-dependent and fishery-independent data. The full compliment of data include information from trawl surveys, adaptive small-scale surveys prior to the start of fishing in each period, and on-going fishery data. This fishery information is gathered by the Committee-at-Sea, as described in the Gulf St Vincent fishery. The stock size, size at capture and stock decline are monitored daily based on these data. Fishing usually does not occur between late December and March and from mid-June to November. Once data are available from surveys, the optimum period to fish specific areas is calculated based on the optimal bio-value (\$/kg) (Carrick 2002, 2003).

Target and limit reference points, and indicators have been put in place in the fishery (Morgan 1996) (Table 2.3). Most notable of these is a target reference point of 50% of virgin spawning stock size (S_{vir}) and a limit reference point of 40% S_{vir} . Fishing areas are opened and closed adaptively throughout the season based on the data collected and the reference points that take into account the size of prawns caught, catch rate, depletion rates, spawning stock status and likely migration patterns of prawns (Carrick 2003).

In addition, there is a complex set of permanent closures:

1. small prawn and vulnerable discard closures
2. variable seasonal closures to optimise value and protect spawning biomass
3. Total Gulf Seasonal closures (December to March, and June to November)
4. Total Gulf moon closures
5. Daylight closures

Table 2.3: Reference points for the Spencer Gulf Fishery management (Carrick 2003)

Factor	Target Point	Reference	Limit Point	Reference	2001/2
Effective Effort (Days)	70-80		80		actual 55.5, effective 76.59
Sy/S _{virgin} (%)	50		40		55-59% depending on data and method
Recruitment (no. of <35mm CL/hr fishing)	40		35		40-45 depending on method used
Size at capture (prawns/kg)	<40 prawns/kg		40 prawns/kg.		27.9/kg

In 1986/87, the catch declined relative to previous years, which was attributed to overexploitation and growth overfishing (Carrick 1996, Morgan 1996). In recent years, the fine-tuning of the reference points and harvest strategies have resulted in resource recovery (Table 2.3). Compared to the Gulf St Vincent fishery, there seems to be higher success in achieving the targets (Table 2.3) especially keeping the size of prawns in the catch at larger sizes and keeping within the agreed target stock size.

2.7 Exmouth Gulf (Input control)

2.7.a History of the fishery

The Exmouth Gulf Prawn (EGP) fishery started in 1963 initially by targeting banana prawns; just as the NPF did in the 1960s. As the fishery expanded in the following years the primary target species changed, and by 1966 due to the introduction of night time trawling, the more valuable tiger prawn became increasingly more important (Penn et al. 1997). By 1975, catches of tiger prawns had reached 1,239 tonnes. Tiger prawns dominated the catch through to 1980 even though there was significant inter-annual variation in the catch. This variation was generally found to be related to cyclonic events (Penn and Caputi 1986). In 1981 and 1982, there was a major decline in recruitment and the subsequent catch of tiger prawns and the resource was declared overfished. By 1983, the tiger prawn catch was at an historical low of only 77 tonnes. Management restrictions were in-

troduced at this time in order to rebuild the tiger prawn stocks. These included variable temporary spatial closures of the main tiger prawn fishing grounds and extension of permanent area closures. These permanent closures were designed to allow a constant escapement of tiger prawns to provide sufficient spawning stock irrespective of annual recruit strength (Penn *et al.* 1997). Since 1984, industry funded buy-back schemes have been in operation and removed 7 vessels.

These management measures allowed the resource to recover so that catches in the 1990s have been similar to that achieved before the 1980s resource collapse (Anon 2002). For example, the catch in 1999/2000 was 1,467t (king prawns 471t, tiger prawns 451t, endeavour prawns 543t, banana prawns 2t). As a result, the EGP fishery is the second largest prawn fishery in WA (Sporer and Kangas 2001).

However, low catches were experienced again in the early 2000s (Anon 2002). This lower than average season, particularly for tiger prawns has been attributed to several factors (Anon 2002). The short-term effects of a cyclone in 1999 appeared to be higher catch rates for all species, particularly endeavour prawns. In 2000, the catch of banana prawns was significantly larger than in previous years, presumably due to high rainfall increasing their availability. However, inshore areas, including prawn nursery habitats, were adversely affected by the cyclone and a survey in November/December 1999 was unable to find significant quantities of juvenile tiger prawns. This was reinforced by the three recruitment surveys undertaken by West Australian Fisheries in March to April 2000, which indicated low recruitment indices in the area considered to contribute to around 70% of the catch for the season. A high proportion of the prawns caught during these surveys were larger prawns, not recent recruits. This low tiger prawn survival to the fishery had a negative impact on the 2000 season (Anon 2002). The very low tiger prawn catch was also due in part to the management controls, which ensured that sufficient tiger prawns were left to become the spawning stock for 2001 and protected the breeding stock by closing the season early (Anon 2002). A strong stock-recruitment relationship has been demonstrated by assessments based on logbook data and unfortunately confirmed by the collapse of the tiger prawn resource (Penn and Caputi 1985; Penn and Caputi 1986; Penn *et al.* 1995; Penn *et al.* 1997).

2.7.b Management System

The fishery has operated under a detailed management regime since the 1960s with catches ranging from 771 to 1,456 tonnes per year over the last 10 years. Limited entry has meant that the fleet is relatively small, from 23 vessels in 1979-82 to 19 (1984) and after 1990 about 16 licences (but only 13 vessels operated in 2003) (Penn *et al.* 1997, Anon 2003). Fifteen of these belong to a single owner (Anon 2003).

There is a complex system of area based zoning, closed seasons, fixed and variable closed areas, gear limitations (e.g. a maximum headrope length and board size) along with a variety of biological controls and with complete Vessel Monitoring System (VMS) coverage of the fleet. Although the fishery generally uses double otter trawl gear, recent allowances have been made to some of the vessels to tow quad gear. Each tow is approximately 60 to 200 minutes in duration. All these controls are subject to regular reviews. The management controls include:

1. limited entry
2. fixed seasonal closures (November-April)
3. Real time monitoring of fleet dynamics
4. variable spawning/size seasonal closures (areas closed or opened depending upon catch rates and sizes of prawns)
5. permanent area closures (~28% of the total area) to preserve sensitive habitats e.g nursery area for prawns and other species
6. time closures including a daytime trawling ban and full moon closures
7. gear and vessel equipment controls e.g. dual gear (some operators carry permits for quad gear), maximum size of otter boards, maximum headrope length, try-gear size, mesh size etc.

Extensive independent surveys are undertaken each year; recruitment surveys in March and April and spawning surveys in August, September and October (Anon 2002).

The fishery is managed under a constant escapement policy. This allows a minimum level of tiger prawn spawning stock during the breeding season and maximises recruitment levels the following year (Penn *et al.* 1997). Using real time monitoring, the main spawning grounds are closed to fishing when a threshold standardised catch rate level of 8-10 kg/hr

is reached by the fleet (Anon 2002). In other words, there is a set season, but if the catch rate of the fleet falls below an average of 10 kg/hr (standardised) in key tiger prawn trawl grounds, the area is closed to fishing for the remainder of the season. If the spawning stock surveys later in the season indicate that the catch rates are significantly above this threshold, the areas may re-open. Furthermore, if the results of the spawning survey at the end of the year are below the threshold, then the catch rate threshold that closes the fishery may be increased in the following season (Anon 2002).

2.8 Queensland trawl (Input control)

2.8.a History of the fishery

Prawns, scallops and other species are otter trawled along the east coast of Queensland from Cape York to the New South Wales border. The fishery can be roughly divided into three regions;

1. the northern trawl fishery which mainly harvests tiger, endeavour and red spot king prawns,
2. the southern fishery which harvests eastern king prawn and saucer scallop, and
3. the Moreton Bay fishery which harvests bay and eastern king prawns, squid and blue swimmer crabs (Williams 2002).

There are eight main species groups trawled in this fishery. Of these species, prawns dominate the catch (Williams 2002). During the period 1988 to 2000, about 27% of the trawl catch would consist of king prawns, about 21% of tiger prawns and about 14% of endeavour prawns (Williams 2002). Banana prawn catch varied from 3% to 11%, and scallops about 11% of the total harvest. The fishery is highly mobile and boats may target more than one species assemblage in a year. Much of this fishery occurs within the Great Barrier Reef Marine Park.

There is great similarity between Queensland and the NPF in the prawn catch composition and corresponding life cycle patterns, although the spatial patterns are dissimilar. The banana prawn species caught in the Queensland trawl fishery is *Penaeus merguensis*, the same species found in the NPF. Their life cycle and behaviour is also very similar to that exhibited in the NPF; key nursery habitats are mangroves, the catch is highly variable in-

ter-annually and the resource is very patchy and aggregated. As a result, major fishing grounds are closely associated with major estuaries that have muddy flats and mangrove areas (Williams 2002). Again similar to the NPF, the tiger prawns caught are *P. esculentus* and *P. semisulcatus*, with the occasional *P. monodon*. These animals are associated with seagrass habitats, which are their nursery areas. Queensland produces about 33% of Australia's tiger prawns (Huber 2003).

On the other hand, eastern king prawns (*P. plebejus*) do not occur in the NPF and are endemic to the east coast of Australia from central Queensland to the Victorian State border. Tagging studies have shown eastern king prawns differ from other prawns in that they are much more oceanic and migratory, having a general offshore and northward migration pattern as they mature (Lucas 1974, Glaister *et al* 1993 in Huber 2003).

Prawn fishing began in the mid 1880s using manually operated nets in inshore waters. The trawl fishery had started by the 1950s in Moreton Bay and expanded northwards mainly to target banana prawns. Within a few years, this spatial expansion was complemented by diversification into other prawns species and scallops (Huber 2003). The number of vessels in the fishery increased so that by 1979, when limited entry was implemented by the Queensland State Government, about 1400 vessels were trawling in the region (Glaister *et al* 1993 in Huber 2003). However, the Commonwealth Government continued to licence new vessels in Commonwealth waters i.e. >3nm offshore.

In 1987, Queensland took over the responsibility of managing the whole fishery under an Offshore Constitutional Settlement. The fishery was originally managed by the Queensland (State) Fisheries Management Authority, but this was replaced by the Queensland Fisheries Service. In 2000, management changed dramatically in this fishery. Until this time, only a limited amount of inputs were used to control effort. These pre-2000 controls included limited entry, area and time closures, and vessel and gear size restrictions (Williams 2002). There were no restrictions on the number of days a vessel could operate in the fishery. Although a unitisation system ("Hull Units") had also been implemented, which included a 2 for 1 licence replacement scheme.

Despite these management measures, effort in the fishery continued to increase. For example, the 2 for 1 replacement policy resulted in smaller vessels being replaced with larger, more efficient vessels (Huber 2003). Even so, estimates of fishing power changes

in Queensland seems to be much lower than that estimated for the NPF (O'Neill *et al.* 2004, Dichmont *et al.* 2003b). Furthermore, this fishery was characterised by enormous latent effort; for example in 1998/1999 the fleet size was about 850 vessels which applied only about 100 000 night's effort; 20-30% below its potential (Dichmont *et al.* 1999; Williams 2002). Effort in the fishery increased from 1988 to a peak in 1995 of about 138 000 days (Williams 2002). A new Management Plan was implemented in 1999 (Williams 2002, Huber 2003). However, this plan was heavily criticised by many stakeholder groups in that it did not include any effort reduction. The revised trawl plan included the introduction of tradeable effort units, a mechanism that caps effort at 1996 levels, and included a penalty system on effort unit trade (Williams 2002, Huber 2003).

2.8.b Management

The new management system of tradeable effort units was introduced in 2001. Effort units are the combination of Hull Units and days fished. This meant that each vessel, based on its Hull Units, was given a specific number of days it can fish in a year. The effort expended by each vessel is monitored using the Vessel Monitoring System. These allocated days are not restricted to a specific target group. Further spatial and temporal closures are also put in place.

A vessel buy-back scheme was also introduced in 2000 (Huber 2003). The first year after the implementation of the revised management plan, the combination of penalties on the trade of effort units and the buy-back scheme resulted in a 14% reduction in the amount of total effort units. This was in addition to the 5% effort unit surrender by the industry prior to 2001 *in lieu* of its contribution to the buy-back scheme. These mechanisms together translated to the removal of 237 trawlers from the fishery (Huber 2003).

Given the spatial size of the fishery and the mobility of the fleet, spatial and seasonal closures are used in an attempt to mitigate serial depletion and reduce growth overfishing. Approximately 32% of the area of the east coast under Queensland fishing jurisdiction is closed to trawling; either through the Great Barrier Marine Park Authority or Queensland Fisheries legislation (Huber 2003). The system of seasonal closures is highly complex and is only briefly and partially described in Table 2.4. There are also rotational spatial closures within the scallop fishery.

Table 2.4: Description of seasonal closures in the Queensland trawl fishery described under the Queensland Trawl Management Plan.

Seasonal closure	Area of application	Period within a yearly cycle
First northern closure	All waters north of 22°S (except deepwater trawl areas)	15 December – end February
Second northern closure - only applies to those vessels which trawled elsewhere in the fishery during the first closure	All waters north of 22°S (except deepwater trawl areas)	1 March – 14 May
First seasonal closure	All water south of 22°S (except deepwater trawl areas and Moreton Bay)	20 September – 1 November
Second seasonal closure - only applies to those vessels which trawled elsewhere in the fishery during the first closure	All water south of 22°S (except deepwater trawl areas and Moreton Bay)	1 November – 12 December

2.9 Torres Strait trawl (Input control)

The fishery started in the early 1970's (Anon 1987). Before 1985, fishers with an endorsement to trawl within Queensland were entitled to fish within the Torres Strait. Even though the East Coast fleet is quite large, only a few vessels entered the remote Torres Strait region. Management of the Torres Strait Prawn Fishery (TSPF) as a separate entity started when the Torres Strait Treaty was ratified in 1985 (Kung *et al.* 2005). The prawn fishery has about 20% access (about 8 000 square kilometres) to the Torres Strait Protected Zone (Anon 2005). The Torres Strait region has a complicated catch sharing arrangement between Papua New Guinea and Australia. For a description of this system see Kung *et al.* (2005). Not all the Queensland endorsed fishers took up the option to obtain a Torres Strait licence. This meant that about 500 vessels were endorsed to fish in the TSPF (Anon 1987). Even so, this was well above the numbers that had previously fished in the area. In 1987, limited entry was introduced with only vessels with historical performance in the TSPF being allowed to remain. This process reduced the fleet size to 150. Furthermore, a freeze on licence transfer was implemented in 1989. Between 1992 and 2004, vessel numbers changed from about 110 to 70 vessels respectively (Kung *et al.* 2005).

In 1993, management arrangements were substantially changed within the fishery when transferable Time Units were introduced (Turnbull and Watson 1995). This means that each vessel's TSPF endorsement is allocated a number of days it is allowed to fish. The allocation process was based on historical performance with an added 10% for time lost due to breakages and other contingencies. This effectively placed a cap on total effort within the fishery. In 1992, the potential effort that could be placed on the fishery was 30 250 fishing days whereas presently potential effort is about 13 000 days (Turnbull and Watson 1995; Kung *et al.* 2005, Anon 2005). Apart from limited entry, management also focused on seasonal (such as recruitment closures) and spatial closures (small prawn closures). Restrictions on the sizes of boats and their gear were implemented in 1997.

Unlike the NPF, the suite of species within the Torres Strait catch is comprised mainly of three species of prawns: brown tiger, blue endeavour and red spot king prawns (Turnbull and Watson 1995). One of the reasons for this paucity of species is that the only nursery habitats which occur within the Torres Strait are seagrass beds (found on coral platforms) (Anon 2005). These prawn stocks are considered to be separate stocks to the neighbouring NPF and Queensland (Watson *et al.* 1996). Torres Straits prawns are caught using quad gear at night. The pattern of offshore and onshore migration that occurs as the prawns mature is similar to that found in the NPF (Anon 2005).

This fishery is characterised by having extensive trawl survey and catch size composition data (Quinn *et al.* 1998; Turnbull and Watson 1995). As an example, monthly research surveys are available from January 1986 to December 1989. Regular annual surveys are available from 1998 (Anon 2005). This is fundamentally different to the NPF in which regular annual surveys only started in 2003 (Dichmont *et al.* 2003c).

Survey data were used in the early 1990s for the estimation of Maximum Constant Yields (MCY) (e.g. Turnbull and Watson 1995). In the latter, the target reference fishing effort level of $F_{0.1}$ was used to estimate the MCY. Thereafter, equilibrium and biomass dynamic assessments were applied to logbook catch and effort data only and the target changed to the effort required to reach the Maximum Sustainable Yield (E_{MSY}). Furthermore, the application of the biomass dynamic model of Haddon and Hodgson (2000) that internally estimates fishing power and a depletion model has also been applied. As part of a broader Management Strategy Evaluation project (O'Neill *et al.* 2004), the NPF tiger prawn assessment (Dichmont *et al.* 2003a) was adapted to the Torres Strait (and Queensland) tiger

prawn trawl resource. These assessments have generally declared the Torres Strait resource as being “fully fished”. In October 2003, Dr David Die of the University of Miami independently reviewed the Torres Strait tiger prawn assessment and recommended incorporating the annual surveys into the assessment. Even so, the resource remained declared fully fished.

2.10 Conclusions

This chapter is not trying to discuss whether input or output controls work best, but rather to describe the diversity of management systems applied to fisheries dependent on short-lived species. While the fisheries in this chapter may be superficially similar, they do share the general feature that in each case the management system has developed in answer to particular problems and issues that have arisen within each fishery. This is true of the NPF as well, of course. This strongly suggests that, irrespective of the management system, the success or failure of the fishery will depend on a typically complex mixture of factors relevant to that fishery. Nevertheless, some general conclusions can be drawn.

2.10.a Input versus output control

Many of the fisheries described in this chapter use, with mixed success, input controls as their major management system. The usual contention is that, for short-lived species where stock size is entirely dependent on a single year’s recruitment, capping effort rather than catch gives higher average yields. Furthermore, since the catch is dominated by recruitment, predicting recruitment with a degree of robustness in advance is technically very difficult. Even so, the South African pelagic fishery successfully uses output controls. The cost-benefit analyses that have been done (e.g. Butterworth *et al.* 1993) have shown this method to be beneficial for this fishery. This is a valuable fishery with a large annual catch (and large annual variability in recruitment) which means that there can be investment in two surveys annually and a detailed MSE to develop management procedures for setting catches. Input controls have been successfully applied, especially in the cases of the Exmouth and Spencer Gulf fisheries.

2.10.b Management strategies

There is only one case in this chapter where management strategies are used to set the effort or catch levels i.e. South African anchovy. Some form of MSE has been produced for the NPF, Torres Strait prawn and Queensland trawl fisheries. The NPF is at present developing management procedures. Geromont *et al.* (1999) discusses the fisheries that have applied an MSE process in southern Africa and finds that they have generally been very successful. In actual fact, the pelagic fishery MSE (amongst others mentioned) do not use a model-based method to set the TAC and TABs, but a simple set of rules based on the survey results. This avoids the need for undertaking an annual assessment, at least in principle. They argue that the advantages of using an MSE is that the TAC setting process is transparent, has been tested for trade-offs between risk and reward and has allowed extensive input from stakeholders. It is therefore clear that, for valuable fisheries at least, this approach to set management strategies should be considered.

2.10.c Within season management

A further common factor between many of the fisheries described here is that they have used some form of within-season management. Again this is related to the inability to accurately predict recruitment in advance and the variable nature of recruitment. Within-season management allows the adjustment of effort or catch during the season to take advantage of good years or to adjust the fishery in poor years. Within season management is applied to the South African pelagic, Falkland Island squid, Spencer Gulf and Gulf St Vincent fisheries, and Exmouth Gulf. The NPF will be moving to this in 2006/7. The Falkland Island squid fishery successfully (until recent years) used in-season management based on logbook data alone, whereas the Gulf St Vincent fishery is unable to adequately manage the resource (in terms of target and limit reference points) without surveys. In comparison, the Spencer Gulf fishery does have good survey data and has managed the fishery well with decision rules. The NPF considers survey data as essential to successfully undertake within season management and it is therefore only now that it has been considered. The options available for within-season management would differ particularly due to the spatial scale of this fishery. For example, the Spencer, Exmouth and Gulf St. Vincent fisheries are much smaller than the NPF. Therefore opening and closing the

whole or very large parts fishery is an option in smaller fisheries as it is possible to move from one end of the fishery to the other without too much steaming time.

CHAPTER 3 DESCRIPTION OF THE MANAGEMENT STRATEGY EVALUATION PROCESS

Ideally the generation of fisheries management advice would follow from a standard procedure. The procedure would include the collection of information about the fishery and the stock, and in the case of ecosystem studies, the components of the ecosystem. Analysis of these data would then either be by fitting a formal model or by using more empirical approaches. For example, in the target species case, the data could either be used to fit formal stock assessment models or by using more empirical approaches such as following trends in indices of relative abundance. The results of the analysis would then be interpreted using an agreed upon set of decision or control rules that would lead to management advice. In most fisheries, there can be many data sources of differing quality so the alternatives available for data analysis are manifold, and decision rules relating the analyses to management advice can also come in many forms. The use of simulation (or the Management Strategy Evaluation (MSE) approach) has been demonstrated to be an effective method for comparing and evaluating the many alternative combinations of data collection, analysis, and decision rules leading to management advice in any particular fishery.

Management (or harvest) strategies have been evaluated for many fisheries at the single or the multi-species level (Punt 1992, De la Mare 1996, Butterworth *et al.* 1997, Punt and Smith 1999, Smith *et al.* 1999, Punt *et al.* 2002) and, in recent years, for ecosystem objectives (Sainsbury *et al.* 2000). The technique came from several sources; the two main ones being management procedure evaluation of whales (e.g. Magnússon and Stefánsson 1989; Kirkwood 1993; de la Mare 1996) and adaptive management (e.g. Walters and Hilborn 1976; Hilborn 1979). Relevant to this thesis is that it has been applied extensively for fisheries management in South Africa (e.g. Punt 1992; Butterworth and Bergh 1993; Butterworth *et al.* 1993; Cochrane *et al.* 1998; de Oliveira 2003) and Australia (e.g. McDonald and Smith 1997; McDonald *et al.* 1997; Punt and Smith 1999; Polacheck *et al.* 1999; Sainsbury *et al.* 2000; Punt *et al.* 2001; Punt *et al.* 2002).

MSE is a simulation framework that models the whole management system and can be used to compare and evaluate the relative performances of different management strategies. The framework (Figure 3.1) generally consists of an operating model that can be considered as a “virtual” resource and is seen as a representation of the actual underlying dynamics of the resource and the fishery. The operating model includes methods for generating the types of data typically collected from the fishery. In addition, there is also an assessment procedure that analyses the fishery and/or monitoring data generated by the operating model (but remains “ignorant” of other “truths” included in the operating model) and a set of decision rules that interpret the results of the assessment procedure and lead to the modelled management advice. Each combination of the types of data used, the assessment-related analysis method applied, and the decisions rules used constitutes a different “management strategy”. The MSE is used to compare a set of alternative management strategies. The outcome from the management strategy (e.g. the level of effort to be applied in the next year) is fed back to the operating model and is used to determine the dynamics of the “true” situation being managed.

The overall performance of a management strategy is summarised using performance measures that are derived from stated management objectives, although, in this study, the economic objectives are described using surrogates rather than formal economic metrics. The values for the performance measures are based on the “true” resource, as encapsulated by the operating model. It is also possible to evaluate the performance of the assessment procedure component of a management strategy by comparing the estimates produced by it with the corresponding (and hence “true”) quantities in the operating model.

It is essential that the complete range of uncertainties (e.g. those related to biology, fleet dynamics, and how management decisions are implemented) are identified and modelled so that the effects of uncertainties on performance measures and estimation performance can be quantified. In this case, an important feature of the management system is that the fishery is managed using input controls thereby requiring explicit modelling of the uncertainty involved in setting and implementing effort levels.

The operating model is almost always more detailed than the models underlying the stock assessment. For example, the operating model may explicitly include multiple stocks even though the stock assessment is based on the assumption of a single homogeneous stock. This mismatch between the operating model and the assessment procedures within each

management strategy is one of the strengths of the MSE approach as it allows the impact of differences between the assumptions of the assessment procedure and “reality” to be quantified. Since the operating model is treated as “reality” it should be reasonably well specified using relevant data from the fishery and resource. It should also include uncertainty through Monte Carlo (or similar) or, if needed, using separate scenarios.

In this thesis, a Management Strategy Evaluation framework is developed to test the effects of the spatial scale, the temporal scale, and the overall complexity of tiger prawn assessment models on their ability to generate appropriate management advice. In addition, the framework is used to compare several alternative management strategies. A multi-species and multi-stock model is constructed and used to represent the “true” resource. A 5-stock, two-species, tiger prawn resource forms the basis for the evaluations. The structure of the tiger prawn resource is based on expert opinion of stock number and boundaries (Dichmont *et al.* 2001) and by estimating model parameters using historical stock and species-group level logbook data (analysed separately to species level). Banana prawns are represented in the operating model by assuming that historical catch levels reflect the best appraisal of future catches. A stock-recruitment relationship is not assumed for banana prawns, although preliminary studies suggest that one may exist (Vance *et al.* 2003).

There are two components that link the operating model and the management strategies together. These are: a) the data generation module, and b) the effort allocation module. The data generation module provides the data used by the assessment procedure component of the management strategy based on simulated monitoring of the “true” biology of the resource, while the effort allocation module determines the fishing mortality on the “true” biological resources given the management recommendations and the vagaries associated with implementing management decisions in the real world.

The data generation module produces the data (with uncertainty) that are needed to undertake the stock assessments that are part of the management strategies. In this study, the data are logbook catch and effort data, either disaggregated to species and week, or aggregated to year and over both tiger prawn species. Once the data have been generated, they are analysed using the stock assessment component of the management strategy and then by its decision rule component. This leads to a total tiger prawn effort and (for some management strategies) specifications for season length.

The total tiger prawn effort and season length is passed back to the operating model, via the effort allocation module which:

1. calculates the actual tiger prawn effort after accounting for implementation uncertainty (uncertainty when implementing a management decision in practice; it was assumed that VMS accurately controls the season length, but that imposing a total effort is subject to uncertainty);
2. calculates the total prawn effort by adding in effort targeted at banana prawns;
3. allocates the total prawn effort by week and removes the banana prawn effort to determine the weekly effort directed at tiger prawns; and
4. allocates the tiger prawn effort to five stock areas and the two species.

3.1 Issues related to terminology

Although the approach described above has been used fairly extensively in fisheries science, the nomenclature remains confused in the scientific literature. Each combination of data collected, analysis method applied, and decision rules used to create management advice is called an “(operational) management procedure” by Butterworth and Punt (1999), a “harvest algorithm” by Cooke (1999), a “management strategy” by Sainsbury *et al.* (2000), and a “harvest strategy” by Punt *et al.* (2001). In its turn, the use of simulation to compare and evaluate the alternative management strategies has been termed “management procedure evaluation” by Butterworth and Punt (1999), “harvest algorithm evaluation” by Cooke (1999), and “management strategy evaluation” by Sainsbury *et al.* (2000) and Punt *et al.* (2001). Variation has also occurred in the terminology applied to components of the whole process. For example, the set of rules used to interpret the results of the assessment procedure to generate management advice have been called the “management procedure” or “management rule” by Cooke (1999), they are not distinguished from the “management procedure” by Butterworth and Punt (1999), Sainsbury *et al.* (2000) and Punt *et al.* (2002) call them “decision rules”, and, Punt *et al.* (2001) call them “catch control laws” in the context of setting TACs.

Which particular set of terms are used is a matter of definition, and confusion can be avoided as long as usage in any single document is consistent. In this present work we refer to the set of rules used to interpret the results of any analysis as the “Decision Rules”. The decision rules in combination with the data collected (or monitoring program) and

analysis (assessment) of the data are referred to as the “Management Strategy”, and the use of simulation to compare and evaluate the alternative management strategies is referred to as “Management Strategy Evaluation” (abbreviated as MSE).

We do not use the terms “harvest strategy” or “harvest strategy evaluation” because during the development of all these ideas the term harvest strategy was often used to refer to such things as a constant yield strategy or a constant fishing mortality strategy (Hilborn and Walters 1992; Hilborn *et al.* 1993). “Harvest strategy” is therefore a term perhaps more at home in the context of risk assessment, which, while it uses simulated projections, does not necessarily require the use of an operating model.

It is necessary to simulate the dynamics of the fishery and the stock(s) being fished and to include the full range of uncertainties affecting the perceived dynamics to conduct an MSE (Butterworth and Punt 1999). The model upon which this simulation is based is referred to as “the operating model” in the present work. This model represents the reality against which the alternative management strategies being evaluated are compared. Part of the operating model needs to include a method of generating the kinds of data collected during fishing operations and any monitoring program related to the fishery. Only these data are provided to the (simulated) management strategy. The aspect that most completely distinguishes MSE from risk assessment is that, at each time step of the operating model, feedback occurs whereby the results of previous management decisions and monitoring are used by the management strategy to revise its appraisal of stock status and hence how management will occur in future. The relative ability of different management strategies to achieve the selected management objectives will differ if they have different biases and respond to uncertainties in different ways (Butterworth and Punt 1999).

The description of the relative performance of different management strategies is another classic area where confusion with terminology can arise. It is common in the stock assessment literature to refer to “performance measures”. For example, in the northern tiger prawn fishery it is standard to use the ratio of the current spawning stock size to the spawning stock size that should give rise to the maximum sustainable yield ($S_{\text{curr}}/S_{\text{MSY}}$; Dichmont *et al* 2003a) as a “performance measure”. Usually, such quantities are considered in the context of management objectives articulated as both limit and target reference points. The potential for confusion arises because there can be formal stock assessments within an MSE whose outputs include such “performance measures”. However, the term

“performance measures” is more commonly used in the context of an MSE (e.g. Sainsbury *et al.* 2000; Punt *et al.* 2002a) to describe the statistics used to assess the relative performance of the different management strategies. The difference between the two is that S_{curr} and S_{MSY} refer to *estimates* from an assessment model within an assessment whereas the performance measures are based on the “*true*” population within the context of an MSE. There is, of course, interest in whether the estimates from the assessment procedure are able to capture the “*true*” values in the operating model adequately. However, the potential for confusion would be great if both of these quantities are referred to as performance measures. In the present work it has been decided to refer to measures of fishery performance within assessments as “output quantities” and to refer to the measures used to compare the performance of assessments within the MSE as “performance measures”.

In summary therefore:

- **Decision Rules** – the agreed upon set of rules that are used to convert or interpret the results of a stock assessment into management advice.
- **Management Strategy** – any combination of data collection, data analysis, and decisions rules that are used to generate management advice.
- **Operating Model** – a model of the dynamics of a fishery and the stock fished that acts as the reality against which the alternative management strategies are compared.
- **Management Strategy Evaluation** – the use of simulation involving an operating model to compare and evaluate the performance of alternative management strategies.
- **Performance Measures** – statistics concerning the performance of a management strategy relative to given management objectives.
- **Output Quantities** – values estimated during an assessment – these may include statistics related to the status of the resource relative to the perceived values for target or limit reference points.

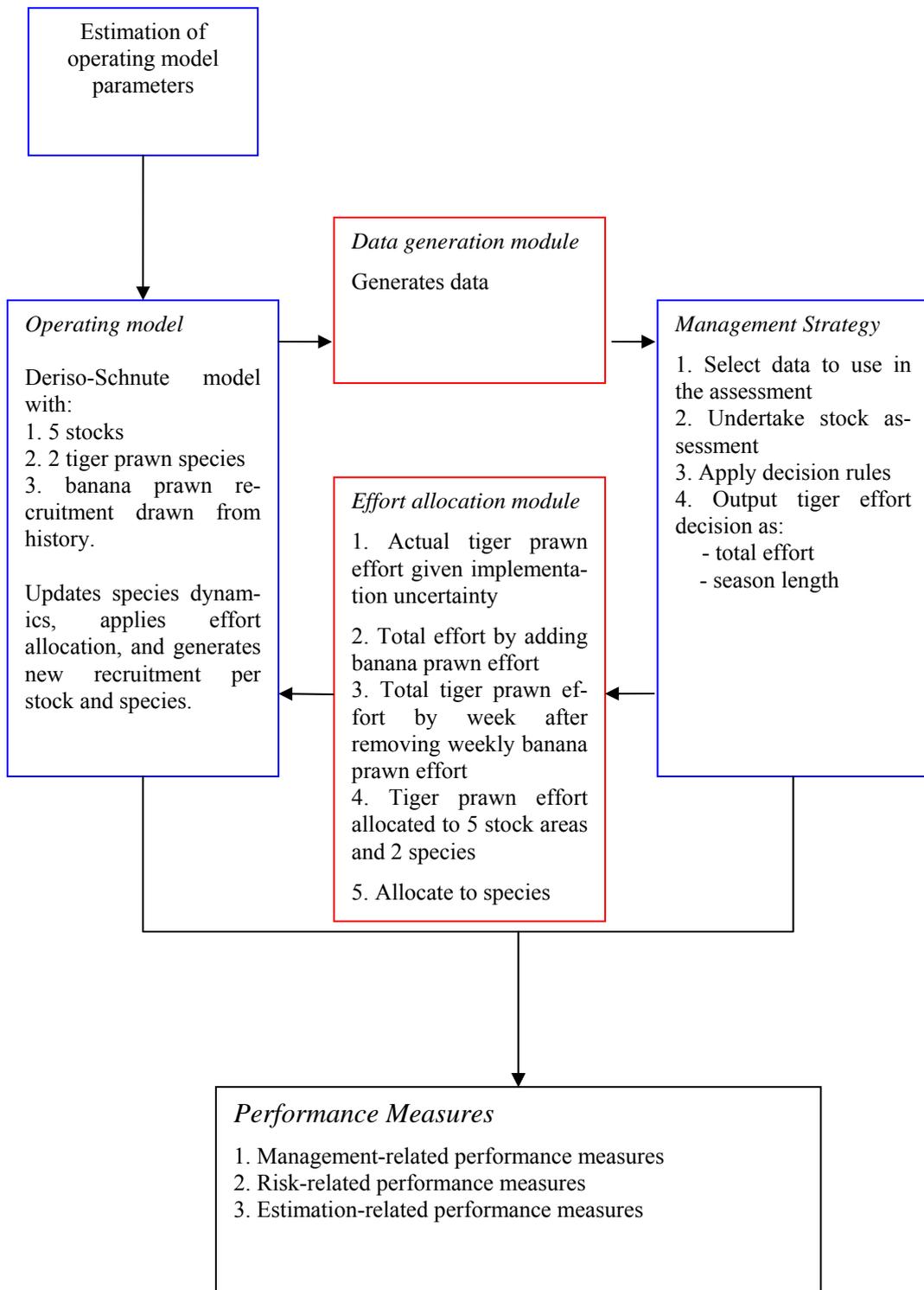


Figure 3.1: Diagrammatic representation of the NPF Management Strategy Evaluation framework.

CHAPTER 4 ACCOUNTING FOR MULTIPLE SPECIES, SPATIAL STRUCTURE AND IMPLEMENTATION UNCERTAINTY WHEN EVALUATING RISK

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Abstract

The Northern Prawn Fishery harvests a variety of prawn species including some short-lived species with highly variable recruitment such as banana prawns and slightly longer-lived tiger prawn with less variable recruitment. An evaluation of stock assessment methods and management strategies for the Northern Prawn Fishery using the Management Strategy Evaluation (MSE) approach requires an (operating) model of the resource to act as the ‘truth’ for the analyses. A five-stock, two tiger prawn species operating model with a weekly time-step is developed and conditioned using more than 30 years of logbook catch and effort data as well as the results of fishery-independent research. The operating model is projected beyond the present using stock-specific stock-recruitment relationships. Banana prawns are not modelled explicitly, but their impact on the management system is simulated empirically. The input control nature of the management system is mimicked using an effort allocation model that allocates effort by species, area and week. This model allows for the impact of changes over time in efficiency, a key uncertainty in the assessment of these species, and the impact of management implementation error, which has historically been substantial. Some of the properties of the operating model are illustrated by projections based on a constant effort policy.

Keywords: Input controls; Monte Carlo simulation; Multi-species modelling; Northern Prawn Fishery; Spatial structure

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4.1 1. Introduction

The Precautionary Approach to Fisheries (FAO, 1996) highlights the need for management systems that can be shown to be robust to the uncertainties inherent in stock assessment and management. It also highlights that the lack of certainty should not prevent implementation of management actions. The tools used for providing fisheries management advice (data collection strategies, analysis methods, and decision rules) can be evaluated in terms of their likely ability to satisfy the management objectives using simulation (Kirkwood and Smith, 1996). Simulation (or the Management Strategy Evaluation (MSE) approach) has been applied extensively for many fisheries at the single- or the multi-species level (Punt, 1992; De la Mare, 1996; Butterworth et al., 1997; Punt and Smith, 1999; Smith et al., 1999; Punt et al., 2002) and, in recent years, for ecosystem objectives (Sainsbury et al., 2000).

The MSE approach (Figure 4.1) distinguishes between the true state of the resource (as represented by the ‘operating model’) and that perceived through data collection strategies and stock assessments (a component of the ‘management strategy’). The management strategy includes not only an assessment procedure, but also a decision rule that uses information on the perception of the status of the system to determine management advice. The management advice determines the management actions and hence any impacts these actions have on the resource and the associated fishery. The MSE approach therefore attempts to consider the whole management system. Representation of uncertainty is a key component of the MSE approach, and the impact of several sources of uncertainty can be evaluated. Specifically, many different operating models may be constructed to capture uncertainty about, for example, the true dynamics of the resource, how the data are collected, etc. Some of these operating models can be quite speculative, designed to determine whether factors not currently supported by existing data, but which are nevertheless not implausible, may impact the robustness of management strategies (Butterworth and Punt, 1999).

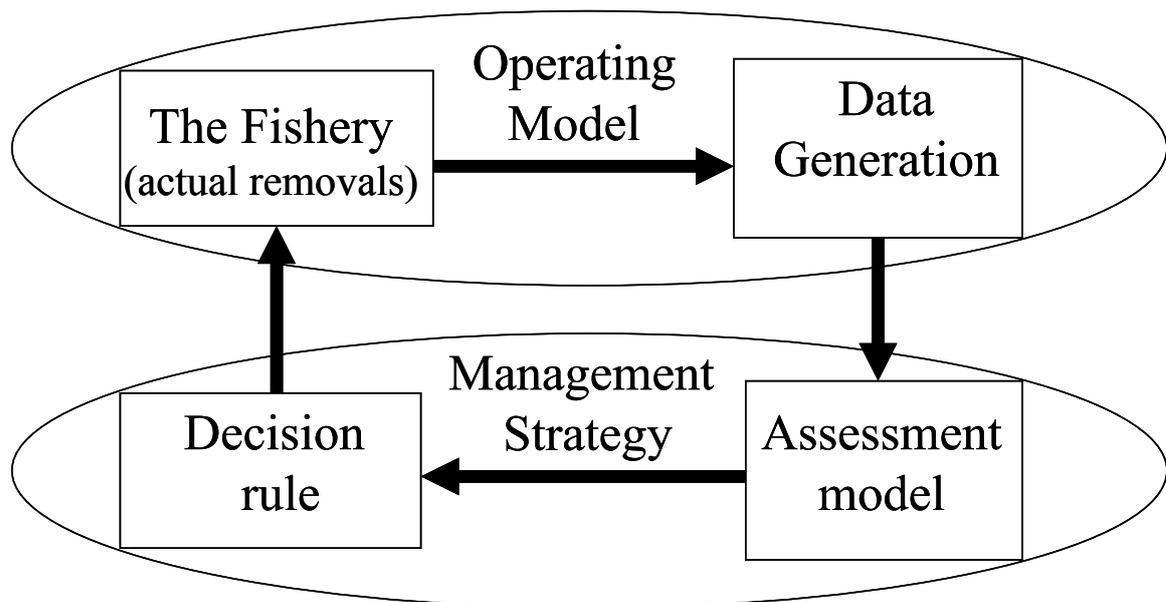


Figure 4.1: Conceptual overview of the MSE approach, indicating the key components of the framework.

Most applications of the MSE approach have focused on longer-lived species managed using output controls (e.g. Butterworth et al., 1997; Punt and Smith, 1999; Smith et al., 1999; Punt et al., 2002). In contrast, many of the world’s most valuable fisheries are those for short-lived species managed using input controls. There are several sources of uncertainty that are specific to fisheries managed using input controls and which need to be considered when the MSE approach is used to evaluate management strategies for such fisheries. This paper illustrates how an operating model can be constructed for a fishery that is managed using input controls and targets several species, based on the actual example of evaluating management strategies for the fishery for tiger prawns (*Penaeus semisulcatus* and *P. esculentus*) in Australia’s Northern Prawn Fishery (NPF).

This operating model can be used to evaluate various aspects of a management system for the NPF, including, for example, a) how different management strategies perform in terms of their ability to satisfy the management objectives (Dichmont et al., 2006a; Dichmont et al., 2006b), b) the advantages of disadvantages of input versus output controls, c) the impact of various uncertainties of the ability of stock assessment methods to provide estimates of quantities such as biomass and MSY. However, owing to space constraints, the examples of this paper are based on evaluating the impact of future levels of fishing effort.

4.1.a Overview of Australia's Northern Prawn Fishery

The NPF is one of the most valuable fisheries managed by the Australian Commonwealth government. Management is through input controls in the form of limited entry, gear restrictions, and time and area closures. Currently, management of this fishery is through a system of tradeable gear units (headrope length). The NPF is based on three prawn species groups (banana, tiger, and endeavour prawns), each of which consists of at least two species (Pownall, 1994; Venables and Dichmont, 2004).

The biological characteristics and harvests of the three species groups differ quite markedly. For example, common banana prawns, *Penaeus merguensis*, are short-lived and appear to be environmentally driven (Die and Ellis, 1999; Vance et al., 1985) while tiger and endeavour (*Metapenaeus endeavouri* and *M. ensis*) prawns are longer-lived (a maximum age of about two years) and appear to exhibit a relationship between stock size and subsequent recruitment (which implies that they can be recruitment overfished). Red-leg banana prawns, *P. indicus*, and the two species of endeavour prawns, have less variable recruitment and lower natural mortality than common banana prawns, but are shorter-lived and more variable than tiger prawns.

The fishery for prawns in the NPF was first focused on banana prawns, but, thereafter years, catches of banana and tiger prawns have been roughly equal (Figure 4.2). Endeavour prawns have not constituted a significant proportion of the total catch. The fishery switches among species during the year. In recent years, the fishery has started in April targeting common banana prawns which are more catchable at that time due to the presence of large aggregations (Die and Ellis, 1999). The fleet switches to tiger prawns for which the catch rate is lower, but less variable, as the abundance of banana prawns drops owing to fishing and natural mortality. In recent years, the fishery has consisted of two sub-seasons split by a mid-year spawning closure. Red-leg banana prawns are only caught during the second sub-season and at neap tides.

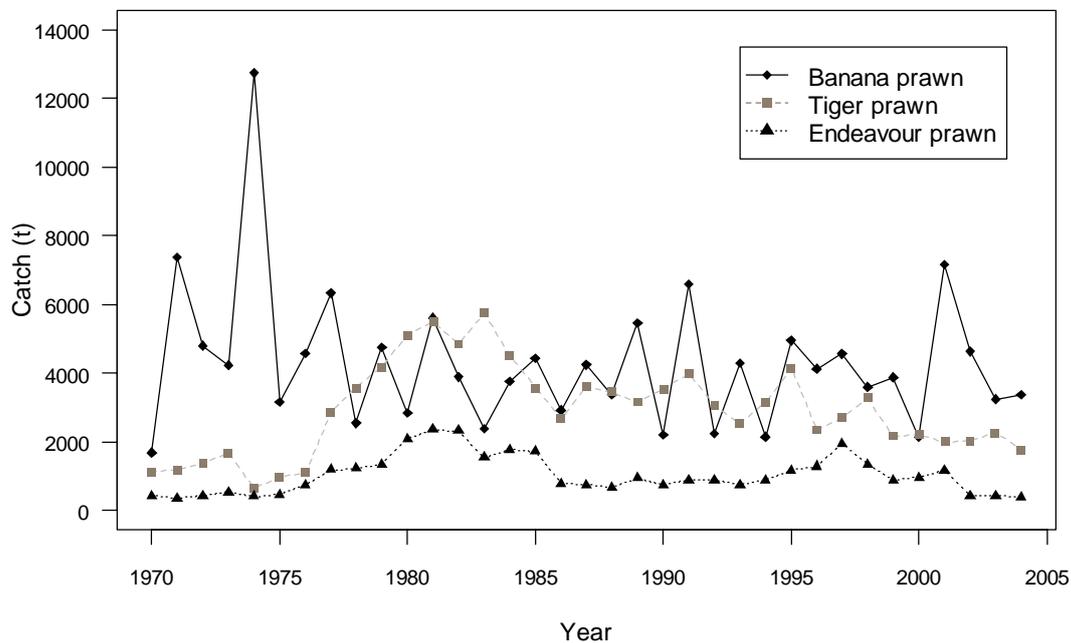


Figure 4.2: Annual landings of banana, tiger and endeavour prawns (tonnes).

Tiger prawns have been the focus for quantitative stock assessments for many years (Somers, 1990; Somers and Wang, 1997; Wang and Die, 1996; Dichmont et al., 2001; Dichmont et al., 2003a) owing to the perception that these species can be recruitment overfished. Endeavour prawns are predominantly a bycatch of targeting tiger prawns and management measures for tiger prawns tend to benefit endeavour prawns. The dynamics of common banana prawns appear to be almost completely environmentally driven. Assessments of tiger prawns have shown that excessive fishing effort during the 1980's and 1990's led to a resource decline (Wang and Die, 1996; Dichmont et al., 2003a), that was only halted through large, controversial and costly reductions in fishing effort. These reductions were achieved through a combination of licence buy-backs, proportional licence surrenders, seasonal closures, and bans on daylight fishing (Cartwright, 2005).

The primary data sources for tiger prawns in the NPF are logbook catch and effort data, and the results of fishery-independent surveys. The catches, which are not reported by species, can be disaggregated to species fairly reliably using the results from fishery-independent surveys (Venables and Dichmont, 2004). Stock assessment of tiger prawns is, however, complicated for several reasons: high natural mortality implies a low probability of a prawn surviving more than a single year, spawning patterns and availability to the

fishery change during the year (Hill and Wassenberg, 1985; Somers et al., 1987; Somers and Kirkwood, 1991), and recruitment is continual throughout the year with a three to four month peak (Somers and Wang, 1997; Dichmont et al., 2003a). Furthermore, extensive changes over time in fishing efficiency (fishing power) are known to have occurred throughout the history of the fishery (Buckworth, 1985; Robins et al., 1998; Bishop et al., 2000; Dichmont et al., 2003b; Bishop et al., 2004), but the magnitude of the change in fishing efficiency remains a key uncertainty.

Finally, although Dichmont et al., (2001) identified seven potential stocks of tiger prawns in the NPF based on catch and effort data, catchment boundaries, regions of seagrass bed habitat (Poiner et al., 1987; Coles et al., 1989), and the results of oceanographic models (Condie et al., 1999), no genetic data are available to distinguish stocks and hence to determine the correct placement of boundaries among putative stocks. As a result, stock assessments are still at the scale of the entire NPF and consequently ignore the impact of potential (but unknown) stock structuring (Dichmont et al., 2003a, 2003b).

4.2 The operating model

The operating model is the underlying ‘truth’ being managed and therefore needs to be sufficiently general to be able to capture all key hypotheses related to the dynamics of the resource and its associated fishery (Butterworth and Punt, 1999). In particular, it needs to be able to capture multiple species and the impact of inputs controls on the dynamics of the fishery. The operating model for the NPF consists of two main components; a biological component of the focus group, tiger prawns, and an effort allocation component. The focus of this section is on the effort allocation component of the operating model because the biological component is virtually identical to the model on which previous assessments have been based (Dichmont et al., 2003a)

Tiger prawns appear to form regional subpopulations that, although not necessarily genetically isolated, do not mix much and need to be managed separately (Die et al., 2001). The biological component of the operating model (see Appendix A for details on the basic dynamics) has a weekly time step and can represent multiple stocks and several species. The stocks interact through the ‘technical interaction’ that results from fishing for one species leading to catches of other species. However, biological interactions among the species,

such as might be predicted through trophodynamics, are ignored. A weekly time-step is adopted to capture the within-year dynamics of the fishery, including how it switches from banana to tiger prawns.

4.2.a Effort allocation component of the model

The effort allocation component of the operating model provides the link between the management decisions and the biological component of the operating model. The input for the effort allocation model is the management advice on the total effort of the fleet (in days) to be targeted towards tiger prawns (aggregated over both species, the entire NPF and the whole season), and the number of weeks during the year that the fishery is open ('the season'), and the output of the effort allocation model is the number of days targeted at each tiger prawn species by week and tiger prawn stock. The effort allocation model captures the impact of banana prawn abundance on the effort targeted towards tiger prawns, management decision implementation error, and how the total fishing effort targeted towards tiger prawns is split by week, stock, and tiger prawn species (see Figure 4.3 for an overview).

The steps used when calculating the effort for each tiger prawn species by stock area and week are as follows:

1. Calculate the total tiger prawn effort that *actually* occurs during year by accounting for the impact of implementation error,
2. Select a banana prawn season and calculate the total effort for all prawn species (including banana prawns).
3. Split the total effort into fleet effort by week.
4. Reduce the fleet effort by week by the amount of weekly effort directed towards banana prawns leaving the weekly tiger prawn effort.
5. Split the effort by week into effort by week and stock area.
6. Split the effort by week and stock area into effort by week, stock-area and (tiger prawn) target species.

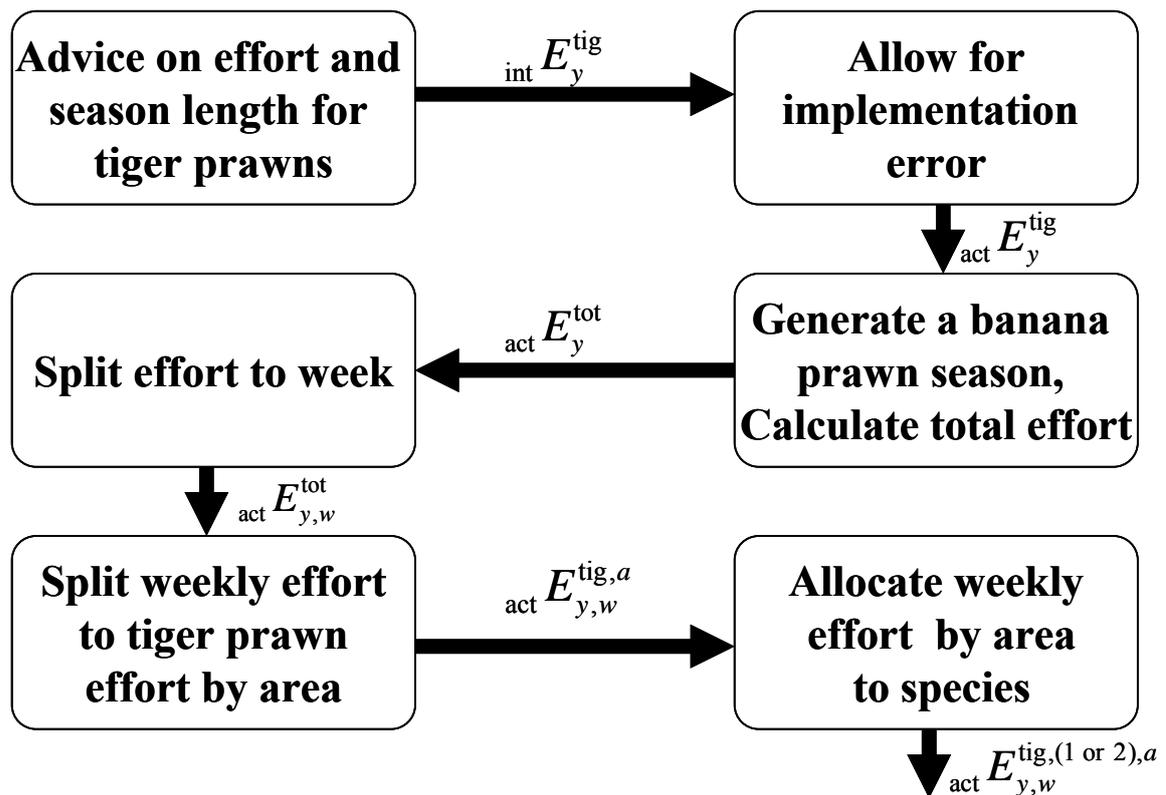


Figure 4.3: Flowchart of the algorithm used to determine the number of days of fishing effort targeted at tiger prawns by species, stock, year and week from the total effort directed towards tiger prawns during the year based on the management strategy. The symbols at the arrows are those output from the origin box and is an input to the destination box. These symbols are described in Table 4.1.

Each of these steps is outlined in more detail below (see Table 4.1 for the notation used). In several of these steps, a random year from 1990-2002 is used to describe the amount of fleet effort during the banana prawn season, the weekly banana and tiger prawn fleet effort patterns, and the areas in which the fleet fishes during a given week. The same random year is used for all these cases because the size of the banana prawn catch and the migration pattern of tiger prawns seem to influence the temporal and spatial pattern of the fishery. A different random year is used for each year of the projection period. The size of the banana prawn catch is highly variable between years and is unpredictable (Figure 4.2).

4.2.a.(i) Calculating the total tiger prawn effort that actually occurs

In this operating model, implementation uncertainty is the difference between the number of days actually fished for tiger prawns and the number of days expected to be fished for tiger prawns based on the management strategy. There are several sources of implementation uncertainty: a) whether a scientific recommendation for a change in effort is accepted by the decision makers, b) the inability to accurately implement management decisions

owing to variability in participation in the fishery, c) the difficulty associated with placing restrictions on fishing mortality when multiple species and stocks are being managed, and d) inadequacies in correcting for changes over time in fishing power, etc. The relationship between, ${}_{\text{int}}E_y^{\text{tig}}$, the management advice on the total effort of the fleet (in days) to be targeted towards tiger prawns (aggregated over both tiger prawn species, the entire NPF and the whole season) during year y and ${}_{\text{act}}E_y^{\text{tig}}$, the amount of effort actually targeted toward tiger prawns during year y , is modelled using the model:

$${}_{\text{act}}E_y^{\text{tig}} = {}_{\text{int}}E_y^{\text{tig}} e^{\varepsilon_y} \quad \varepsilon_y \sim N(0; \sigma^2) \quad (1)$$

where the value for σ is determined by fitting model (1) to the actual effort expended in the NPF and the effort intended to expended based on the minutes of the Management Advisory Committee for the fishery for the years 1987-2002, ignoring information for the years in which there was no intention to change the amount of effort targeted at tiger prawns.

Table 4.1. Symbols used in the effort allocation model.

${}_{\text{int}}E_y^{\text{tig}}$	Fishing effort (in days) during year y directed towards tiger prawns based on the management strategy.
${}_{\text{act}}E_y^{\text{tig}}$	Fishing effort (in days) during year y actually directed towards tiger prawns (after accounting for implementation error).
${}_{\text{act}}E_y^{\text{tot}}$	Fishing effort (in days) during year y directed towards all prawn species (i.e. banana and tiger prawns combined).
${}_{\text{act}}E_{y,w}^{\text{tot}}$	Fishing effort (in days) during week w of year y directed towards all prawn species (i.e. banana and tiger prawns combined).
${}_{\text{act}}E_{y,w}^{\text{tig}}$	Fishing effort (in days) during week w of year y directed towards tiger prawns.
${}_{\text{act}}E_{y,w}^{\text{tig},a}$	Fishing effort (in days) directed towards tiger prawns in stock area a during week w of year y .
${}_{\text{act}}E_{y,w}^{\text{tig},s,a}$	Fishing effort (in days) directed towards tiger prawns of species s in stock area a during week w of year y .
$O_{y,w}$	Set equal to 1 if the application of the management strategy allows fishing to occur during week w of year y .
y'	Year sampled at random from 1990-2002 (excluding 1994)
$\lambda_{y,w}$	Fraction of the effort during week w of year y that was targeted towards banana prawns (Figure 4.4).

$\pi_{w,act}^a$	Average proportion of the effort during week w in stock area a that is targeted at <i>P. semisulcatus</i>
σ	Variation in the relationship between the intended and actual amount of effort directed at tiger prawns.

4.2.a.(ii) Accounting for the impact of the fishing for banana prawns

The main impact of the fisheries for the two banana prawn species relates to the number of fishing days available for fishing for tiger prawns (i.e. high recruitment of banana prawns will lead to a shorter tiger season and *vice versa*). No attempt is made to model the population dynamics of banana prawns given the lack of understanding of the environmental factors that determine the success of banana prawn recruitment, and the likely inability to predict how such environmental factors will change in the future. Instead, an empirical approach is taken to predicting future banana prawn fishing. Specifically, a random year y' is selected at random from the years 1990–2002 (excluding 1994 which was anomalous due to its very early first sub-season opening date; this date was stable around 1 April for the remaining years) and the fraction of the total possible effort ‘lost’ to banana fishing is set to that for year y' . These years were selected because the start and end dates of their fishing seasons are considered to be most representative of those likely to occur in future and because the number of boats in the fleet was much higher prior to 1990 than at present.

Given the selection of a year, y' , to determine the nature of the banana prawn fishery during year y , the total effort (directed at all prawn species) during the year y , ${}_{act}E_y^{tot}$, is calculated by scaling the actual effort directed towards tiger prawns up by the fraction of the total effort during year y that was directed towards tiger prawns, i.e.:

$${}_{act}E_y^{tot} = {}_{act}E_y^{tig} \frac{{}_{act}E_{y'}^{tot}}{{}_{act}E_{y'}^{tig}} \quad (2)$$

4.2.a.(iii) Allocating effort to week

The tiger prawn temporal effort pattern is influenced by the sub-season start dates, the size of the banana season catch and its persistence over time. Let $O_{y,w}$ be a variable that is 1 if week w of year y is open to fishing and 0 if it is not. The values for $O_{y,w}$ are determined by

the management strategy or, as in this paper, pre-specified. The effort directed towards all species is therefore allocated equally to weeks open to fishing according to the formula:

$${}_{\text{act}} E_{y,w}^{\text{tot}} = O_{y,w} {}_{\text{act}} E_y^{\text{tot}} / \sum_{w'} O_{y,w'} \quad (3)$$

Equation (3) assumes that all vessels fish throughout the season, but not necessarily all of the effort is directed at tiger prawns. The assumption that all vessels fish throughout the year has not always been true towards the end of a season, but is in general true. The effort directed towards tiger prawns during week w of (future) year y , ${}_{\text{act}} E_{y,w}^{\text{tig}}$ is given by:

$${}_{\text{act}} E_{y,w}^{\text{tig}} = {}_{\text{act}} E_{y,w}^{\text{tot}} (1 - \lambda_{y,w}) \quad (4)$$

where $\lambda_{y,w}$ is the fraction of the actual effort during week w of random year y' that was targeted at either common or red-leg banana prawns (see Figure 4.4). The proportion of effort directed at banana prawns is highly variable and may increase at the end of the first season if total effort is very low. Major season and effort changes (including a shorter season) were introduced in 2002, which resulted in a dramatic change in the patterns compared to previous years.

4.2.a.(iv) Splitting the effort to stock area

Although models exist for how vessel effort in the NPF is distributed spatially (e.g. Chapman and Beare, 2002), these models are not at the same temporal and spatial resolution as the biological component of the operating model. Therefore, rather than using a detailed process model to split the effort by week, to the effort by week and stock area an empirical approach is used instead for this purpose (see Appendix B). The model was fitted to data from 1980 onwards even though y' was selected from 1990 onwards. This is because by 1980 the fishery had reached a certain maturity and its maximum fleet size, with well established spatio-temporal patterns and a good deal of resistance to change in fishing patterns. The largest effect on the initial tiger prawn spatio-temporal effort pattern is the nature of banana prawn season that occurs and its persistence through time. It was considered necessary to calibrate the model with as many years of data as possible to include a wide variety of possible banana season events in the analysis.

4.2.a.(v) *Splitting the effort to tiger species*

The final step of the effort allocation component is to allocate the effort by week and stock-area to tiger species (1 is *P. semisulcatus* and 2 is *P. esculentus*). This is achieved using the formula:

$$E_{y,w}^{\text{act,tig},1,a} = \pi_{w,\text{act}}^a E_{y,w}^{\text{tig},a} \quad E_{y,w}^{\text{act,tig},2,a} = (1 - \pi_{w,\text{act}}^a) E_{y,w}^{\text{tig},a} \quad (5)$$

where $\pi_{w,\text{act}}^a$ is the average proportion of the effort during week w in stock area a that is targeted at *P. semisulcatus* (see Venables and Dichmont (2004) for how $\pi_{w,\text{act}}^a$ is estimated).

Equation 5 has no error associated with it as this has been shown to be small (Dichmont et al., 2001).

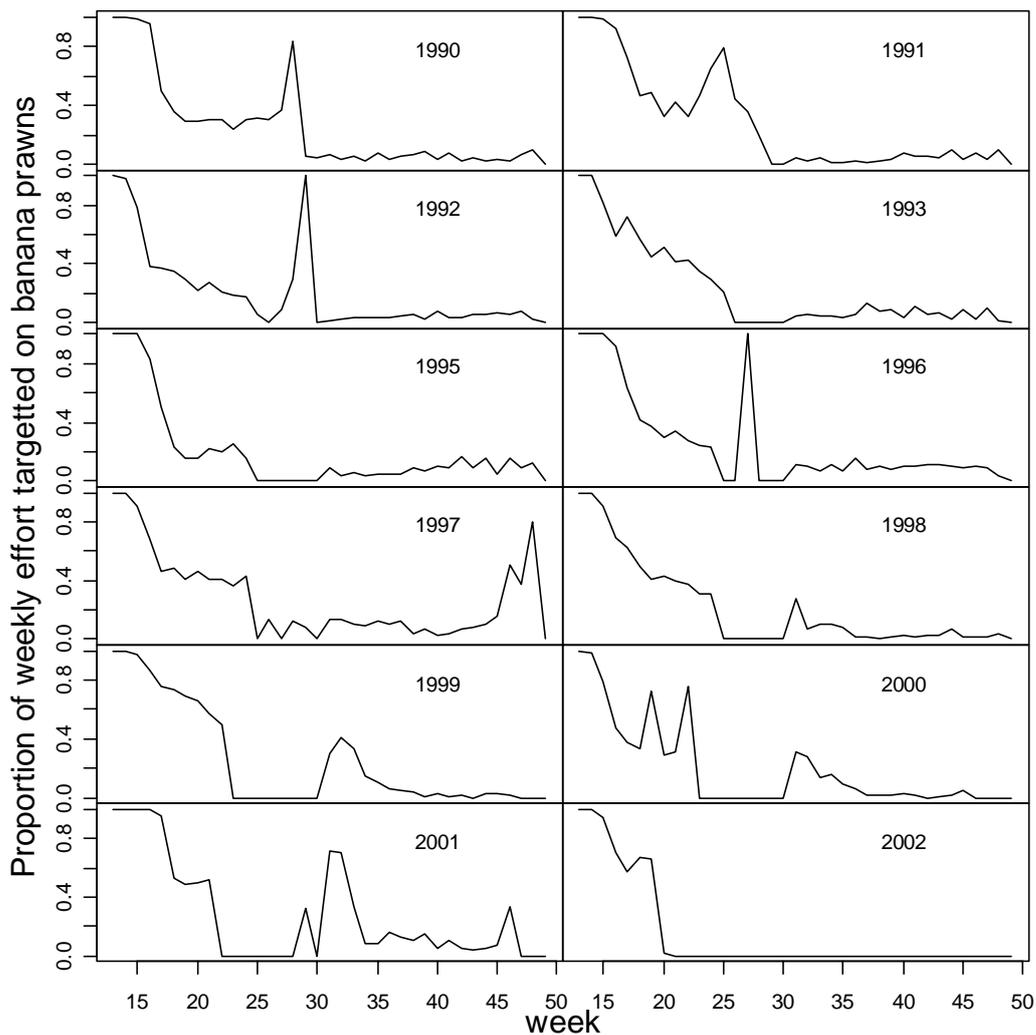


Figure 4.4: Proportion of effort by week targeted at the two species of banana prawns.

4.2.b Application to the Northern Prawn Fishery

The operating model for the NPF is based on a five-stock, two-species tiger prawn resource. A total of seven putative tiger prawn stock areas have been identified (Figure 4.5). However, the numbers of tiger prawns in two of the three areas outside the Gulf of Carpentaria are very small. Therefore, the areas ‘JB Gulf’, ‘Melville’ and ‘N. Arnhem’ had to be combined into a single stock area denoted ‘Outside GOC’. This leads to a total of five stock areas, four of which are in the Gulf of Carpentaria.

The illustrative example of this paper is based on setting future fishing effort to that for 2002 and the specifications for the fishing season to that for 1999 (chosen because 1999 was the last year before major changes in effort and season length occurred). The operating model uses the Base Case High fishing power series (Figure App.A.1), which is a ‘worst case scenario’ in terms of the current status of the resource (Dichmont et al., 2003a). The projections also ignore any migration among stock areas, which could also be considered to lead to a ‘worst case scenario’ because the impact of excessive effort in one stock area cannot be compensated for to some extent by movement into that stock area from other less exploited stock areas.

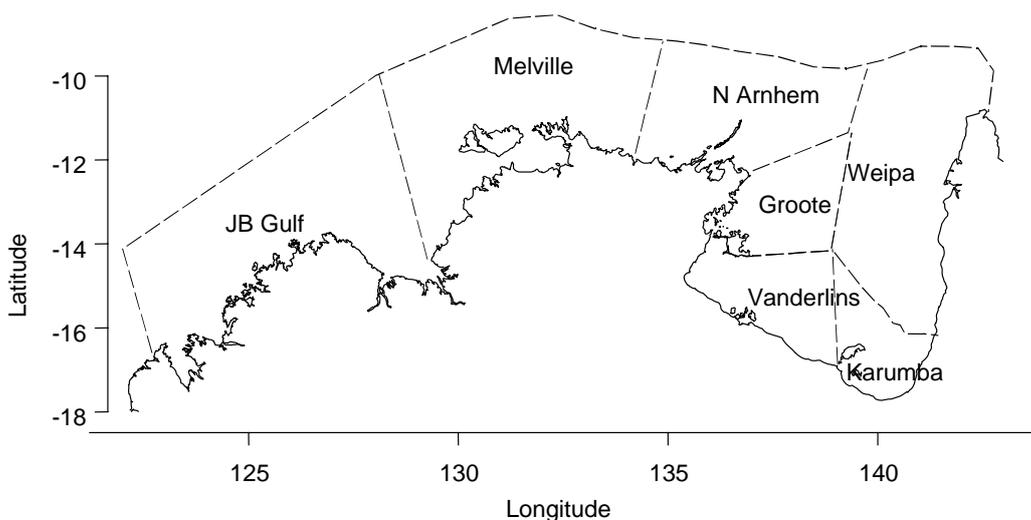


Figure 4.5: The stock boundaries identified by Dichmont et al. (2001). The combination of the stocks areas Groote, Vanderlins, Karumba, and Weipa constitute the Gulf of Carpentaria.

4.3 Results and Discussion

4.3.a Extent of implementation error

Implementation error relates to how well management decisions and policies are applied in practice (Rosenberg and Brault, 1993) and to differences between management advice and the final management decisions in a political and consensus-based decision-making process. This source of uncertainty is often substantially greater than previously believed (Hilborn et al., 2001). Figure 4.6 plots the effort that was actually to be targeted at tiger prawns *versus* the effort that was intended to be targeted at tiger prawns based on the records of the Management Advisory Committee. For cases where the minutes of the Advisory Committee did not state to which species a change in effort applied, the change was assumed to apply to both tiger species. There are several sources for the differences between the intended and actual effort evident in Figure 4.6, but broadly speaking they can be divided into two classes: a) differences between the actual and intended effort and b) differences between the recommendations from the scientific community regarding effort given agreed decision rules and reference levels and the effort actually selected via the management process. More detailed explanations for the differences in Figure 4.6 are:

1. The inability to predict the size of the banana prawn catch in a given year. A large banana prawn catch retains effort on banana prawns thereby indirectly causing a reduction in effort on tiger prawns and *vice versa*.
2. The inability to predict the behaviour of fishers after an effort reduction aimed at countering increases in fishing power. The fishery is presently managed by controlling headline length using a trade-able gear unit system. When a reduction in effort takes place, each vessel's headline length is reduced. Given this, fishers can either: a) trade in gear units to return to their previous headline length (so some vessels have to leave the fishery) or b) fish with smaller nets. The nett effort reduction depends on the choices the fishery makes. For example, a smaller fleet result in a much larger effort reduction than the same fleet fishing with smaller gear (Venables et al., 2003). In some years, reductions in effort also involved shortening the fishing season. In general, it seems that management under-estimated the

impact of shortening the season so that the reduction in effort achieved by a change in season exceeded that intended.

3. Errors in determining how fishing efficiency has changed over time. For example, no allowance was made for changes over time in fishing efficiency before the late 1980's; a 5% increase per annum was assumed during the 1990's, after which, yearly changes in fishing efficiency have been modelled. These changes have meant that scientific uncertainty has contributed to implementation error.
4. At times, the scientific management advice suggested a reduction in effort, but this was not accepted by management. Consequently, recommended changes in effort were implemented only about one time out of three.

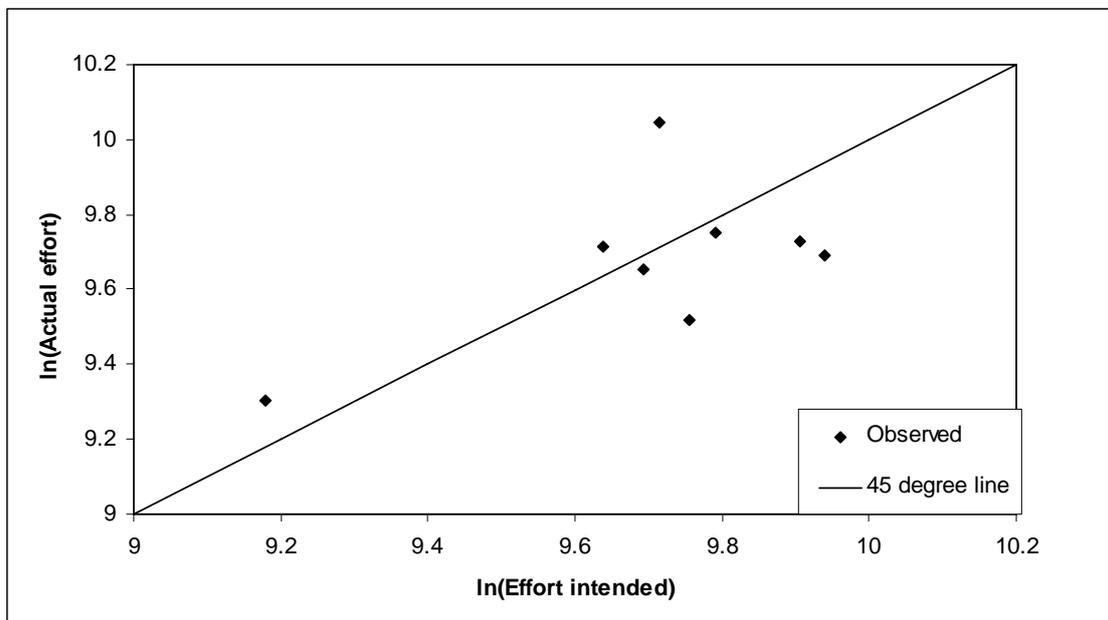


Figure 4.6: Log-log plot of the effort that was actually to be targeted at tiger prawns *versus* the effort that was intended to be targeted at tiger prawns.

There is only a very weak relationship between targeted and actual effort and the data would not preclude rejection of the hypothesis that actual effort is independent of intended effort. However, it is reasonable to expect a 1:1 relationship between actual and intended effort. For example, if the intention was to close the fishery, effort would end up being close to zero. The coefficient of variation about the 1:1 line is 0.18 but some of the deviations between the actual and intended effort are as high as 0.3 suggesting that implementation error is quite high. The projections are based on using the 1:1 line because this assumption is effectively the same as the assumption that actual effort is independent

of intended effort at the effort levels represented in Figure 4.6, but it behaves more realistically for intended effort levels outside of this range.

One common source of implementation uncertainty involves misreporting of catches, either through black-market landings, misreporting of the species composition of the catch, or high-grading and discarding (Butterworth and Punt, 1999). This source of implementation uncertainty is not, however, relevant to this fishery because there is little incentive to hide information about outputs.

Implementation uncertainty has largely been ignored in the evaluation of management strategies. One exception to this is Christensen (1997) who accounted for two sources of implementation uncertainty when evaluating the implications of an effort level or a TAC for the prawn *Pandalus borealis*. These two sources were: a) the chance that industry pressure would mean that a recommended change in a management measure was not implemented and b) high-grading or discarding. Christensen (1997) concluded that, as expected, if the management measures are modified by a political TAC setting procedure, the fishing mortality may be substantially larger than expected given the management strategy, which would in turn reduce the average long-term resource rent. Die and Watson (1992) investigated implementation error in the form of non-compliance with spatial closures for the prawn fisheries in the Torres Strait, Australia. They showed that even low levels of implementation error could dissipate most benefits of spatial management for tropical prawn species.

4.3.b Estimating the values for the parameters of the operating model

The posterior median time-trajectories of indices of recruitment (with their associated 90% probability intervals) from the operating model are shown in Figures 4.7 and 4.8. The results shown in these and the following figures are based on the Base Case High fishing power series and the catchability coefficient estimated by Wang (1999). The estimates of recruitment for the years before the mid-1970s are less precise and vary more inter-annually than those for the years thereafter. There is a slight downward trend in the recruitment for both tiger prawn species after 1980 for all stock areas except Groote.

Some stock areas (e.g. Groote, Vanderlins, and Karumba) contain a relatively large biomass of both species, while two areas only contain large numbers of only one species (*P. semisulcatus* in Weipa; *P. esculentus* in Karumba). In areas where numbers of a species are very small, their biomass was assumed to be zero and any catch and effort data are allocated to a nearby stock area (catch of *P. esculentus* in Weipa to Karumba; catch of *P. semisulcatus* in Karumba to Vanderlins). This means that Karumba is assumed to consist exclusively of *P. esculentus* and Weipa of *P. semisulcatus*.

The stock-recruitment relationships differ markedly among species and stock area (Figures 4.9 and 4.10). For example, some of the stock-recruitment relationships exhibit little evidence for compensation at low stock size, which is surprising, but has been a common outcome of assessments for tiger prawns in the NPF (e.g. Wang and Die, 1996; Dichmont et al., 2003a). Furthermore, although a Ricker stock-recruitment relationship has been fitted to the data in Figures 4.9 and 4.10, there is little evidence for a reduction in recruitment at high spawning stock size. As a result, the sensitivity of the results of population projections to the form of the stock-recruitment relationship (Beverton-Holt or Ricker) needs to be included when evaluating the performance of management strategies.

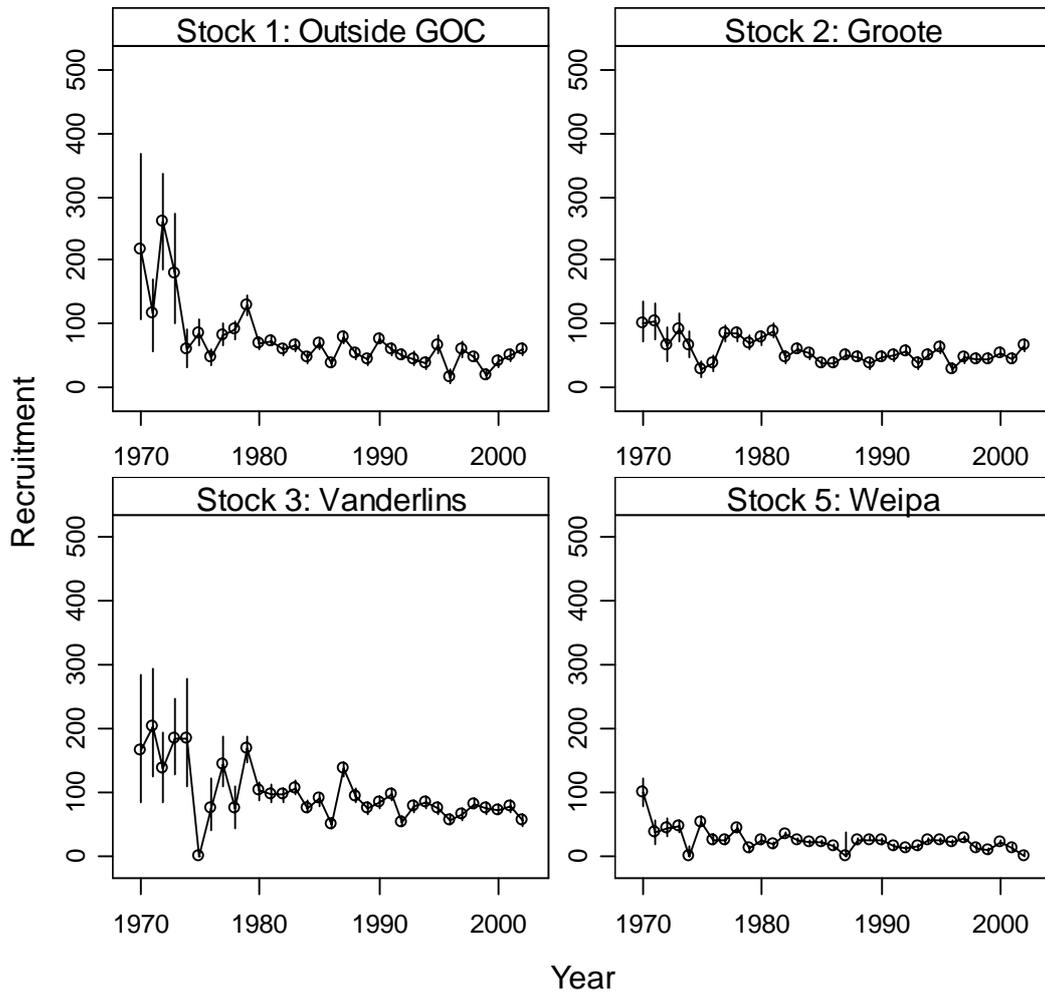


Figure 4.7: Recruitment indices (with posterior 5th and 95th percentiles) for *P. semisulcatus* for four stock areas (results for the Karumba area are omitted because of the assumed absence of *P. semisulcatus* from this area).

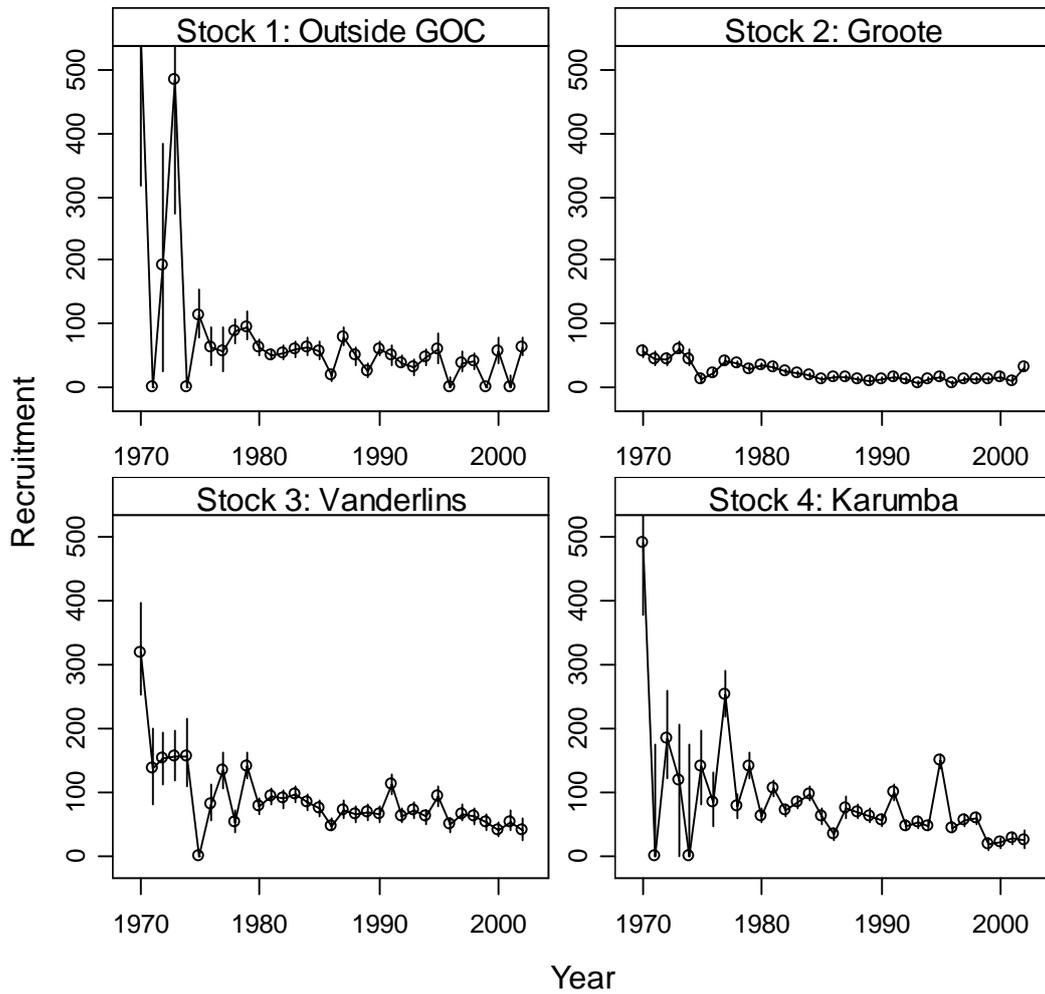


Figure 4.8: Recruitment indices (with posterior 5th and 95th percentiles) for *P. esculentus* for four stock areas (results for the Weipa area are omitted because of the assumed absence of *P. esculentus* from this area).

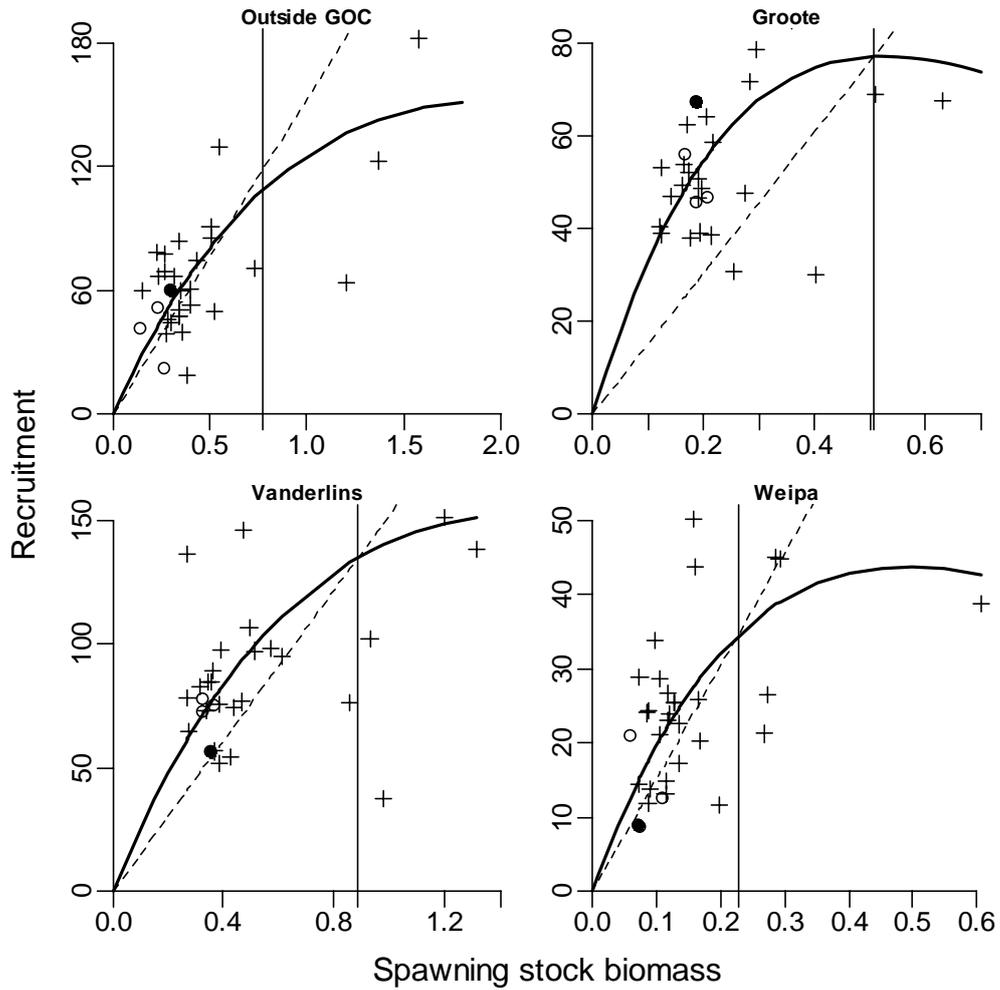


Figure 4.9: Ricker stock-recruitment relationships for *P. semisulcatus* for four of the five stock areas. The solid dots are the maximum likelihood estimates of recruitment of latest year, the circles are the estimates of 2nd – 4th latest years and the crosses are those of the other years. The solid lines are the estimated stock-recruitment relationships. The dashed line is the replacement line - the amount of recruitment required to replace the original spawning biomass with no fishing mortality.

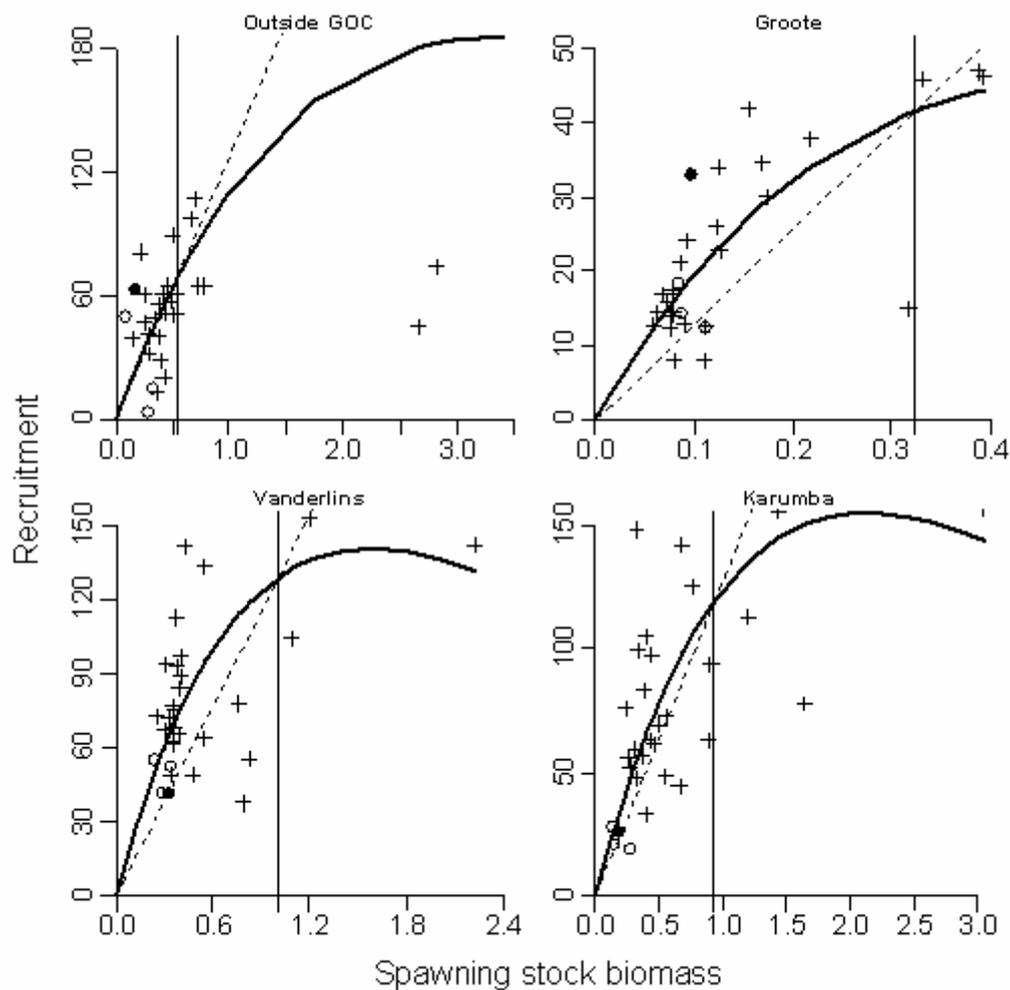


Figure 4.10: As for Figure 4.9, except that the results pertain to *P. esculentus*.

There are some noteworthy correlations between the deviations about the fitted stock-recruitment relationships among stocks and between tiger prawn species (Figure 4.11). There are strong positive correlations between tiger prawn species within a stock area (e.g. 0.69, 0.80, 0.79 for Outside GOC, Groote, Vanderlins respectively) and within a species between adjacent stock areas (e.g. 0.52 for *P. semisulcatus* in Groote and Vanderlins; 0.65 for *P. esculentus* in Vanderlins and Karumba). There are no strong negative correlations.

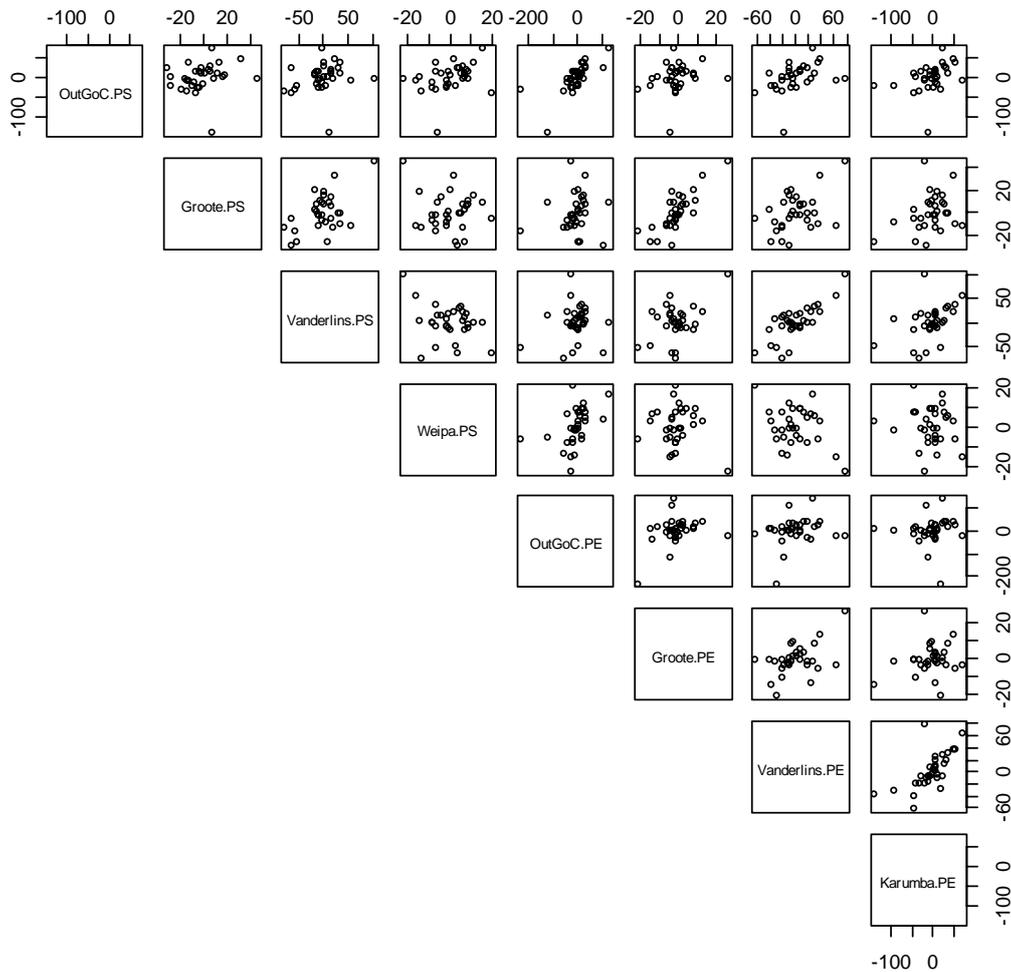


Figure 4.11: Inter-stock and -species correlation in the deviations about the estimated stock-recruitment relationship based on the fit of the operating model to the data. ‘PS’ is *P. semisulcatus* and ‘PE’ is *P. esculentus*.

4.3.c Constant effort projection

The purpose of the example application is to illustrate the behaviour of the operating model and to highlight the complications of a fishery being managed using input controls. The performance of a level of effort is illustrated by plotting the time-trajectories of spawning stock size by species (aggregated over stock area) relative to the spawning stock size that would achieve Maximum Sustainable Yield (S_{MSY}), the annual effort by species relative to that required to achieve the MSY in expectation (E_{MSY}), and the catch by species (e.g. Figure 4.12). The inter-simulation variation in catches is a consequence of variation in effort directed at each tiger prawn stock, and that about the stock-recruitment relationship. Variation in the effort directed towards each species is due to variation in the

algorithm that splits effort spatially and variation in the length of the fishery for banana prawns. For example, a large banana prawn catch delays the switching behaviour from banana to tiger prawns which then also affects which areas are fished (and which tiger prawn species dominates the catch). For example, *P. semisulcatus* tend to migrate beyond the trawl grounds in winter (Crococ and Van der Velde, 1995) and does not occur in Karumba, which is a good banana prawn catch area. As a result, a poor banana prawn season would result in tiger prawns becoming a target during winter which would predominantly consist of *P. esculentus* in the Karumba and neighbouring areas.

Both species were depleted to below S_{MSY} in 2002 with *P. esculentus* stocks being more depleted than *P. semisulcatus* stocks. Since the effort used for projection purposes is much smaller than E_{MSY} , recovery to well above S_{MSY} occurs within a few years (Figures 4.12 and 4.13) and catches increase as catch rates recover. This is the basis of the economic argument that, within limits, a large resource produces higher catch rates which increases profit margins (Rose and Kompas, 2004).

Adding implementation error widens the intervals describing the range of effort expended annually by species (Figure 4.12), which then impacts catch and stock status. The median effort trajectory changes only slightly, as would be expected given that the actual effort equals the intended effort in expectation (Figure 4.6).

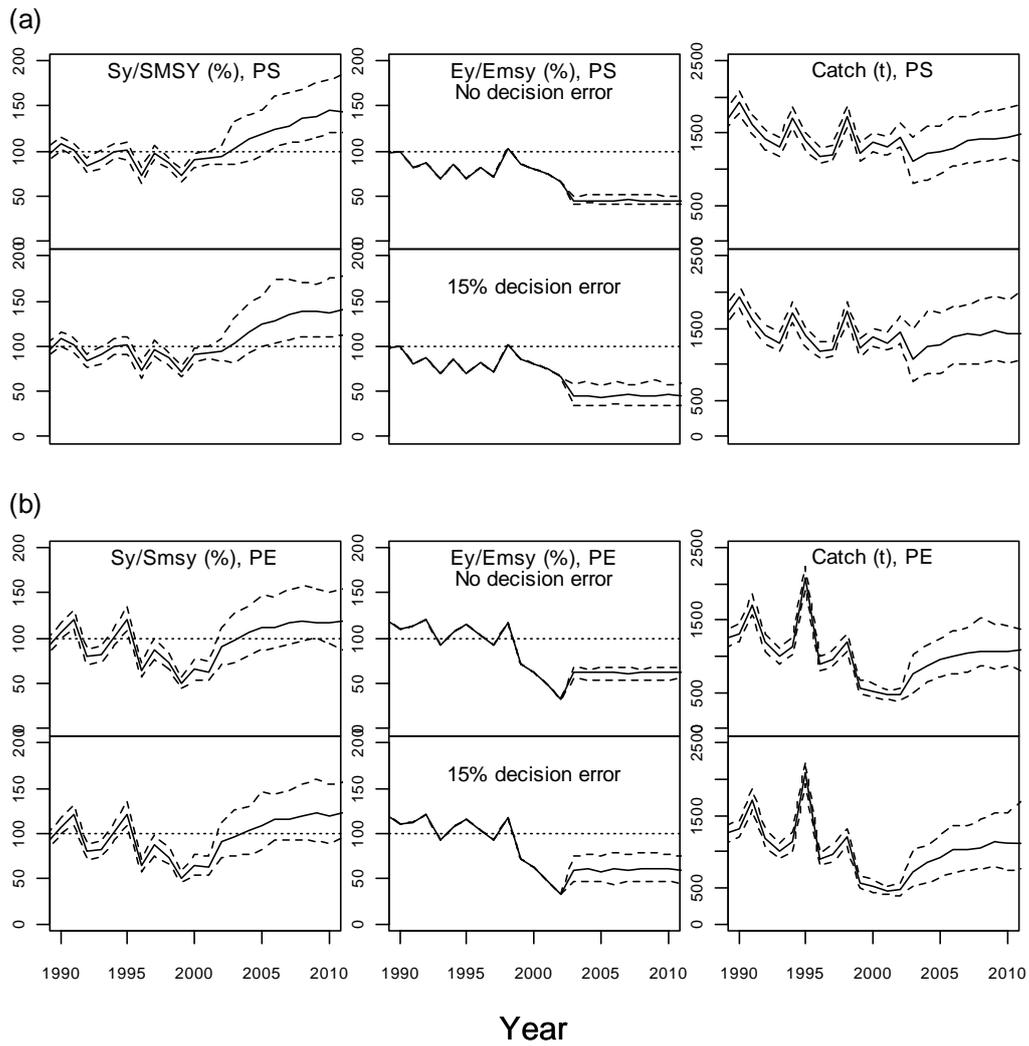


Figure 4.12: Time-trajectories of spawning stock size relative to S_{MSY} (%), effort levels relative to E_{MSY} (%) and the total catch (t) for (a) *P. semisulcatus* (PS) and (b) *P. esculentus* (PE). Results are shown for 1990-2010, with and without implementation error.

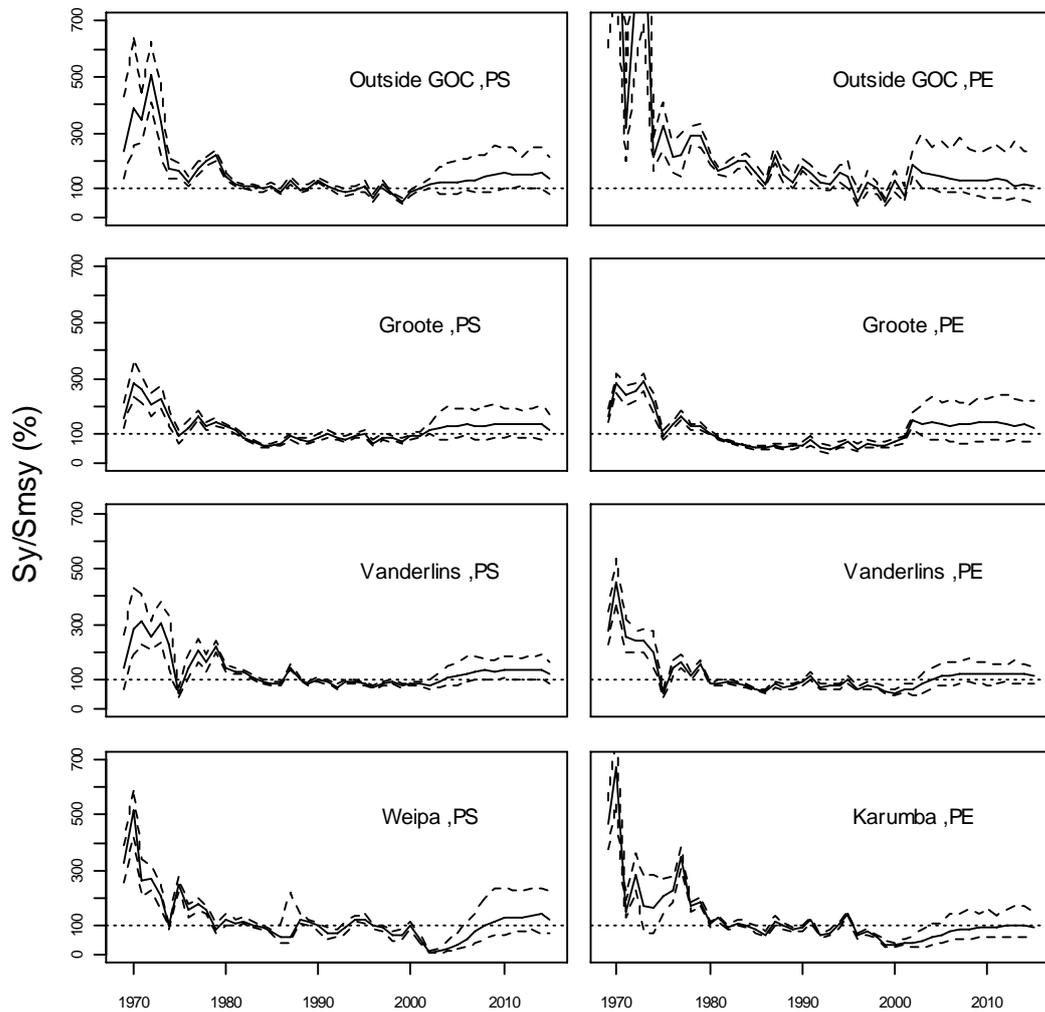


Figure 4.13: Spawning stock size relative to S_{MSY} by stock area and species. The results in this figure ignore implementation error.

4.4 Concluding remarks

A model which can act as the operating model for use in applications of the Management Strategy Evaluation approach is developed. This model is fairly general and can capture the dynamics of multiple stocks of several species. Unlike previous operating models, it can be applied in cases in which management is based on input rather than output controls because it includes a model of effort allocation which, although based primarily on empirical considerations rather than models of individual fisher behaviour, captures the spatial and temporal variation in fishing mortality caused by targeting of other species (in the case of the NPF, banana prawns), and the inter-annual variation in the spatial distribution of fishing effort. The operating model includes implementation error, which can arise from a

variety of sources. In the case of the NPF, implementation error is adequately captured by the assumption that the effort levels actually applied equal those intended, but subject to random (and log-normal) error. However, it would be straightforward to incorporate different models of implementation error such as those considered by Christensen (1997).

The example application of this paper is limited to a simple constant effort projection although, unlike most fisheries projections, account is taken in that projection of multiple species and stocks, and implementation error. Dichmont et al. (2006a, b) use this operating model to evaluate the performance of management strategies for tiger prawns which are candidates for actual use in the NPF, and identify the sources of uncertainty which have the greatest impact on the performance of such management strategies and hence which should be the focus for research.

4.5 Acknowledgements

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4.6 References

- Bishop, J., Die, D., Wang, Y-G., 2000. A generalized estimating equations approach for analysis of the impact of new technology on a trawl fishery. *Aust. NZ. J. Stat.* 42, 159–177.
- Bishop, J., Venables, W.N., Wang, Y-G., 2004. Analysing commercial catch and effort data from a Penaeid trawl fishery: a comparison of linear models, mixed models, and generalised estimating equations approaches. *Fish. Res.* 70, 179–193.
- Buckworth, R.C., 1985. Preliminary results of a study of commercial catches, spawning and recruitment of *Penaeus esculentus* and *P. semisulcatus* in the western Gulf of Carpentaria. In: Rothlisberg, P.C., Hill, B.J., Staples, D.J. (Eds.), *Proceedings of the Second Australian National Prawn Seminar (NPS2)*, Cleveland, Australia, pp. 213–

- Butterworth, D.S., Cochrane, K.L., De Oliveira, J.A.A., 1997. Management procedures: A better way to manage fisheries? The South African experience. In: Pikitch, E.K., Huppert, D.D., Sissenwine, M.P. (Eds), Global trends: fisheries management. Am. Fish. Soc. Symp. 20, 83–90.
- Butterworth, D.S., Punt, A.E., 1999. Experiences in the evaluation and implementation of management procedures. ICES J. Mar. Sci. 56, 985–998.
- Cartwright, I., 2005. The Australian Northern Prawn Fishery. In: Cunningham, S., Bostock, T. (Eds.), Successful Fisheries Management Issues, Case Studies and Perspectives. SIFAR/World Bank Study of good management practice in sustainable fisheries, Eburon Academic Publishers, The Netherlands, pp. 197-231.
- Chapman, L., Beare, S., 2002, Economic Impact of the Northern Prawn Fishery Amendment Plan. ABARE Report prepared for the Fisheries and Aquaculture Branch, Agriculture, Fisheries and Forestry, Canberra, Australia, 35 pp.
- Christensen, S., 1997. Evaluation of management strategies – a bioeconomic approach applied to the Greenland Shrimp Fishery. ICES J. Mar. Sci. 54, 412–426.
- Coles, R.G., Poiner, I.R., Kirkman, H., 1989. Regional studies – seagrasses of north-eastern Australia. In: Larkum, A.W.D., McComb, A.J., Shepherd, S.A. (Eds), Biology of Seagrasses: Aquatic Plant Studies 2. Elsevier, Amsterdam, Ch.9., pp. 261–278.
- Condie, S.A., Loneragan, N.R., Die, D.J., 1999. Modelling the recruitment of tiger prawns *Penaeus esculentus* and *P. semisulcatus* to nursery grounds in the Gulf of Carpentaria, northern Australia: implications for assessing stock-recruitment relationships. Mar. Ecol. Prog. Ser. 178, 55–68.
- Crocos, P.J., Van der Velde, T.D., 1995. Seasonal, spatial and interannual variability in the reproductive dynamics of the grooved tiger prawn *Penaeus semisulcatus* in Albatross Bay, Gulf of Carpentaria, Australia: The concept of effective spawning. Mar. Biol. 122, 557–570.
- De la Mare, W.K., 1996. Some recent developments in the management of marine living resources. In: Floyd, R.B., Shepherd, A.W., De Barro, P.J. (Eds), Frontiers of Population Ecology. CSIRO Publishing, Melbourne, Australia, pp. 599–616.
- Dichmont, C.M., Die, D., Punt, A.E., Venables, W., Bishop, J., Deng, A., Dell, Q., 2001. Risk Analysis and Sustainability Indicators for the Prawn Stocks in the Northern

- Prawn Fishery. Report of FRDC 98/109. CSIRO Marine Research, Cleveland, 187 pp.
- Dichmont, C.M., Punt, A.E., Deng, A., Dell, Q., Venables, W., 2003a. Application of a weekly delay-difference model to commercial catch and effort data for tiger prawns in Australia's Northern Prawn Fishery. *Fish. Res.* 65, 335–350.
- Dichmont, C.M., Bishop, J., Venables, W.N., Sterling, D., Penrose, J., Rawlinson, N., Eayrs, S., 2003b. A new approach to fishing power analyses and its application in the Northern Prawn Fishery. Report of AFMA Research Fund R99/1494. CSIRO Marine Research, Cleveland, 700 pp.
- Dichmont, C.M., Deng, A., Punt, A.E., Venables, W.V., Haddon, M., 2006a. Management strategies for short lived species: the case of Australia's Northern Prawn Fishery. 2. Choosing appropriate management strategies using input controls. *Fish. Res.* submitted.
- Dichmont, C.M., Deng, A., Punt, A.E., Venables, W.V., Haddon, M., 2006b. Management strategies for short lived species: the case of Australia's Northern Prawn Fishery. 3. Factors affecting management and estimation performance. *Fish. Res.* submitted.
- Die, D., Ellis, N., 1999. Aggregation dynamics in penaeid fisheries: banana prawns (*Penaeus merguensis*) in the Australian Northern Prawn Fishery. *Aust. J. Mar. Freshw. Res.* 50, 667–675.
- Die, D., Loneragan, N., Haywood, M., Vance, D., Manson, F., Taylor, B., Bishop, J., 2001. Indices of recruitment and effective spawning for tiger prawn stocks in the Northern Prawn Fishery. Report of FRDC 95/014. CSIRO Marine Research, Cleveland, 180 pp.
- Die, D.J., Watson, R.A., 1992. A per-recruit simulation model for evaluating spatial closures in an Australian penaeid fishery. *Aquat. Liv. Res.* 5, 145–153.
- FAO. 1996. Precautionary approach to capture fisheries. Part 2: scientific papers. FAO Fish. Tech. Pap. No. 350, Part 2. Rome, FAO. 210 pp.
- Gelman, A., Carlin, J.B., Stern, H.S., Rubin, D.B., 1995. *Bayesian Data Analysis*. Chapman and Hall, London.
- Hastings, W.K., 1970. Monte Carlo sampling methods using Markov chains and their applications. *Biometrika* 57, 97–109.
- Hilborn, R., Maguire, J-J, Parma, A.M., Rosenberg, A.A., 2001. The precautionary approach and risk management: can they increase the probability of successes in fishery management? *Can. J. Fish. Aquat. Sci.* 58, 99–107.

- Hill, B.J., Wassenberg, T.J., 1985. A laboratory study of the effect of streamer tags on mortality, growth, moulting and duration of nocturnal emergence of the tiger prawn *Penaeus esculentus* (Haswell). *Fish. Res.* 3, 223–235.
- Kirkwood, G.P., Smith, A.D.M., 1996. Assessing the precautionary nature of fishery management strategies. *FAO Fish. Tech. Pap. No. 350, Part 2*, pp. 141–158.
- Kirkwood, G.P., Somers, I.F., 1984. Growth of two species of tiger prawn, *Penaeus esculentus* and *P. semisulcatus*, in the western Gulf of Carpentaria. *Aust. J. Mar. Freshw. Res.* 35, 703–712.
- Poiner, I.R., Staples, D.J., Kenyon, R., 1987. Seagrass communities of the Gulf of Carpentaria, Australia. *Aust. J. Mar. Freshw. Res.* 38, 121–131.
- Pownall, P. (Ed.), 1994. *Australia's Northern Prawn Fishery: the First 25 Years*. NPF25, Cleveland, Australia, 179 pp.
- Punt, A.E., 1992. Selecting management methodologies for marine resources, with an illustration for southern African hake. *S. Afr. J. Mar. Sci.* 12, 943–958.
- Punt, A. E., Smith, A.D.M., 1999. Harvest strategy evaluation for the eastern stock of gemfish (*Rexea solandri*). *ICES J. Mar. Sci.* 56, 860–875.
- Punt, A.E., Smith, A.D.M., Cui, G., 2002. Evaluation of management tools for Australia's South East Fishery 1. Modelling the South East Fishery taking account of technical interactions. *Mar. Freshw. Res.* 53, 615–629.
- Robins, C.M., Wang, Y-G., Die, D., 1998. The impact of global positioning systems and plotters on fishing power in the northern prawn fishery, Australia. *Can. J. Fish. Aquat. Sci.* 55, 1645–1651.
- Rose, R., Kompas, T., 2004. Management options for the Australian Northern Prawn Fishery: an economic assessment. *ABARE eReport 04.12*. Report for Fisheries Resources Research Fund, Canberra, 47 pp.
- Rosenberg, A.A., Brault, S., 1993. Choosing a management strategy for stock rebuilding when control is uncertain. In: Smith, S.J., Hunt, J.J., Rivard, D. (Eds), *Risk evaluation and biological reference points for fisheries management*. *Can. Spec. Publ. Fish. Aquat. Sci.* 120, 243–249.
- Sainsbury, K.J., Punt, A.E., Smith, A.D.M., 2000. Design of operational management strategies for achieving fishery ecosystem objectives. *ICES J. Mar. Sci.* 57, 731–741.

- Smith, B.J., 2004. Bayesian Output Analysis Program (BOA) version 1.1 User's Manual. R Library, 43 pp. (<http://www.public-health.uiowa.edu/boa/BOA.pdf>).
- Smith, A.D.M., Sainsbury, K.J., Stevens, R.A., 1999. Implementing effective fisheries-management systems – management strategy evaluation and the Australian partnership approach. *ICES J. Mar. Sci.* 56, 967–979.
- Somers, I.F., 1990. Manipulation of fishing effort in Australia's penaeid prawn fisheries. *Aust. J. Mar. Freshw. Res.* 41, 1–12.
- Somers, I. and Wang, Y., 1997. A simulation model for evaluating seasonal closures in Australia's multispecies Northern Prawn Fishery. *N. Am. J. Fish. Manage.* 17, 114–130.
- Somers, I.F., Crocos, P.J., Hill, B.J., 1987. Distribution and abundance of the tiger prawns *Penaeus esculentus* and *P. semisulcatus* in the north-western Gulf of Carpentaria, Australia. *Aust. J. Mar. Freshw. Res.* 38, 63–78.
- Somers, I.F., Kirkwood, G.P., 1991. Population ecology of the grooved tiger prawn, *Penaeus semisulcatus*, in the north-western Gulf of Carpentaria, Australia: growth, movement, age structure and infestation by the bopyrid parasite *Epipenaeon ingens*. *Aust. J. Mar. Freshw. Res.* 42, 349–367
- Vance, D.J., Staples, D.J., Kerr, J.D., 1985. Factors affecting year-to-year variation in the catch of banana prawns (*Penaeus merguensis*) in the Gulf of Carpentaria, Australia. *J. Cons Ciem.* 42, 83–97.
- Venables, W.N., Dichmont, C.M., 2004. A generalized linear model for catch allocation: an example from Australia's Northern Prawn Fishery. *Fish. Res.* 70, 405–422.
- Venables, W.N., Dichmont, C.M., Toscas, P., Bishop, J., Ye, Y., Deng, R., 2003. Report to NORMAC on effort trade-off proposals for the NPF. AFMA Research Fund project 2003, 53 pp.
- Wang, Y-G., 1999. A maximum-likelihood method for estimating natural mortality and catchability coefficient from catch-and-effort data. *Mar. Freshw. Res.* 50, 307–311.
- Wang, Y-G., Die, D., 1996. Stock-recruitment relationships of the tiger prawns (*Penaeus esculentus* and *Penaeus Semisulcatus*) in the Australian Northern Prawn Fishery. *Mar. Freshw. Res.* 47, 87–95.

Appendix A: Technical details of the operating model

4.6.a Basic dynamics

The following equations pertain to each stock area and species. These equations ignore migration among stocks (as this is assumed to be negligible). Therefore, the subscripts for stock area and species are suppressed in the following equations. Table App.A.1 lists how each of the parameters of the operating model are determined.

The dynamics of the recruited biomass and recruited numbers of each tiger prawn species in each stock area are governed by the equations:

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

and

$$\tilde{N}_{y,w+1} = \tilde{N}_{y,w} e^{-Z_{y,w}} + \alpha_{y,w} R_{\tilde{y}(y,w)}^- \quad (\text{A.1})$$

where $B_{y,w}$ is the biomass of recruited prawns (of both sexes) at the start of week w of year y ;

$\tilde{N}_{y,w}$ is the number of recruited prawns (of both sexes) at the start of week w of year y ;

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

$$Z_{y,w} = M + F_{y,w} \quad (\text{A.2})$$

α_w is the fraction of the annual recruitment that occurs during week w (assumed to be constant across years);

M is the instantaneous rate of natural mortality (assumed to be independent of sex, age, species and stock area);

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

$R_{\tilde{y}(y,w)}^-$ is the recruitment during ‘biological year’ $\tilde{y}(y,w)$;

w_a is the mass of a prawn of age a (k is the age at recruitment);

ρ is the Brody growth coefficient; and

$\tilde{y}(y,w)$ is the ‘biological year’ corresponding to week w of year y :

$$\tilde{y}(y, w) = \begin{cases} y & w < 40 \\ y + 1 & \text{otherwise} \end{cases} \quad (\text{A.3})$$

Equation A.3 implies that the ‘biological year’ ranges from week 40 (roughly the start of October) until week 39 (roughly the end of September). This choice is based on data on recruitment indices from surveys (Somers and Wang, 1997).

The fishing mortality during week w of year y on one of the two tiger prawn species, $F_{y,w}$, includes contributions from targeted fishing on that species as well as from fishing on the other tiger prawn species, changes over time in fishing efficiency, and changes over the year in availability.

$$F_{y,w} = \tilde{q}' A_w q_{y,w} (E_{y,w}^T + E_{y,w}^B / q_b) \quad (\text{A.4})$$

where $E_{y,w}^T$ is the effort during week w of year y ‘targeted’ towards the species under consideration;

$E_{y,w}^B$ is the ‘by-catch’ effort during week w of year y (the effort targeted at the other species);

$\tilde{q}' = \tilde{q} / P_s$ is the catchability coefficient for each stock area;

\tilde{q} is the overall NPF-wide catchability coefficient (i.e. the catchability coefficient for the first week of 1993);

P_s is the fraction of the total NPF which the stock area under consideration consists - based on historical logbook data;

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 :

$$q_{y,w} = (\omega_y)^{(w-1)/52} \prod_{y' < y} \omega_{y'} / \prod_{y'' < 1993} \omega_{y''} \quad (\text{A.5})$$

ω_y is the efficiency increase during year y .

The value for the overall catchability coefficient, \tilde{q} , was estimated using data for 1993 (Wang, 1999) and hence applies to 1993. As a result, Equation A.5 is defined so that fishing efficiency is 1 at the start of 1993 (hence the division by the term $\prod_{y'' < 1993} \omega_{y''}$).

Specification of the values for the ω_y 's in Equation A.5 is difficult. The exact nature (and to some extent magnitude) of the change in efficiency is uncertain. Therefore, two alternative scenarios for how fishing efficiency may have changed over time ('Base Case High' and 'Base Case Low'; Dichmont *et al.* 2003b) are considered (Figure App.A. 1).

The spawning stock size index for calendar year y , S_y , is given by:

$$S_y = \sum_w \beta_w \frac{1 - e^{-Z_{y,w}}}{Z_{y,w}} \tilde{N}_{y,w} \quad (\text{A.6})$$

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

The recruitment for each species in each stock area for biological year $y+1$ is assumed to be related to the spawning stock size for (calendar) year y , S_y (see Equation A.6), according to a Ricker stock-recruitment relationship:

$$\hat{R}_{y+1} = \tilde{\alpha} S_y e^{-\tilde{\beta} S_y} \quad (\text{A.7})$$

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, and

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

The relationship between the actual recruitment and the conditional mean accounts for serial-correlation:

$$R_y = \hat{R}_y e^{\eta_y} \quad \eta_{y+1} = \rho_r \eta_y + \sqrt{1 - \rho_r^2} \xi_{y+1} \quad \xi_{y+1} \sim N(0; \sigma_r^2) \quad (\text{A.8})$$

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 impact of inter-stock correlation in the deviations about the stock-recruitment relationship can be examined by estimating the extent of this correlation based on the fit of the operating model to the data.

The recruitment for biological year $y+1$ depends on the spawning stock size in calendar year y . However, recruitment is deemed to start from 1 October and end at the end of September (the ‘biological’ year) whereas spawning follows a calendar year. This three-month overlap of spawners and next year’s recruitment is dealt by:

- a) generating a recruitment residual for biological year $y+1$, η_{y+1} (see Equations A.7 and A.8); and
- b) projecting the model from the start to the end of year y for different choices of R_{y+1} until the equation $R_{y+1} = \tilde{\alpha} S_y e^{-\tilde{\beta} S_y} e^{\eta_{y+1} - \sigma_r^2/2}$ is satisfied.

Unfortunately, the projection from week 40 until the end of the year depends on the effort by week, stock area and species which, in turn, depends on the recruitment for biological year $y+1$ through the catches. In principle, this system of 5 stock areas x 2 tiger species non-linear equations, and can be solved numerically for R_{y+1} , for each combination of stock area and tiger species, although this is complicated because of the inclusion of random elements in the effort allocation component. Therefore, a simpler formulation has been adopted here. This involves solving for R_{y+1} for each combination of stock area and tiger species by setting the effort splits by stock area and tiger species for year $y+1$ equal to that for year y and solving for R_{y+1} .

Likelihood functions

The likelihood function is based on how well the model is able to mimic the historical catch data, i.e. assuming that some function of observed catch-in-weight is normally distributed, and ignoring constants independent of the model parameters:

$$L = \sum_y \sum_w \left\{ \log \sigma_c + \frac{1}{2\sigma_c^2} [k(Y_{y,w}^{obs}) - k(Y_{y,w})]^2 \right\} \quad (\text{A.9})$$

where σ_c is the residual standard deviation;

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

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

$$Y_{y,w} = \frac{F_{y,w}}{Z_{y,w}} B_{y,w} (1 - e^{-Z_{y,w}}) \quad (\text{A.10})$$

$k()$ is the transformation function (in this case, square root).

Estimation of the four parameters of the stock-recruitment relationship ($\tilde{\alpha}$, $\tilde{\beta}$, ρ_r and σ_r) involves minimising the following objective function:

$$L = \log\left(\sqrt{\det(\Omega + V)}\right) + \frac{1}{2} \sum_{y_1} \sum_{y_2} \left(\log R_{y_1} - \log \hat{R}_{y_1}\right) ([V + \Omega]^{-1})_{y_1, y_2} \left(\log R_{y_2} - \log \hat{R}_{y_2}\right) \quad (\text{A.11})$$

where Ω represents the temporal correlation among the annual recruitments due to environmental fluctuations. The entries in the matrix Ω are determined from the assumed autocorrelation structure in recruitment (see Equation A.8) which implies that the correlation between the recruitments for years y_1 and y_2 is $\rho_r^{|y_1 - y_2|}$, i.e. the entries in the Ω matrix are $\sigma_r^2 \rho_r^{|y_1 - y_2|}$. The V matrix is the (asymptotic) variance-covariance matrix obtained by fitting the population dynamics model to the catch and effort data. 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).

Quantification of uncertainty

Parameter uncertainty is quantified by drawing parameter vectors from a joint Bayesian posterior distribution. Independent uniform prior distributions are assumed for each of the log-recruitments, and hence only vague prior knowledge. This allows the likelihood itself to dominate the posterior distribution. The samples from the posterior distribution are drawn using an MCMC algorithm (Hastings, 1970; Gelman et al., 1995); convergence was evaluated using the program CODA (Smith, 2004).

Table App.A.1: Summary of the base-specific specifications for the parameters of the operating model.

(a) Recruitment and spawning

Parameter	Base Case Specification (Both species)
Annual recruitment, R_y	Estimated
Relative weekly recruitment, α_w	Dichmont et al. (2003a)
Relative weekly spawning, β_w	Dichmont et al. (2003a)
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	Base Case Specification (Both species)
Overall catchability by week, \tilde{q}	0.000088 (Wang, 1999) or 2×0.000088
Relative weekly availability, A_w	Dichmont et al. (2003a)
By-catch catchability, q_b	11.11 (<i>P. esculentus</i>), 8.26 (<i>P. semisulcatus</i>) (Somers and Wang, 1997)
Annual efficiency increase, ω_y	Base-case High / Low
Target effort, $E_{y,w}^T$	Venables and Dichmont (2004)
By-catch effort, $E_{y,w}^B$	Venables and Dichmont (2004)
Catches, $Y_{y,w}^{obs}$	Venables and Dichmont (2004)

(Table App.A.1 Continued)

(c) Growth

Parameter	Base Case Specification (<i>Penaeus semisulcatus</i>)	Base Case Specification (<i>Penaeus esculentus</i>)
Brody growth coefficient, ρ	0.979	0.982
Von Bertalanffy growth parameters, $\ell_{\infty}^s, \kappa^s$	Males: 37.5mm and 0.062wk ⁻¹ Females: 51.6 mm and 0.043 wk ⁻¹ (Somers and Kirkwood, 1991)	Males: 37.5mm and 0.034 wk ⁻¹ Females: 44.8mm and 0.041 wk ⁻¹ (Kirkwood and Somers, 1984)
Length-weight parameters, e^s, f^s	Males: 0.00265, 2.648 Females : 0.00195, 2.746	Males: 0.003739, 2.574 Females: 0.0027, 2.764
Length-at-recruitment, ℓ_r^s	Males: 26 mm Females: 28 mm	Males: 26 mm Females: 28 mm
Weight-at-recruitment, w_k	Assumed known	Same
Weight the week prior to recruit- ment, w_{k-1}	$((1 + \rho)w_k - w_{k+1}) / \rho$	Same

(d) Other parameters

Parameter	Base Case Specification (<i>P. semisulcatus</i>)	Base Case Specification (<i>P. esculentus</i>)
Average rate of natural mortality, M	0.045 week ⁻¹ (Wang and Die, 1996)	0.045 week ⁻¹ (Wang and Die, 1996)
Catch in weight residual standard deviation, σ_c	Estimated	Estimated
Fraction of the NPF in each stock area		
Outside GOC	0.396	0.301
Groote	0.140	0.090
Vanderlins	0.319	0.288
Karumba	N/A	0.321
Weipa	0.145	N/A

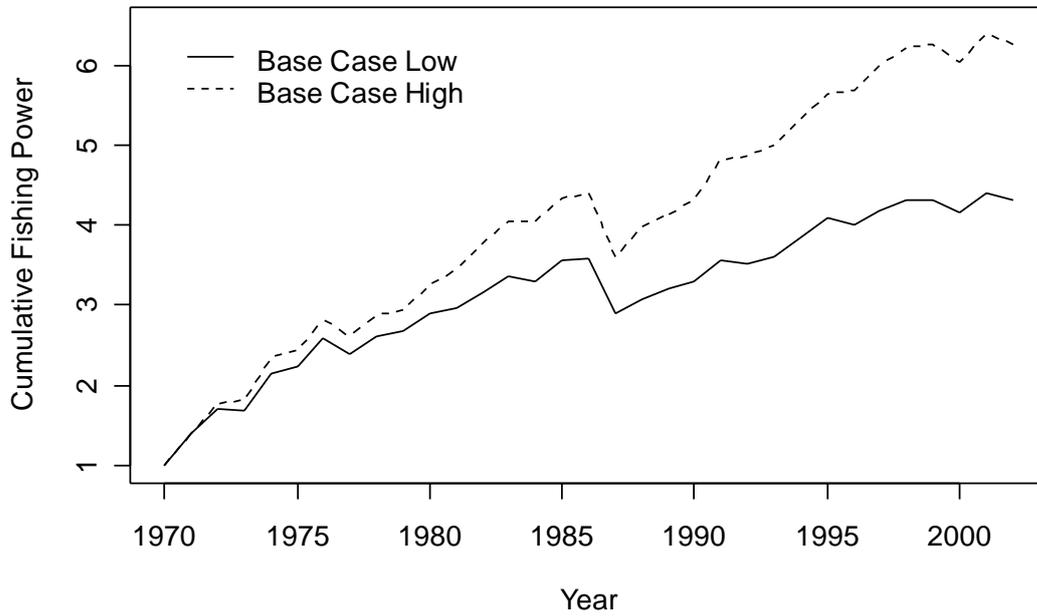


Figure App.A. 1: The two fishing power scenarios (Dichmont et al., 2003b).

Appendix B: Splitting the total effort to stock area

Data from the years 1980–2003 were used to construct an empirical model that predicts the proportions of the weekly effort allocated to each stock area as a function of the year, week and, if available, the previous week’s catch-rate for each of the five stock areas:

1. The weekly nominal effort for each of the five stock areas was treated as multinomial variate and a multiple logistic model fitted. If \mathbf{x} is the vector of predictor variables for any specific week, then the expected proportions for year y , week w , and stock area a , are:

$$p_{y,w}^a = \frac{\exp(\mathbf{x}^T \boldsymbol{\beta}_a)}{\sum_{a=1}^5 \exp(\mathbf{x}^T \boldsymbol{\beta}_a)}, \quad \text{where, for identification, we set } \boldsymbol{\beta}_1 = \mathbf{0} \quad (\text{B.1})$$

2. For calibration purposes, only weeks where the total tiger effort exceeded 50 days were used. The predictors used for the model for each area were:
 - a. A separate constant for each combination of year and sub-season (the first sub-season is defined as weeks 1-27 and second as weeks 27-52).
 - b. A natural spline in the week of the year with knots at 15, 21, 29, 35, 40 and 45 weeks, and boundary knots at 1 and 52 weeks.
 - c. For week w , the $\log(\text{CPUE})$ for week $w-1$ for each of the stock areas, where CPUE was arbitrarily truncated below at 0.5 kg/day and above at 1000 kg/day. These truncations are to reduce the artificial leverage effect of outlying CPUE values.
3. For stability reasons, the parameters of the model were estimated in two stages.
 - a. At the first stage, all weeks where the total tiger effort exceeded 50 days were used, and a model was fitted using the year/season constants and the natural splines for week as predictors.
 - b. At the second stage, only weeks that had a CPUE for the previous week were used. The linear components, $\mathbf{x}^T \boldsymbol{\beta}_a$, from the model fitted in the first stage were

used as an offset and only the log(CPUE) values, for each stock area, for the preceding week were used as new predictors.

The prediction of the spatial distribution of the fishing effort for the first week of the season is based on the first stage model only, and for subsequent weeks on the second stage model. This indirect approach provides greater stability to the process than is achievable by trying to include all the data in a single phase. A further refinement of the technique was needed to ensure the stability of the process. The spatial distribution of effort was allocated using a weighted combination of (a) the historical effort pattern determined from the first stage model and (b) the dynamically varying effort pattern determined from the second stage model. The weights used were either in the proportion 1:1 or 1.5:1. The results from equal weighting are presented in this paper.

4. The operating model uses a conditional multinomial allocation of effort that can be described as:

$$\{\text{act } E_{y,w}^{\text{tig},a}, a = 1, \dots, 5\} | \varepsilon_{y,w}^a \sim \text{Multinomial} \left(\text{act } E_{y,w}^{\text{tig}} \cdot P_{y,w}^a = \frac{\exp(\mathbf{x}_{y,w}^T \boldsymbol{\beta}_a + \varepsilon_{y,w}^a)}{\sum_{a=1}^5 \exp(\mathbf{x}_{y,w}^T \boldsymbol{\beta}_a + \varepsilon_{y,w}^a)} \right) \quad (\text{B.2})$$

where $\varepsilon_{y,w}^a \sim N(0, \sigma^2)$. Experiments suggest that $\sigma^2 = 0.275$ conveys an appropriate amount of overdispersion.

Note that the effort allocation for any particular week in the operating model, other than the initial week of the first and second sub-season, involves the catch and effort data for the previous week. The initial week's effort allocation is based on the predicted proportions based on the week of the year and the year/season constants from a random year chosen from the calibration set, 1980–2003. After the initial week's effort allocation the effort allocation component is 'self-sustaining'.

CHAPTER 5 CHOOSING APPROPRIATE MANAGEMENT STRATEGIES USING IN- PUT CONTROLS

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5.1 Abstract

A Management Strategy Evaluation framework is used to evaluate management strategies based on input controls for the fishery for two tiger prawn species (*Penaeus esculentus* and *P. semisulcatus*) in Australia's Northern Prawn Fishery. Three "assessment procedures" are considered and two forms of decision rule. The performance of the management strategies is evaluated in terms of whether stocks are left at (or above) the spawning stock size at which Maximum Sustainable Yield is achieved (S_{MSY}), the long-term discounted total catch, and the extent of inter-annual variation in catches. The focus of the analysis is on management strategies based on the current method of stock assessment because an alternative method of assessment based on a biomass dynamics model is found to be highly variable. None of the management strategies tested is able to leave the spawning stock size of *P. esculentus* near S_{MSY} if the target spawning stock size used in the management strategy is set to E_{MSY} . Accounting for stock structure through the application of a spatially- (stock-) structured assessment approach fails to resolve this problem. Since the assessment method is generally close to unbiased, the failure to leave the stocks close to S_{MSY} is because the measure of control is total effort and the two species are found (and caught) together. Reducing the target effort level to below E_{MSY} increases the final stock size, but the reduced risk comes at a cost of reduced catches. The best management strategy in terms of leaving both species close to S_{MSY} is found to be one that changes the timing of the fishing season so that effort is shifted from *P. esculentus* to *P. semisulcatus* and sets more precautionary effort targets for *P. esculentus*.

Keywords: Input controls; Monte Carlo simulation; Multi-species modelling; Northern Prawn Fishery; Spatial structure, Management Strategy Evaluation

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5.2 Introduction

Australia's Northern Prawn Fishery (NPF) started mainly as a banana prawn (*Penaeus merguensis*) fishery in the 1960s, but expanded over time to be a multi-species prawn fishery with tiger prawns (brown and grooved tiger prawns; *P. esculentus* and *P. semisulcatus*) as the most valuable component of the catch (Pownall, 1994). Initially, the vessels in the fishery were small wooden quad-rigged otter trawlers with brine storage tanks. In contrast, the vessels in use today are large steel specialized prawn trawlers with computers, GPS and plotters that use spotter planes during the banana prawn season. The fleet now lands between 6–8,000 tonnes of prawns annually from the NPF. Over the period 1992/93 to 2001/02, real revenue for operators fluctuated between AU\$115.8–AU\$185.7 million, with an average of AU\$146.8 million (2002-03 dollars) (Galeano et al., 2004), making the NPF one of Australia's most valuable fisheries.

Input controls (attempts to manage effort) rather than output controls (e.g. catch quotas) have formed the basis for management of the NPF. Changes to an allocated effort unit (similar in concept to a tradeable quota) and season length are used to implement changes in effort. Management of the NPF since the 1980s has been characterized by attempts to restructure the fishery and reduce effort. This was driven by the substantial increases in fishing mortality as new technologies were adopted. Approaches to reducing the size of the fleet (Table 5.1) have led to a marked drop in the number of vessels in the fishery (from 280 vessels in the 1980's to the present fleet of 85; Dichmont et al., in press). However, this did not equate to a equivalent reduction in fishing mortality because, for example, of the fleets' increased ability to locate and catch prawns through changes in fishing power (or fishing efficiency) (Bishop et al., 2000; Dichmont et al., 2003a; Cartwright, 2005).

Table 5.1: History of management decisions relating to target species control within the NPF.

Year	Scientific advice and management development
1980	Introduction of limited entry.
1985	Statutory Fishery Rights granted in the form of A-units. Voluntary buyback scheme introduced which tended to reduce only latent effort.
1987	Reduction from quad to twin gear, mid-year closure, ban on daylight trawling during the tiger prawn season.
1988	Restriction on headrope-length of nets.
1990	Voluntary industry-funded buyback scheme with loans from the government (failed to reduce the fleet as much as intended although 172 trawlers left the fishery).
1993	Compulsory, industry-funded, buy-back scheme (reduced the fleet to 137 (128 active) vessels). Removal of net-size restrictions (but use of twin gear only remains).
1995	Start of annual assessments of tiger prawns.
1997	The fishery is closed 3 weeks earlier at the end of the 2 nd sub-season and during the mid-season closure for 1998.
1998	Mandatory introduction of satellite-based Vessel Monitoring System across the fleet. The end-of-season closure reverts to the end of November and a large spatial closure is implemented on 1 November.
1999	The spatial closure implemented in 1998 is replaced by larger mid-year and end-of-year closures.
2000	Gear-based management starts in July and gear is reduced by 15%. Turtle Excluder Devices become compulsory in the tiger prawn fishery.
2001	Gear units are reduced by a further 25%. Turtle Excluder Devices become compulsory in banana prawn fishery. The recovery target of S_{MSY} is set to be achieved by 2006.
2002	The mid-season closure is extended.
2005	The target for the fishery is changed to Maximum Economic Yield and gear is reduced by a further 25%.

Between 1985 and 2001, each vessel was assigned a transferable Statutory Fishing Right (a form of individual property right) in the form of a number of “A-units”, a quantity based on vessel volume and engine horse power. This system was inflexible, however, because even small reductions in the number of A-units that was allowed in the fishery could result in boats being unable to fish, which impeded fleet restructures. A Statutory Fishing Right is now defined in terms of headrope lengths, with a specified total length for the fleet. A 25% reduction in gear units leads to a 25% reduction in headrope length per vessel. Vessels can either buy more units to restore their total headrope length (thereby leading to vessels leaving the fishery) or fish with a smaller net. As a result, a reduction in the number of gear units leads to an overall decline in fishing effort through the combination of a fleet restructure or vessels fishing with reduced fishing power.

The fishery generally starts at the beginning of April and there is a mid-season spawning closure from mid-May to end July. The length of the mid-season closure has also been used to control effort in the past; the differential migration of the two tiger prawn species (Dichmont et al., 2001, and references therein, Dichmont et al., 2003b) leads to *P. esculen-*

tus being more available to the fishery in winter than *P. semisulcatus*. As a result, a shorter season in the winter months would tend to shift effort from *P. esculentus* to *P. semisulcatus* and a change to the season at the end of the calendar year would have the opposite effect.

Management Strategy Evaluation (MSE) is a simulation framework that considers the whole management system (see Figure 4.1 of Dichmont et al., 2006a for an outline of the approach). It consists of an operating model that can be regarded as a representation of the “true” underlying dynamics of the resource and the fishery and which can be used to generate the types of data typically collected from the fishery. In addition, there is a management strategy that analyses the fishery and/or monitoring data generated by the operating model (but remains “ignorant” of the underlying dynamics of the operating model) and a set of decision rules that determine the management actions to be taken given the results of assessment (*e.g.* the level of effort to be applied in the next year). The modelled management advice is fed back to the operating model where it can influence the dynamics of the “true” stocks being managed. An initial phase, referred to as conditioning, is required to determine the values for the parameters of the operating model so that these are consistent with the available historical information. The performance of a management strategy is summarised using performance measures that are derived from stated management objectives. The values for the performance measures are based on the “true” resource, as defined by the operating model. The performance of the assessment procedure component of a management strategy can be evaluated by comparing the estimates produced by it with the corresponding (and hence “true”) quantities in the operating model.

The MSE approach has been demonstrated to be an effective way to compare and evaluate alternative management strategies (combinations of data collection schemes, methods of data analysis, and decision rules). Management strategies have been evaluated for many fisheries at the single- or the multi-species level) and, in recent years, for ecosystem objectives (Dichmont et al., 2006a and references therein).

It is essential that the complete range of uncertainties (*e.g.* those related to biology, fleet dynamics, and how management decisions are implemented) are identified and modelled so that the effects of uncertainties on performance measures and estimation performance can be quantified. In the case of the NPF, an important feature of the management system

is that the fishery is managed using input controls thereby requiring explicit modelling of the uncertainty involved in setting and implementing effort levels.

This paper uses the operating model of Dichmont et al. (2006a) to examine management strategies and assessment procedures considered for actual use in the NPF. Three alternative assessment models are used to determine the total amount of effort to be expended on tiger prawns in a year, and in some cases, also the season length. These three assessment models differ in terms of complexity, population dynamic assumptions, and spatial and temporal resolution. The analyses of this paper explore the performance of several management strategies for one operating model while Dichmont et al. (2006b) explore the impact of the specifications for the operating model for one decision rule using the three alternative assessments. The multi-species and input control nature of this fishery makes it relevant to similar trawl and non-trawl fisheries worldwide.

5.3 Methods

5.3.a The operating model

Dichmont et al. (2006a) provide the detailed specifications of the operating model. In brief, the tiger prawn resource is represented using a 5-stock, two-species population dynamics model with the number of tiger prawn stocks and their boundaries determined using expert opinion (see Dichmont et al., (2001) for details). Banana prawns are represented in the operating model by assuming that historical catch levels reflect the best appraisal of future catches.

The operating model and the management strategies are linked through the data generation, and the effort allocation modules; the data generation module provides the data (with uncertainty) used by the assessment procedure based on simulated monitoring of the “true” resources, while the effort allocation module determines the fishing mortality on the “true” resources given the output from the decision rule and the vagaries associated with implementing management decisions in the real world.

The data used for assessment purposes are logbook catch and effort data, either disaggregated to species and week, or aggregated to year and over both tiger prawn species. These data are assumed to be measured without error. No errors are assumed between the boundaries used for stock assessment and the true boundaries among the stocks, although

this could be examined in future using the methods of Punt et al. (1995) and Punt (2003). Once the data have been generated, they are analysed using the stock assessment component of the management strategy and then by its decision rule component. This leads to a total tiger prawn effort and (for some management strategies) specification of season length. The total tiger prawn effort and season length are passed back to the operating model and determines the tiger prawn effort by stock area, week and tiger prawn species (see Dichmont et al. (2006a) for details).

5.3.b Management strategies

The management strategies are based on choices regarding the assessment procedure and the decision rules. A total of 17 management strategies are considered in the analyses of this paper. The following sections outline how these management strategies were designed.

5.3.b.(vi) Assessments methods

Three stock assessment methods are evaluated: a linear regression of catch rate on time, a biomass dynamic model, and a Deriso-Schnute delay-difference model. The model types, the data they use, and the species and spatial scale at which they can be applied are described in Table 5.2. The details of the biomass dynamic and Deriso-Schnute models as applied to the NPF are described in Haddon (2001) and Dichmont et al. (2003b) respectively. These assessment procedures capture a range from very simple (a linear regression of log catch-rate on time) to fairly complicated (an age- and stock-based assessment model). The linear regression approach is not a stock assessment method *per se*, but is rather a simple analysis from which to produce management advice; its performance can be used as a base-line against which to evaluate the relative utility of applying management strategies based on the more complex stock assessment models.

Table 5.2: The specifications of the stock assessment methods.

Model	Overview	Data used	Species	Number of stocks
Linear	The slope of a linear regression of log-catch-rate on year over the past five years	Unstandardised catch rate over five years	Species-aggregated	Single stock
Biomass dynamic	A biomass dynamic model that estimates six parameters	Total annual tiger prawn catches and annual catch rates standardised with respect to week and stock area	Species-aggregated	Single stock
Deriso-Schnute	A weekly model that estimates annual recruitment and a stock-recruitment relationship.	1. Catch, effort, fishing power 2. Catch, effort, fishing power, and survey index	Species-disaggregated	1. Single stock 2. Multiple stocks

Some of these assessment methods can be refined further in terms of the data used (e.g. raw catch rates, standardised catch rates, survey data) and the spatial scale at which they can be applied (e.g. NPF-wide or by “stock area”). The most obvious differences are that the cpue regression approach does not assess the status of the resource, uses annual data and is not species-specific, the biomass dynamic model assesses the status of the two tiger prawn species combined on an annual basis, and the Deriso-Schnute model assesses the status of each tiger prawn species separately using a weekly model that accounts for inter-annual changes in recruitment. Other fundamental differences among the assessment methods relate to: a) whether account is taken of changes over time in fishing efficiency (“fishing power”) and how the catchability coefficient is determined. Fishing power and catchability are not used in the cpue regression approach, are estimated internally in the biomass-dynamic model, and are input parameters for the Deriso assessment. It should be noted that the Deriso-Schnute model (referred to hereafter as the “Deriso model”) is presently the standard stock assessment model used in the management of the NPF tiger prawn fishery.

The output quantities obtained from the three assessment procedures differ:

- 1) Linear regression (prefix “C” in the management strategies) – the slope and intercept of a straight line regression of the catch rates on year for the most-recent five years.

- 2) Biomass dynamic model (prefix “B”) – the intrinsic growth rate, carrying capacity, Pella-Tomlinson shape parameter, the catchability coefficient in 1993, and biomass time-trajectory.
- 3) The Deriso model (prefix “D”) – the time-series of recruitments, and the parameters of the stock-recruitment relationship (steepness, virgin stock size, stock-recruitment variance and temporal autocorrelation in recruitment) by species.

5.3.b.(vii) Decision rules to calculate tiger prawn target effort and season length

The tiger prawn effort (aggregated over stock area) and the season length are determined according to one of two options depending on whether an assessment is conducted or not. Note that to mimic past practice, scientific recommendations to change effort levels are only implemented with a probability of 1/3 (Dichmont et al., 2006a).

An assessment is not conducted

If no stock assessment is conducted, the intended effort targeted at tiger prawns during year y , $E_{\text{target},y}^{\text{int}}$, is determined using the equation:

$$E_{\text{target},y}^{\text{int}} = \sum_a E_{a,y-1} (1.0 + \frac{1}{2} \text{Slope})$$

where $E_{a,y-1}$ is the effort targeted at tiger prawns during year $y-1$ for stock area a ; and

Slope is the slope of the linear regression of catch-rate on year.

The season length for this management strategy is fixed equal to that for 1995 and the regression for year y is conducted using data for years $y-5$ to $y-1$. Whether the effort intended increases or decreases from the previous year depends on the sign of the slope and the extent to which it increases/decreases depends on the magnitude of the slope.

An assessment is conducted

If a stock assessment is conducted using either the biomass dynamic or Deriso models, the effort decisions are based on attempting to move the spawning stock size to some fraction of that at which MSY is achieved (S_{MSY}). Three input settings determine how precautionary the effort level will be: a) the maximum proportion of E_{MSY} (the effort at which MSY is achieved on average) at which tiger prawn effort can be set, b) the proportion of S_{MSY} at which this maximum proportion of E_{MSY} is set, and c) the spawning stock size below

which effort is zero (Figure 5.1). This decision rule can be tuned to leave the spawning stock size at, below, or above S_{MSY} . The effort directed towards tiger prawns is the sum of the efforts estimated to be targeted at each tiger prawn species separately.

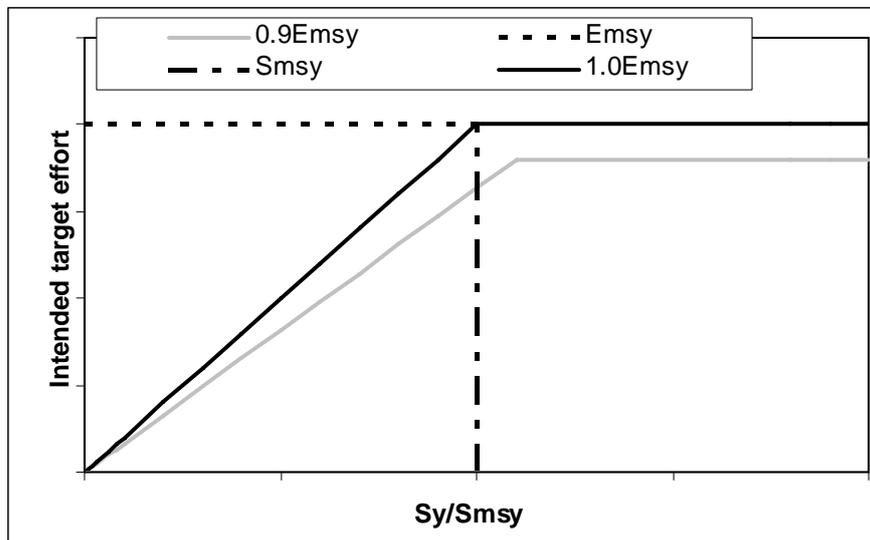


Figure 5.1: The tiger prawn effort decision rule. Two example decision rules are given; one with S_{MSY} as the target and another that is more precautionary.

Determining the season length from the results of the assessment is not straightforward because there is little historical precedent. However, the decision rules described in Figure 5.2, which use the estimate of the ratio of the spawning stock size for the most recent year to S_{MSY} describes past decisions adequately; the mid-year season closure is generally extended when the brown tiger prawn assessment is pessimistic whereas the end of year season date and the second season start date are generally adjusted based on the results of the assessment of grooved tiger prawns. The start of the season was fixed to be 1 April because this has been the start date of the fishery for many years (except for 2004 when a mid-April start date was implemented). The ideal season opening and closed dates are calculated separately for each species using Figure 5.2. Since only a single set of season dates are ultimately implemented, the intersection of the weeks of overlap is selected as the season to be implemented – this can be interpreted as conservative, but realistic. This means that only weeks which were set as open for both species independently of each other would be fished.

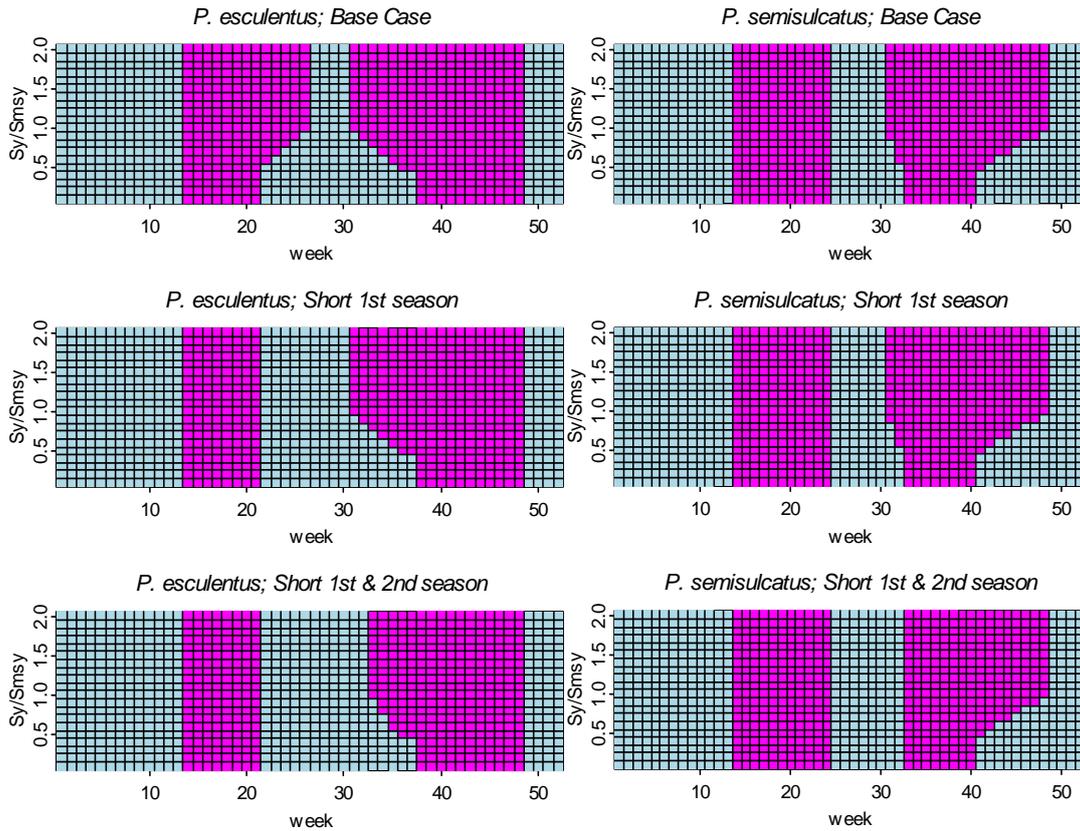


Figure 5.2: Options used when determining the specifications for the season (dark grey is open to fishing and light grey is closed) as a function of the ratio of the current spawning stock size to S_{MSY} for each species. Three options are shown; the Base Case, “short 1st season” and “short 1st and 2nd season”.

Three additional ways of changing the season in response to changes to the estimates of S_y/S_{MSY} by species (Figure 5.2) are explored in the light of the generally poor performance at leaving the spawning stock size of *P. esculentus* at or above S_{MSY} . The “Short 1st season” option (Figure 5.2, centre panels) is the same as the “Base Case” option (Figure 5.2 upper panels), except that it opens the season in week 14 and closes it in week 22 (closing the fishery after week 21 is a means of eliminating the catch of tiger prawns, which consist mostly of *P. esculentus*, during the first season) while the “Short 1st and 2nd season” option (Figure 5.2, lower panels) is the same as the “Short 1st option, except that the opening date for the second season is moved from week 31 to week 33 to reduce the effort directed towards *P. esculentus*.

5.3.c Performance Measures

The analyses involved 120 simulations in which the operating model was projected from 2003 to 2015. This number of simulations provides greater than 95% certainty that 95% of

the distribution is covered. Only three performance measures are considered in this paper (see Dichmont et al. (2006b) for a complete list of the performance measures considered in the full MSE) because these are sufficient to illustrate the key aspects of the performances of the various management strategies. The risk-related performance measure is the ratio of the spawning stock size in 2010 to S_{MSY} (abbreviation S_{2010}/S_{MSY}) and the two economic-related performance measures are: a) catch variability (AAV - the median over simulations of the average annual absolute variation in catches expressed as percentage of the total catch) and b) long term catch (Dcatch – the median over simulations of the annual discounted catch; the discount rate is assumed to be 5% per annum - T. Kompas, Australian National University, *pers comm*). The estimation-related performance measures are the magnitude of the relative error (expressed as a percentage) between the estimated and the true values for annual recruitment, S_y/S_{MSY} , the steepness of the stock-recruitment relationship, E_{MSY} , and S_{MSY} .

5.4 Results

The results are based on a single operating model with the objective to identify which management strategies are able to leave the spawning stock size for both tiger prawn species close to the target reference point, S_{MSY} . In addition, an ideal management strategy should avoid possible adverse consequences:

- 1) it should not have a low long-term discounted catch; and
- 2) it should not have high inter-annual variation in catches.

An assessment of resource status is undertaken each year, which then determines the total effort level and the season length for the management strategies based on the biomass dynamic and the Deriso models. In contrast, no assessment of resource status is made for the cpue regression approach, but the decision rule is applied every year.

5.4.a Alternative “assessment” methods

5.4.a.(viii) Management-related performance

The “Base Case” management strategies based on the three assessment procedures in which the data are aggregated over stock (abbreviations “B-1 stock BC”, “C-1 stock BC”, and “D-1 stock BC”) are compared in Table 5.3. This table lists the medians and 90% intervals for S_{2010}/S_{MSY} for *P. semisulcatus* and *P. esculentus*, and the median and 90%

intervals for the two economic-related performance measures. The target effort for both species is E_{MSY} . None of the management strategies leaves the spawning stock sizes for both species above S_{MSY} simultaneously. The cpue regression approach (“C-1 stock BC”) leaves the spawning stock size of *P. semisulcatus* above S_{MSY} in median terms and that of *P. esculentus* slightly below S_{MSY} in median terms. The higher spawning stock sizes achieved by the cpue regression approach compared to the Deriso-based management strategy come at a cost of slightly (about 5% in median terms) lower total discounted catches. Interestingly, “C-1 stock BC” performs better than “D-1 stock BC” in terms of minimizing inter-annual catch variability (median AAVs of 10.3% compared to 12.9%). Management strategies “B-1 stock BC” and “D-1 stock BC” both leave the spawning stock size for *P. semisulcatus* close to the target level on average, but are unable to do so for *P. esculentus*, the spawning stock size of which is generally well below S_{MSY} in 2010. The management strategy based on the biomass dynamic model (“B-1 stock BC”) leads to the largest inter-simulation variance in the values for the economic-related performance measures although the median values for S_{2010}/S_{MSY} are similar to those for management strategy “D-1 stock BC” (Table 5.3).

Table 5.3: Specifications for the 17 management strategies and the resultant values for the performance measures (medians and 90% intervals).

Abbreviation	First season dates (weeks)	Second season dates (weeks)	Target Effort (fraction of E_{MSY})	Target Reference Point (fraction of S_{MSY})	No. of Assumed stocks	S_{2010}/S_{MSY} (%) <i>P. semisulcatus</i>	S_{2010}/S_{MSY} (%) <i>P. esculentus</i>	Discounted Catch: DCatch ('000t)	AAV
B-1 stock BC	14-26	31-48	1	1	1	103 (81 – 128)	82 (57 - 106)	24.9 (22.4 – 27.5)	17.3 (11.2 - 43.7)
C-1 stock BC	14-26	31-48	1	1	1	115 (94 - 148)	95 (69 - 120)	24.1 (21.9 – 26.7)	10.4 (6.3 – 15.3)
C-3 stock	14-26	31-48	1	1	3	116 (94- 148)	95 (70 - 120)	24.1 (21.8 – 26.7)	10.3 (6.3 – 15.3)
C-4 stock	14-26	31-48	1	1	4	116 (94 - 148)	95 (70 - 120)	24.1 (21.8 – 26.7)	10.2 (6.2 – 15.3)
D-1 stock BC	14-26	31-48	1	1	1	100 (79 - 128)	80 (58 – 104)	25.5 (22.8 – 28.7)	12.9 (9.2 – 18.3)
D-3 stock	14-26	31-48	1	1	3	97 (84 - 130)	79 (56 – 100)	26.0 (24.1 – 27.9)	12.1 (8.6 – 16.1)
D-4 stock	14-26	31-48	1	1	4	95 (83 - 129)	78 (55 - 99)	26.1 (24.0 – 27.8)	12.1 (8.3 – 16.1)
D-0.8Emsy	14-26	31-48	0.8	1.2	1	115 (92 - 146)	93 (70 - 119)	24.3 (21.7 – 27.4)	11.3 (6.8 – 16.5)
D-0.6Emsy	14-26	31-48	0.6	1.5	1	130 (104 – 163)	107 (82 - 136)	21.7 (19.2 – 24.4)	13.3 (8.4 – 18.6)
D-0.4Emsy	14-26	31-48	0.4	1.6	1	145 (117 - 178)	121 (94 – 154)	18.1 (15.8 – 20.2)	17.4 (12.8 - 22.4)
D-mixed TE 1	14-26	31-48	1.0 for PS; 0.7 for PE	1.0 for PS; 1.3 for PE	1	106 (85 - 137)	87 (64 - 111)	25.1 (22.4 – 28.1)	11.9 (7.7 – 17.7)
D-mixed TE 2	14-26	31-48	1.2 for PS; 0.4 for PE	0.8 for PS; 1.6 for PE	1	101 (82 - 129)	82 (57 – 105)	25.5 (22.8 – 28.5)	12.1 (7.4 – 17.3)
D-mixed TE 3	14-26	31-48	1.0 for PS; 0.2 for PE	1.0 for PS; 1.8 for PE	1	117 (101 - 149)	99 (70 - 123)	24.0 (22.4 – 25.4)	10.3 (6.7 – 16.8)
D-mixed TE 4	14-26	31-48	1.0 for PS; 0.6 for PE	1.0 for PS; 1.4 for PE	1	108 (92 - 139)	89 (64 – 111)	25.4 (23.3 – 26.7)	11.7 (7.9 – 17.5)
D-short 1 st season	14-21	31-48	1	1	1	97 (76 - 125)	86 (62 – 109)	25.6 (22.8 – 28.8)	12.7 (8.6 – 18.1)
D-short 1 st and 2 nd season	14-21	33-48	1	1	1	97 (76 - 124)	86 (62 - 110)	25.6 (22.8 – 28.7)	12.8 (8.6 - 18.4)
D-mixed TE 2 Short 1 st season	14-21	31-48	1.0 for PS; 0.6 for PE	1.0 for PS; 1.4 for PE	1	105 (90 - 138)	95 (67 - 117)	25.4 (23.4 – 26.8)	11.3 (7.7 - 17.0)

The results in Table 5.2 are mimicked when expressed by stock area (Figure 5.3); some stocks are left close to S_{MSY} while others are left above or below this level. The poorest performance occurs for *P. esculentus* in the Karumba stock area.

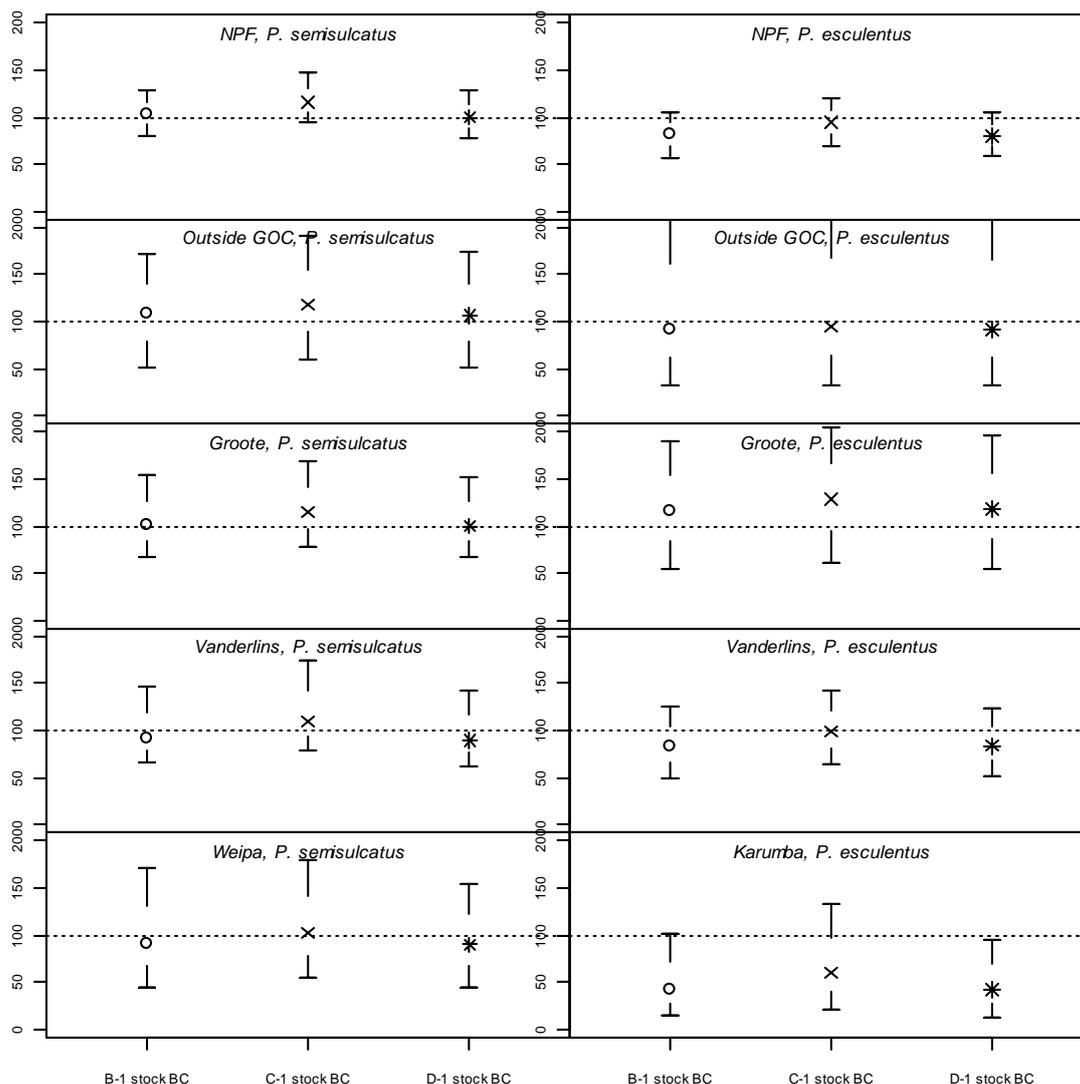


Figure 5.3: Medians and 90% intervals for the spawning stock size in 2010 relative to S_{MSY} , for each of the stock areas and species in the operating model. Results are shown for the “B-1 stock BC” (bio-mass dynamic model), the “C-1 stock BC” (cpue regression approach), and the “D-1 stock BC” (Deriso model) management strategies.

5.4.a.(ix) Performance of the assessment

Relative error distributions for spawning stock size and recruitment for the Deriso model assessment procedure when it is applied in 2010 and relative error distributions for S_{MSY} , E_{MSY} and stock-recruitment steepness for this model when it is applied in 2003, 2006, and 2010 are given in Figure 5.4. The estimates of recruitment for *P. semisulcatus* are, apart from those for the early years and for 2002, generally unbiased. The estimates of stock-recruitment steepness for *P. semisulcatus* are, however, negatively biased which leads to bias in the estimates of management-related quantities such as S_{MSY} (positively) and E_{MSY} (negatively). Any bias in the ratio S_y/S_{MSY} is therefore due primarily to bias associated with S_{MSY} . There are no obvious signs that the estimates of recruitment for *P. esculentus* are positively or negatively biased. Furthermore, the estimates of S_{MSY} are also close to unbiased, even though the estimates for E_{MSY} and steepness are negatively biased (Figure 5.4). It is surprising then that the “D-1 stock BC” management strategy is able to leave the spawning stock size of *P. semisulcatus* close to S_{MSY} , whereas this strategy leaves the spawning stock size of *P. esculentus* well below S_{MSY} . It is perhaps noteworthy that there is no evidence for learning, because the estimates of S_{MSY} , E_{MSY} and stock-recruitment steepness are as biased in 2010 as they were in 2003.

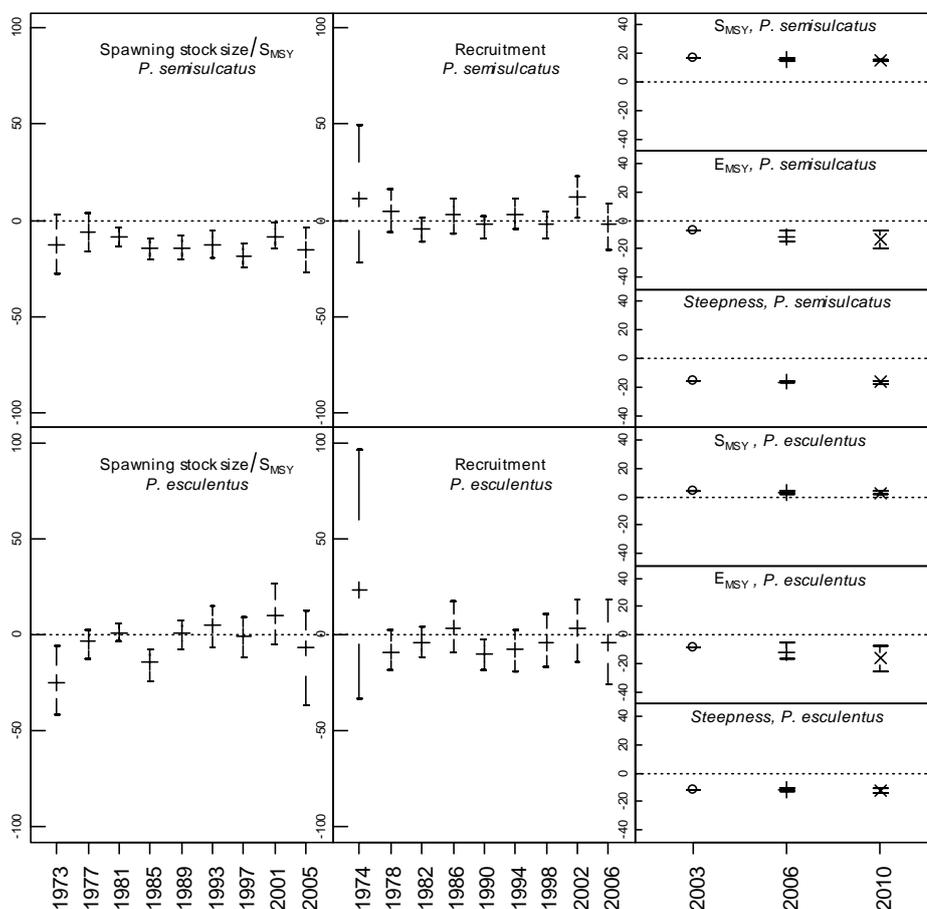


Figure 5.4: Medians and 90% intervals of the percentage relative error distributions for the “Base case” Deriso assessment model (management strategy “D-1 stock BC”). Results are shown for spawning stock size and recruitment by year when the assessment is conducted in 2010, and S_{MSY} , E_{MSY} and the steepness of the stock-recruitment relationship for assessments conducted in 2003, 2006 and 2010.

The estimates of the parameters of the biomass dynamic model imply a resource that is huge and very unproductive (results not shown). Furthermore, the parameter estimates vary substantially among simulations. This variation is reflected by the larger inter-simulation variation in the values for the economic-based performance measures for the “B-1 stock BC” management strategy in Table 5.3.

5.4.b Multi-stock assessment methods

5.4.b.(x) Management-related performance

Performance measures for management strategies based on assessments that are applied at finer spatial resolution than the “Base Case” management strategies are shown in Table

5.3. It might be expected that these management strategies would perform better than the “Base case” management strategies because they would better capture the true underlying stock structure. The variant of the “Deriso” management strategy based on a 3-stock assessment (abbreviation “D-3 stock”) includes an outside Gulf stock (“Outside GOC”; see Dichmont et al. 2006a for a map), a western Gulf stock (the Groote and Vanderlins stock areas combined) and an eastern Gulf stock (the Karumba and Weipa stock areas combined) whereas that based on a 4-stock assessment (abbreviation “D-4 stock”) is based on assuming that each of the Outside GOC, Groote and Vanderlins stock areas contain a single stock, and that the eastern Gulf (the Karumba and Weipa stock areas combined) is a single stock. The 4-stock assessment is equivalent to the true stock structure in the operating model because *P. semisulcatus* is assumed not to be found in the Karumba stock area and *P. esculentus* is assumed not to be found in the Weipa stock area in the operating model (Dichmont et al. 2006a).

Unfortunately, there is little evidence for improved performance in terms of leaving the spawning stock size close to S_{MSY} when assessments better reflect the true underlying stock structure (Figure 5.5) although the inter-simulation variability and inter-annual variation in catches is less for the management strategies based on the 3- and 4-stock assessments.

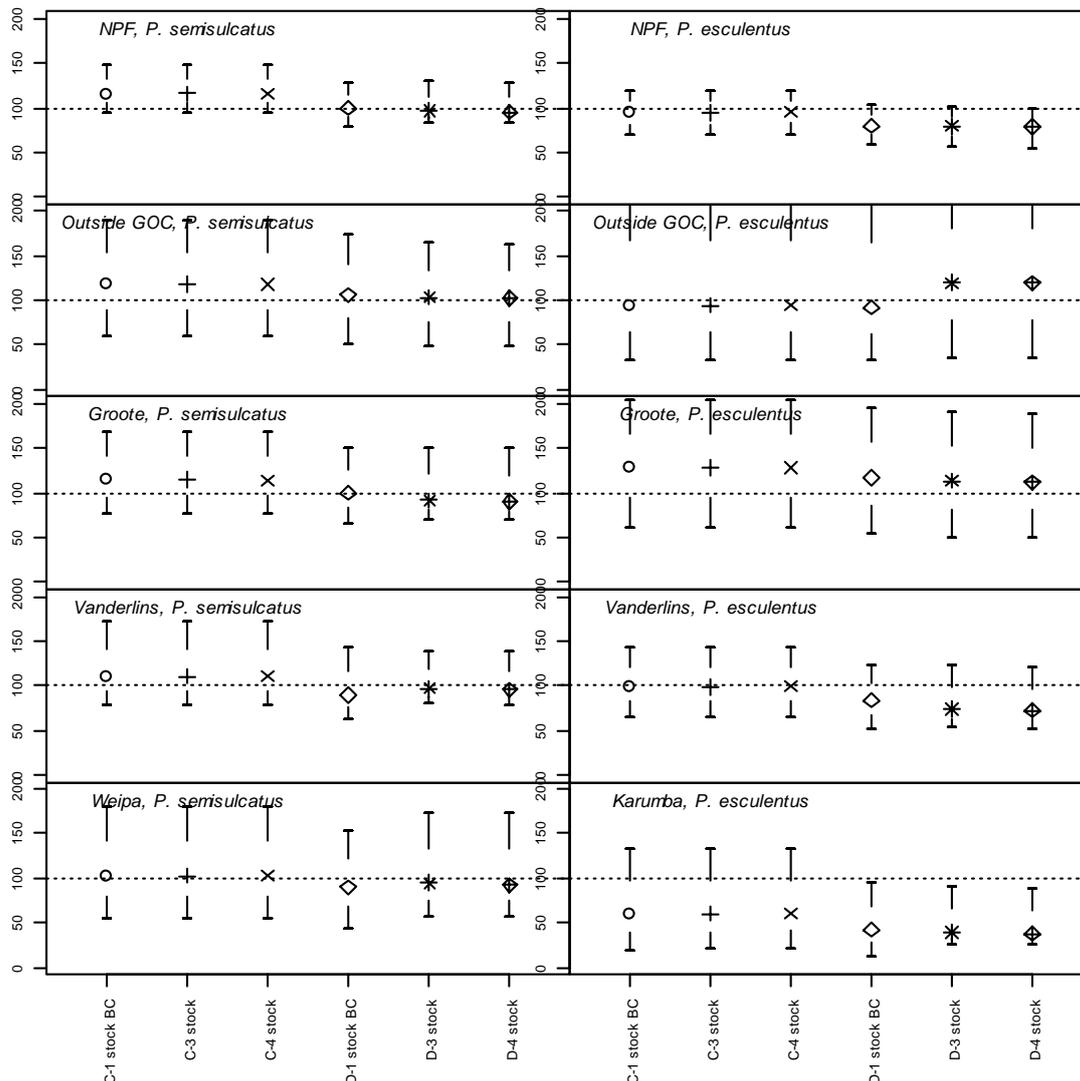


Figure 5.5: Medians and 90% intervals for the spawning stock size in 2010 relative to S_{MSY} , for each of the stock areas and species in the operating model. Results are shown for the Deriso model-based (prefix “D”) management strategies and the cpue regression (prefix “C”) based on a single stock (“1 stock BC”), 3 stocks (“3 stock”), and 4 stocks (“4 stock”).

5.4.b.(xi) Estimation Performance

There are some noteworthy differences in estimation performance between the 4-stock Deriso assessments (Figure 5.6; the results for the 3-stock assessments are similar to those for the 4-stock assessments, and are consequently not shown) and those for the corresponding single-stock assessments (Figure 5.4). Specifically, the bias of S_y/S_{MSY} for *P. semisulcatus* becomes increasingly negative over time in the eastern Gulf (Weipa in Figure 5.6); this trend pertains to *P. semisulcatus* in the Weipa stock area because *P. semisulcatus* is not found in the Karumba stock area. The widths of the intervals in Figure 5.6 tend to be wider than those in Figure 5.4, although this is perhaps not surprising given that the multi-stock

assessments estimate more parameters from the same amount of data. This is perhaps most evident for the estimates of S_y/S_{MSY} for *P. esculentus*. Unlike the case when considering a single stock (Figure 5.4), the estimates of E_{MSY} , steepness and S_{MSY} are biased for some of the putative stocks (e.g. *P. semisulcatus* in the “Weipa” stock area, *P. esculentus* in the “Groote” stock area). What is perhaps somewhat disturbing is that the relative error distributions for S_{MSY} and E_{MSY} actually get larger in some stocks as time progresses; the reasons for this remain unclear.

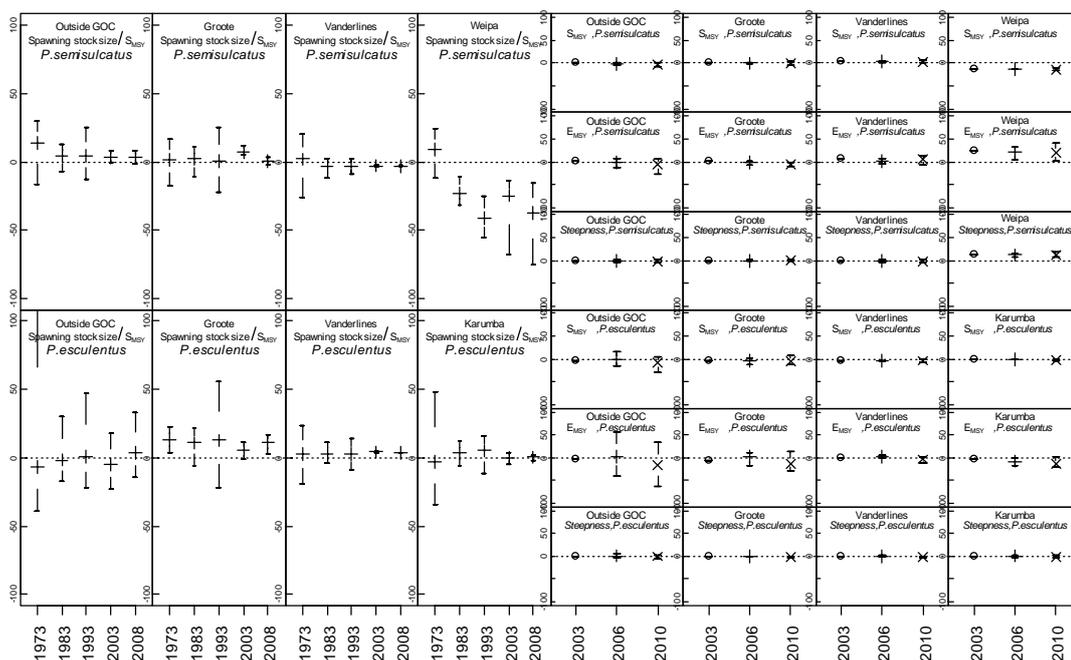


Figure 5.6: Medians and 90% intervals of the percentage relative error distributions for the 4-stock Deriso assessment model. Results are shown for spawning stock size and recruitment by year when the assessment is conducted in 2010, and S_{MSY} , E_{MSY} and the steepness of the stock-recruitment relationship for assessments conducted in 2003, 2006 and 2010.

5.4.c Changing the total effort

The probability of leaving the stocks at (or above) S_{MSY} is less than desired when the decision rule is based on setting effort to E_{MSY} when the stock is perceived to be above S_{MSY} . The sensitivity of the performance measures for the Deriso model-based management strategies to changing maximum proportion of E_{MSY} at which tiger prawn effort can be set is therefore explored in Table 5.3. As expected, both risk (e.g. S_{2010}/S_{MSY}) and economic performance measures are reduced as this proportion (Target Effort or TE) is decreased from 1.0 to 0.4. The spawning stock size of *both* species exceeds S_{MSY} in 2010 with greater than 50% probability only when TE is 0.6 or less. There is a greater than 70% probability

that the spawning stock size will exceed S_{MSY} in 2010 when TE is between 1.0 and 0.8 for *P. semisulcatus* and 0.6 and 0.4 for *P. esculentus*. This conclusion remains generally valid even when the results are analysed by stock area, except that *P. esculentus* in the Karumba stock area does not quite recover to S_{MSY} even when TE is set to 0.4.

The values for the economic- and risk-related performance measures change in different ways as TE is decreased from 1.0 to 0.8. Specifically, the proportional increase in spawning stock size is much greater than the proportional reduction in catch (Figure 5.7). However, large reductions in the economic-related performance measures occur once TE decreases below 0.8. There is thus a large reduction in risk by decreasing TE from 1.0 to 0.8, with only a relatively small loss in reward.

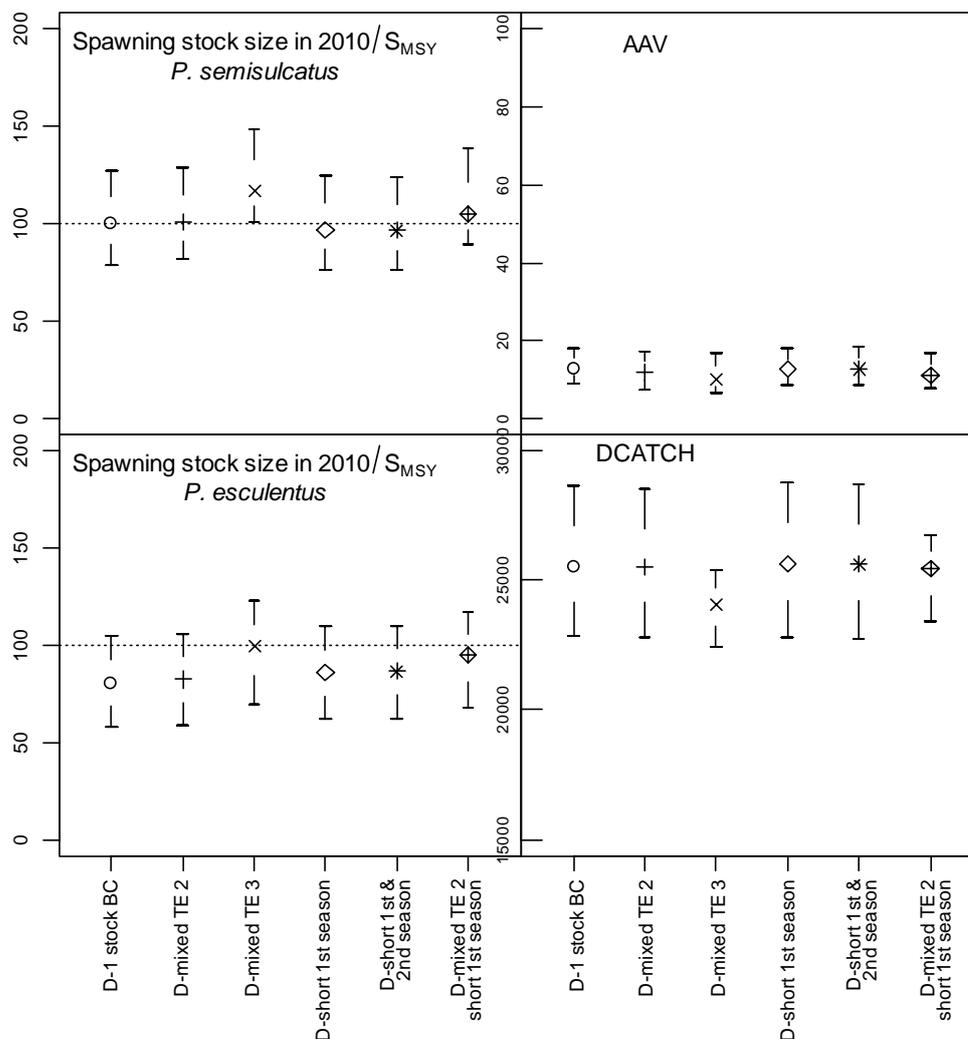


Figure 5.7: Management and economic-related performance (medians and 90% intervals) for Deriso (D) model-based management strategies which differ in terms of the target effort level and/or the season dates (see Table 5.3 for the specifications of the management strategies).

Performance measures for several species-specific choices for TE are also given in Table 5.3: “D-mixed TE 1” (1.0 for PS and 0.7 for PE), “D-mixed TE 2” (1.2 for PS and 0.4 for PE), “D-mixed TE 3” (1.0 for PS and 0.2 for PE) and “D-mixed TE 4” (1.0 for PS and 0.6 for PE). The specifications for these management strategies are based on the results above, which suggest that the probability of leaving the spawning stock size of *P. esculentus* at or above S_{MSY} is improved by decreasing TE. The probability of being above S_{MSY} is higher for both species for management strategy “D-mixed TE 2”, but this management strategy still results in a median spawning stock size less than S_{MSY} for *P. esculentus*. This is possibly because the total effort from the management strategy applies to both tiger prawn species combined, so that S_{2010} for *P. semisulcatus* is increased even though the aim was to reduce fishing pressure on *P. esculentus*.

The inability to leave both species near S_{MSY} by manipulating the species-specific TE values is further evidence that the overlapping geographical distributions of the two tiger prawn species, combined with their differing biology and the lack of spatial management, makes attempting to manage them separately very difficult.

5.4.d Changing how the season length is set

Changing how the season length is modified given the results of the assessment does not impact estimation performance (results not shown). A more restrictive first season (“D-short 1st season”) seems to move the effort directed towards *P. esculentus* by management strategy “D-1 stock BC” to being directed at *P. semisulcatus* as the effort gets concentrated into the second season (Table 5.3; Figure 5.7). One consequence of this is that, although there is some increase in the probability of the spawning stock size of *P. esculentus* being above S_{MSY} , there is now less than a 0.5 probability of the spawning stock size of *P. semisulcatus* being above S_{MSY} (Table 5.3). Shortening the first season and starting the second season later (“D-short 1st and 2nd season”) causes only a slight shift in effort from *P. esculentus* to *P. semisulcatus* (Figure 5.7). Overall, therefore, changing how season length is modified in response to changes in abundance (without changing the total effort) is not sufficient to allow the management strategies to leave the spawning stock size of both species at or above S_{MSY} .

5.4.e Combining different input mechanisms

The impact of simultaneously varying the maximum proportion of E_{MSY} at which tiger prawn effort is set (TE) and the weeks that define the season is highlighted in Figure 5.7. Of the various management strategies in Figure 5.7, “D-mixed TE 2 short 1st season” comes closest to leaving both species at S_{MSY} in median terms. Interestingly, this management strategy also performs well in that it does not reduce discounted catch or increase inter-annual variability in catches compared to “D-1 stock BC”. This management strategy also exhibits less inter-simulation variance in discounted catch than “D-1 stock BC”.

5.5 Discussion

The objective of this paper is not to determine which target reference point is most appropriate for the NPF (this is largely a socio-political decision), but rather, given a target reference point (in this case S_{MSY}), how well are we able to achieve it with input controls, preferably without compromising catch stability or catch itself. The focus on S_{MSY} is because S_{MSY} was selected in 2001 to be the target for the fishery and that recovery to S_{MSY} should occur by 2006 (see Table 5.1), after which S_{MSY} would be a limit reference point, and the spawning stock size at which Maximum Economic Yield is achieved would be the target reference point (Annie Jarrett, Northern Prawn Management Advisory Committee secretary, *pers. commn*).

5.5.a Choosing the appropriate assessment method

None of the management strategies managed to leave the spawning stock size of both tiger prawn species at S_{MSY} in median terms simultaneously, even though species-specific assessments are conducted for the management strategies based on the “Deriso” model. Furthermore, the comparison of the results for the cpue regression approach (which does not involve fitting dynamic models to data) and those for the management strategies based on the “Deriso” model demonstrates that the additional complexity of a stock assessment based on a population dynamic model does not reduce necessarily risk. Several factors, either alone or in combination, probably contribute to the inability of the management strategies based on the sophisticated assessment model to out-perform the simpler management strategy:

1. the assessment is biased to some extent;

2. a global effort and season length are set by the management strategy whereas the seasonal *and spatial* pattern of fishing determines the amount of effort expended on each species (i.e. vessels are able to expend the available effort in any stock area; there is no spatial management); and/or
3. the capture of pre-spawning individuals is difficult to avoid using only controls on total effort.

It seems likely that management will continue to expect estimates of management-related quantities such as spawning stock size relative to S_{MSY} . The problem associated with basing management decisions on the cpue-based decision rule is that there is no information on stock status for the managers unless an assessment is also undertaken. This means that the resources needed to provide scientific management recommendations are unlikely to be reduced if management was based on the cpue-based decision rule. Therefore, future management recommendations would have to be based, to some extent, on a management strategy that involves a stock assessment of some sort. In terms of the assessment models to be applied, of the two stock assessment methods considered in this study, there seems little reason not to continue with the use of the Deriso model-based assessment technique as it is the *status quo* and because without additional constraints, the alternative stock assessment method (the biomass dynamic model) appears to be unstable.

5.5.b Countering fishery mobility

Management of fleets and fisheries that harvest multiple stocks is complicated. The less productive stocks in a mix of stocks may suffer unsustainable mortality while the more-productive stocks continue to support sustainable catches. Stocks harvested together may be at a very different status relative to safe biological limits, which leads to the need for several different harvest strategies in the same fisheries (Kell et al., 2004). This multi-species nature of the fishery is common in, amongst others, prawn fisheries, e.g. Queensland trawl (Williams, 2002), Gulf of Mexico shrimp (Garcia, 1997; Nance, 1994).

At present, the NPF controls effort through season length and the number of gear units. The “Base Case” management strategies of this paper therefore operationalise, through decision rules, the spirit of what management is trying to achieve and how it is trying to do it, i.e. effort is not allocated separately to each tiger prawn species, but the aim is nevertheless that the stocks of each species are left at or above S_{MSY} . Unfortunately, the extent to which

each species is impacted by the effort level set depends mainly on the time of year and area being fished. Allocating effort NPF-wide means the fleet is able to choose which areas to fish. The implication of this is that it is not possible to leave the spawning stock size of *P. semisulcatus* near S_{MSY} while at the same time leaving the spawning stock size of *P. esculentus* near S_{MSY} . This result reflects the long-held expectation that it is not possible to achieve a catch of *MSY* for multiple species in a mixed-species fishery simultaneously.

Basing a management strategy on an assessment method that attempts to estimate stock status by species and area does not increase the probability of leaving the spawning stock size close to S_{MSY} . Rather, the inability to achieve the management goal is probably due to effort not being allocated directly to a specific stock area and species (which negates some of the possible benefits of a multi-stock / multi-area assessment). The Groote, Vanderlins and Karumba stock areas are likely to receive most of the effort irrespective of the total level of effort because the total biomass of all prawn species is high in these stock areas. Clearly, to be most efficient, input controls should allocate effort to each stock area directly. However, this solution is not likely to be perfect either because the two species mix spatially and temporally.

While it should be fairly straightforward to determine the amount of effort by area with high accuracy because all of the vessels in the fishery are monitored using a Vessel Monitoring System, only through a (costly) observer program would be possible to monitor the spatial resolution of the catches with sufficient accuracy for legal enforcement purposes. This is because a vessel may fish in several areas during a trip.

5.5.c Setting appropriate effort levels

Reference points can be Limits or Targets, depending on their intended usage (see Caddy and Mahon, 1995; Sissenwine and Shepherd, 1987). The difference between a target reference point (TRP) and a limit reference point (LRP) is important. The TRP is assumed to be the ideal state for the fishery (where the balance between long-term productivity and sustainability is optimized (Caddy and Mahon, 1995)). On the other hand, the LRP is an agreed upon threshold state beyond which a fishery requires immediate and strong management measures to move it back towards the TRP. In the case of the NPF, the fishery moved in 2005 to using the Maximum Economic Yield as its TRP. However, this TRP is not considered in this paper because it is as yet undefined at the species level.

Since tiger prawn effort is not species-specific, mechanisms to maintain biological conservation objectives need necessarily be indirect. Three options are available: setting target effort by species, changing the season dates to shift effort from one species to the other (without changing the total effort), or a combination of the two.

5.5.c.(xii) Different target effort levels

Decreasing the maximum proportion of E_{MSY} at which tiger prawn effort can be set (TE) leads to higher spawning stock sizes (less risk) and lower catches (less reward). However, there is some non-linearity in the relationship between risk and reward as TE is decreased from 1 to 0.8. Given this non-linearity, the benefits of decreasing TE to slightly below 1 seem to outweigh the costs. However, costs, in terms of reduced catch, increase as TE is decreased below this threshold and, for example, if the TE is 0.4 the lowest catch during the projection period is close to 1000t per annum and the median discounted catch is only about 70% of that for a TE of 1. Catch rates would be higher if the stock size is higher (i.e. the profit for each vessel per unit effort may increase) and this will tend to offset the economic cost of the lower catches to some extent. However, the optimum value of TE cannot be quantified in the absence of detailed information about costs.

Interestingly, using different TEs for each species, which could be seen as a compromise between being risk averse and risky, often results in a median spawning stock size less than S_{MSY} for *P. esculentus*. This is because the total effort from the management strategy applies to both species, so that S_{2010} for *P. semisulcatus* is increased when TE is reduced despite the effort reduction directed towards *P. esculentus*. Obviously, setting and maintaining effort by species would best achieve the target reference point, but this is impossible to implement using input controls particularly because the two species mix spatially. In principle, output controls could be used to implement catch limits by species, but, as noted above, this would require major changes to the monitoring and compliance system in the fishery.

5.5.c.(xiii) Changing the season

Since the season dates are changed in the simulations any time there is a need to do so (whereas there is only a 1/3 chance of changing total effort levels if this is deemed to be required), the specifications for season length may be an important factor in determining whether the spawning stock size is left at or above S_{MSY} . Furthermore, which weeks are

open and which are closed to fishing indirectly determines how much effort is expended on each species. For example, much of the effort directed at tiger prawns during the first season and during the early part of the second season is automatically focused on *P. esculentus* because *P. semisulcatus* is generally unavailable at those times due to its migration pattern. It should be borne in mind that in these simulations a change in season does not reduce the total effort.

Another reason for the inability to leave the spawning stock at S_{MSY} on average is that the season length set when the spawning stock is assessed to be above the target level is such that capture of pre-spawning prawns is likely. Changing the algorithm that specifies season length was examined. However, unless the method used to specify the total effort is also changed, modifying this algorithm to avoid catching *P. esculentus* leads to a reduction in the spawning stock size of *P. semisulcatus*.

5.5.c.(xiv) Mixed total effort and season inputs

A combination of shortening the first season and using a mixture of TEs by species produced the best results in terms of both risk and economic performance measures. This management strategy is also relatively easy to implement, results in no loss of economic performance and does not require effort to be allocated by area or species. However, the ability to utilize years of very good tiger prawn recruitment is effectively eliminated because tiger prawn catch during the first season is greatly reduced.

The management of fisheries through input controls is particularly common in short-lived species, for example, the Falkland Island squid (Agnew et al., 1998; Barton, 2002), several prawn resources (Exmouth Gulf, Australia (Penn et al., 1997), Queensland trawl, Australia (Williams, 2002), Torres Strait trawl (Turnbull and Watson, 1995), Gulf of Mexico shrimp (Garcia, 1997). The results presented in this paper are very relevant to these fisheries as they manage effort between species using input controls.

5.6 Concluding remarks

The results of this paper highlight the difficulty of identifying simple management strategies for multi-species fisheries. None of the management strategies tested were able to leave the spawning stock size of *P. esculentus* (particularly that in Karumba stock area)

near S_{MSY} if the target spawning stock size used in the management strategy was set to S_{MSY} even though the assessment model was based on the most of the same assumptions as the operating model. Trying to account for stock structure by conducting a spatially-structured assessment did not resolve this problem, most likely because, even if assessments are conducted spatially, there remain no restrictions on where in the NPF fishing is to occur. Since some stock areas have much higher abundances, and are consequently almost always heavily fished; effort remains in those stock areas irrespective of the status of the species present and much higher effort moves to those stock areas than is required to leave the spawning stock size of *P. esculentus* at (or above) S_{MSY} . Even reducing the total effort (by decreasing the target effort level in the decision rule) does not achieve the desired goal of reducing effort in stock areas such as Karumba and Mornington. It seems clear that some form of spatial management and allocation of effort may be required to ensure that all stocks of both species are at or above S_{MSY} . This may necessitate spatially-structured stock assessments. However, although spatially-structured assessments may reduce the bias caused by applying an assessment method to data for several stocks simultaneously, it should be noted that a spatially-structured assessment will be less precise because it needs to estimate more parameters from the same amount of data. In addition, stock boundaries, if they exist, are poorly known, with those available based only on expert opinion. Other concerns associated with moving to a spatially-structured stock assessment relate to the true number of stocks and the implications of movement among such stocks.

In the meantime, a combination of a short first season (or a mechanism that allows for banana prawn fishing but prevents tiger prawn fishing, such as a night-time closure) and a mixture of target effort levels that are much more precautionary for *P. esculentus* than for *P. semisulcatus* is needed to have a high likelihood of leaving the spawning stock sizes of both species near S_{MSY} .

In conclusion therefore, it is clear that the essential difficulty with regard to satisfying the current target reference point for each species is that the measure of control is total effort and that the species co-occur. The complex spatial and temporal changes in the relative distribution of the tiger prawn species means that even fairly complicated management strategies do not satisfy the management goals without being highly precautionary.

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5.8 References

- Agnew, D.J., Baranowski, R., Beddington, J.R., des Clers, S., Nolan, C.P., 1998. Approaches to assessing stocks of *Loligo gahi* around the Falkland Islands. *Fish. Res.* 35, 155–169.
- Barton, J., 2002. Fisheries and fisheries management in Falkland Islands Conservation Zones. *Aquat. Conserv.: Mar. Freshwat. Ecosyst.* 12, 127-135.
- Bishop, J., Die, D., Wang, Y-G., 2000. A generalized estimating equations approach for analysis of the impact of new technology on a trawl fishery. *Aust. NZ J. Statist.* 42, 159–177.
- Caddy, J. F., Mahon, R., 1995. Reference points for fisheries management. FAO, *Fish. Tech. Pap.* 347, 83 pp.
- Cartwright, I., 2005. The Australian Northern Prawn Fishery. In: Cunningham, S., Bostock, T. (Eds), *Successful Fisheries Management Issues, Case Studies and Perspectives*. SIFAR/World Bank Study of good management practice in sustainable fisheries, Eburon Academic Publishers, The Netherlands, pp. 197-231.
- Dichmont, C.M., Die, D., Punt, A.E., Venables, W., Bishop, J., Deng, A. Dell, Q., 2001. Risk Analysis and Sustainability Indicators for the Prawn Stocks in the Northern Prawn Fishery. Fisheries Research and Development Corporation 98/109. 187 pp.
- Dichmont, C.M., Bishop, J., Venables, W.N., Sterling, D., Rawlinson, N., Eayrs, S. 2003a. A new approach to fishing power analyses and its application in the Northern Prawn Fishery. AFMA Research Fund R99/1494. 700 pp.
- Dichmont, C.M., Punt, A.E., Deng, A., Venables, W., 2003b. Application of a weekly delay-difference model to commercial catch and effort data for tiger prawns in Australia's

- Northern Prawn Fishery. *Fish. Res.* 65, 335–350.
- Dichmont, C.M., Deng, A., Punt, A.E., Venables, W.V., Haddon, M., 2006a. Management Strategies for short lived species: the case of Australia's Northern Prawn Fishery. 1. Accounting for multiple species, spatial structure and implementation uncertainty when evaluating risk. *Fish. Res.* in prep.
- Dichmont, C.M., Deng, A., Punt, A.E., Venables, W.V., Haddon, M., 2006b. Management Strategies for short lived species: the case of Australia's Northern Prawn Fishery. 3. Factors affecting management and estimation performance. *Fish. Res.* in prep.
- Galeano, D., Langenkamp, D., Shafron, W., Levantis, C., 2004. Australian Fisheries Surveys Report 2003, ABARE, Canberra. 68 pp.
- Garcia, A. 1997. Simulated and actual effects of the brown shrimp, *Penaeus aztecus*, closure in Mexico. *Mar. Fish. Rev.* 59(2), 18-24.
- Haddon, M., 2001. Modelling and Quantitative Methods in Fisheries. Chapman & Hall/CRC press. 406 pp.
- Kell, L.T., Crozier, W.W., Legault, C.M., 2004. Mixed and Multi-Stock Fisheries - Introduction. *ICES J. Mar. Sci.* 61, 1330.
- Nance, J.M., Martinez, E.X., Klima, E.F., 1994. Feasibility of improving the economic return from the Gulf of Mexico brown shrimp fishery. *N. Am. J. Fish. Manage.* 14(3), pp. 522-536.
- Penn, J.W., Watson, R.A., Caputi, N., Hall, N., 1997. Protecting vulnerable stocks in multi-species prawn fisheries. In: Hancock, D.A., Smith, D.C., Grant, A., Beumer, J.P. (Eds). *Developing and Sustaining World Fisheries Resources: The State of Science and Management*. 2nd World Fisheries Congress, pp. 122- 129.
- Pownall, P. (Ed.), 1994. Australia's Northern Prawn Fishery: the First 25 Years. NPF25, Cleveland, Australia, 179 pp.
- Punt, A.E., 2003. The performance of a size-structured stock assessment method in the face of spatial heterogeneity in growth. *Fish. Res.* 65, 391–409.
- Punt, A.E., Butterworth, D.S., Martin, J., 1995. The effects of errors in the placement of the boundary between the west and south coast hake *Merluccius* spp. stocks on the performance of the current hake management procedure. *S. Afr. J. Mar. Sci.* 15, 83–98.
- Sissenwine, M.P., Shepherd, J.G., 1987. An alternative perspective on recruitment over-fishing and biological reference points. *Can. J. Fish. Aquat. Sci.*, 44, 913–918.

- Turnbull, C., Watson, R., 1995. Torres Strait Prawns 1994, Stock Assessment Report, Torres Strait Fisheries Assessment Group, Australian Fisheries Management Authority, Canberra, 30 pp.
- Williams, L. E. 2002. Queensland's fisheries Resources - Current condition and recent trends 1988 - 2000. DPI Information Series No. QI02012, Brisbane, Department of Primary Industries, Queensland, 180 pp.

CHAPTER 6 FACTORS AFFECTING MANAGEMENT AND ESTIMATION PERFORMANCE

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6.1 Abstract

Management strategies for tiger prawns, *Penaeus semisulcatus* and *P. esculentus*, in Australia's Northern Prawn Fishery (NPF), Australia are evaluated in terms of conservation- and economic-related performance measures. A two-stage process is used to determine the factors to which these performance measures are most sensitive. The first stage involves identifying the possible factors and their interactions, constructing a partial factorial design to allow the impact of first- and second-order interactions on the performance measures to be identified, and analysing the resultant performance measures using generalised linear models. The second stage entails an experiment based on a balanced design of the possible combinations of the key factors. The factors found to have the greatest impact on the performance measures are: a) how fishing efficiency has changed over time and whether or not the assessment is based on the correct trend in fishing efficiency, b) the catchability coefficient used to convert from fishing effort to fishing mortality, c) the difference between the intended fishing effort and the actual fishing effort expended (implementation error), and d) whether recruitment is spatially correlated among stocks or not.

6.2 Introduction

Australia's Northern Prawn Fishery (NPF) is an input-controlled multi-stock and -species fishery targeting predominantly tiger and banana prawns. A fleet of less than 100 vessels trawls an area of about 200,000 km² (Mick Haywood, CSIRO, pers. commn). Management of the target species is through limits on the length of the fishing season (including a temporal closure that divides the year into two periods) and a system of individual tradeable gear (fishing effort) units that controls the total amount of headrope length in the fleet. At present, the status of the two species of tiger prawns (*Penaeus semisulcatus* and *P. esculentus*) is assessed using a weekly delay-difference model that treats each species separately (Dichmont et al., 2003a). The assessment involves estimating annual recruitment and indices of spawning stock size from catch and fishing effort data, and using these estimates to estimate the parameters of a stock-recruitment relationship.

In common with many fisheries worldwide, the NPF does not have a long-term fishery-independent index of abundance so management is based on inferences based on fitting models to catch and effort data. This, combined with the longevity of the target species and the input control nature of the fishery, makes estimation of the values for some of parameter of the assessment model difficult. For example, it has proved impossible to estimate the extent to which fishing power has changed over time (Dichmont et al., 2003b). As a result, stock assessments are conducted for several scenarios related to this (bounded by the "Base Case High" (H) and "Base Case Low" (L) scenarios). A second complication is that the data are not informative about the catchability coefficient (the constant of proportionality between fishing effort and fishing mortality) so assessments are based on catchability coefficients estimated from auxiliary analyses (e.g. Wang (1999)). Nevertheless, Dichmont et al. (2003a) found that recruitment and spawning stock size are estimated robustly and had declined substantially by 2000, but that the status of the resource relative to MSY-based reference points was uncertain.

The Management Strategy Evaluation (MSE) approach has been applied to several fisheries around the world (e.g. Punt, 1992; De la Mare, 1996; Butterworth et al., 1997; Punt and Smith, 1999; Smith et al., 1999; Punt et al., 2002a, 2002b, 2002c). The major benefit of the MSE approach is that the effects of different management strategies can be evaluated by managing a "virtual" resource. The resource is represented using an "operating model",

and future management actions are based on a management strategy (usually, but not always, the combination of a data collection scheme, a method of stock assessment, and a decision rule that converts the results of the assessment into specifications for management actions – such as levels of fishing effort). The operating model therefore represents the “truth” for the evaluations.

Dichmont et al. (2006a, 2006b) apply the MSE approach to the NPF. The analyses are based on a two-species, 5-stock operating model, and examine the performance of some possible management strategies for the NPF tiger prawns, and specifically how assumptions made regarding spatial structure impact performance. Banana prawns are not modelled explicitly, but their impact on the management system is simulated empirically. This latter approach is reasonable as there is no stock assessment for banana prawns and no evidence that the catches of banana and tiger prawns are correlated. Three “assessment procedures” are considered (simple catch rate regression, biomass dynamic and delay-difference models) and two types of management action (setting the total fishing effort and setting the season start and end dates). The performance of the management strategies is evaluated in terms of whether stocks are left at (or above) the spawning stock size at which Maximum Sustainable Yield is achieved (S_{MSY}), the long-term discounted total catch, and the extent of inter-annual variation in catches.

This paper examines the performance of management strategies (as opposed to the assessments themselves) for the NPF tiger prawns to determine which factors impact performance to the greatest extent. Attempts to resolve these uncertainties could be the focus of future research. Overall therefore, Dichmont et al. (2006a, b) and the present paper provide the basis for developing management strategies that are robust to the key uncertainties that have been identified to date for tiger prawns in the NPF.

6.3 Methods

6.3.a Performance measures

There are two types of performance measures in the context of an MSE: a) management-related performance measures, and b) estimation-related performance measures. Management-related performance measures relate to the ability of a management strategy to satisfy (to the extent possible) the management objectives for the fishery, while estimation-related

performance measures quantify how well stock assessment methods are able to estimate quantities that are of interest to the decision makers (such as MSY , E_{MSY} , and current spawning stock biomass). It should be noted that management-related performance measures are obtained only from the operating model (i.e. the “truth”) rather from the assessment procedure in the management strategy (i.e. the perception of truth based on assessment model settings and data). In common with previous MSE exercises in Australia (e.g. Polacheck et al., 1999; Punt et al., 2001a, 2001b; Campbell and Dowling, 2003), this paper focuses on management-related performance measures related to the sustainability of the stocks and of the fishery.

6.3.a.(xv) Conservation-related performance measures

Unfortunately, prior to 2001, NPF-specific management goals were incompletely articulated as “set the fishing effort to that corresponding to MSY ” and thereafter were revised to relate to recovering the spawning stock size to the level at which, in expectation, MSY is achieved (S_{MSY}). The conservation-related performance measures considered in this study are therefore based primarily on the size of the spawning stock relative to S_{MSY} (which is now treated as a limit reference point, i.e. success is defined as leaving the spawning stock size above S_{MSY}) although other ‘biological bottom lines’, $0.2 S_{VIR}$ (20% of the pre-fishery or virgin spawning stock size) and S_{low} (the lowest spawning stock size encountered to date) are also considered. Note that there is no evidence that depleting a resource to below S_{MSY} , $0.2 S_{VIR}$ or S_{low} will necessarily lead to severe biological problems. Nevertheless, these measures are still useful to define the (relative) risk to the resource due to exploitation. In the results, we present the probability that the spawning stock size in 2010 has fallen below these reference points (e.g. $p(S_{2010}/S_{MSY})$), as well as the actual ratio of S_{2010}/S_{MSY} .

6.3.a.(xvi) Economic-related performance measures

There are two approaches to developing performance measures that capture the economic aspects of the outcomes of the use of a management strategy. The first is to develop a model that explicitly considers fleet dynamics and the costs of harvesting, and can determine the profitability of the fishery for different management strategies. The second, which forms the basis for this paper, is to assess economic performance using simple proxies. The four proxies used for the economic performance of the management strategies are:

- a) Total discounted annual total catch, i.e.:

$$C^T = \sum_y C_y e^{-\delta(y-2003)} \quad (1)$$

where C_y is the catch (aggregated over prawn species, weeks, and area) during year y ; and

δ is the economic discount rate (assumed to be 5% for the analyses of this paper).

- b) Percentage of years that the catch is less than some critical level, C_{crit} , $P(C_y < C_{crit})$; the value of C_{crit} is taken to be 2000t, a level below which the profits to the industry are likely to be negative (Kompas, Australian National University, pers commn.).
- c) C_{low} , the lowest catch taken over the period 2003–15. The median and the lower 5th percentile of the discounted total catch across simulations are reported.
- d) Stability of catches. The stability of the catches is measured by the average absolute (percentage) change in landed catches from year to year, AAV:

$$AAV = \frac{100 \sum_{y=2003}^{2015} |C_y - C_{y-1}| e^{-\delta(y-2003)}}{\sum_{y=2003}^{2015} C_y e^{-\delta(y-2003)}} \quad (2)$$

Equation (2) is based on the total catch of all tiger prawn species over all weeks and areas. This equation implicitly assumes that the value of the catch is independent of week, area, and species. In principle, allowance could be made for week-, species- and area-specific prices and costs, but such an evaluation is beyond the scope of the present study.

6.3.b Factors affecting performance measures

A completely balanced test of all factors to identify which are most influential on the performance measures would have been computationally infeasible, and in a practical sense unnecessary. A two stage process was therefore used to, firstly, identify which factors (singly or combined with others, both in terms of specifications for the operating model and those for the management strategies) significantly affect the performance measures, and secondly, to investigate in detail what this affect is in terms of trend and degree.

Viewed as an experimental design, the set for the first test is unbalanced, but is nevertheless able to permit the identification of the key factors. The second part uses a balanced test of the significant factors.

The management strategies are based on three “assessment procedures” (the Deriso delay-difference model that forms the basis for current assessments of the resources, a biomass dynamics model, and a simple linear regression-based empirical method – see Dichmont et al. (2006b) for additional details). Table 6.1 lists the factors (apart from “assessment procedure”) considered in the experiment and the levels for each factor. The factors in Table 6.1 include the six sources of error and uncertainty that can be incorporated into a risk assessment identified by Francis and Shotton (1997). Four of these sources (process uncertainty, observation uncertainty, model uncertainty and implementation uncertainty) pertain to the operating model and the other two (estimation and error structure uncertainty) pertain to fitting models to data. Note that not all combinations of factor levels can be chosen to create a scenario. For example, the “simple regression” approach only uses catch-rate data and so does not make an assumption regarding changes over time in fishing efficiency.

Table 6.1: Description of the factors (other than assessment procedure) examined in main experiment, their abbreviations, and the levels for each factor (in parenthesis). Factors superscripted by “B”, “C” and “D” are not relevant to the biomass dynamics model, cpue regression approach, and Deriso management strategies respectively. Full descriptions how the factors related to management strategies are implemented are given by Dichmont et al. (2006b).

Abbreviation	Description
<i>Factors relevant to the operating model</i>	
FpOp	True scenario regarding changes over time in efficiency (Base Case High – BCH; Base Case Low – BCL)
qOp	The catchability coefficient in the operating model (q from Wang (1999) – “q”; twice the value of q from Wang (1999) – “2q”)
OE	Coefficient of variation of observation error on catch (CV = 0; CV = 10%)
SCR	Is recruitment spatially correlated? (no; based on the historical correlations of the residuals about the fit of the stock-recruitment relationship for each area and species)
DE	Coefficient of variation of the extent of implementation error (CV = 0; CV = 15%; CV = 30%)
Rval	Method for selecting parameter vectors (generated from the variance-covariance matrix; generated from a Bayesian posterior distribution)
PSeason	Is the season length changed annually? (Yes; 1 chance in 3)
PEffort	Is the effort level changed annually? (Yes; 1 chance in 3)
<i>Factors relevant to the management strategies</i>	
FpAss ^{B,C}	Assumed scenario regarding changes over time in efficiency (Base Case High – BCH; Base Case Low – BCL)
qAss ^{B,C}	The catchability coefficient in the assessment model (q from Wang (1999) – “q”; twice the value of q from Wang (1999) – “2q”)
CWt ^D	Area allocation weight to past cpue (1; 1.5)
RefPt ^C	The fractions of S_{MSY} and E_{MSY} used when determining target effort (1 / 1; 1.2 / 0.8)
RefYear ^{B,C}	The range of years used when determining E_{MSY} (1993-2002; most-recent 10 years)

The medians of the performance measures for each scenario are analysed by species and “assessment procedure”. The following process is used to analyse the each performance measure:

1. a linear model with all possible main effects is fit;
2. the most parsimonious main effects model is selected according to the ‘Bayesian Information Criterion’ (BIC);
3. the most complete possible main and second order effects model is fit using an ANOVA; and
4. the most parsimonious final model is selected using the BIC based on this 2nd order model, but the BIC itself uses the estimate of variance computed from by the most parsimonious main effects model chosen at step 2. This process ensures a reasonable variance estimate is used and avoids the problems of using a variance estimate from an over-fitted linear model.

The conservation-related performance measures are calculated for each year, but are only analysed and presented for 2010. Since these performance measures are proportions, they are transformed by $\arcsin(\sqrt{P})$ to obtain a response variable for which the residual variance about the regression is independent of the estimate. Since the conservation-related performance measures relate to the “true” resource being managed, there are conservation-related performance measures for each of the eight species×stock combinations. In addition, the spawning stock sizes can be added together and NPF-wide conservation-related performance measures produced. However, little is gained by analysing the performance measures for each stock area individually or by excluding some of the stock areas. The analyses therefore focus on performance measures aggregated over stock areas (i.e. NPF-wide) by species. The analyses of the economic-related performance measures that were not proportions were based on log-transformed values.

The second stage of determining the sensitivity of the performance measures to the various factors involves investigating the effects of each of the key factors using a series of balanced simulation experiments. The most appropriate method to illustrate these effects is graphical (rather than numerical) because graphs can highlight the size of effects, and permits simple visual appreciation of any trends.

6.4 Results and discussion

6.4.a Identifying factors that affect performance measures: an unbalanced design

Figure 6.1 summarizes all of the conservation-related performance measures (aggregated over all of the simulations on which the unbalanced experiment (Table 6.1) is based). There is generally a very small probability of the spawning stock size in 2010 being below the lowest spawning stock size encountered historically and a small probability of the spawning stock size in 2010 being below 20% of the pre-exploitation spawning stock size. The remaining analyses of this paper therefore focus on the performance measure $P(S_{2010} > S_{MSY})$ (by species) because it is more discriminating.

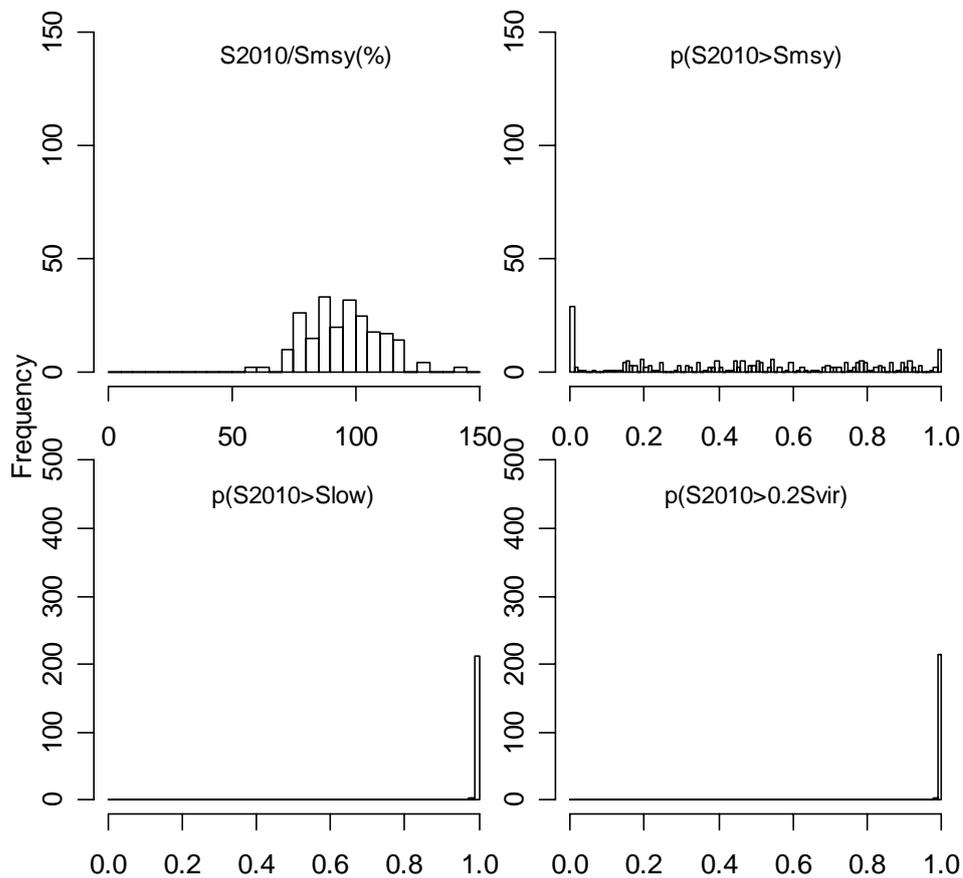


Figure 6.1: Frequency distributions of the NPF-wide conservation-related performance measures across all scenarios for the unbalanced experiment. Figure (clockwise from upper left) are the spawning stock size in 2010 expressed as a percentage of the spawning stock size at which MSY is achieved, the probability that S_{2010} is greater than S_{MSY} , the probability of S_{2010} is higher than S_{low} , and the probability that S_{2010} is higher than $0.2S_{VIR}$.

Tables 6.2 and 6.3 provide a summary of the factors that are highly significant ($P < 0.05$) in the linear model fits to $P(S_{2010} > S_{MSY})$ and the four economic-related performance measures. Table 6.2 demonstrates that assumptions regarding fishing power, catchability, whether recruitment is correlated spatially among stocks, the extent of implementation error, and the target spawning stock size used in the decision rule, have the largest impact on the values of the conservation-related performance measures. In contrast, more of the factors appear to influence the values of the economic-related performance measures (Table 6.3), and there are quite noteworthy differences in which factors are most influential among the four economic performance measures. In addition to all of the factors that are highly significant for $P(S_{2010} > S_{MSY})$, how the parameter vectors used to represent parameter uncertainty in the operating model are generated, as well as some of the interactions between the fishing power assumed when conducting Deriso-model-based assessments and other factors are also highly significant factors determining the values for the economic-related performance measures.

Table 6.2: Summary of the regression results for the management-related performance measure $P(S_{2010} > S_{MSY})$ (PS=*P. semisulcatus*, PE=*P. esculentus*.) The checked factors (see Table 6.1 for details) are significant at the 5% level and are included in the final model. ‘n/a’ means not applicable.

Factor	PS De- riso	PE De- riso	PS bio- mass dynamic	PE bio- mass dynamic	PS cpue re- gression	PE cpue re- gression
FpOP	√	√				
FpASS	√	√	n/a	n/a	n/a	n/a
DE	√				√	√
SCR	√	√	√	√	√	√
qOp	√	√				
qAss	√		n/a	n/a	n/a	n/a
Rval	√		√		√	
RefPt	√	√	√	√		
RefYear	√		n/a	n/a	n/a	n/a
FpOP:FpASS	√		n/a	n/a	n/a	n/a
FpASS:DE	√		n/a	n/a	n/a	n/a
FpASS:SCR	√	√	n/a	n/a	n/a	n/a
FpASS:qOp	√		n/a	n/a	n/a	n/a
FpAss:qAss	√		n/a	n/a	n/a	n/a
FpAss:Rval	√		n/a	n/a	n/a	n/a
FpAss:RefYear	√		n/a	n/a	n/a	n/a
FpOp:qOp		√				
DE:qOp	√					
SCR:DE			√	√	√	√

Table 6.3: Summary of the final models for the economic-related performance measures. Checked factors (see Table 6.1 for details) are significant at the 5% level and are included in the final models. “n/a” indicates “not applicable”, “D”, “C”, and “B” denote the “Deriso”, “cpue regression” and “biomass dynamics” management strategies respectively.

Factor	Total discounted catch			AAV			C_{low}			$P(C_y < 2000t)$		
	D	C	B	D	C	B	D	C	B	D	C	B
FpOP	√						√					
FpASS	√	n/a	n/a	√	n/a	n/a	√	n/a	n/a		n/a	n/a
qOP	√						√					
Rval	√	√	√					√	√	√	√	√
RefPt	√		√			√			√			
FpOP:FpASS	√	n/a	n/a		n/a	n/a		n/a	n/a		n/a	n/a
FpOP:qOP	√						√					
FpOP:RefPt	√	n/a	n/a		n/a	n/a		n/a	n/a		n/a	n/a
FpASS:RefPt	√	n/a	n/a		n/a	n/a		n/a	n/a		n/a	n/a
FpASS:DE		n/a	n/a	√	n/a	n/a		n/a	n/a		n/a	n/a
SCR		√	√	√	√	√		√	√		√	√
DE		√		√	√	√	√	√	√	√	√	√
SCR:DE		√		√	√	√		√				
SCR:qAss		n/a	n/a	√	n/a	n/a		n/a	n/a		n/a	n/a
OE			√			√			√			
OE:SCR			√									
qAss		n/a	n/a	√	n/a	n/a		n/a	n/a		n/a	n/a
PEffort						√						

6.4.b Key factors that affect performance measures: balanced design

The key factors affecting performance identified in the unbalanced experiment were: 1) fishing power; 2) catchability; and 3) fishing power and catchability combined, while the factors of lesser importance were: 4) the extent of implementation error; 5) whether recruitment is correlated spatially among stocks or not; and 6) the method used to capture parameter uncertainty. As a result, the key factors determining the performance measures fall within the categories of process error (#5), implementation uncertainty (#4), and model uncertainty (#s 1, 2, 3 and 6). Observation error does not turn out to be a major source of uncertainty, although some authors consider uncertainty about fishing power a source of observation error (e.g. Punt and Butterworth 1999). The following sections explore the impact of each of these six factors using a balanced set of simulation trials. Factorial experimental designs are rarely used in simulation studies, but see also Kell et al. 1999).

6.4.b.(xvii) Fishing power

There is considerable uncertainty regarding the extent to which fishing power in the NPF has changed over time (Wang and Die, 1996; Haddon, 1997, 2000; Dichmont et al.,

2003b). Furthermore, assumptions regarding changes over time in fishing power can have substantial impacts on the results of stock assessments of tiger prawns (Dichmont et al., 2001, 2003a). It is therefore not surprising that the performance measures from the MSE are also very sensitive to which of the two fishing power series considered (BCH and BCL) is correct.

Table 6.4(a) explores the effects of assumptions regarding changes over time in fishing power on the performance measures for two management strategies and two operating models based on the “Deriso” management strategy and the Base Case operating model:

- “D – BC” – both the operating model and the management strategy are based on BCH;
- “D – L_op L_ms” – both the operating model and the management strategy are based on BCL;
- “D – H-q_op L-q_ms” – the operating model is based on BCH and the management strategy on BCL; and
- “D – L-q_op H-q_ms” – the operating model is based on BCL and the management strategy on BCH.

Table 6.4: Settings and performance measures (medians with 90% intervals in parenthesis). PS is *P. semisulcatus*, PE is *P. esculentus*. “¹” includes a Decision Error CV of 15%, “²” includes a Decision Error CV of 30%, and “³” includes spatially correlated recruitment.

Acronym	Operating model	Management strategy	P _{S2010} > S _{msy}		S ₂₀₁₀ /S _{msy} PS (%)	S ₂₀₁₀ /S _{msy} PE (%)	Total discounted catch ('000 t)	AAV	C _{low} (‘000 t)
			PS	PE					
	Fishing power, Catchability	Fishing power, Catchability							
(a) Varying the fishing power in the operating model and the assessment									
D – BC	H, q	H, q	0.67	0.16	99.9 (78.8 - 127.6)	79.8 (58.1 - 104.4)	25.5 (22.8 – 28.7)	12.9 (9.2 - 18.3)	1.9 (1.7 – 2.3)
D – L_op L_ms	L, q	L, q	0.82	0.30	109.6 (87.1 - 136.6)	87.2 (64.1 - 112.2)	27.2 (24.2 – 30.7)	15.2 (11.1 - 20.3)	1.9 (1.6 – 2.3)
D – H-q_op L-q_ms	H, q	L, q	0.14	0.20	82.3 (65.3 - 107.7)	63.4 (44.5 - 87.8)	26.0 (23.1 – 29.4)	16.1 (12.1 - 22.2)	1.9 (1.6 – 2.2)
D – L-q_op H-q_ms	L, q	H, q	0.99	0.62	126.6 (102.4 - 158.3)	104.5 (79.6 - 132)	25.1 (22.2 – 28.2)	13.1 (8.8 - 17.8)	1.9 (1.7 – 2.2)
(b) Varying the catchability coefficient in the operating model and the assessment									
D – BC	H, q	H, q	0.67	0.16	99.9 (78.8 - 127.6)	79.8 (58.1 - 104.4)	25.5 (22.8 – 28.7)	12.9 (9.2 - 18.3)	1.9 (1.7 – 2.3)
D – 2q_op 2q_ms	H, 2q	H, 2q	0.83	0.17	108.8 (87.4 - 136.6)	82.5 (60.6 - 109.8)	25.4 (22.6 – 28.3)	12.2 (7.9 - 17.3)	2.0 (1.7 – 2.3)
D – 2q_ms	H, q	H, 2q	0.69	0.23	102.2 (81.0 - 130.7)	84.7 (62.1 - 108.5)	25.3 (22.8 – 28.5)	12.6 (8.1 – 17.0)	1.9 (1.7 – 2.3)
D – 2q_op	H, 2q	H, q	0.78	0.11	106.3 (85.2 - 132.9)	79.0 (57.8 - 105.1)	25.4 (22.6 – 28.3)	12.7 (8.6 - 17.1)	2.0 (1.6 – 2.3)
(c) The biomass dynamic model (“B”) and cpue regression method (“C”) management strategies.									
B – BC	H, q	n/a, n/a	0.68	0.20	102.7 (80.6 - 128.2)	82.4 (56.6 - 105.8)	24.9 (22.4 – 27.5)	17.3 (11.2 - 43.7)	1.9 (0.8 – 2.2)
B – 2q_op	H, 2q	n/a, n/a	0.89	0.36	112.8 (93.6 - 141.4)	89.8 (63.5 - 116.2)	27.2 (24.8 – 29.3)	15.1 (9.5 - 23.4)	2.1 (1.6 – 2.4)
C – BC	H, q	n/a, n/a	0.92	0.47	115.5 (94.2 - 147.7)	94.6 (69.4 – 120.0)	24.1 (21.9 – 26.7)	10.4 (6.2 - 15.2)	1.9 (1.7 – 2.2)
C – 2q_op	H, 2q	n/a, n/a	0.97	0.57	121.3 (100.4 - 149.9)	98.8 (72.0 - 126.4)	26.8 (24.5 – 29.0)	9.9 (5.8 - 15.1)	2.3 (2.0 – 2.5)
(d) The extent of implementation error.									
D – BC	H, q	H, q	0.67	0.16	99.9 (78.8 - 127.6)	79.8 (58.1 - 104.4)	25.5 (22.8 – 28.7)	12.9 (9.2 - 18.3)	1.9 (1.7 – 2.3)
D – 15% DE ¹	H, q	H, q	0.44	0.15	92.3 (74.1 - 127.8)	76.9 (55.0 - 106.9)	25.2 (22.4 – 29.1)	16.7 (10.6 - 24.9)	1.8 (1.5 – 2.3)
D – 30% DE ²	H, q	H, q	0.44	0.14	92.9 (72.5 - 129.7)	77.5 (53.6 – 106.0)	25.0 (22.1 – 29.2)	24.9 (14.9 - 34.9)	1.6 (1.1 – 2.1)
(e) Spatial auto-correlation in recruitment success									
B – BC	H, q	n/a, n/a	0.68	0.20	102.7 (80.6 - 128.2)	82.4 (56.6 - 105.8)	24.9 (22.4 – 27.5)	17.3 (11.2 - 43.7)	1.9 (0.8 – 2.2)
B – with correlation ³	H, q	n/a, n/a	0.58	0.0	96.4 (89.9 - 99.2)	71.5 (63.0 - 76.7)	24.3 (23.0 – 25.1)	14 (10.7 - 44.4)	1.9 (0.4 – 2.1)
C – BC	H, q	n/a, n/a	0.92	0.47	115.5 (94.2 - 147.7)	94.6 (69.4 – 120.0)	24.1 (21.9 – 26.7)	10.4 (6.2 - 15.2)	1.9 (1.7 – 2.2)
C – with correlation ³	H, q	n/a, n/a	1.00	0.0	111.2 (108.0 - 114.1)	85.7 (81.3 - 90.1)	23.0 (22.0 – 24.0)	4.3 (2.8 - 6.4)	2.0 (1.7 – 2.1)
D – BC	H, q	H, q	0.67	0.16	99.9 (78.8 - 127.6)	79.8 (58.1 - 104.4)	25.5 (22.9 – 28.7)	12.9 (9.2 - 18.3)	1.9 (1.7 – 2.3)
D – with correlation ³	H, q	H, q	0.52	0.0	96.2 (92.3 - 99.4)	73.5 (70.2 – 78.0)	24.3 (23.2 – 25.1)	7.6 (5.8 - 10.2)	2.0 (1.8 – 2.2)

As expected, the largest effects occur when the fishing power series underlying the operating model differs from that underlying the management strategy. The spawning stock size is above S_{MSY} (substantially so for *P. semisulcatus*) when the management strategy is based on BCH, but “reality” is BCL (“D – L-q_op H-q_ms” in Table 6.4(a)) and is below S_{MSY} (substantially so for *P. esculentus*) when the management strategy is based on BCL, but “reality” is BCH (“D – H-q_op L-q_ms” in Table 6.4(a)). Somewhat surprisingly, the lowest catches and the total discounted catches for “D – H-q_op L-q_ms” and “D – L-q_op H-q_ms” are fairly similar, although this result should be interpreted with some caution because changing the fishing power scenario in the operating model also changes the current status and productivity of the “true” population..

The MSE can be used to explore the impact of assumptions regarding changes over time in fishing power on estimation ability. As expected, the estimates of key model outputs are relatively unbiased when the assessment is based on the correct fishing power scenario, but substantial biases occur when this is not the case. For example, the estimate of E_{MSY} is positively biased when the assessment is based on BCL, but reality is BCH and the estimates of steepness and E_{MSY} are negatively biased and those of S_{MSY} positively biased when the assessment is based on BCH, but reality is BCL. This suggests that estimation bias is a key reason for the differences in performance that occur when the assumed fishing power series differs from the true fishing power series.

6.4.b.(xviii) Catchability

The value assumed for the catchability coefficient during 1993, \tilde{q} , has a substantial influence on the results of the Deriso model-based assessment of tiger prawns in the NPF (Dichmont et al. 2003a). The estimate of \tilde{q} obtained by Wang (1999) may be negatively biased because its calculation is based on the assumption that there is no recruitment during October when, in fact, recruitment is expected to be increasing (Somers, 1990; Somers and Wang, 1997; Wang and Die, 1996). Current practice when developing scientific management advice is therefore to conduct assessments for the value of \tilde{q} obtained by Wang (1999) and twice this value (the “q” and “2q” scenarios).

Table 6.4(b) explores the effects of assumptions regarding \tilde{q} on the performance measures for two management strategies and two operating models based on the “Deriso” management strategy and the Base Case operating model:

- “D – BC” – both the operating model and the management strategy are based on “q”;
- “D – 2q_{op} 2q_{ms}” – both the operating model and the management strategy are based on “2q”;
- “D – 2q_{ms}” – the operating model is based on “q” and the management strategy on “2q”; and
- “D – 2q_{op}” – the operating model is based on “2q” and the management strategy on “q”.

The management-related performance measures are less sensitive to assumptions regarding \tilde{q} than to assumptions regarding fishing power. Also, these performance measures are more sensitive to assumptions regarding how \tilde{q} is treated in the assessment than to how it is treated in the operating model. How \tilde{q} is treated in the assessment also impacts estimation ability. For example, and as expected, the estimates are more conservative when the assessment procedure is based on “2q” rather than on “q”.

6.4.b.(xix) Biomass dynamic and cpue regression

In contrast to the management strategies based on the Deriso model, the management strategies based on the biomass dynamic model and on the cpue regression approach are sensitive (the latter less so) to the true value of \tilde{q} in the operating model (Table 6.4(c)). Catchability is estimated within the assessment based on the biomass dynamic model. However, the estimate is about an order of a magnitude smaller than the true value, and there is no large increase in the estimate of catchability from the biomass dynamic model when catchability in the operating model is “2q”. Therefore, although it would be ideal to estimate catchability within the assessment, there seems little ability to do so given the available data.

6.4.b.(xx) Fishing power and catchability

This section explores the impact of the interaction between the value for \tilde{q} and the fishing power series in the operating model and the value for \tilde{q} and the fishing power series in the assessment. An investigation of all sixteen possible combinations of these two factors is undertaken for management strategies based on the Deriso model.

The effectiveness of a management strategy at leaving the spawning stock size at (or above) S_{MSY} is influenced substantially by the combination of catchability and fishing power selected when conducting the assessment and how this relates to catchability and fishing power assumed in the operating model. There are trade-offs between the size of the spawning stock size for each species and the discounted catch taken from the fishery. An efficient way of illustrating these trade-offs, given the number of possible combinations, is to plot the median S_{2010}/S_{MSY} (%) against the median discounted catch for each management strategy (Figure 6.2). Results are grouped by operating model in Figure 6.2.

It should be noted that the results in Figure 6.2 range from the assessment model being based on the correct assumptions about catchability and fishing power to it being based on completely incorrect assumptions. The ideal management strategy would perform best for all of the operating models.

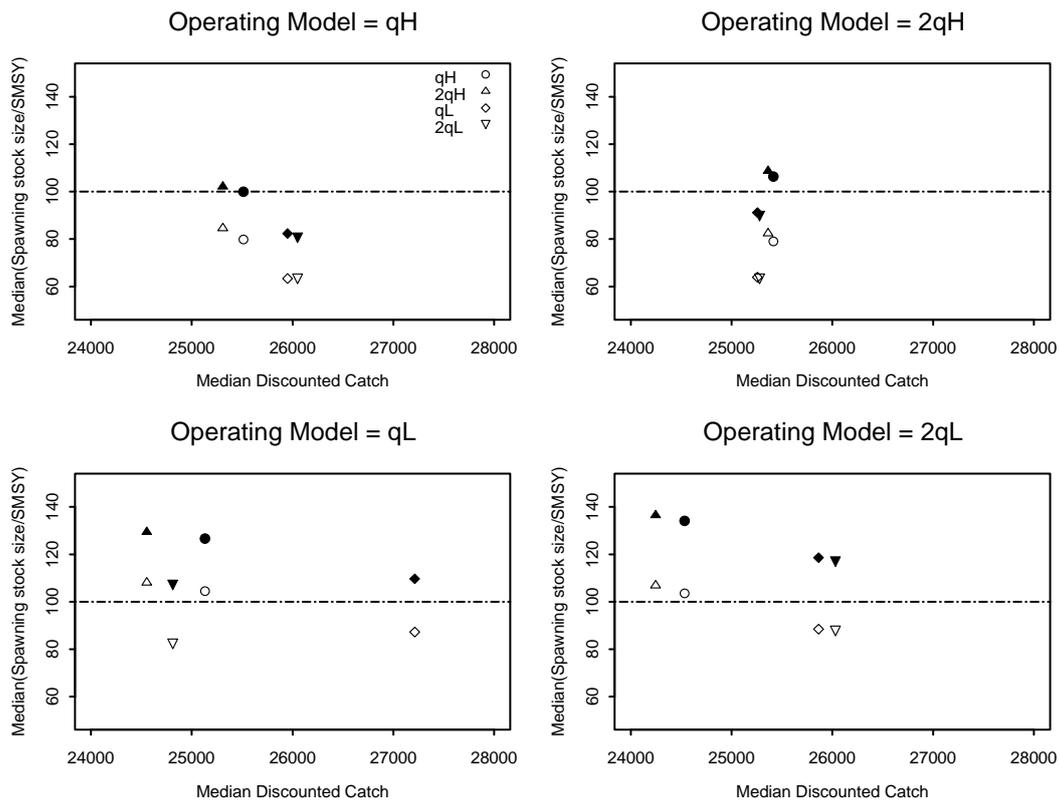


Figure 6.2: Median values for S_{2010}/S_{MSY} versus median discounted catches for four management strategies based on the Deriso model-based assessment procedure for each of four operating models. The specifications for the operating models / management strategies depend on the value for \tilde{q} (“q” and “2q”) and the fishing power series (Base Case High – “H” and Base Case Low – “L”). The results for *P. semisulcatus* are indicated by the solid symbols and those for *P. esculentus* by the open symbols.

A few general patterns emerge (Figure 6.2):

1. there is a trade-off between the status of the resource in 2010 and the total catch; this trade-off is most obvious for the “2qL”, “qL” and “qH” operating models;
2. basing the assessment model on a catchability value of “2q” and the “Base Case High” fishing power series (triangles in Figure 6.2) leads to the most conservative performance in terms of S_{2010}/S_{MSY} , irrespective of the settings in the operating model; and
3. the “2qH” and “qH” management strategies (triangles and circles in Figure 6.2) are the “best” options in terms of trade-offs for the operating model “2qH” - they lead to higher median discounted catches and higher spawning stock sizes in 2010 than the “qL” or “2qL” management strategies (i.e. these latter two management strategies are “dominated” by the “2qH” management strategy for this operating model).

Given that all of the management strategies that were based on the Deriso assessment procedure tend to leave the spawning stock size of *P. esculentus* below the target level of S_{MSY} in median terms, it would appear to be more precautionary to select conservative assessment model settings until a management strategy is developed that is better able to leave the spawning stock size of *P. esculentus* above S_{MSY} . Assuming the Base Case High fishing power series when conducting assessments leads to a higher probability of leaving the spawning stock size at (or above) S_{MSY} for both tiger prawn species (Figure 6.2). Of the management strategies based on the “Base Case High” fishing power series, that based on setting \tilde{q} to “q” is more conservative than that based on setting \tilde{q} to “2q”, although the difference is slight, at least compared to the impact of the choice of the fishing power series.

Figure 6.3 explores estimation performance for the four management strategies by plotting the median relative errors of the estimates of S_{2005}/S_{MSY} against those of S_{MSY} . Setting \tilde{q} to “q” and assuming the Base Case High fishing power series (circles in Figure 6.3) leads to the highest estimates of S_{MSY} while setting \tilde{q} to “2q” and assuming the Base Case Low fishing power series (downward triangles in Figure 6.3) leads to the lowest estimates of S_{MSY} . In contrast, the most positively biased estimates of S_{2005}/S_{MSY} occur when the Base Case Low fishing power series is assumed when conducting the assessment while assuming the Base Case High fishing power series when conducting assessments leads to the most negatively biased estimates of S_{2005}/S_{MSY} .

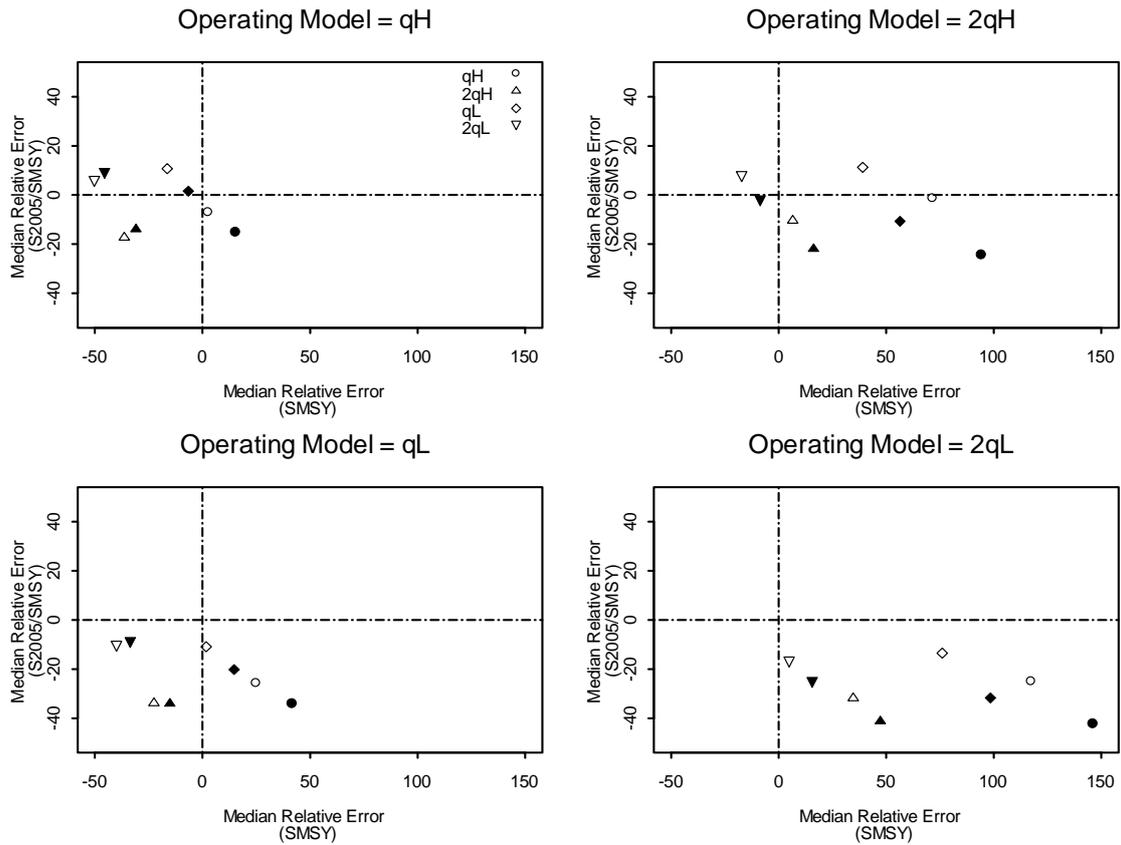


Figure 6.3: Median relative errors for S_{2005}/S_{MSY} and S_{MSY} when the Deriso model-based assessment procedure is applied in 2010. Results are shown for four variants of the assessment procedure and for four operating models. The specifications for the operating models / management strategies depend on the value for \tilde{q} (“q” and “2q”) and the fishing power series (Base Case High – “H” and Base Case Low – “L”). The results for *P. semisulcatus* are indicated by the solid symbols and those for *P. esculentus* by the open symbols.

6.4.b.(xxi) Implementation error

Implementation error relates to the difference between the actual fishing effort expended in the fishery and that intended from the outcomes of the management strategy (Dichmont et al., 2006a). Dichmont et al. (2006a) estimate that the coefficient of variation of the amount of implementation error in the NPF tiger prawn fishery is 18% on average, but it could be as high as 30% in some years. Note that implementation error is assumed to relate only to the total amount of fishing effort, because it is assumed that VMS makes it possible to ensure that the length of the season (including the mid-season closure) is implemented exactly.

Table 6.4(d) contrasts the values for the management-related performance measures from management strategies based on the Deriso model assessment procedure with three scenarios regarding the extent of implementation error (0, 15% and 30%). There is relatively

little impact of different levels of implementation error on the management-related performance measures based on S_{2010}/S_{MSY} and total discounted catch (Table 6.4(d)). In contrast, implementation error has a marked impact on the values for some of the economic-related performance measures. Specifically, larger amounts of implementation error lead to higher inter-annual variation in catches (AAV), and a lower lowest catch (C_{low}). These results are perhaps not unexpected because there is no “bias” caused by implementation error; rather the average fishing effort level will be imposed as anticipated, but with larger inter-annual variation for larger amounts of implementation error.

6.4.b.(xxii) Spatial correlation in recruitment among stocks

The Base Case operating model only includes within-stock temporal (i.e. inter-annual) correlation in recruitment (Dichmont et al., 2006a). This implies that each stock acts totally independently of all other stocks, and that recruitment during a year is only affected by the previous year’s spawning stock size and the environment within the area in which the stock is found. However, it is possible that a (currently unidentified) environmental variable affects recruitment success over a much larger area than a single stock area. The extent of inter-stock correlation in the deviations about the stock-recruitment relationship was estimated based on the fit of the operating model to the data, and this was then used when generating future recruitment. This approach to allowing for spatial correlation in recruitment assumes that the environmental variable(s) that affected the spatial correlation in recruitment in the past will do so in the future.

The probability of being above S_{MSY} for both tiger prawn species is reduced when allowance is made for spatial correlation in recruitment (Table 6.4(e)). The estimation performance of the Deriso model assessment procedure is not affected substantially by allowing for spatial correlation in recruitment. However, unlike the case for the Base Case operating model, there is evidence for positive bias in the estimates of S_y/S_{MSY} for *P. esculentus* from 2006 when there is spatial correlation in recruitment.

Studies of the effects of environmental factors such as temperature and rainfall on recruitment have been undertaken over decades with mixed success (e.g. Francis et al., 1989; Sparholt, 1996). In this study, the mechanism that impacts recruitment over large spatial scales is not known, but rather the environment is included as a generic inter-annual auto-correlation matrix based on that observed in the available data. Many studies consider that

robust management strategies should be developed in spite of this source of uncertainty (e.g. Walters and Collie, 1989) rather than place emphasis on detailed studies of direct statistical correlations and mechanisms (e.g. Parker, 1989; Laevastu, 1992; Ulltang, 1996).

6.5 General discussion

It is clear that, for the management strategies based on the Deriso model-based assessment procedure, how the 1993 catchability coefficient is determined and fishing power values chosen are important factors that influence the ability to satisfy the management objectives. Not unexpectedly, the target spawning stock size used in the decision rule is also important; problems with the MSE system would have been flagged if this was not the case. It is perhaps surprising that whether recruitment is correlated spatially or not had an important impact on the results. This implies that any future work on stock boundaries and stock-specific assessments should consider this issue and attempt should perhaps be made to gain some understanding of the underlying mechanisms.

The ideal when managing a fishery is to apply an unbiased and precise stock assessment method and to implement a management system that achieves the management objectives. However, if this ideal cannot be achieved, it is better to use a biased stock assessment procedure with a management system that achieves the management objectives, rather than an unbiased stock assessment procedure and a management system that does not. Finally, given that the management strategies based on the Deriso assessment procedure tend to leave the spawning stock size of *P. esculentus* below the target level of S_{MSY} in median terms, a case could be made for choosing one of the more conservative management strategies, at least until a management strategy is identified that performs better for *P. esculentus*.

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6.7 References

- Butterworth, D.S., Cochrane, K.L., De Oliveira, J.A.A., 1997. Management procedures: A better way to manage fisheries? The South African experience. In: Pikitch, E.K., Huppert, D.D., Sissenwine, M.P., Duke, M. (Eds), Global trends: fisheries management. Am. Fish. Soc. Symp. 20, 83–90.
- Campbell, R., Dowling, N., 2003. Development of an operating model and evaluation of harvest strategies for the Eastern Tuna and Billfish Fishery CSIRO, Hobart, Tasmania (Australia). vp.
- De la Mare, W.K., 1996. Some recent developments in the management of marine living resources. In: Floyd, R.B., Shepherd, A.W., De Barro, P.J. (Eds), Frontiers of Population Ecology. CSIRO Publishing, Melbourne, Australia, pp. 599–616.
- Dichmont, C.M., Punt, A.E., Deng, A., Venables, W., 2003a. Application of a weekly delay-difference model to commercial catch and effort data for tiger prawns in Australia's Northern Prawn Fishery. Fish. Res. 65, 335-350.
- Dichmont, C.M., Bishop, J., Venables, W.N., Sterling, D., Rawlinson, N., Eayrs, S., 2003b. A new approach to fishing power analyses and its application in the Northern Prawn Fishery. AFMA Research Fund R99/1494. 700pp.
- Dichmont, C.M., Deng, A., Punt, A.E., Venables, W.V., Haddon, M., 2006a. Management Strategies for short lived species: the case of Australia's Northern Prawn Fishery. 1. Accounting for multiple species, spatial structure and implementation uncertainty when evaluating risk. Fish. Res. in prep.
- Dichmont, C.M., Deng, A., Punt, A.E., Venables, W.V., Haddon, M., 2006b. Management Strategies for short lived species: the case of Australia's Northern Prawn Fishery. 2. Choosing appropriate management strategies using input controls. Fish. Res. in prep.
- Francis, R.C., Adlerstein, S.A., Hollowed, A., 1989. Importance of environmental fluctuations in the management of Pacific hake (*Merluccius productus*). International Recruitment Investigations in the Subarctic (IRIS) and International North Pacific Fisheries Commission (INPFC) Symposium, Vancouver, B.C. (Canada), 26 Oct 1987, Can. Spec. Publ. Fish. Aquat. Sci.
- Francis, R.I.C.C., Shotton, R., 1997. 'Risk' in fisheries management: A review. Can. J. Fish. Aquat. Sci. 54, 1699-1715.

- Haddon, M., 1997. A biomass-dynamic model of the Northern Tiger Prawn Fishery: an alternative estimation of potential yields. NPFAG Working paper 97/1. 28pp.
- Haddon, M., 2001. Modeling and Quantitative Methods in Fisheries. Chapman & Hall/CRC Press. 406pp.
- L. T. Kell, C. M. O'Brien, M. T. Smith, T. K. Stokes, and B. D. Rackham., 1999. An evaluation of management procedures for implementing a precautionary approach in the ICES context for North Sea plaice (*Pleuronectes platessa* L.). ICES J. Mar. Sci. 56, 834–845.
- Laevastu, T., 1992. Interactions of size-selective fishing with variations in growth rates and effects on fish stocks. ICES, Copenhagen (Denmark).
- Parker, K.S., 1989. Influence of oceanographic and meteorological processes on the recruitment of Pacific halibut, *Hippoglossus stenolepis*, in the Gulf of Alaska. International Recruitment Investigations in the Subarctic (IRIS) and International North Pacific Fisheries Commission (INPFC) Symposium, Vancouver, B.C. (Canada), 26 Oct 1987, Can. Spec. Publ. Fish. Aquat. Sci.
- Polacheck, T., Klaer, N.L., Millar, C., Preece, A.L., 1999. An initial evaluation of management strategies for the southern bluefin tuna. ICES J. Mar. Sci. 56, 811-826.
- Punt, A.E., 1992. Selecting management methodologies for marine resources, with an illustration for southern African hake. S. Afr. J. Mar. Sci. 12, 943–958.
- Punt, A.E., Smith, A.D.M., 1999. Harvest strategy evaluation for the eastern gemfish (*Rexea solandri*). ICES J. Mar. Sci. 56, 860–875.
- Punt, A.E., Campbell, R.A., Smith, A.D.M., 2001a. Evaluating empirical indicators and reference points for fisheries management: application to the broadbill swordfish fishery off eastern Australia. Mar. Freshwater Res. 52, 819-832.
- Punt, A.E., Cui, G., Smith, A.D.M., 2001b. Defining robust harvest strategies, performance indicators and monitoring strategies for the SEF. Fisheries Research and Development Corporation 98/102, 170 pp.
- Punt, A.E., Walker, T.I., Prince, J.D., 2002a. Assessing the management-related benefits of fixed station fishery-independent surveys in Australia's southern shark fishery. Fish. Res. 55, 281-295.

- Punt, A.E., Smith, A.D.M., Cui, G., 2002b. Evaluation of management tools for Australia's South East Fishery 2. How well can management quantities be estimated? *Mar. Freshwater Res.* 53, 631-644.
- Punt, A.E., Smith, A.D.M., Cui, G., 2002c. Evaluation of management tools for Australia's South East Fishery 3. Towards selecting appropriate harvest strategies. *Mar. Freshwater Res.* 53, 631-644.
- Smith, A.D.M, Sainsbury, K.J., Stevens, R.A., 1999. Implementing effective fisheries management systems – management strategy evaluation and the Australian partnership approach. *ICES J. Mar. Sci.* 56, 967-979.
- Somers, I.F., 1990. Manipulation of fishing effort in Australia's penaeid prawn fisheries. *Aust. J. Mar. Freshw. Res.* 41, 1–12.
- Somers, I., Wang, Y., 1997. A simulation model for evaluating seasonal closures in Australia's multispecies Northern Prawn Fishery. *N. Am. J. Fish. Manage.* 17, 114–130.
- Sparholt, H., 1996. Causal correlation between recruitment and spawning stock size of central Baltic cod? *ICES J. Mar. Sci.* 53, 771-779.
- Ulltang, Ø., 1996. Stock assessment and biological knowledge: can prediction uncertainty be reduced. *ICES J. Mar. Sci.* 53, 659-675.
- Wang, Y-G., 1999. A Maximum-likelihood method for estimating natural mortality and catchability coefficient from catch-and-effort data. *Mar. Freshwater Res.* 50, 307-311.
- Wang, Y-G, Die, D., 1996. Stock-recruitment relationships of the tiger prawns (*Penaeus esculentus* and *Penaeus semisulcatus*) in the Australian Northern Prawn Fishery. *Mar. Freshw. Res.* 47, 87–95.
- Walters, C.J., Collie, J.S., 1989. An experimental strategy for groundfish management in the face of large uncertainty about stock size and production. International Recruitment Investigations in the Subarctic (IRIS) and International North Pacific Fisheries Commission (INPFC) Symposium, Vancouver, B.C. (Canada), 26 Oct 1987, *Can. Spec. Publ. Fish. Aquat. Sci.*, 26 pp.

6.8 Appendix C: additional scenarios tested

The below scenarios are not included in the paper, but are useful to include for completeness. Model settings of the scenario acronyms mentioned in this appendix are given in Table App.C.2.

6.8.a Method of capturing parameter uncertainty

Uncertainty about the true values for the parameters of the operating model needs to be accounted for when conducting a Management Strategy Evaluation. Two alternative methods have been used in this study to generate the parameter vectors on which the projections are based: a) generated using the variance-covariance matrix obtained by inverting the Hessian matrix² corresponding to the minimum of the negative log-likelihood function, and b) generated from a numerical approximation to the Bayesian posterior distribution that arises when uniform priors are assigned to the logarithms of the annual recruitments.

Figures App.C.1 to App.C.4 below contrast the distributions for the recruitment parameters for 1970, 1980, 1990 and 2000 for each of the eight stocks included in the operating model with the same parameter settings as described in Chapter 4 from the two methods of parameter vector generation. There is generally little difference between the distributions based on the variance-covariance matrix and those from the Bayesian method, with most distributions being approximately normal, though the distributions from the Bayesian method deviate more often from normal. Where there are differences, they relate to the early years of the assessment period (e.g. 1970) and to years for which recruitment was low. For example, the posterior distribution for the logarithm of the 1970 recruitment for *P. semisulcatus* in the “Outside GOC” stock area (see the upper left panel of Figure App.C.1) is more skewed and has a larger variance than the distribution for the logarithm of this recruitment obtained from the variance-covariance matrix.

It would not be expected that the approach used to generate the parameter sets would have a marked impact on the management-related performance measures and the estimation per-

² The Hessian matrix is the matrix of second derivatives of a multivariate function. That is, the gradient of the gradient of the function.

formance of stock assessment methods and this is borne out by the results in Figure App.C.5 (management-related performance measures) and Figure App.C.6 (estimation-related performance measures). There are, however, some differences, such as that the lowest catches and the total discounted catches tend to be slightly lower when the parameters for the operating model are based on the samples from the Bayesian posterior.

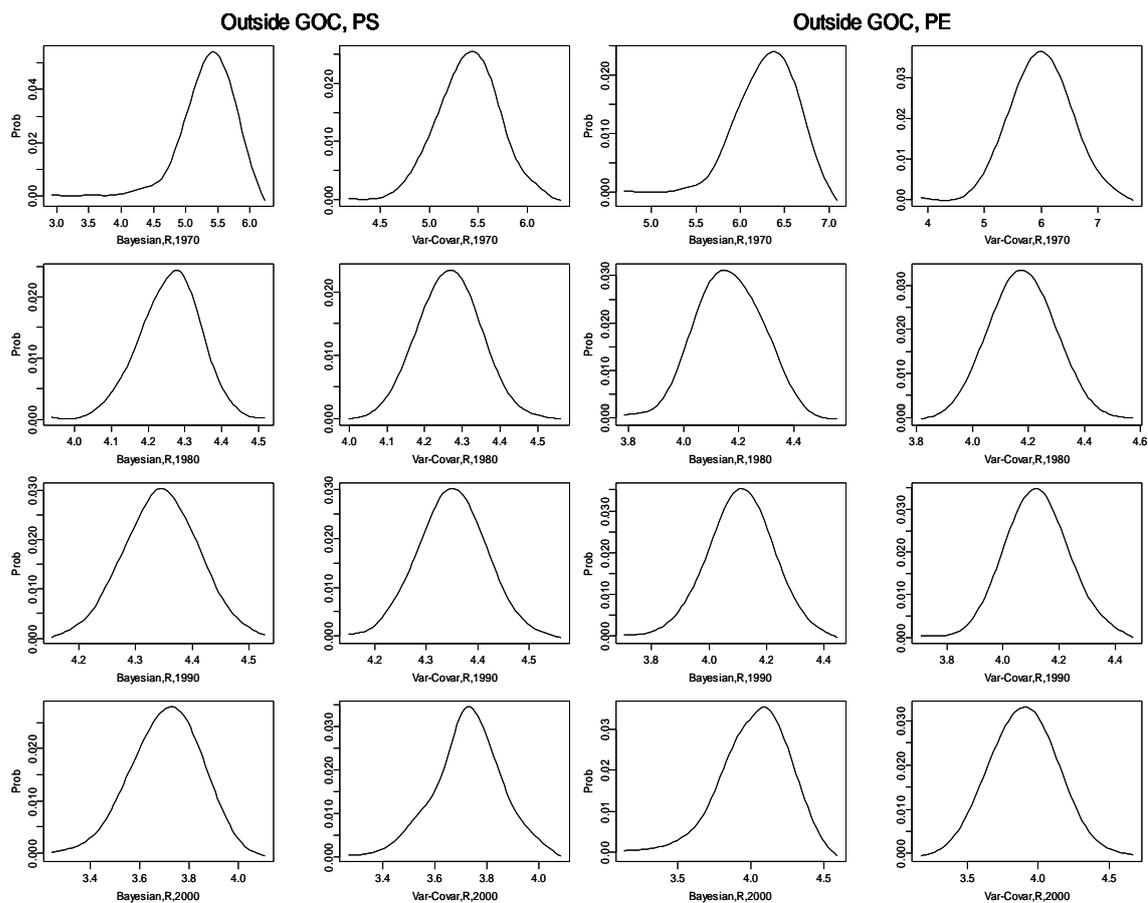


Figure App.C.1: Probability distributions for the estimates of recruitment for 1970, 1980, 1990 and 2000 for the “Outside Gulf” stock area based on the variance-covariance matrix and the Bayesian posterior. “PS” is *P. semisulcatus* and “PE” is *P. esculentus*.

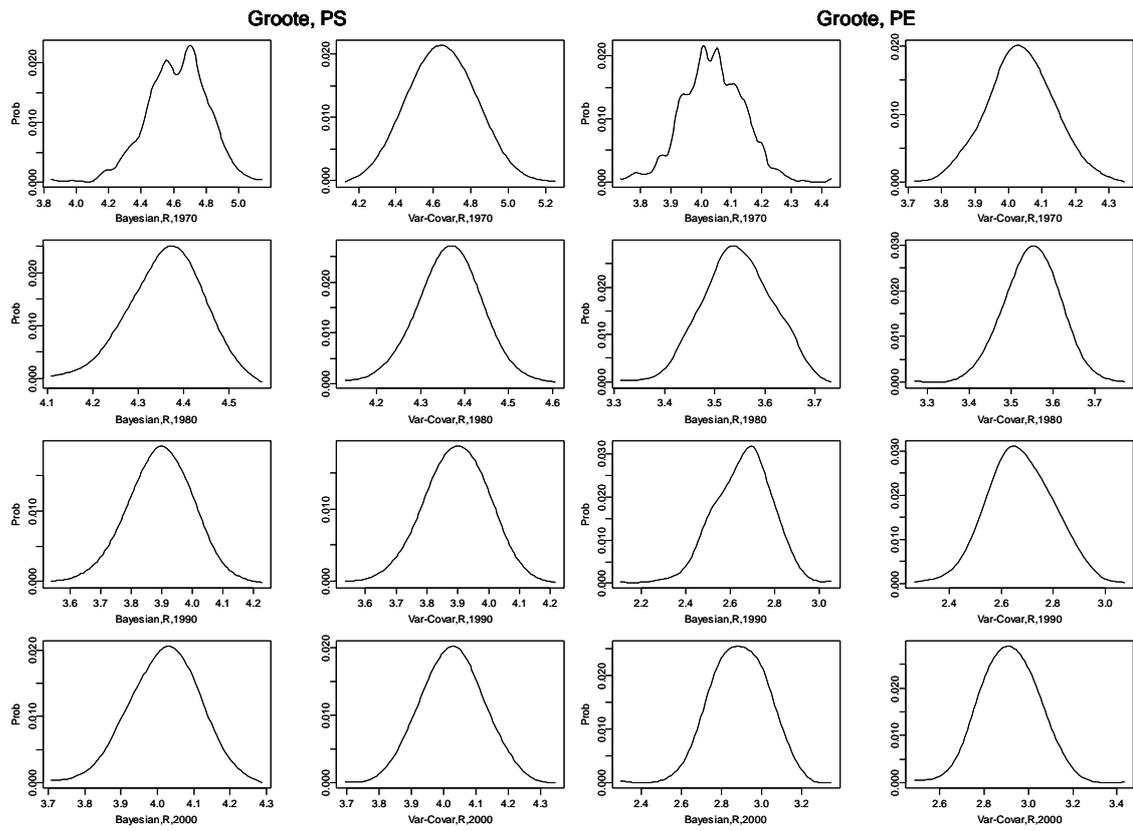


Figure App.C.2: Probability distributions for the estimates of recruitment for 1970, 1980, 1990 and 2000 for the Groote stock area based on the variance-covariance matrix and the Bayesian posterior. “PS” is *P. semisulcatus* and “PE” is *P. esculentus*.

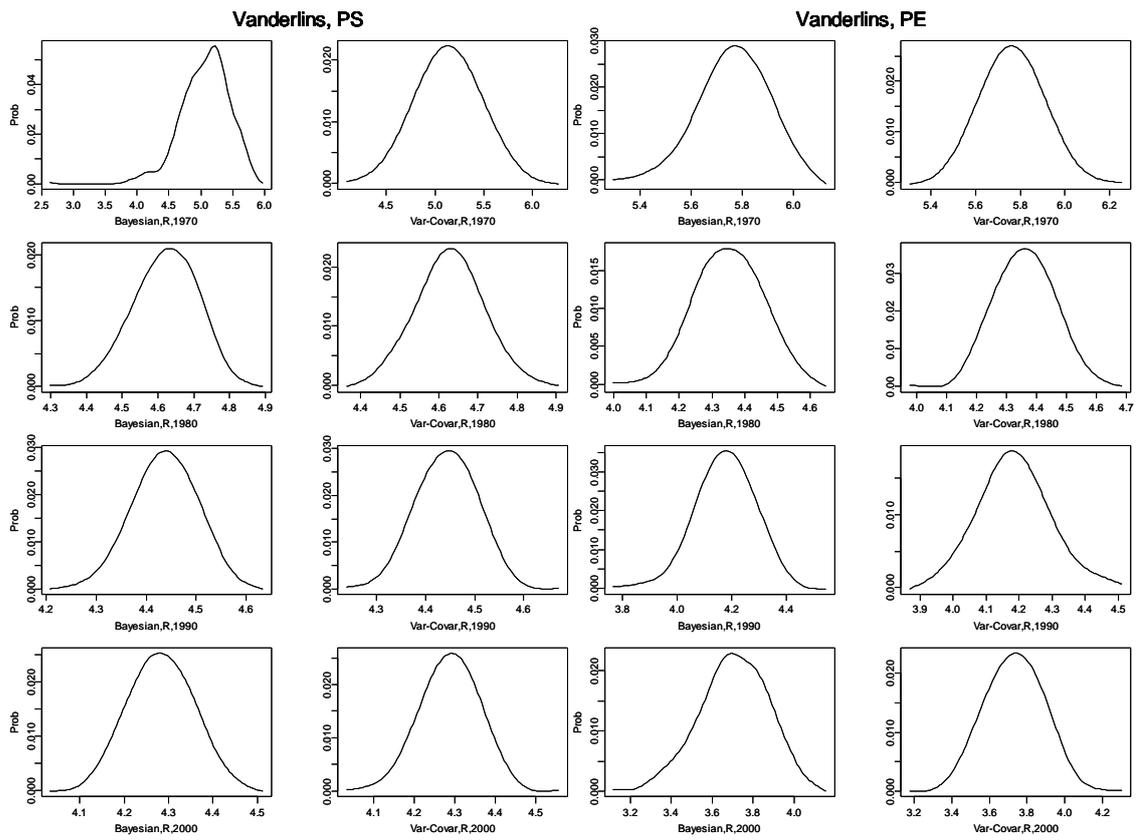


Figure App.C.3: Probability distributions for the estimates of recruitment for 1970, 1980, 1990 and 2000 for the Vanderlins stock area based on the variance-covariance matrix and the Bayesian posterior. “PS” is *P. semisulcatus* and “PE” is *P. esculentus*.

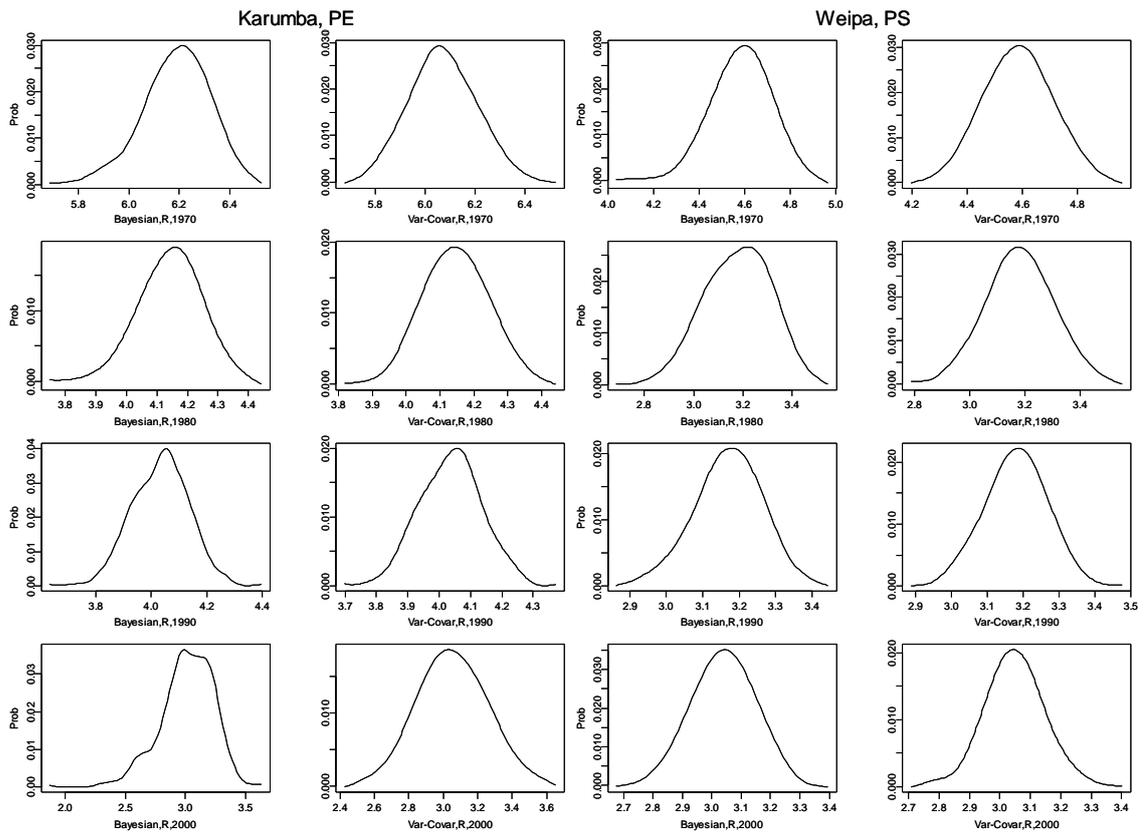


Figure App.C.4: Probability distributions for the estimates of recruitment for 1970, 1980, 1990 and 2000 for the Karumba stock area (*P. esculentus*) and the Weipa stock area (*P. semisulcatus*) based on the variance-covariance matrix and the Bayesian posterior. “PS” is *P. semisulcatus* and “PE” is *P.esculentus*.

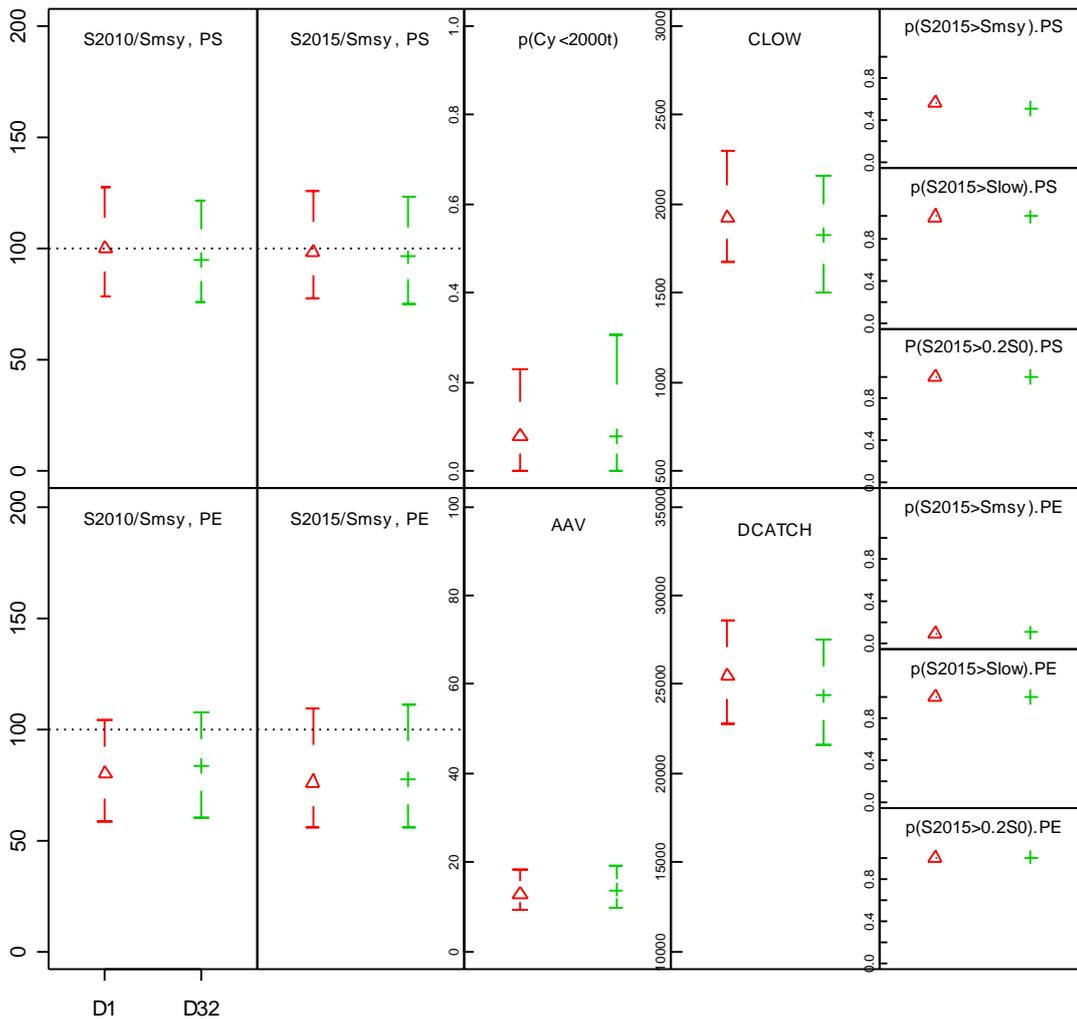


Figure App.C.5: Comparison of the management-related performance of the Deriso model-based management strategy for two variants of the Base Case operating model: D1 – parameters sets generated from the variance-covariance matrix; D32 – parameter sets generated from a Bayesian posterior distribution.

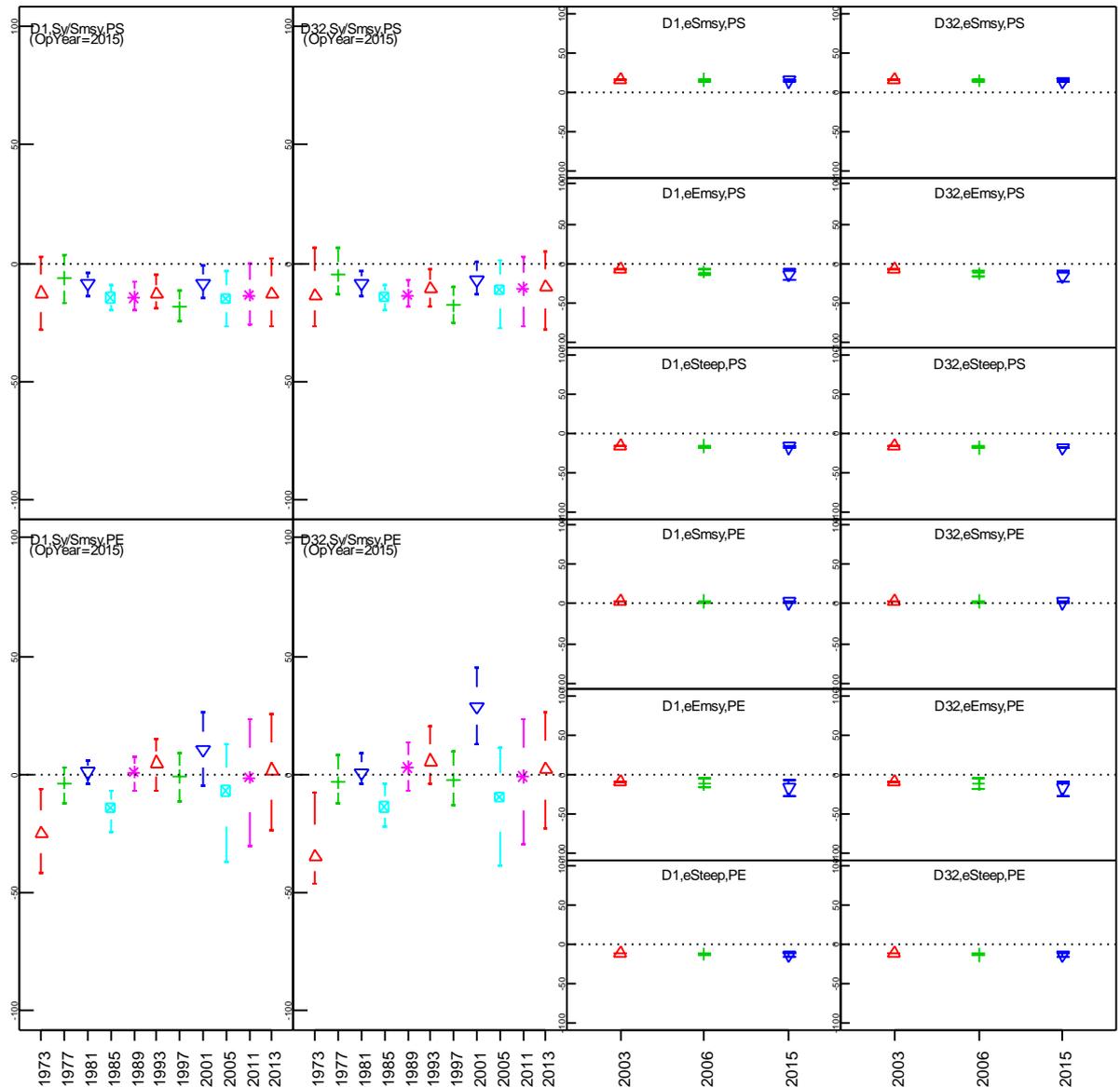


Figure App.C.6: Sensitivity of the relative error (%) distributions for the Deriso assessment method to whether the parameter sets are generated from the variance-covariance matrix (D1) or from a Bayesian posterior (D32). OpYear is the year in which the assessment took place. The years on the x-axis for S_Y/S_{MSY} relate to the assessment year, i.e. “D1 S_Y/S_{MSY} (OpYear=2015)” is the relative error of $S_{(1974,1984,1994,2004)}/S_{MSY}$ as determined by an assessment conducted in 2015 for case D1. eSteep, eEmy and eSmY are respectively the relative errors associated the estimates of the steepness parameter, E_{MSY} and S_{MSY} .

6.8.b Observation error

Bishop *et al.* (2000) and Dichmont *et al.* (2001) have shown that the coefficient of variation of the method used to derive the catch and effort data by species as well as the impact of augmenting the database in the years where the logbook data are incomplete is ap-

proximately 10%. Adding observation error with a coefficient of variation of 10% to the catch data has almost no impact on the management-related performance measures (Figure App.C.7) while it results in a slight decrease in the estimates from the Deriso stock assessment method (Figure App.C.8).

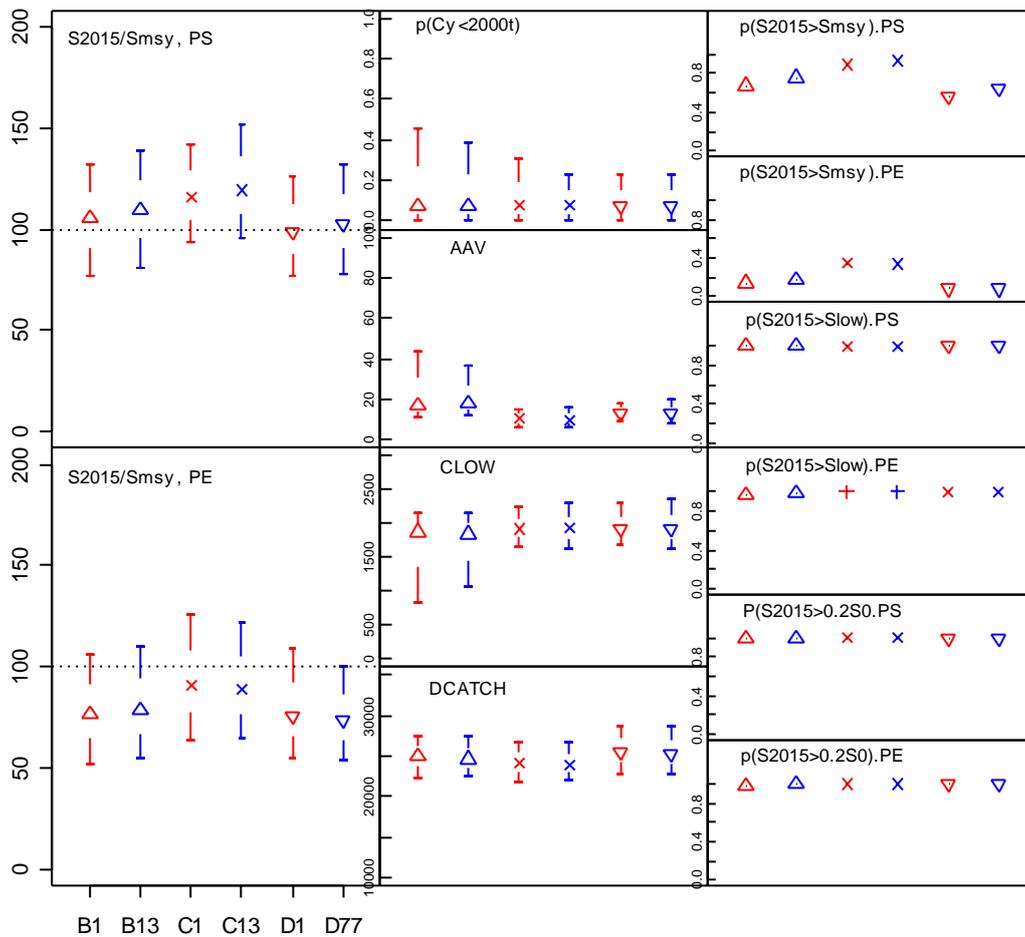


Figure App.C.7: Management-related performance measures for management strategies based on the biomass dynamic model (prefix “B”), the cpue regression approach (prefix “C”) and the Deriso model (prefix “D”) when the operating model includes (cases B13, C13 and D77) and ignores (case B1, C1 and D1) observation error on the catch data with a coefficient of variation of 10%.

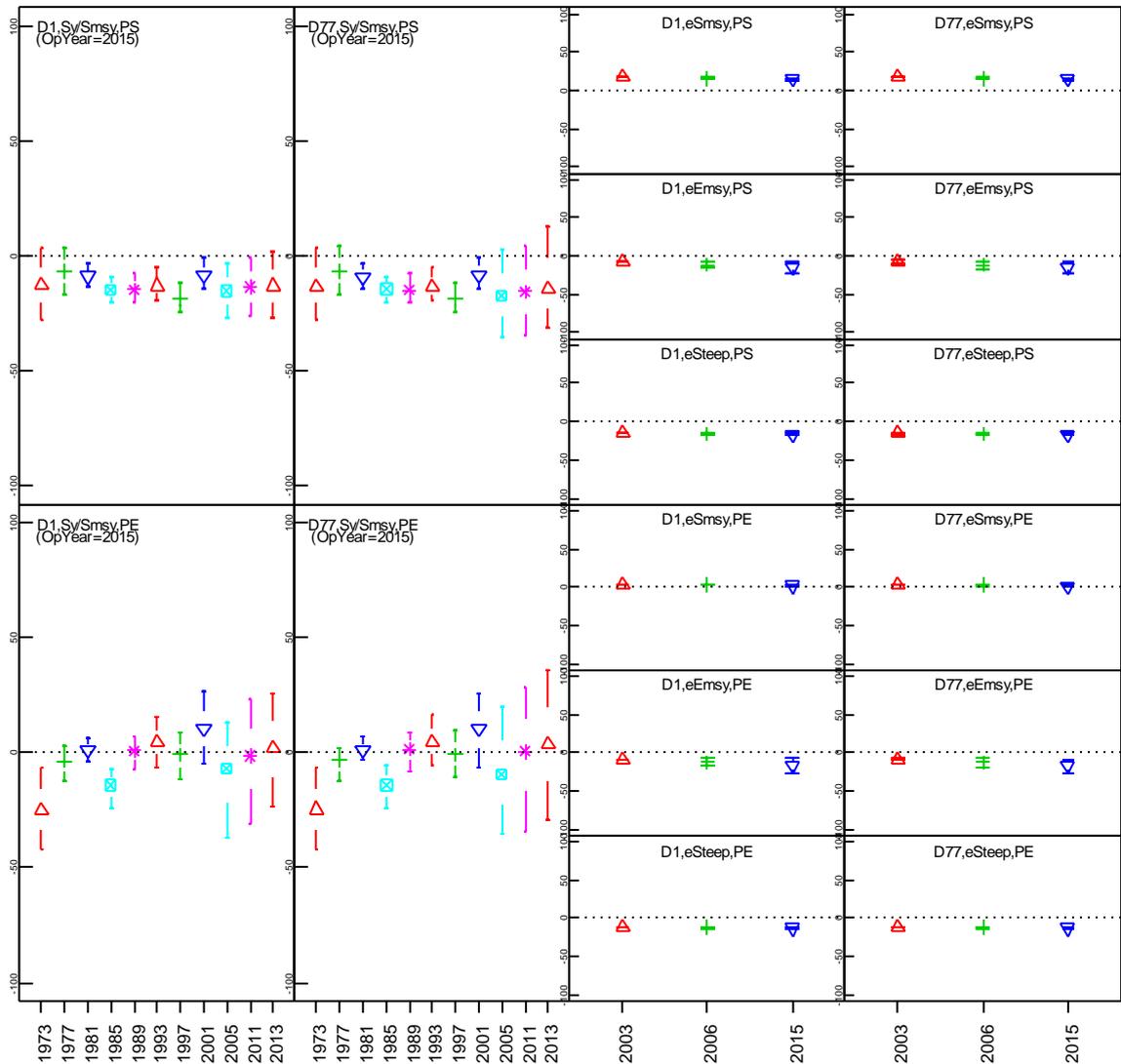


Figure App.C.8: Sensitivity of the relative error (%) distributions for the Deriso assessment method to whether (case D77) or not (case D1) observation error with a coefficient of variation of 10% is added to the catch data used for assessment purposes. OpYear is the year in which the assessment took place. The years on the x-axis for S_Y/S_{MSY} relate to the assessment year, i.e. “D1 S_Y/S_{MSY} (OpYear=2015)” is the relative error of $S_{(1973,1983,1993,2005)}/S_{MSY}$ as determined by an assessment conducted in 2015 for case D1. eSteep, eEmsy and eSmy are respectively the relative errors associated the estimates of the steepness parameter, E_{MSY} and S_{MSY} .

6.8.c Biomass dynamic model estimates

The estimates of the parameters of the biomass dynamic model imply a resource that is huge and very unproductive (Table App.C.). Furthermore, the parameter estimates vary substantially among simulations. This variation is reflected by the larger inter-simulation variation in the values for the economic-based performance measures associated with the

B1 management strategy. Since most of the parameter values and MSY-related reference points are defined very differently for the biomass dynamic model to how they are defined in the operating model (the absolute values of E_{MSY} and MSY are not really comparable between the operating model and the biomass dynamic model), only estimates of ratios, such as B_Y/B_{MSY} are usefully compared between the operating model and the biomass dynamic model.

Table App.C.1: Parameter estimates from the biomass dynamic model in 2010 when the data are generated by the operating model described in Chapter 4. q_{inc} is set at 1.05 until 2002 after which it is set to 1.0.

Parameter	Parameter name	5 th percentile	median	95 th percentile
r	Intrinsic growth rate	0.11	0.17	0.33
K	Carrying capacity (t)	34,797	49,439	62,390
B_0	Initial biomass (t)	47,168	80,742	137,843
p	Pella-Tomlinson shape parameter	0.18	0.40	0.70
q_0	Catchability (yr^{-1})	1.58E-06	2.62E-06	4.43E-06
MSY	Maximum Sustainable Yield (t)	2,219	2,606	3,128
B_{MSY}	Biomass corresponding to MSY (t)	16,285	21,100	25,500
E_{MSY}	Effort corresponding to MSY (days)	14,685	16,322	41,807
CurrB	Current Biomass (t)	11,846	17,132	25,563

6.8.d Increasing management responsiveness

The evaluation of the management strategies in the previous sections is based on the assumption that there is a one-in-three chance of a recommendation to change effort being implemented. The implications of this lack of responsiveness to scientific management recommendations is examined by contrasting the results for management strategies D1, C1 and B1 with these management strategies when the level of effort is changed each time the management strategy is applied (denoted as management strategies D38, C40 and B28). Note that fishing season remains the same for all years in the management strategies that used the cpue regression approach (C1 and C40) while the season length is changed each time the management strategy is applied for the two other management strategies.

The estimation performance of a stock assessment cannot be affected by whether a scientific management recommendation is adopted or not. Therefore, the focus of this section is on the values for the risk- and economic-related performance measures and the distribution

of effort across the year (Figure App.C.9 and Figure App.C.10). Apart from a reduced probability of the catch dropping below 2000t, there is no obvious impact of increased management responsiveness for the Deriso model-based management strategy. The spawning stock size in 2015 is lower with increased management responsiveness for the cpue regression-based management strategy (and discounted catch is larger). The impact of increased management responsiveness for the biomass dynamic-based management strategy is substantial, and initially surprising; the spawning stock size in 2015 is lower and the inter-simulation variability is much larger (Figure App.C.9). The latter occurs because the biomass dynamic model is fairly unstable so management recommendations can change substantially from one year to the next (the value of the AAV statistic is much larger for the management strategies based on biomass dynamic model than for the other management strategies). The variability of the biomass dynamic model is also reflected in the distribution of effort by week and year (Figure App.C.10) which changes fairly substantially when management responsiveness is increased. These results suggest that there would be a need for additional constraints to reduce variability in effort levels if the biomass dynamic model were to be used to provide scientific management advice for the NPF.

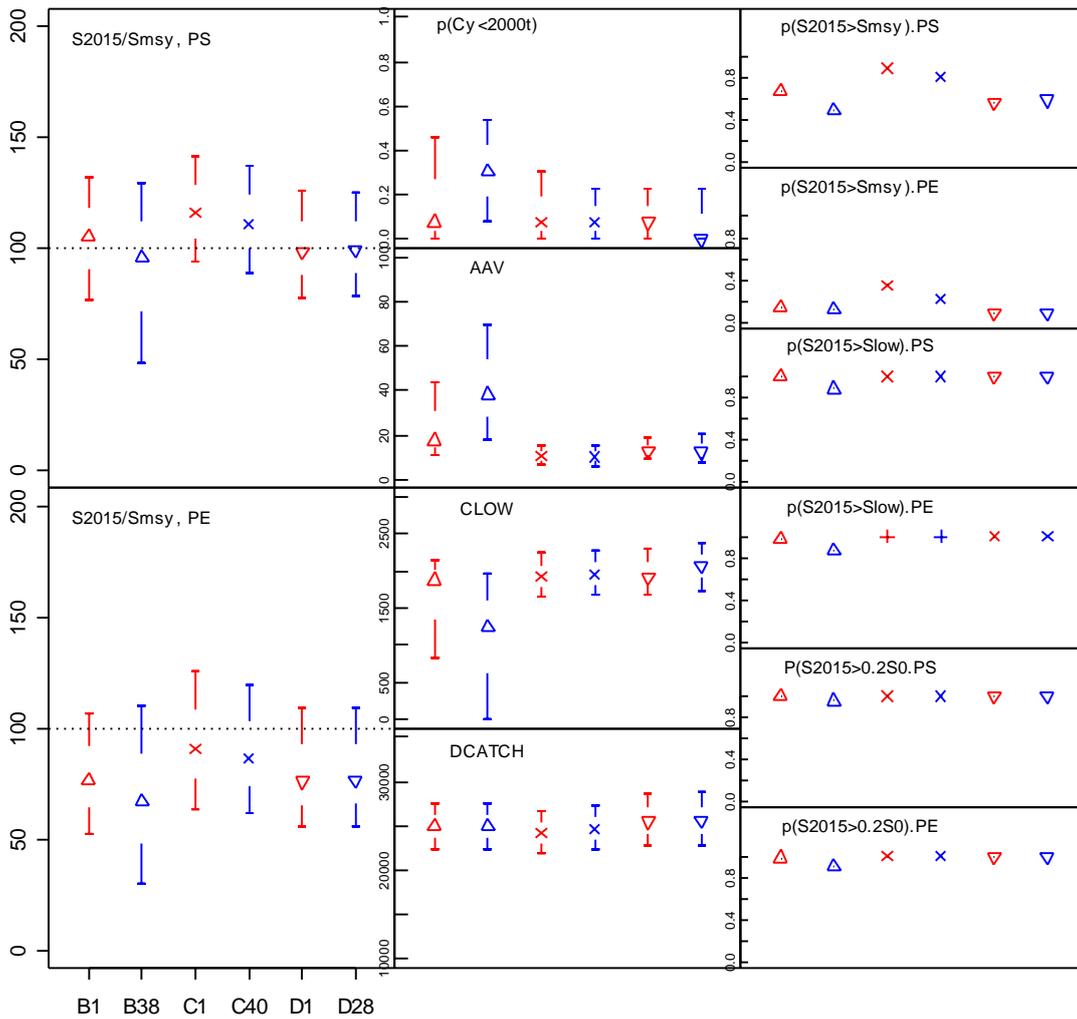


Figure App.C.9: Comparison of the performances of management strategies for which the probability of adopting recommendations for changes in effort levels is one-in-three (management strategies B1, C1 and D1) and for which such recommendations are always adopted (management strategies B38, C40 and D28). The results in this figure are based on the Base Case operating model.

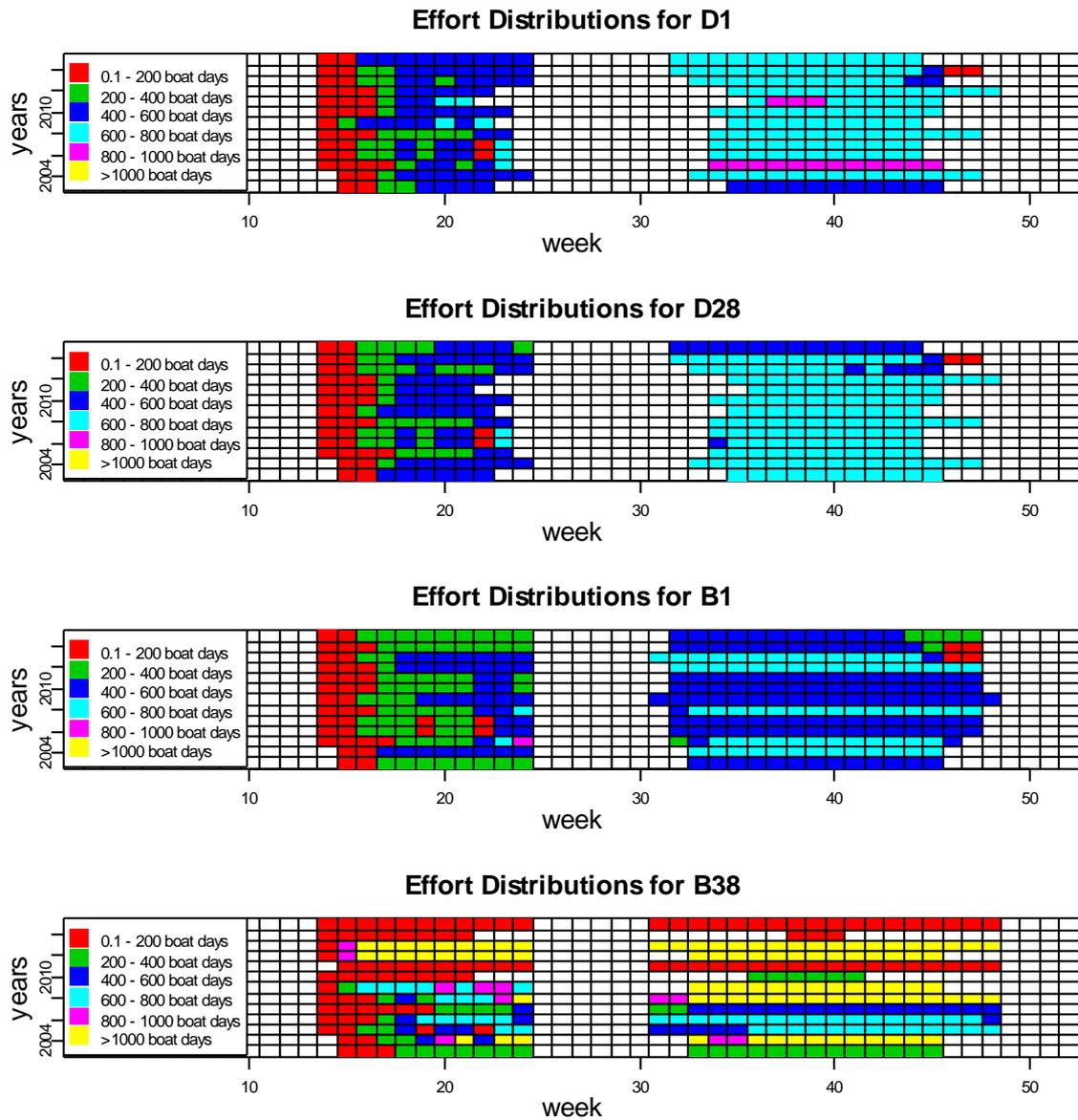


Figure App.C.10: Effort directed towards tiger prawns by week (2003–2015) for the D1, D28, B1 and B38 management strategies for a single simulation. The results in this figure are based on the Base Case operating model.

6.8.e Changing the slope when using the cpue regression method

In all of the previous sections, the management strategies that used the cpue regression approach set the effort level based on $\frac{1}{2}$ the size of the slope of the regression (i.e. $E_y = E_{y-1}(1 + 0.5\text{Slope})$). To examine the sensitivity of the management-related performance measures to the value of this slope multiplier, two additional options are examined in Figure App.C.11, viz. 0.25 (C44) and 0.75 (C45) in addition to 0.5 (C1). The management-related performance measures appear remarkably insensitive to the slope multiplier; there

is less inter-simulation variation in the probability of a catch $< 2000t$ for a multiplier of 0.75 but that is offset by a very slightly reduced likelihood of attaining the S_{MSY} by 2015 for both species.

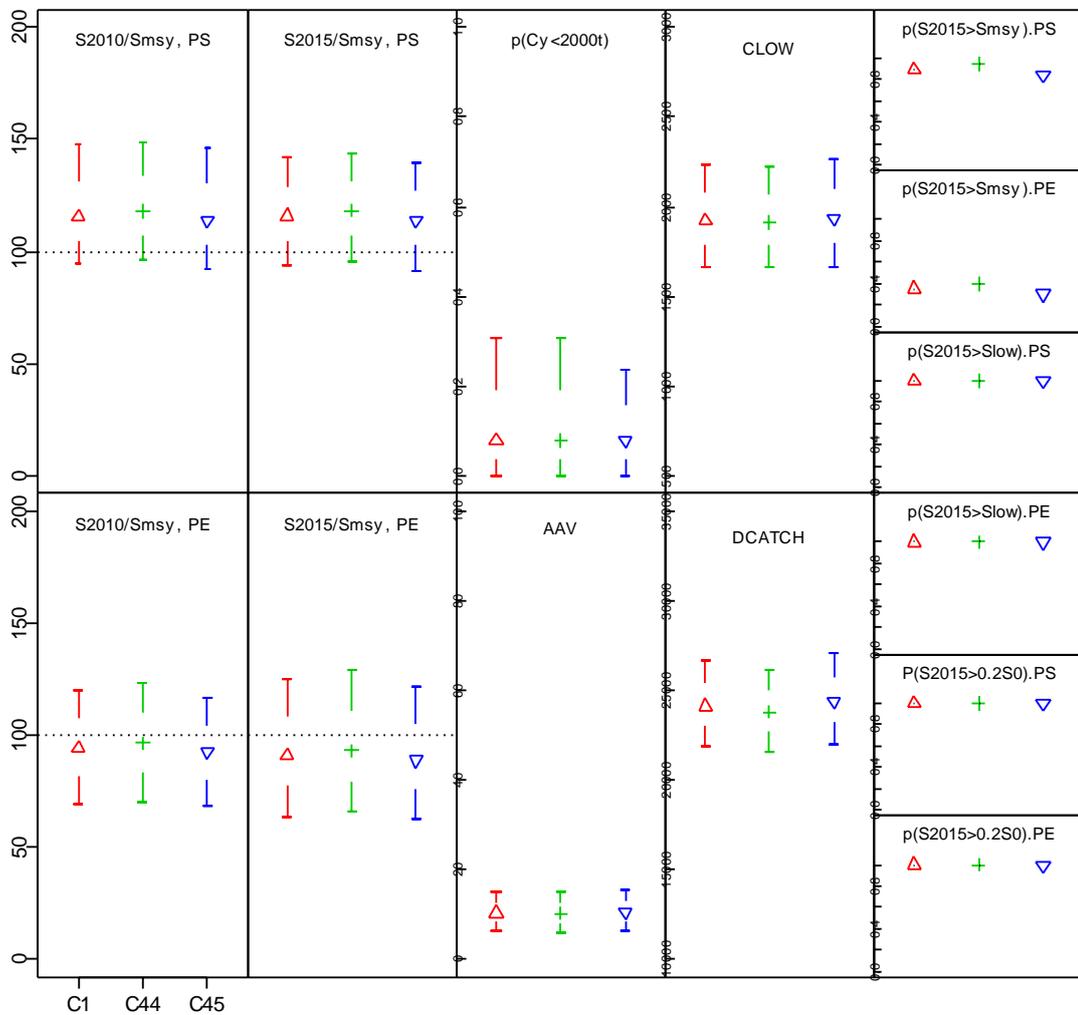


Figure App.C.11: Management-related performance measures for variants of the cpue regression approach in which the slope of the catch rates are multiplied by 0.5 (C1), 0.25 (C44) and 0.75 (C45). The results in this figure are based on the Base Case operating model.

Table App.C.2: Settings of the scenarios mentioned in Appendix C.

Scenario	Operating model	Management strategy	Decision Error	Spatially Correlated Recruitment	Recruitment Monte Carlo values	Implementation of effort changes (1:3 or 1:1)	Decision multiplier on regression slope
	Catchability/ Fishing power	Catchability/ Fishing power					
D1	q/H	q/H	0	None	Variance-covariance matrix	3	N/A
D32	q/H	q/H	0	None	Bayesian	3	N/A
B1	q/BCH	N/A	0	None	Variance-covariance matrix	3	N/A
B13	q/BCH	N/A	0.1	None	Variance-covariance matrix	3	N/A
C1	q/BCH	N/A	0	None	Variance-covariance matrix	3	0.5
C13	q/BCH	N/A	0.1	None	Variance-covariance matrix	3	0.5
D77	q/H	q/H	10	None	Variance-covariance matrix	3	N/A
B38	q/BCH	N/A	0	None	Variance-covariance matrix	3	N/A
C40	q/BCH	N/A	0	None	Variance-covariance matrix	1	0.5
D28	q/H	q/H	0	None	Variance-covariance matrix	1	N/A
C44	q/BCH	N/A	0	None	Variance-covariance matrix	3	0.25
C45	q/BCH	N/A	0	None	Variance-covariance matrix	3	0.75

CHAPTER 7 FUTURE DIRECTIONS

1. No management strategy could be found that left the spawning stock sizes of both species of tiger prawns above S_{MSY} without reducing catches substantially. Specifically, most of the Deriso-model based management strategies that were explored failed to leave the spawning stock size for brown tiger prawns (*Penaeus esculentus*) above S_{MSY} . Further exploration of management strategies that incorporate features that are expected to conserve the *P. esculentus* resource better may identify one that achieves the management objectives more successfully. For example, there are indications that the use of a multi-stock assessment in combination with spatially-based effort limits may perform better than any of the management strategies considered to date. Two (of many) ways of implementing the approach are to:
 - a) assess the resource using an assessment procedure based on the assumption that there is a single stock of each species, and allocate the total effort level to stock area based on survey results³; and
 - b) assess the resource using a four-stock assessment procedure and allocate the total effort level to stock area based on the effort levels estimated for each stock area. The compliance mechanism for this would have to be investigated.
2. There is a lack of knowledge concerning the true underlying stock structure and movement of prawns among putative stocks. Work on stock structure, mobility, and the reasons for correlations in recruitment among stock areas should be an essential component of working towards a multi-stock NPF assessment.
3. The estimates of the ratio S_Y/S_{MSY} for the Karumba and Weipa stock area are biased when the assessment is based on three or four stocks, and this bias increases with time. The reasons for this bias (and its trend over time) need to be explored, understood, and removed before substantial attention is focused on management strategies that rely on multi-stock assessment procedures.

4. This thesis focuses exclusively on two of the target species of the fishery. Given the increasing legislative requirement to consider the broader economic and ecosystem effects of fishing, there is a need to develop performance measures that explicitly consider: a) the ecosystem impacts of fishing (to provide a better way to quantify the broader implications of the different management strategies), and b) the dynamics and behaviour of the fishing fleet. This requires expanding the operating model to include ecosystem and economic components⁴.
5. The recruitment surveys in the Gulf of Carpentaria have value beyond their immediate objectives. Care should be taken that the data have enough information to estimate stock size *and* catchability if catchability is estimated within the assessment (as is the case for the biomass dynamic model). At present, only logbook data are available for assessment purposes and it seems unlikely that there is enough contrast in stock size and exploitation rate to estimate both stock size and catchability without substantial bias and model instability. The recruitment surveys, started in 2002, have the potential to provide the data required to estimate the values for parameters such as recruitment, and, together with the logbook data, may provide enough information to estimate catchability as well. This is in contrast to the present situation where catchability is either pre-specified (as is the case for the Deriso model) or poorly estimated (as is the case for the biomass dynamic model). Once the time-series of survey data is long enough, say 10 years, the assessment should be updated to include these data and to also estimate catchability.
6. Update the MSE to include economic, effects of trawling and ecosystem components in both the operating and management procedure. This will move the MSE to investigate management strategies for Ecosystem Based Fisheries Management.

³ In principle, the surveys would need to be of the vulnerable prawn biomass by species and stock area. At present the only surveys are recruitment surveys in the Gulf and the time series is, as yet, too short in length.

⁴ The inclusion of ecosystem effects and fleet dynamics into the operating model has already been funded as FRDC 2004/022 (“Bringing economic analysis and stock assessment together in the NPF: a framework for a biological and economically sustainable fishery”).

CHAPTER 8 REFERENCES

- Agnew, D.J., Baranowski, R., Beddington, J.R., des Clers, S., Nolan, C.P., 1998. Approaches to assessing stocks of *Loligo gahi* around the Falkland Islands. Fisheries Research 35: 155–169.
- Agnew, D.J., Hill, S., Beddington, J.R., 2000. Predicting the recruitment strength of an annual squid stock: *Loligo gahi* around the Falkland Islands. Canadian Journal of Fisheries and Aquatic Science. 57: 2479–2487.
- Alverson, D. L., Freeberg, M. H., Murawski, S. A., Pope, J. G., 1994. A Global assessment of fisheries bycatch and discards. FAO Fisheries Technical Paper No. 339. 233 pp.
- Andrew, N. L., Pepperell, J. G., 1992. The by-catch of shrimp trawl fisheries. Oceanography and Marine Biology: an Annual Review 30: 527-565.
- Anon, 1987. Synopsis of the major Torres Strait fisheries. M.J. Storrs (Ed.). Resource Management Section, Aust. Fisheries Service. Mimeo. 108pp. Dept Primary Industry: Canberra.
- Anon, 1998. Marine Living Resources Act of South Africa. Department of Environment Affairs and Tourism, South African Government.
- Anon, 2002. Application to environment Australia for the Exmouth Gulf prawn fishery against the guidelines for the ecologically sustainable management of fisheries for continued listing on Section 303DB of the Environmental Protection and Biodiversity Conservation Act 1999. Department of Fisheries Western Australia, Perth. 142 pp.
- Anon, 2003. Exmouth Gulf Prawn Fishery ESD Report Series No. 1. Department of Fisheries, Western Australia, 125pp.
- Anon, 2005. Draft assessment report: Torres Strait Prawn Fishery. Commonwealth Government Printer, Canberra, 110pp.
- Arkhipkin, A. I., Grzebielec, R., Sirota, A. M., Remeslo, A. V., Polishchuk, I. A., Middleton, D. A. J., 2004. The influence of seasonal environmental changes on ontogenetic

migrations of the squid *Loligo gahi* on the Falkland shelf. Fisheries and Oceanography 13(1): 1–9.

Australian and New Zealand Environment and Conservation Council Task Force on Marine Protected Areas 1999, Strategic Plan of Action for the National Representative System of Marine Protected Areas: a guide for Action by Australian Governments. Environment Australia, Canberra, pp. 80.

Baldwin, J. D., Bass, A. L., Bowen, B. W., Clark, W. H., 1998. Molecular phylogeny and biogeography of the marine shrimp *Penaeus*. Molecular Phylogenetics and Evolution 10: 399-407.

Barton, J., 2002. Fisheries and fisheries management in Falkland Islands Conservation Zones. Aquatic Conservation: Marine and Freshwater Ecosystems 12: 127-135.

Basson, M., 1999. The importance of environmental factors in the design of management procedures. ICES Journal of Marine Science 56: 933-942.

Basson, M., Beddington, J.R., Crombie, J.A., Holden, S.J., Purchase, L.V., Tingley, G.A., 1996. Assessment and management techniques for migratory annual squid stocks: the *Illex argentinus* fishery in the Southwest Atlantic as an example. Fisheries Research 28: 3–27.

Beddington, J.R., Rosenberg, A.A., Crombie, J.A., Kirkwood, G.P., 1990. Stock assessment and the provision of management advice for the short fin squid fishery in Falkland Islands waters. Fisheries Research 8: 351–365.

Bishop, J., Die, D., Wang, Y-G., 2000. A generalized estimating equations approach for analysis of the impact of new technology on a trawl fishery. Australian and New Zealand Journal of Statistics 42: 159–177.

Bishop, J., Venables, W.N., Wang, Y-G., 2004. Analysing commercial catch and effort data from a Penaeid trawl fishery: a comparison of linear models, mixed models, and generalised estimating equations approaches. Fisheries Research 70: 179-193.

Blaber, S., Brewer, D., Burridge, C., Farmer, M., Milton, D., Salini, J., You-Gan Wang, Wassenberg, T., Buxton, C., Cartwright, I., Eayrs, S., Rawlinson, N., Buckworth, R., Gill, N., MacCartie, J., Mounsey, R., Ramm, D., 1997. Effects of Trawl Design on

Bycatch and Benthos in Prawn and Finfish Fisheries. FRDC Project 93/179 Final Report. 190 pp.

Bomba, F.V.A., 2004. Shrimp bycatch policy in Moçambique. In: S.T. Fennessy, G.K. Mwatha, W. Thiele, (Eds.) FAO Report of the Regional workshop on approaches to reducing shrimp trawl bycatch in the western Indian ocean, Mombasa, Kenya, 13–15 April 2003.

Brewer, D. T., Griffiths, S., Zhou, S., Heales, D. S., Dell, Q., Tonks, B. R., Kuhnert, P., Miller, M., Whitelaw, W., M., Taylor, In progress. Design, trial and implementation of an integrated, long-term bycatch monitoring program, road tested in the NPF. FRDC Project 2002/035.

Brewer, D. T., Heales, D. S., Eayrs, S. J., Taylor, B. R., Day, G., Sen, S., Wakeford, J., Milton, D. A., Stobutzki, I. C., Fry, G. C., van der Velde, T. D., Jones, P. N., Wang, Y-G., Dell, Q., Austin, M., Carter, D., Nelson, C., Nichols, J., Gofton, T., 2004. Assessment and improvement of TEDs and BRDs in the NPF: a co-operative approach by fishers, scientists, fisheries technologists, economists and conservationists. FRDC Project 2000/173 Final report. Canberra. 405 pp.

Brewer, D. T., Rawlinson, N., Eayrs, S., Burridge, C. Y., 1998. An assessment of Bycatch Reduction Devices in a tropical Australian prawn trawl fishery Fisheries Research 36: 195-215.

Brunetti, N.E., Ivanovic, M.L., 1992. Distribution and abundance of early life stages of squid (*Illex argentinus*) in the South-west Atlantic. ICES Journal of Marine Science 49(2): 175-183.

Buckworth, R.C., 1985. Preliminary results of a study of commercial catches, spawning and recruitment of *Penaeus esculentus* and *P. semisulcatus* in the western Gulf of Carpentaria. In: Rothlisberg, P.C., Hill, B.J., Staples, D.J. (Ed.), Second Australian National Prawn Seminar (NPS2), pp. 213–225.

- Buckworth, R.C., 1987. Changes in fishing effort and catching power in the DMZ tiger prawn fishery. Northern Prawn Information Notes, February 1987, CSIRO Division of Fisheries, Cleveland, Australia.
- Butterworth, D.S., Bergh, M.O., 1993. The development of a management procedure for the South African anchovy resource. In: Smith, S.J., Hunt, J.J., Rivard, D. (Ed.), Risk Evaluation and Biological Reference Points for Fisheries Management. Canadian Special Publication of Fisheries and Aquatic Science 120: 83-99.
- Butterworth, D.S., Cochrane, K.L., De Oliveira, J.A.A., 1997. Management procedures: A better way to manage fisheries? The South African experience. In: Pikitch, E.K., Huppert, D.D., Sissenwine, M.P., Duke, M.(Eds), Global trends: fisheries management. American Fisheries Society Symposium 20: 83–90.
- Butterworth, D.S., De Oliveira, J.A.A., Cochrane, K.L., 1993. Current initiatives in refining the management procedure for the South African anchovy resource. pp. 439-473. In: Kruse, G., Eggers, D.M., Marasco, R.J., Pautzke, C., Quinn, T.J. II. (Eds). Proceedings of the International Symposium on Management Strategies for Exploited Fish Populations, Alaska Sea Grant College Program Report 93-02.
- Butterworth, D.S., Punt, A.E., 1999. Experiences in the evaluation and implementation of management procedures. ICES Journal of Marine Science 56: 985-998.
- Caddy, J. F., Mahon, R., 1995. Reference points for fisheries management. FAO, Fisheries Technical Paper, 347, 83 p.
- Campbell, R., Dowling, N., 2003. Development of an operating model and evaluation of harvest strategies for the Eastern Tuna and Billfish Fishery CSIRO, Hobart, Tas. (Australia). vp.
- Carrick, N.A., 1982. Spencer Gulf Prawn Fishery – fisheries increase our knowledge. SAFISH, August 1982 6(4): 1-33.
- Carrick, N.A., 1996. Key factors which affect prawn recruitment and implications to harvesting prawn stocks. FRDC Project No. 91/3, 50 pp.
- Carrick, N.A., 2002. Preliminary assessment of the stock and development of harvest strategies for the Spencer Gulf prawn fishery. Report to the Prawn Fishery Management Committee, March 2002.

- Carrick, N.A., 2003. Spencer Gulf Prawn (*Melicertus latisulcatus*) Fishery: Fishery Assessment Report to PIRSA Fisheries and the Prawn Fishery Management Committee. SARDI Aquatic Sciences Publication Number RD03/0079-2, 108pp.
- Carrick, N.A., Williams, H., 2001. Spencer Gulf and West Coast prawns. Fishery Assessment Report to PIRSA for the Prawn Fishery Management Committee. South Australian Fisheries Assessment Series 01/08.
- Cartwright, I., 2005. The Australian Northern Prawn Fishery. In: Sifar/World Bank Study Of Good Management Practice In Sustainable Fisheries. (in press).
- Chapman, L. Beare, S., 2002, Economic Impact of the Northern Prawn Fishery Amendment Plan, ABARE Report prepared for the Fisheries and Aquaculture Branch, Agriculture, Fisheries and Forestry – Australia, Canberra.
- Christensen, S., 1997. Evaluation of management strategies -- a bioeconomic approach applied to the Greenland Shrimp Fishery. ICES Journal of Marine Science 54: 412-426.
- Clarke, A., Rodhouse, P.G. and Gore, D.J. 1994. Biochemical composition in relation to the energetics of growth and sexual maturation in the ommastrephid squid *Illex argentinus*. Phil. Transactions of the Royal Society of London, Series B. 344: 201-212.
- Cochrane, K. L., Butterworth, D. S., De Oliveira, J. A. A., Roel, B. A., 1998. Management procedures in a fishery based on highly variable stocks and with conflicting objectives: experiences in the South African pelagic fishery. Reviews in Fish Biology and Fisheries 8: 177-214.
- Coles, R.G., Poiner, I.R., Kirkman, H., 1989. Regional studies - seagrasses of north-eastern Australia. In: Larkum, A.W.D., McComb, A.J., Shepherd, S.A., Biology of Seagrasses: a treatise on the biology of seagrasses with special reference to the Australian region. Elsevier Science Publishing Company Inc., New York, USA. pp. 261–277.
- Condie, S.A., Loneragan, N.R., Die, D. J., 1999. Modelling the recruitment of tiger prawns (*Penaeus semisulcatus* and *P. esculentus*) to nursery grounds in the Gulf of Carpentaria, northern Australia: implications for assessing stock-recruitment relationships. Marine Ecology Progress Series 178: 55-68.

- Copes, P., 1986. Prawn Fisheries Management in South Australia, with specific reference to problems in the Gulf St Vincent and Investigator Strait. Consultancy for the Minister of Fisheries, South Australia.
- Crococ, P.J., Van der Velde, T.D., 1995. Seasonal, spatial and interannual variability in the reproductive dynamics of the grooved tiger prawn *Penaeus semisulcatus* in Albatross Bay, Gulf of Carpentaria, Australia: The concept of effective spawning. *Marine Biology* 122: 557-570.
- Dall, W., Hill, B.J., Rothlisberg, P.C., Staples, D.J., 1990. The Biology of the Penaeidae. *Advances in Marine Biology* 27: 1–489.
- De la Mare, W.K., 1996. Some recent developments in the management of marine living resources. In: Floyd, R.B., Shepherd, A.W., De Barro, P.J. (Eds), *Frontiers of Population Ecology*. CSIRO Publishing, Melbourne, Australia, pp. 599–616.
- De Oliveira, J.A.A., 2003. The development and implementation of a joint management procedure for the South African pilchard and anchovy resources. PhD Thesis, University of Cape Town. [iv]+319 pp.
- De Oliveira, J.A.A., Butterworth, D.S., 2004. Developing and refining a joint management procedure for the multi-species South African pelagic fishery. *ICES Journal of Marine Sciences* 61: 1432-1442.
- De Oliveira, J.A.A., Butterworth, D.S., Roel, B.A., Cochrane, K.L., Brown, J.P., 1998. The application of a management procedure to regulate the directed and bycatch fishery of the South African sardine. *South African Journal of Marine Science*. 19: 449-469.
- Deng, A.J., Dichmont, C.M., 2003. Status of tiger prawns at the end of 2002. NPFAG Working Paper May 2003, 36pp.
- Deng, A.J., Dichmont, C.M., Venables, W., Ye, Y., 2004. Status of tiger prawns at the end of 2003. NPFAG Working Paper June 2004, 35pp.
- Deriso, R., 2001. A Review of the 2001 Assessment of Tiger Prawns in the Northern Prawn Fishery. 18pp.

- Dichmont, C.M., Haddon, M., Yeomans, K., Kelly, K., 1999. Proceedings of the south-east Queensland's Stock Assessment Review Workshop. DPI Information Series. 200 pp.
- Dichmont, C.M., Die, D., Punt, A.E., Venables, W., Bishop, J., Deng, A., Dell, Q., 2001. Risk Analysis and Sustainability Indicators for the Prawn Stocks in the Northern Prawn Fishery. FRDC 98/109 Final Report, 187 pp.
- Dichmont, C.M., Burrridge, C., Deng, A., Jones, P., Taranto, T., Toscas, P., Vance, D., Venables, W., 2002. Designing an integrated monitoring program for the NPF optimising costs and benefits. AFMA MAC Initiated Research Fund Project Number R01/1144 100 pp.
- Dichmont, C.M., Punt, A.E., Deng, A., Venables, W., 2003a. Application of a weekly delay-difference model to commercial catch and effort data for tiger prawns in Australia's Northern Prawn Fishery. Fisheries Research 65: 335-350.
- Dichmont, C.M., Bishop, J., Venables, W.N., Sterling, D., Rawlinson, N., Eayrs, S. 2003b. A new approach to fishing power analyses and its application in the Northern Prawn Fishery. AFMA Research Fund R99/1494. 700 pp.
- Dichmont, C.M., Vance, D., Burrridge, C., Pendrey, R., Deng, A., Ye, Y. and Loneragan, N. (2003c). Designing, implementing and assessing an integrated monitoring program for the NPF. FRDC 2002/101 Final report 166 pp.
- Dichmont, C.M., Deng, A., Venables, W., 2003d. Effort patterns by target species in the Northern Prawn Fishery. NORMAC 54 document, 20 pp.
- Dichmont, C.M., Deng, A.R., Venables, W.N., Punt, A.E., Haddon, M., Tattersall, K., 2005. A new approach to assessment in the NPF: spatial models in a management strategy environment that includes uncertainty. FRDC 2001/002 Final report 167 pp.
- Dichmont, C.M., Deng, A., Punt, A.E., Venables, W.V., Haddon, M., 2006a. Management Strategies for short lived species: the case of Australia's Northern Prawn Fishery. 1. Accounting for multiple species, spatial structure and implementation uncertainty when evaluating risk. Fisheries Research in prep.
- Dichmont, C.M., Deng, A., Punt, A.E., Venables, W.V., Haddon, M., 2006b. Management Strategies for short lived species: the case of Australia's Northern Prawn Fishery. 2.

- Choosing appropriate management strategies using input controls. Fisheries Research in prep.
- Dichmont, C.M., Deng, A., Punt, A.E., Venables, W.V., Haddon, M., 2006c. Management Strategies for short lived species: the case of Australia's Northern Prawn Fishery. 3. Factors affecting management and estimation performance. Fisheries Research in prep.
- Die, D. 1996. Northern Prawn Fishery 1994: Stock Assessment Report. Australian Fisheries Management Authority.
- Die, D., Bishop, J. 1999, 1998 tiger prawn stock assessment. NPFAG Working paper, 4pp.
- Die, D., Bishop, J. In: NORMAC 42. 1997. Australian Fisheries Management Authority.
- Die, D., Ellis, N., 1999. Aggregation dynamics in penaeid fisheries: banana prawns (*Penaeus merguensis*) in the Australian Northern Prawn Fishery. Australian Journal of Marine and Freshwater Research 50: 667-675.
- Die, D., Loneragan, N., Haywood, M., Vance, D., Manson, F., Taylor, B., Bishop, J. 2001. Indices of recruitment and effective spawning for tiger prawn stocks in the Northern Prawn Fishery. Fisheries Research and Development Corporation 95/014. 180pp.
- Die, D., Wang, Y-G., 1998. 1997 tiger prawn stock assessment. NPFAG Working paper, 98/2, 4pp.
- Die, D., Wang, Y-G., Bishop, J., 1997. 1996 tiger prawn stock assessment. NPFAG Working paper, 97/2. 4pp.
- Eayrs, S. E., Bose, S. 2001. An assessment of the TED performance in the NPF banana prawn fishery – Final report. AFMA Research Fund R01/0228. 15 pp.
- FAO, 1999. FAO Yearbook 1997. Fishery Statistics Capture Production, vol 84.
- FAO, 2005. Review of the state of world marine resources. FAI Fisheries Technical paper 457, 235 pp.
- Francis, R.C., Adlerstein, S.A., Hollowed, A., 1989. Importance of environmental fluctuations in the management of Pacific hake (*Merluccius productus*). International Recruitment Investigations in the Subarctic (IRIS) and International North Pacific

- Fisheries Commission (INPFC) Symposium, Vancouver, B.C. (Canada), 26 Oct 1987, Canadian Special Publication of Fisheries and Aquatic Science.
- Francis, R.I.C.C., Shotton, R., 1997. 'Risk' in fisheries management: A review. *Canadian Journal of Fisheries and Aquatic Science* 54: 1699-1715.
- Galeano, D., Langenkamp, D., Shafron, W., Levantis, C., 2004, Australian Fisheries Surveys Report 2003, ABARE, Canberra.
- Gelman, A., Carlin, J.B., Stern, H.S., Rubin, D.B., 1995. *Bayesian Data Analysis*. Chapman and Hall, London.
- Geromont, H.F., De Oliveira, J.A.A., Johnson, S.J., 1999. Development and application of management procedures for fisheries in southern Africa. *ICES Journal of Marine Science* 56: 952-966.
- Gillanders, B. M., Kingsford, M. J., 2002. Impact of changes in flow of freshwater on estuarine and open coastal habitats and the associated organisms. *Oceanography and Marine Biology: an Annual Review* 40: 233-309.
- Glaister, J.P., Pond, P.C., Storey, J.L., 1993. Framework for management for the East Coast trawl fishery. Queensland Fish Management Authority, Queensland (Australia), Unknown pp.
- Haddon M., Hodgson K., 2000. Spatial and Seasonal stock dynamics of Northern Tiger Prawns using fine-scale commercial catch-effort data. FRDC 1999/100 Final report. Tasmanian Aquaculture and Fisheries Institute, University of Tasmania.
- Haddon, M., 1997. A biomass-dynamic model of the Northern Tiger Prawn Fishery: an alternative estimation of potential yields. NPFAG Working paper 97/1. 28pp.
- Haddon, M., 2000. A stock production model of the Northern Tiger Prawn Fishery: Stock status and potential long-term yields. NPFAG Document March 2000 77 pp.
- Haddon, M., 2001. *Modelling and Quantitative Methods in Fisheries*. Chapman & Hall/CRC press. 406pp.
- Hampton, I., 1992. The role of acoustic surveys in the assessment of pelagic fish resources on the South African continental shelf. *South African Journal of Marine Science* 12: 1031-1050.

- Hastings, W.K., 1970. Monte Carlo sampling methods using Markov chains and their applications. *Biometrika* 57: 97–109.
- Hatfield, E.M.C., Rodhouse, P.G., 1994. Distribution and abundance of juvenile *Loligo gahi* in Falkland Island waters. *Marine Biology* 121: 267–272.
- Hatfield, E.M.C., Rodhouse, P.G., Porebski, J., 1990. Demography and distribution of the Patagonian squid (*Loligo gahi*, d'Orbigny) during the austral winter. *Journal du Conseil* 46: 306–312.
- Haywood, M., Hill, B.J., Wassenberg, T.J. in progress. Quantifying the effects of trawling on the seabed biota of the NPF; 2002-2005. FRDC project 2002/102.
- Hilborn, R., Maguire, J.-J., Parma, A.M., Rosenberg, A.A., 2001. The precautionary approach and risk management: can they increase the probability of successes in fishery management? *Canadian Journal of Fisheries and Aquatic Science* 58: 99-107.
- Hill, B. J., Wassenberg, T. J., 1990. Fate of Discards from prawn trawlers in Torres Strait. *Australian Journal of Marine and Freshwater Research* 41:53-64.
- Hill, B.J., Haywood, M.D.E., Gordon, S.R., Condie, S.A., Ellis, N., Tyre, A.J., Vance, D.J., Dunn, J.R., Mansbridge, J., Moeseneder, C., Bustamante, R., Pantus, F., Venables, W., 2002. Surrogates 1 - predictors, impacts, management and conservation of the benthic biodiversity of the Northern Prawn Fishery. CSIRO Division of Marine Research, Cleveland, Qld. FRDC project 2000/160 Final report 437 pp.
- Hill, B.J., Wassenberg, T.J., 1985. A laboratory study of the effect of streamer tags on mortality, growth, moulting and duration of nocturnal emergence of the tiger prawn *Penaeus esculentus* (Haswell). *Fisheries Research* 3: 223-235.
- Hill, B.J., Wassenberg, T.J. 2000. The probable fate of discards from prawn trawlers fishing near coral reefs. A study in the northern Great Barrier Reef, Australia. *Fisheries Research*. 48: 277-286.

- Hobday, A., Smith, A., Stobutzki, I., Bruce, B., Bustamante, R., Butler, A., Chesson, J., Deng, R., Dennis, D., Garvey, J., Hartmann, K., Knuckey, I., Ling, S., Manson, F., Milton, D., Pitcher, R., Sainsbury, K., Stevens, J., Walker, T., Wayte, S., Webb, H., Wise, B., Young, J., 2004. Ecological Risk Assessment for Australian Commonwealth Fisheries: Final report – Stage 1. Hazard Identification and Preliminary Risk Assessment. AFMA Report No. R01/0934, 158 pp.
- Huber, D., 2003. Audit of the Management of the Queensland East Coast Trawl Fishery in the Great Barrier Reef Marine Park. Great Barrier Marine Park Authority Report, 193 pp.
- IMCRA, 1998. Interim Marine and Coastal Regionalisation for Australia: An ecosystem-based classification for marine and coastal environments. R Thackway and I D Cresswell (Eds). Environment Australia, Department of Environment, June 1998, 102pp.
- Kangas, M., Jackson, W.B., 1997. Gulf St Vincent prawn fishery. SARDI South Australian Assessment Series 99/05.
- Kell, L.T., Crozier, W.W., Legault, C.M., 2004. Mixed and Multi-Stock Fisheries. ICES Journal of Marine Science 61: 1330
- Kennelly, S. J. 1995. The issue of bycatch in Australia's demersal trawl fisheries. Reviews in Fish Biology and Fisheries 5: 213-234.
- Kenyon, R. A., Jarrett, A., Bishop, J., Taranto, T., Dichmont, C., Zhou, S., 2004b. Documenting the history of and providing protocols and criteria for changing existing or establishing new closures in the NPF. Report to the Australian Fisheries Management Agency: Report Number R02/0881. 49pp, including 4 appendices.
- Kenyon, R.A., Loneragan, N.R., Manson, F.J., Vance, D.J., Venables, W.N., 2004a. Distribution of juvenile red-legged banana prawns (*Penaeus indicus*) and juvenile white

banana prawns (*Penaeus merguensis*) among nursery habitats, and proximity of the offshore fishery, in the Joseph Bonaparte Gulf, north-west Australia. *Journal of Experimental Marine Biology and Ecology* 309: 79-108.

Kirkwood, G.P., 1993. Incorporating allowance for risk in management, The Revised Management Procedure of the International Whaling Commission. ICES, Copenhagen (Denmark). 11, 6 pp.

Kung, J., Turnbull, C., Murphy, R., Taylor, S., Marrington, J., 2005. *Torres Strait Handbook 2005*. Australian Fisheries Management Authority. Canberra, 129pp.

Laevastu, T. 1992. Interactions of size-selective fishing with variations in growth rates and effects on fish stocks. ICES, Copenhagen (Denmark).

Larkin, P.A., 1977. An epitaph for the concept of maximum sustained yield. *Transactions of the American Fisheries Society* Vol. 106, no. 1, pp. 1-11.

Last, P. R., Stevens, J. D., 1994. *Sharks and Rays of Australia*. CSIRO Australia.

Lavery S., Chan, T.Y., Tam, Y.K., Chu, K. H., 2004. Phylogenetic relationships and evolutionary history of the shrimp genus *Penaeus s.l.* derived from mitochondrial DNA. *Molecular Phylogenetics and Evolution* 31: 39-49

Loneragan NR, Conacher CA, Haywood MDE, Heales DS, Kenyon RA, Pendrey RC, Vance DJ, 1996. The role of coastal nursery habitats in determining the long-term productivity of prawn populations in the Northern Prawn Fishery. FRDC Report No. 92/45.

Loneragan, N.R., Kenyon, R.A., Staples, D.J., Poiner, I.R., Conacher, C.A., 1998. The influence of seagrass type on the distribution and abundance of postlarval and juvenile tiger prawns in the western Gulf of Carpentaria, Australia. *Journal of Experimental Marine Biology and Ecology* 228: 175-196.

Lucas, C., 1974. Preliminary estimates of stocks of the king prawn, *Penaeus plebejus*, in south-east Queensland. *Australian Journal of Marine and Freshwater Research* 25(1): 35-47.

- Lucas, C., Kirkwood, G., Somers, I., 1979. An assessment of the stocks of the banana prawn *Penaeus merguensis* in the Gulf of Carpentaria. Australian Journal of Marine and Freshwater Research 30: 639-652.
- MacDonald, N., 1998. Management plan for the Spencer Gulf and West Coast Prawn Fisheries. Internal document, Primary Industries and Resources, South Australia. 23 pp.
- Magnússon, K.G., Stefánsson, G., 1989. A feedback strategy to regulate catches from a whale stock. In: Donovan, G.P. (Ed.), Reports of the International Whaling Commission (Special Issue 11), 171–189.
- McAllister, M. K., Hill, S.L., Agnew, D.J., Kirkwood, G.P., Beddington, J.R., 2004. A Bayesian hierarchical formulation of the De Lury stock assessment model for abundance estimation of Falkland Islands' squid (*Loligo gahi*). Canadian Journal of Fisheries and Aquatic Science. 61: 1048–1059.
- McDonald, A.D., Smith, A.D.M., 1997. A tutorial on evaluating expected returns from research for fishery management. Natural Resource Modeling 10: 185-216.
- McDonald, A.D., Smith, A.D.M., Punt, A.E., Tuck, G.N. Davidson, A.J., 1997. Empirical evaluation of expected returns from research on stock structure for determination of total allowable catch. Natural Resource Modeling 10: 3-29.
- Milton, D. M., 2001. Assessing the susceptibility to fishing of populations of rare trawl bycatch: sea snakes caught by Australia's Northern Prawn Fishery. Biological Conservation 101: 281-290.
- Morgan, G., 1995. Assessment, management and research support for the Gulf St Vincent Prawn Fishery. Primary Industries South Australia. 16 pp.
- Morgan, G., 1996. Review of research and management of the Spencer Gulf Prawn fishery. South Australian Fisheries Management Series 20, 25 pp.
- Munro, I., 1988 In: Mawson, V., Tranter, D.J. (Eds). CSIRO at Sea., CSIRO Marine Laboratories, Hobart, pp.149–155.

NOAA News release., 2002. United States extends ban on shark finning to Pacific Ocean.

<http://www.publicaffairs.noaa.gov/releases2002/feb02/noaa02018.html>

NORMAC 39. 1996. Australian Fisheries Management Authority.

NORMAC 41. 1997. Australian Fisheries Management Authority.

NORMAC 42. 1997. Australian Fisheries Management Authority.

NORMAC 43. 1998. Australian Fisheries Management Authority.

NORMAC 45. 1999. Australian Fisheries Management Authority.

NORMAC 51. 2001. Australian Fisheries Management Authority.

NORMAC 54. 2003. Australian Fisheries Management Authority.

NORMAC 56. 2004. Australian Fisheries Management Authority.

NORMAC, 1998. Northern Prawn Fishery Bycatch Action Plan, 1998. Australian Fisheries Management Authority. 21 pp.

NORMAC, 2003. Northern Prawn Fishery Bycatch Action Plan, 2003. Australian Fisheries Management Authority. 32 pp.

NPFAG, 2004. The status of tiger prawn stocks at the end of 2003. NPFAG Document 2004, 37pp.

O'Neill, M.F., Courtney, A.J., Good, N.M., Turnbull, C.T., Yeomans, K.M., Staunton-Smith, J., Shootingstar, C., 2004. Reference point management and the role of catch-per-unit effort in prawn and scallop fisheries. FRDC 1999/120 Final report 284 pp.

Otter Research Ltd. <http://otter-rsch.com/admodel.htm>

Palha de Sousa, L., Brito, A., Abdula, S., Caputi, N. in prep. Assessment of the industrial shallow-water multi-species shrimp fishery in Sofala Bank in Mozambique.

- Palha de Sousa, L., Brito, A., Abdula, S., Caputi, N., 2002. The industrial shallow water shrimp fishery at Sofala Bank in Mozambique. Instituto Nacional de Investigação Pesqueira. 55 p. (unpublished report).
- Park, Y.C., 1999. Reproductive dynamics, emergence behaviour, and stock assessment of endeavour prawns, *Metapenaeus endeavouri* and *M. ensis* in Albatross Bay, Gulf of Carpentaria: implications for the bioeconomic optimisation of the night time prawn fishery. PhD Thesis, 31 March 1999 243 pp.
- Parker, K.S., 1989. Influence of oceanographic and meteorological processes on the recruitment of Pacific halibut, *Hippoglossus stenolepis*, in the Gulf of Alaska. International Recruitment Investigations in the Subarctic (IRIS) and International North Pacific Fisheries Commission (INPFC) Symposium, Vancouver, B.C. (Canada), 26 Oct 1987, Canadian Special Publication of Fisheries and Aquatic Science.
- Pender, P.J., Willing, R.S., Cann, B., 1992. NPF bycatch a valuable resource? Australian Fisheries 51: 30-31.
- Penn, J.W., Watson, R.A., Caputi, N., Hall, N., 1997. Protecting vulnerable stocks in multi-species prawn fisheries. In: Hancock, D.A., Smith, D.C., Grant, A., Beumer, J.P. (Eds). Developing and Sustaining World Fisheries Resources: The State of Science and Management. 2nd World Fisheries Congress pp. 122- 129.
- Penn, J.W., Caputi, N., 1985. Stock recruitment relationships for the tiger prawn, *Penaeus esculentus*, fishery in Exmouth Gulf, Western Australia, and their implications for management. In: Rothlisberg, P.C., Hill, B.J., Staples, D.J. (Eds). Second Australian National Prawn Seminar, Cleveland, Australia pp.165-173.
- Penn, J.W., Caputi, N., 1986 Spawning stock-recruitment relationships and environmental influences on the tiger prawn (*Penaeus esculentus*) fishery in Exmouth Gulf, Western Australia. Australian Journal of Marine and Freshwater Research 37: 491-505.
- Penn, J.W., Caputi, N., Hall, N.G., 1995. Stock-recruitment relationships for the tiger prawn (*Penaeus esculentus*) stocks in Western Australia. ICES Marine Science Symposium 199: 320-333.

- Pérez-Farfante, I., Kensley, B.F., 1997. Penaeoid and sergestoid shrimps and prawns of the world: Keys and diagnoses for the families and genera. *Mémoires du Muséum National d'Histoire Naturelle* 175: 1-233.
- Poiner, I. R., Buckworth, R. C., Harris, A. N. M. 1990. Incidental capture, and mortality of sea turtles in Australia's Northern Prawn Fishery. *Australian Journal of Marine and Freshwater Research* 41: 97-110.
- Poiner, I.R., Conacher, C.A., Loneragan, N.R., 1992. Maintain or modify — alternative views of managing critical fisheries habitat — how much can we lose? Invited presentation. Australian Society of Fish Biology, Workshop. Victor Harbour, South Australia, August, 1992.
- Poiner, I.R., Peterken, C. 1995. Seagrasses. In Zann, L.P., Kailola, P. (Eds) *The State of the Marine Environment Report for Australia, Technical Annex 1. The Marine Environment*. Department of Environment, Sport and Territories: 107–117.
- Poiner, I.R., Staples, D.J., Kenyon, R. 1987. Seagrass communities of the Gulf of Carpentaria, Australia. *Australia Journal of Marine and Freshwater Research* 38: 121-132.
- Poiner, I.R., Walker, D.I., Coles, R.G., 1989. Regional studies - seagrasses of tropical Australia. In: Larkum, A.W.D., McComb, A.J. and Sheperd, S.A. (Eds). *The Biology of Seagrasses - An Australian Perspective*. Elsevier, New York.
- Polacheck, T., Klaer, N.L., Millar, C., Preece, A.L., 1999. An initial evaluation of management strategies for the southern bluefin tuna. *ICES Journal of Marine Science* 56: 811-826.
- Potter, I.C., Manning, R.J.G., Loneragan, N.R., 1991. Size, movements, distribution and gonadal stage of the western king prawn (*Penaeus latisulcatus*) in a temperate estuary and local marine waters. *Journal of Zoology, London* 223: 419-445.
- Pownall, P. (Ed.), 1994. *Australia's Northern Prawn Fishery: the First 25 Years*. NPF25, Cleveland, Australia.

- Punt, A. E., 1992. Selecting management methodologies for marine resources, with an illustration for southern African hake. *South African Journal of Marine Science* 12: 943–958.
- Punt, A. E., Smith, A.D.M., 1999. Harvest strategy evaluation for the eastern stock of gemfish (*Rexea solandri*). *ICES Journal of Marine Science* 56: 860–875.
- Punt, A.E. 2003. The performance of a size-structured stock assessment method in the face of spatial heterogeneity in growth. *Fisheries Research* 65: 391-409.
- Punt, A.E., 1989. Pilchard TAC determination using a maximum-likelihood catch-at-age approach. Cape Town: Sea Fisheries Research Institute, Unpublished report WG/SEP/89/P/3. 12 pp.
- Punt, A.E., 1992. Selecting management methodologies for marine resources, with an illustration for southern African hake. *South African Journal of Marine Science* 12: 943–958.
- Punt, A.E., 1996. Progress report: Fitting the Deriso model to NPF catch and effort data. Report presented to MDP meeting, Cleveland, Jan 1996. 26pp.
- Punt, A.E., Butterworth, D.S., Martin, J., 1995. The effects of errors in the placement of the boundary between the west and south coast hake *Merluccius* spp. stocks on the performance of the current hake management procedure. *South African Journal of Marine Science* 15: 83-98.
- Punt, A.E., Smith, A.D.M., 1999. Harvest strategy evaluation for the eastern gemfish (*Rexea solandri*). *ICES Journal of Marine Science* 56: 860–875.
- Punt, A.E., Campbell, R.A., Smith, A.D.M., 2001a. Evaluating empirical indicators and reference points for fisheries management: application to the broadbill swordfish fishery off eastern Australia. *Marine and Freshwater Research* 52(6): 819-832.
- Punt, A.E., Cui, G., Smith, A.D.M., 2001b. Defining robust harvest strategies, performance indicators and monitoring strategies for the SEF. *Fisheries Research and Development Corporation* 98/102, 170 pp.
- Punt, A.E., Smith, A.D.M., Cui, G., 2002. Evaluation of management tools for Australia's South East Fishery 1. Modelling the South East Fishery taking account of technical interactions. *Marine and Freshwater Research* 53: 615-629.

- Punt, A.E., Smith, A.D.M., Cui, G., 2002b. Evaluation of management tools for Australia's South East Fishery 2. How well can management quantities be estimated? *Mar. Freshwater Res.* 53: 631-644.
- Punt, A.E., Smith, A.D.M., Cui, G., 2002c. Evaluation of management tools for Australia's South East Fishery 3. Towards selecting appropriate harvest strategies. *Mar. Freshwater Res.* 53: 631-644.
- Punt, A.E., Walker, T.I., Prince, J.D., 2002. Assessing the management-related benefits of fixed station fishery-independent surveys in Australia's southern shark fishery. *Fisheries Research* 55: 281-295.
- Punt, A.E., Walker, T.I., Prince, J.D., 2002a. Assessing the management-related benefits of fixed station fishery-independent surveys in Australia's southern shark fishery. *Fish. Res.* 55: 281-295.
- Quinn, T.J. II; Turnbull, C.T.; Fu, C. 1998. A length-based population model for hard-to-age invertebrate populations. In: Funk, F., Quinn II, T.J., Heifetz, J., Ianelli, J.N., Powers, J.E., Schweigert, J.F., Sullivan, P.J., Zhang, C-I. (Eds) . *Fishery Stock Assessment Models*. pp. 531-556. Lowell Wakefield Fisheries Symposium Series No. 15.
- Quirk *et al.* (1991). Report to the select committee of the house of assembly on the St Vincent Gulf prawn fishery, 13 pp.
- Robins, C.M., Goodspeed, A.M., Poiner, I., Harch, B.D., 2003. Monitoring the catch of turtles in the Northern Prawn Fishery. Fisheries Research and Development Corporation Final Report, Canberra.
- Robins, C.M., Wang, Y-G., Die, D., 1998. The impact of global positioning system and plotters on fishing power in the northern prawn fishery, Australia. *Canadian Journal of Fisheries and Aquatic Sciences* 55: 1645-1651.
- Robins, J., Eayrs, S., Campbell, M., Day, G., McGilvray, J., 2000. Commercialisation of bycatch reduction strategies and devices within northern Australian prawn trawl fisheries. Queensland Department of Primary Industries Report No QO00006. 40 pp.
- Rose, R., Kompas, T., 2004. Management options for the Australian Northern Prawn Fishery: an economic assessment. ABARE eReport 04.12. 47pp.

- Rosenberg, A.A., Brault, S., 1993. Choosing a management strategy for stock rebuilding when control is uncertain. In: Risk evaluation and biological reference points for fisheries management. Canadian Special Publication of Fisheries Aquatic Science 120: 243-249
- Rosenberg, A.A., Kirkwood, G.P., Crombie, J.A., Beddington, J.R., 1990. The assessment of stocks of annual squid species. Fisheries Research 8: 335–350.
- Rothlisberg, P., Staples, D, Poiner, I., Wolanski, E., 1988. Possible impact of the greenhouse effect on commercial prawn populations in the Gulf of Carpentaria. In: Pearman, G.I. (Ed.), Greenhouse: planning for climate change, CSIRO Publications, East Melbourne, Australia. pp. 216–227.
- Rothlisberg, P.C., Church, J.A., Fandry, C.B., 1995. A mechanism for nearshore concentration and estuarine recruitment of postlarval *Penaeus plebejus* Hess (Decapoda, Penaeidae). Estuarine Coastal and Shelf Science 40: 115-138.
- Rothlisberg, P.C., Craig, P.D., Andrewartha, J.R., 1996. Modelling penaeid prawn larval advection in Albatross Bay, Australia: defining the effective spawning population. Marine Freshwater Research 47:157-168.
- Sainsbury, K.J., Punt, A.E., Smith, A.D.M., 2000. Design of operational management strategies for achieving fishery ecosystem objectives. ICES Journal of Marine Science 57: 731–741.
- Schnute, J.T. 1985. A general theory for analysis of catch and effort data. Canadian Journal of Fisheries and Aquatic Science 42: 414–429.
- Shelton, P. A., Hutchings, L., 1982. Transport of anchovy, *Engraulis capensis* Gilchrist, eggs and early larvae by a frontal jet current. Journal du Conseil International pour l'Exploration de la Mer 40: 185e198.
- Sissenwine, M. P., Sheperd, J. G., 1987. An alternative perspective on recruitment overfishing and biological reference points. Canadian Journal of Fisheries and Aquatic Science 44: 913-918.

- Smith, A.D.M, Sainsbury, K.J., Stevens, R.A., 1999. Implementing effective fisheries management systems – management strategy evaluation and the Australian partnership approach. *ICES Journal of Marine Science* 56, 967-979.
- Smith, B.J., 2004. Bayesian Output Analysis Program (BOA) version 1.1 User's Manual. R Library.
- Somers, I. F., 1985 Maximising value per recruit in the fishery for banana prawns, *Penaeus merguensis*, in the Gulf of Carpentaria. Rothlisberg, P. C, Hill, B. J., and Staples, D. J. Second Australian National Prawn Seminar. 185–191. 85. NPS2, Cleveland, Queensland, Australia.
- Somers, I. F., 1994a. No resource, no fishery: prawns and their habitat. In: Pownall, P.C. (Ed.). Australia's Northern Prawn Fishery: the first 25 years. NPF25, Cleveland, Australia. pp 49-65.
- Somers, I. F., 1994b. Species composition and distribution of commercial penaeid prawn catches in the Gulf of Carpentaria, Australia, in relation to depth and sediment type. *Australian Journal of Marine and Freshwater Research* 45: 317-335.
- Somers, I., Taylor, B., 1990. Industry co-operation saves on NPF research bill. *Australian Fisheries* 179: 46-47
- Somers, I., Wang, Y., 1997. A simulation model for evaluating seasonal closures in Australia's multispecies Northern Prawn Fishery. *North American Journal of Fisheries Management*, 17: 114–130.
- Somers, I.F., 1990. Manipulation of fishing effort in Australia's penaeid prawn fisheries. *Australian Journal of Marine and Freshwater Research* 41: 1-12.
- Somers, I.F., 1992. The status of tiger prawn stocks in the western Gulf of Carpentaria. *Northern Prawn Fishery Information Notes* 4-10.
- Somers, I.F., Crocos, P.J., Hill, B.J., 1987. Distribution and Abundance of the Tiger Prawns *Penaeus esculentus* and *P. semisulcatus* in the North-western Gulf of Carpentaria, Australia. *Australian Journal of Marine and Freshwater Research* 38: 63-78.

- Somers, I.F., Kirkwood, G.P., 1991. Population Ecology of the Grooved Tiger Prawn, *Penaeus semisulcatus*, in the North-western Gulf of Carpentaria, Australia: Growth, Movement, Age Structure and Infestation by the Bopyrid Parasite *Epipenaeon ingens*. Australian Journal of Marine and Freshwater Research 42, 349-367
- Sousa, B., 2004. Mozambique. In: Fennessy, S.T., Mwatha, G.K., Thiele, W. (Eds). FAO Report of the Regional workshop on approaches to reducing shrimp trawl bycatch in the western Indian Ocean, Mombassa, Kenya, 13–15 April 2003.
- Sparholt, H., 1996. Causal correlation between recruitment and spawning stock size of central Baltic cod? ICES Journal of Marine Science 53: 771-779.
- Sporer E., Kangas M., 2001. Exmouth Gulf Prawn Managed Fishery status report. In: Penn, J.W. (Ed.). State of the Fisheries Report 1999-2000. Fisheries Western Australia, pp. 35-38.
- Staples, D. J., Vance, D. J., Heales, D.S., 1985. Habitat requirements of juvenile penaeid prawns and their relationship to offshore fisheries. In: Rothlisberg, P. C., Hill, B. J. & Staples, D. J. (Eds) Second Australian National Prawn Seminar, NPS2, Cleveland, Australia, p 47-54.
- Staples, D. J., Vance, D.J., 1986. Emigration of juvenile banana prawns *Penaeus merguensis* from a mangrove estuary and recruitment to offshore areas in the wet-dry tropics of the Gulf of Carpentaria, Australia. Marine Ecology Progress Series 27: 239-252
- Stobutzki, I. C., Blaber, S. J. M., Brewer, D. T., Fry, G. C., Heales, D. H., Miller, M. J., Milton, D. A., Salini, J. P., Van der Velde, T. D., Wassenberg, T. J., Jones, P. N., Wang, Y-G., Dredge, M., Courtney, A. J., Chilcott, K., Eayrs, S. J., 2000. Ecological Sustainability of Bycatch and Biodiversity in Prawn Trawl Fisheries. FRDC Project 96/257, 512pp.

- Stobutzki, I. C., Miller, M. J., Heales, D. H., Brewer, D. T., 2002. Sustainability of elasmobranchs caught as bycatch in a tropical prawn (shrimp) trawl fishery. *Fishery Bulletin* 100: 800-821.
- Stobutzki, I. C., Miller, M. J., Jones, P. N., Salini, J. P., 2001b. Bycatch diversity and variation in a tropical Australian penaeid fishery; the implications for monitoring. *Fisheries Research* 53 (3): 283-301.
- Stobutzki, I., Farmer, M. J., Brewer, D. T., 2001a. Sustainability of fisheries bycatch: a process for assessing highly diverse and numerous bycatch. *Environmental Conservation* 28: 167-181.
- Stone, T., 2005. Do secure access rights and co-management guarantee sustainability? A case study of Australia's northern fisheries. In 'Proceedings of The Third Workshop on Factors of Unsustainability in Fisheries' (in press).
- Svane, I., 2003. Gulf St Vincent Prawn Fishery (*Merlicertus latisulcatus*): Fishery Assessment Report to PIRSA for the Prawn Fishery Management Committee. SARDI Aquatic Sciences Publication No: RD03/0063-2. 57 pp.
- Taylor, B., 1994. A delicate balancing act: management of the fishery. In: Pownall, P.C. (Ed.). *Australia's Northern Prawn Fishery: the first 25 years*. NPF25, Cleveland, Australia. pp 113-130.
- Taylor, B., Die, D., 1999. Northern Prawn Fishery 1997 & 1998. AFMA Report 49 pp.
- Turnbull, C., Watson, R., 1995. Torres Strait Prawns 1994, Stock Assessment Report, Torres Strait Fisheries Assessment Group, Australian Fisheries Management Authority, Canberra.
- Ulltang, Ø., 1996. Stock assessment and biological knowledge: can prediction uncertainty be reduced. *ICES Journal of Marine Science* 53: 659-675.

- Vance, D. J., Haywood, M. D. E., Heales, D. S., Kenyon, R. A., Loneragan, N.R., 1998. Seasonal and annual variation in abundance of postlarval and juvenile banana prawns, *Penaeus merguensis*, and environmental variation in two estuaries in tropical northeastern Australia: a six-year study. Marine Ecology Progress Series 163: 21-36
- Vance, D.J., Staples, D.J., Kerr, J.D., 1985. Factors affecting year-to-year variation in the catch of banana prawns (*Penaeus merguensis*) in the Gulf of Carpentaria. ICES Journal of Marine Science 42: 83-97.
- Vance, D.J., Bishop, J., Dichmont, C.M., Hall, N., McInnes, K., Taylor, B.R., 2003. Management of common banana prawn stocks of the Gulf of Carpentaria: Separating the effects of fishing from those of the environment. CSIRO, Cleveland, Qld. (Australia). 116 pp.
- Vance, D.J., Haywood, M.D.E., Heales, D.S., Kenyon, R.A., Loneragan, N.R., Pendrey, R.C., 1996. How far do prawns and fish move into mangroves? Distribution of juvenile banana prawns *Penaeus merguensis* and fish in a tropical mangrove forest in northern Australia. Marine ecology progress series 131(1-3): 115-124.
- Vasconcellos, M. and Cochrane, K. 2005. Overview of world status of data-limited fisheries: inferences from landings statistics. In: Kruse, G.H., Galluci, D.E., Hay, R.I., Perry, R.I., Peterman, R.M., Shirley, T.C., Spencer, P.D., Wilson, B. and Woodby, D. (Eds). Fisheries Assessment and Management in Data-limited Situations. Alaska Sea Grant College Program, University of Alaska Fairbanks, 958 pp.
- Venables, W.N., Ripley, B.D. 2002. Modern and Applied Statistics with S. 4th Edition. Springer-Verlag, New York, 495 pp.
- Venables, W.N., Dichmont, C.M., Toscas, P., Bishop, J., Ye, Y. and Deng, A. 2003. Report to NORMAC on Effort Trade-off Proposals for the NPF. AFMA report 53pp.

- Venables, W.N., Dichmont, C.M., 2004. A Generalized Linear Model for catch allocation: An example from Australia's Northern Prawn Fishery. *Fisheries Research* 70, 409–426.
- Walters, C. J., Hilborn, R., 1976. Adaptive control of fishing systems. *Journal of Fisheries Research Board Canada* 33: 145–159.
- Walters, C.J., Collie, J.S., 1989. An experimental strategy for groundfish management in the face of large uncertainty about stock size and production. International Recruitment Investigations in the Subarctic (IRIS) and International North Pacific Fisheries Commission (INPFC) Symposium, Vancouver, B.C. (Canada), 26 Oct 1987, Canadian Special Publications of Fisheries and Aquatic Science.
- Wang, Y.-G., 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.
- Wang, Y-G., 1999. A Maximum-likelihood method for estimating natural mortality and catchability coefficient from catch-and-effort data. *Marine and Freshwater Research* 50: 307-311.
- Watson, R.A., Turnbull, C.T., Derbyshire, K.J., 1996. Identifying tropical penaeid recruitment patterns. *Marine and Freshwater Research* 47(1): 77-85.
- Williams, L.E. (Ed.) 2002. Queensland's fisheries resources: current condition and recent trends 1988-2000. Queensland Department of Primary Industries, 180 pp.
- Ye, Y., 2000. Is recruitment related to spawning stock in penaeid shrimp fisheries? *ICES Journal of Marine Science*. 57: 1103–1109.
- Ye, Y., Dichmont, C.M., Vance, D., BurrIDGE, C., Pendrey, B., Van Der Velde, T., Donovan, A., Deng, A., 2004. Designing, implementing and assessing an integrated monitoring program for the NPF: Developing an application to stock assessment FRDC Project No. 2003/075.
- Zacherin, W. (Ed.), 1997. Management plan for the South Australian Gulf St Vincent prawn fishery. South Australian Fishery Management Series Paper No 30, 26 pp.

APPENDIX 1 – THE DERISO MODEL



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Application of a weekly delay-difference model to commercial catch and effort data for tiger prawns in Australia's Northern Prawn Fishery

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Abstract

The two species of tiger prawn (*Penaeus semisulcatus* and *P. esculentus*) harvested in Australia's Northern Prawn Fishery are assessed by fitting a Deriso–Schnute delay-difference model to catch and effort data. The population dynamics model has a weekly time-step and allows for week-specificity in recruitment, spawning, availability and fishing mortality. The stock–recruitment relationship is fitted assuming temporally correlated environmental variability and by downweighting recruitments that are poorly determined by the catch and effort data. Uncertainty is quantified through sensitivity tests, variance estimation and future projections. The projections account for the technical interaction between the two species in that effort directed at one species leads to some mortality on the other species. Recruitment and spawning stock size are robustly estimated to have declined substantially but the status of the resource relative to MSY-based reference points is uncertain. The three factors to which the results are most sensitive are the value assumed for the catchability coefficient, the rate of change over time in fishing efficiency, and the future within-year effort distribution. Seasonal closures are shown to lead to increased yields at similar levels of risk to the resource, particularly for *P. semisulcatus*.

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Keywords: Tiger prawns; Stock assessment; Delay-difference model; Stock–recruitment; Catchability; Sensitivity

1. Introduction

The Northern Prawn Fishery (NPF) is the most valuable fishery managed by the Australian Commonwealth Government through its statutory body the Australian Fisheries Management Authority (AMFA). The NPF is managed using input controls in the form of limited entry, gear restrictions, and time and spatial closures. Management of this fishery has re-

cently moved from a system of tradeable vessel units (vessel engine power and hull size) to a system of gear units (headrope length). The NPF is based on three prawn species groups (banana, tiger and endeavour prawns), each of which includes at least two species.

Compared with tiger and endeavour prawns, common banana prawns (*Penaeus merguensis*) appear to be more heavily influenced by the environment than by fishing pressure (Vance et al., 1985; Die and Ellis, 1999). Therefore, quantitative stock assessments are not conducted for these species at present. Although endeavour prawns (*Metapenaeus endeavouri*

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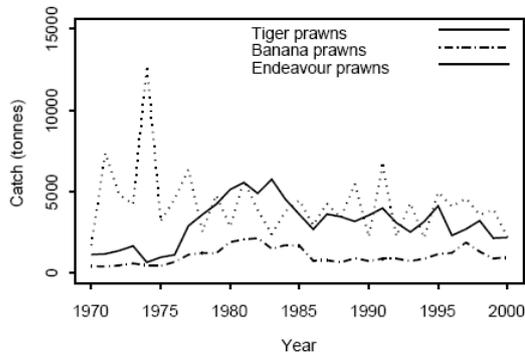


Fig. 1. Catch series (1970–2000) for the three groups of prawn species in the Northern Prawn Fishery.

and *M. ensis*) constitute a significant proportion of the catch in the NPF in recent years (Fig. 1), there are currently insufficient data on which assessments for these species could be based. Tiger prawns (*Penaeus semisulcatus* and *P. esculentus*), on the other hand, have been the focus for quantitative assessments for many years (Somers, 1990; Wang and Die, 1996; Somers and Wang, 1997) and have even been shown to be prone to recruitment overfishing (Wang and Die, 1996; Die et al., 2000). Excessive fishing effort during the 1980s led to an estimated decline in the size of the tiger prawn spawning stock, which was only halted through large, controversial and costly reductions in fishing effort. These reductions were achieved through a combination of licence buy-backs, proportional licence surrenders, additional seasonal closures and bans on daylight fishing (Wang and Die, 1996).

Assessments of the two tiger prawn species are complicated for several reasons: very high natural mortality implies that only a small proportion of prawns survive a year, availability to the fishery changes during the year (Hill and Wassenberg, 1985; Somers and Kirkwood, 1991), the catch is not divided to species in logbooks, and the only information available for determining the values for the parameters of the assessment model is a time-series of catch-rate data for the entire history of the fishery. Information from surveys (e.g. Somers, 1994) and about the length–composition of the catch is available for some years and areas of the fishery. However, the latter are not available

over a sufficiently long period and wide spatial extent for use in an assessment model. The commercial length–frequency information, although potentially informative about fishing mortality, is not currently in a form that is amenable to inclusion in the stock assessment.

The Northern Prawn Management Advisory Committee (NORMAC) is responsible for the provision of advice on species caught within the NPF to AFMA and agreed that the key operational management objective for the NPF is to set the level of fishing effort to that level, E_{MSY} , at which maximum sustainable yield (MSY) is achieved, with the underlying assumption that this will lead to the spawning stock being on average at the level at which MSY is achieved, S_{MSY} . Assessments are conducted annually by the Northern Prawn Fishery Assessment Group (NPFAG), which consists of scientists, managers and fishers. Ideally, the effort in the fishery would be adjusted annually to reflect changes to the estimate of E_{MSY} and the impact of changes over time in fishing efficiency (fishing power). Such changes are known to have occurred throughout the history of the fishery (Buckworth, 1985; Robins et al., 1998; Bishop et al., 2000), although the magnitude of change in fishing power constitutes a key uncertainty.

This paper outlines the approach currently used to assess the two tiger prawn species. Emphasis is placed on examining the uncertainty associated with the predictions through sensitivity analyses (changing the assumptions of the assessment model and the values assumed for some of its parameters), estimation of variance, and future projections. This paper extends the assessment framework developed by Wang and Die (1996), who conducted the first assessment of the two tiger prawn species using a fully age-structured model. The future projections represent the first attempt to use models to make dynamic predictions for tiger prawns that consider recruitment variability and serial correlation about the stock–recruitment function.

Although the indices of spawning stock size and recruitment are estimated independently for each species, estimation of the MSY-based reference points, S_{MSY} and E_{MSY} , and the future projections allow for technical interactions between the two species, in that effort directed at one species leads to some mortality on the other species.

2. Methods

The assessment relies on the use of the information on fishing mortality and recruitment contained in the within-season catch-rate dynamics. The calculation of the quantities of interest to management involves a three-step process:

- Estimation of indices of spawning stock size and recruitment using a delay-difference model.
- Estimation of the parameters of a Ricker stock–recruitment relationship based on the output from this model.
- Estimation of MSY , E_{MSY} , and S_{MSY} .

The indices of spawning stock size and recruitment are estimated separately from the parameters of the stock–recruitment relationship. This is, *inter alia*, to avoid assumptions about the form of the stock–recruitment relationship and the extent of variation and inter-annual correlation in the residuals about that relationship impacting the estimates of spawning stock size and recruitment.

2.1. Estimation of spawning stock size and recruitment

The approach used to estimate the time-series of historical recruitment and the indices of spawning stock size is based on a variant of the delay-difference model developed by Deriso (1980) and Schnute (1985). The model operates on a weekly time-step¹ and allows spawning and recruitment to the fishable population to occur each week. Allowance is also made for weekly changes in availability. Although the model does not explicitly consider the age-structure of the population unlike the model developed by Wang and Die (1996), this is not relevant because recruitment and maturity are reasonably assumed to occur at the same size/age.

The following sections outline the model for a given species and how the values for its free parameters are

¹ The weekly time-step is needed given the high natural mortality, high growth rate, and, particularly in recent years, short fishing season. Shorter time-steps (e.g. days) might be desirable to better capture the underlying dynamics of the resource but the basic catch and effort data cannot be extracted at this level of temporal resolution.

estimated. For ease of presentation, the equations below ignore the dependence on species.

2.1.1. Basic population dynamics

The dynamics of the recruited biomass and recruited numbers are governed using the equations:

$$\begin{aligned}
 B_{y,w+1} &= (1 + \rho)B_{y,w} e^{-Z_{y,w}} - \rho e^{-Z_{y,w}} \\
 &\quad \times (B_{y,w-1} e^{-Z_{y,w-1}} + W_{k-1}\alpha_{w-1}R_{\tilde{y}(y,w-1)}) \\
 &\quad + W_k\alpha_w R_{\tilde{y}(y,w)} \quad \text{and} \quad \tilde{N}_{y,w+1} \\
 &= \tilde{N}_{y,w} e^{-Z_{y,w}} + \alpha_w R_{\tilde{y}(y,w)} \quad (1)
 \end{aligned}$$

where $\tilde{N}_{y,w}$ is the number of recruited prawns (of both sexes) at the start of week w of year y , $B_{y,w}$ the biomass of recruited prawns (of both sexes) at the start of week w of year y , $Z_{y,w}$ the total mortality during week w of year y :

$$Z_{y,w} = M + F_{y,w} \quad (2)$$

α_w the fraction of the annual recruitment that occurs during week w (assumed to be independent of week); M the instantaneous rate of natural mortality (assumed to be independent of sex and age); $F_{y,w}$ the fishing mortality during week w of year y ; R_y the recruitment during ‘biological year’ y ; $\tilde{y}(y, w)$ the ‘biological year’ corresponding to week w of year y :

$$\tilde{y}(y, w) = \begin{cases} y & w < 40 \\ y + 1 & \text{otherwise} \end{cases} \quad (3)$$

ρ is the Brody growth coefficient (Ricker, 1975), W_{k-1} the average weight of a prawn the week before it recruits (in week k) to the fishery, and W_k the average weight of a prawn when it recruits to the fishery.

Eq. (3) implies that the ‘biological year’ ranges from week 40 (roughly the start of October) until week 39 (roughly the end of September). This choice is based on recruitment index data from surveys (Somers and Wang, 1997).

The fishing mortality during week w of year y on one of the two tiger species, $F_{y,w}$, includes contributions from targeted fishing on that species as well as from fishing on the other tiger prawn species, changes over time in fishing efficiency, and changes over the year in availability:

$$F_{y,w} = \tilde{q}A_wq_{y,w} \left(E_{y,w}^T + \frac{E_{y,w}^B}{q_b} \right) \quad (4)$$

$E_{y,w}^T$ is the effort during week w of year y ‘targeted’ towards the species under consideration, $E_{y,w}^B$ the ‘by-catch’ effort during week w of year y (the effort targeted at the other tiger prawn species), \tilde{q} the overall catchability coefficient (i.e. the catchability coefficient for the first week of 1993), q_b the by-catch catchability (the number of days of by-catch effort that is equivalent to a single ‘targeted’ effort day), A_w the relative availability during week w , $q_{y,w}$ the relative efficiency during week w of year y :

$$q_{y,w} = (\omega_y)^{(w-1)/52} \frac{\prod_{y' < y} \omega_{y'}}{\prod_{y'' < 1993} \omega_{y''}} \quad (5)$$

where ω_y is the efficiency increase during year y .

The value for the overall catchability coefficient, \tilde{q} , was estimated using data for 1993 (Wang, 1999) and hence applies to 1993. As a result, Eq. (5) is defined so that fishing efficiency is 1 at the start of 1993 (hence the division by the term $\prod_{y'' < 1993} \omega_{y''}$).

Specification of the values for the ω_y is difficult. It is clear to all participants in the fishery that 1 day’s fishing in the last decade of the 1990s when boats were modern and possessed the latest technical equipment is much more efficient (i.e. leads to larger fishing mortality) than 1 day’s fishing in 1970. However, the exact nature (and to some extent magnitude) of the change in efficiency is uncertain. Therefore, two alternative scenarios for how fishing efficiency may have changed over time (a constant rate and year-specific rates) are considered in the assessments (Fig. 2).

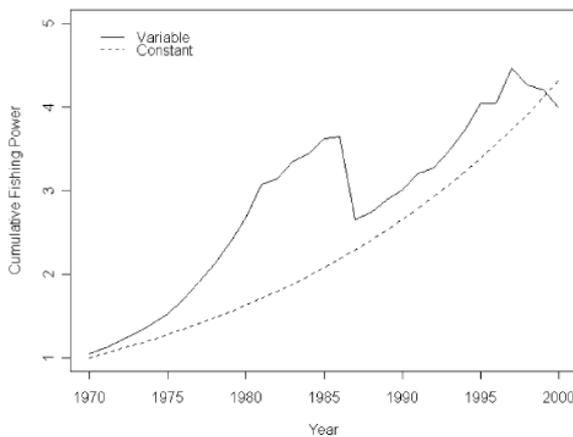


Fig. 2. Two alternative fishing power time-series. The base-case corresponds to a constant 5% rate of increase in fishing power.

Sensitivity tests also examine the impact of different (yet plausible) levels of change over time in efficiency. The two scenarios in Fig. 2 were selected by NORMAC and NPFAG based on analyses of catch-rate data, information on changes of over time in vessel design, information on changes in regulations regarding nets, and comments by commercial fishers. For example, the 5% figure is based, in part, on an analysis of changes in the amount of net trawled by each boat over the early years of the fishery (Buckworth, 1985), and measurements of the impact of the introduction of GPS and plotters from 1988 to 1992 (about 2.5% per annum) based on analyses of catch-rate data (Robins et al., 1998; Bishop et al., 2000).

The spawner stock size index for calendar year y , S_y , is given by

$$S_y = \sum_w \beta_w \frac{1 - e^{-Z_{y,w}}}{Z_{y,w}} \tilde{N}_{y,w} \quad (6)$$

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

2.1.2. The likelihood function

The values for the bulk of the parameters of the model are assumed known based on auxiliary information (Table 1). The values for the parameters that are not pre-specified (i.e. the annual recruitments for 1970–1999) are obtained by minimising an objective function involving the catch-in-weight data. Assuming that some function of observed catch-in-weight is normally distributed, the objective function is

$$L = \sum_y \sum_w \{ \log \sigma_c + \frac{1}{2\sigma_c^2} [k(Y_{y,w}^{obs}) - k(Y_{y,w})]^2 \} \quad (7)$$

where σ_c is the residual standard deviation, $Y_{y,w}^{obs}$ the observed catch (in weight) during week w of year y , $Y_{y,w}$ the model estimate of the catch (in weight) during week w of year y :

$$Y_{y,w} = \frac{F_{y,w}}{Z_{y,w}} B_{y,w} (1 - e^{-Z_{y,w}}) \quad (8)$$

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

The summations in Eq. (7) 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

Table 1

The values assumed for the parameters of the population dynamics model that are based on auxiliary information (source (unless stated otherwise): Dichmont et al., 2001)

Quantity	Value	Major data source
Relative weekly recruitment, α_w	Fig. 3a	Monthly survey data spanning several years
Relative weekly spawning, β_w	Fig. 3b	Monthly survey data spanning several years
Relative weekly availability, A_w	Fig. 3c	Survey data for <i>P. semisulcatus</i> ; experimental and survey data for <i>P. esculentus</i>
Overall catchability, \tilde{q}	0.000088	1993 catch and effort data (Wang, 1999)
By-catch catchability, q_b	11.11 (<i>P. esculentus</i>), 8.26 (<i>P. semisulcatus</i>)	Catch and effort data (Somers and Wang, 1997)
Annual efficiency increase, ω_y	Fig. 2	Selected by the assessment group
Length-at-recruitment	Males: 26 mm, females: 28 mm	Survey data (Wang and Die, 1996)
Brody growth coefficient, ρ	0.982 (<i>P. esculentus</i>), 0.979 (<i>P. semisulcatus</i>)	Tagging data (Kirkwood and Somers, 1984; Somers and Kirkwood, 1991)
Weight-at-recruitment, W_k	18.4 g (<i>P. esculentus</i>), 16.5 g (<i>P. semisulcatus</i>)	Tagging data (Kirkwood and Somers, 1991)
Weight the week prior to recruitment, W_{k-1}	17.4 g (<i>P. esculentus</i>), 15.1 g (<i>P. semisulcatus</i>)	Tagging data (Kirkwood and Somers, 1984; Somers and Kirkwood, 1991)
Rate of natural mortality, M	0.045 per week	Tagging data and literature from other fisheries (Wang and Die, 1996)

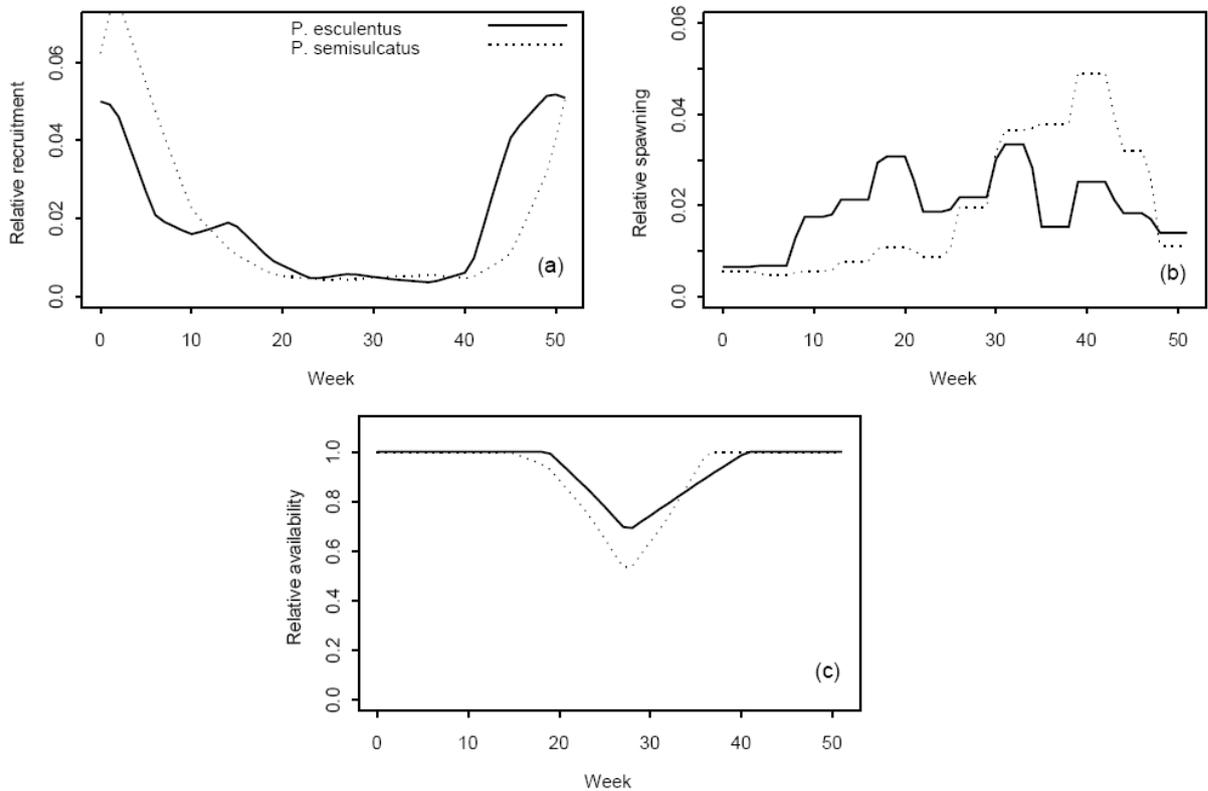


Fig. 3. Within-year patterns of recruitment, spawning and availability for the two tiger prawn species.

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.

The recruitment in the first year (1969/1970) is assumed to be same as that in the second year (1970/1971), while the recruitment for the last year (2000/2001) is fixed to be equal to that for 1999/2000. The former assumption is made because there are no catches for 1969, so the 1969 recruitment is essentially non-estimable. However, it is needed so that population age-structure for 1970 can be initiated. Given the high natural mortality rate, the results are insensitive to this assumption. The 2000/2001 recruitment is not an estimable parameter of the model because the data for 2000 provide very little information about the magnitude of this recruitment. This is due to the fact that only a small fraction of the 2000 fishery occurred after October (when the 2000/2001 year-class first recruited to the fishery).

2.1.3. Calculating the catch and effort by week and species

Survey work (mainly in the Gulf of Carpentaria; see, for example, Somers (1994) and references therein) suggests that the tiger prawn species at a particular location is determined primarily by the substrate. However, lack of detailed information on substrate, the reporting of catches in logbooks at a fairly coarse spatial scale (the $6' \times 6'$ grid in which most of the night's fishing was done²), spatial variability in substrate type, and the fact that hauls may cover a very large area, imply that splitting the catch to species is non-trivial. The approach used in this paper to split the catch by $6' \times 6'$ grid to species was proposed by Somers and Wang (1997). It assumes that the species split for a given grid in the NPF is time-invariant:

1. Calculate a relative split, by weight, for each species for all grid squares included in the surveys.
2. If a logbook catch is ascribed to a $6' \times 6'$ grid for which a survey-based split proportion estimate is available, partition the catch using that estimate.

² Up to 1400 $6' \times 6'$ grids have been fished in a given year.

3. In other cases, use the split proportions for the geographically nearest grid for which a survey-based proportion estimate is available.

This approach does not assume the $6' \times 6'$ grids are homogeneous in substrate composition. Rather, it assumes 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.

2.2. Fitting the stock–recruitment relationship

The recruitment for biological year $y+1$ is assumed to be related to the spawning stock size for (calendar) year y , S_y (see Eq. (6)) according to a Ricker³ stock–recruitment relationship:

$$\hat{R}_{y+1} = \tilde{\alpha} S_y e^{-\tilde{\beta} S_y} \quad (9)$$

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; and $\tilde{\alpha}$, $\tilde{\beta}$ the parameters of the stock–recruitment relationship.

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

$$R_y = \hat{R}_y e^{\eta_y}, \quad \eta_{y+1} = \rho_r \eta_y + \sqrt{1 - \rho_r^2} \xi_{y+1}, \\ \xi_{y+1} \sim N(0; \sigma_r^2) \quad (10)$$

where ρ_r is the environmentally driven temporal correlation in recruitment, and σ_r the (environmental) variability in recruitment about the stock–recruitment relationship.

Estimation of the four parameters of the stock–recruitment relationship ($\tilde{\alpha}$, $\tilde{\beta}$, ρ_r and σ_r) involves minimising the following objective function:

$$L = \log \left(\sqrt{\det(\Omega + V)} \right) + \frac{1}{2} \sum_{y_1} \sum_{y_2} (\log R_{y_1} \\ - \log \hat{R}_{y_1}) ([V + \Omega]^{-1})_{y_1, y_2} (\log R_{y_2} - \log \hat{R}_{y_2}) \quad (11)$$

³ Results (not shown here) indicate that the estimates of MSY , E_{MSY} and S_{MSY} are insensitive to whether recruitment is related to spawner stock size according to the Beverton–Holt or Ricker stock–recruitment relationships (Dichmont et al., 2001; Table 2).

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 Eq. (10)) which implies that the correlation between the recruitments for years y_1 and y_2 is $\rho_r^{|y_1-y_2|}$, i.e. the entries in the Ω matrix are $\sigma_r^2 \rho_r^{|y_1-y_2|}$. The V matrix is the (asymptotic) variance–covariance matrix obtained by fitting the population dynamics model (Eqs. (1)–(8)) to the catch and effort data. 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).

2.3. Estimation of E_{MSY}

The calculation of E_{MSY} and MSY for each of the two species 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.

E_{MSY} is assumed to be different for *P. semisulcatus* and *P. esculentus* although E_{MSY} cannot be estimated separately for each species because, through Eq. (4), targeted fishing for *P. semisulcatus* implies some fishing mortality on *P. esculentus* and vice versa. Therefore, E_{MSY} (and consequently MSY and S_{MSY}) are obtained by maximising the sum of the catches of the two species. Simply summing the catches of the two species when defining MSY is appropriate in this case because the price is independent of species.

The equilibrium catch for one of the species from an annual cohort as a function of the total annual effort targeted on the two species, $C(E)$, is computed as $C(E) = \tilde{C}(E)R(E)$, 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 (Eq. (1)) forward for 10 years under the assumption that recruitment is unity (i.e. $R_y = 1$) in the first year and then zero thereafter. The choice of 10 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 weight (see

Eq. (8)) over time. A by-product of the 10-year projection is the spawning index (per recruit) as a function of effort, $\tilde{S}(E)$. Recruitment as a function of effort is computed from the stock–recruitment relationship (see Eq. (9)), 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 this leads to

$$R(E) = \frac{\log(\tilde{\alpha}S(E))}{\tilde{\beta}S(E)} \quad (12)$$

It is necessary to specify the within-year pattern of effort in order to calculate $\tilde{C}(E)$ and hence E_{MSY} and MSY. This pattern has changed over the history of the fishery due to changes to the management regulations, such as the introduction of a mid-year spawning closure and a seasonal closure over the December/January period. The base-case assumption of this paper is that the average pattern of effort over the years 1993–2000 provides the ‘best’ appraisal of the future within-year distribution of effort.

2.4. Representing uncertainty and conducting projections

The uncertainty associated with the values for the parameters of the population dynamics model can be determined from the asymptotic variance–covariance matrix obtained by inverting the Hessian matrix. It is, however, also necessary to have a set of alternative vectors of model parameters in order to conduct the projections and to compute the variances of quantities that are functions of the parameters. These vectors are generated from the variance–covariance matrix assuming that the parameters are normally distributed.⁴

The projections involve pre-specifying the future time-series of fishing effort (both target and by-catch effort, and split to week) and projecting from the final year of the assessment (2000) for the pre-specified number of years. 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 (2000).

⁴ This approach is referred to as the ‘numerical delta’ method by Patterson et al. (2001).

- (c) For each year, y , from the last year of the assessment until the final year of the projection:
- (i) generate a recruitment residual for biological year $y + 1$, η_{y+1} (see Eq. (10));
 - (ii) project the model from the start to the end of year y for different choices of R_{y+1} until the equation $R_{y+1} = \tilde{\alpha} S_y e^{-\tilde{\beta} S_y} e^{\eta_{y+1} - \sigma_r^2/2}$ is satisfied.

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

3. Results and discussion

The results from the stock assessment are voluminous (e.g. recruitment numbers by week), and need to be summarised further. For the purposes of this paper, the results are summarised by the four quantities of greatest interest to the decision makers:

- (a) Steepness: the expected recruitment at 20% of the virgin spawner stock size (Francis, 1992).
- (b) The ratio (expressed as a percentage) of the spawner stock index for 2000 to S_{MSY} (abbreviation ‘ S_{2000}/S_{MSY} ’).
- (c) MSY: the (deterministic) maximum sustainable yield.
- (d) E_{MSY} : the effort level at which MSY is achieved.

The steepness of the stock–recruitment relationship is reported as it indicates the relative productivity of the resource. S_{2000}/S_{MSY} and E_{MSY} are quantities that relate to the current management objectives for the fishery (values for S_{2000}/S_{MSY} less than 100% indicate over-exploitation, while employing a fishing effort equal to E_{MSY} is a current management objective for the fishery). For consistency with the definition of fishing power (see Eq. (5)), E_{MSY} is expressed in terms of 1993 days.

3.1. Choice of transformation function for the catch-in-weight data

The assessments conducted by Wang and Die (1996) assumed the errors in catch-in-weight were independent of the size of the catch-in-weight (i.e. the function $k()$ in Eq. (7) was set to the identity

function). However, this choice of transformation function leads to somewhat non-normal error distributions (Fig. 4). In contrast, assuming that the square root of the catch-in-weight is normally distributed removes this problem (Fig. 4). The remaining analyses of this paper are consequently based on the square root transformation.

3.2. The base-case analyses

The base-case analyses use the square root transformation when fitting to the catch-in-weight data and assume a 5% annual constant increase in fishing power (Fig. 2; ‘constant’). Fig. 5 shows the time-trajectories for recruitment and spawning stock size (with 90% confidence intervals) and Fig. 6 shows the fit of the Ricker stock–recruitment relationship to the spawning stock size and recruitment data for the base-case analyses. The time-series of spawning stock size and recruitment are both one-way trips (essentially continuous declines in spawning stock size and recruitment with some stability in the most recent years). The patterns of recruitment are mimicked in those of spawner stock size because, given the high rate of natural mortality, the bulk of the spawner stock size for a particular calendar year consists of the recruits from the previous year.

Fig. 5 shows that the uncertainty associated with the estimates of recruitment is greatest for the earliest and (to a much lesser extent) the most recent years. This pattern is as expected from results for age-based virtual population analyses (e.g. Butterworth et al., 1990). This uncertainty is taken into account when fitting the stock–recruitment relationship (Eq. (11)), because the poorly determined recruitments are downweighted. It should be noted, however, that the error bars in Fig. 5 almost certainly underestimate the true extent of uncertainty because the analyses on which Fig. 5 are based involve fixing many of the parameters based on auxiliary information and ignoring among-year variation in availability, recruitment and spawning. The estimates of steepness (e.g. 0.302 and 0.271 for *P. esculentus* and *P. semisulcatus*, respectively) are low compared to estimates of steepness for teleost fish species (e.g. Myers et al., 1999). This is particularly surprising given that the time-series nature of the stock and recruitment data is likely to lead to positively biased estimates of steepness (Walters, 1985).

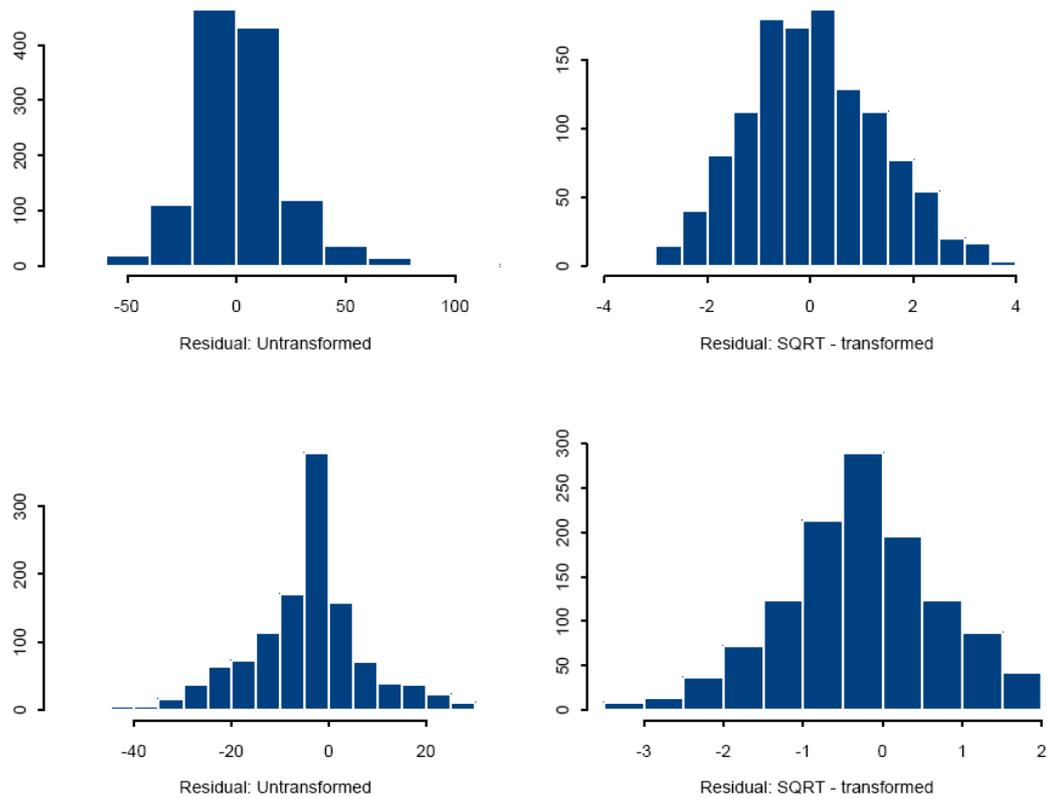


Fig. 4. Residuals about the fits to the catch-in-weight data for *P. esculentus* and *P. semisulcatus* (upper and lower panels, respectively). Results are shown in the left panels when the untransformed catches-in-weight are assumed to be normally distributed and in the right panels when the catches-in-weight after square root transformation are assumed to be normally distributed.

3.3. Assessment sensitivity tests

An extensive examination of sensitivity was conducted (Dichmont et al., 2001; Table 2). The results from the assessments were, however, highly sensitive to only three factors: the assumed value for the overall catchability coefficient, the assumed rate of efficiency increase, and the fishing effort pattern used to calculate the yield per recruit.

3.3.1. The overall catchability coefficient

The base-case and all previous assessments have assumed (rather than estimated) the value for the overall catchability coefficient. Fig. 7 shows a likelihood profile for this parameter. Somewhat unexpectedly, the best fits to the data occur for very low values for the overall catchability coefficient (corresponding to an essentially infinite population size). However, the

relationship between recruitment and spawner stock size becomes increasingly linear (a value for steepness closer to 0.2) as the assumed value of the overall catchability coefficient is reduced (Fig. 7, upper right panel). Values for steepness of 0.2 are, however, unrealistic as they imply no surplus production. The ratio of current effort to E_{MSY} is largely independent of the overall catchability coefficient although this is not the case for the ratio S_{2000}/S_{MSY} .

Ye (2000) overviews the information on stock and recruitment for a range of short-lived prawn species. The estimates of steepness for tiger prawns implied by the data in Ye (2000) range from 0.2 to 0.8. This range would suggest that values for catchability lower than that in Table 1 are probably implausible. In principle, the information in Ye (2000) could be included more formally in the assessment through some sort of penalty function (or prior) on steepness. However,

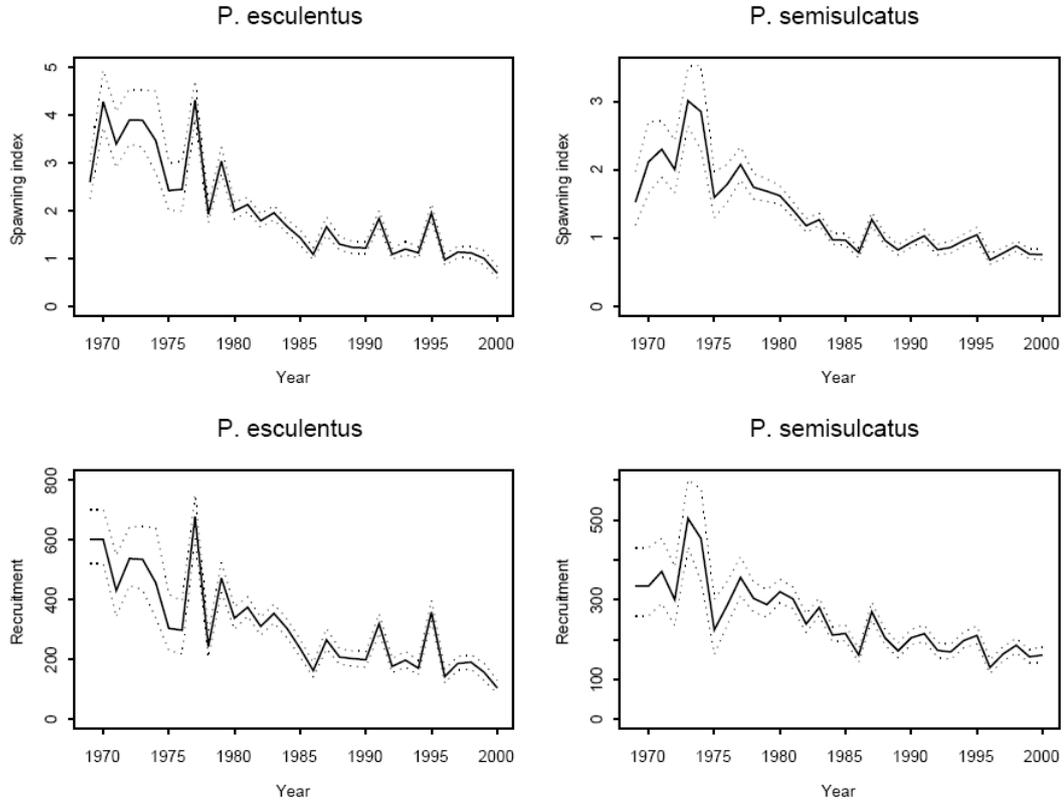


Fig. 5. Medians and 90% confidence intervals for the time-trajectories of spawning stock size and recruitment for the base-case analyses.

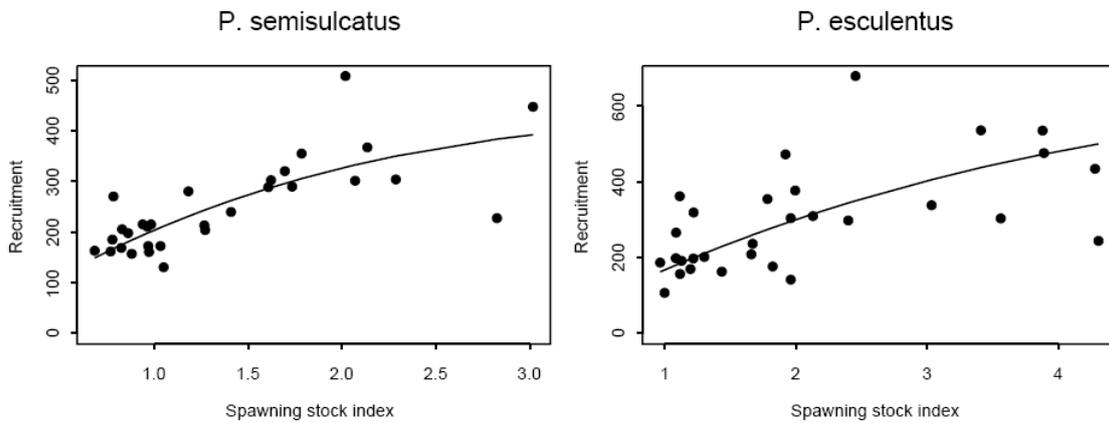


Fig. 6. The stock–recruitment relationships for the base-case analyses.

Table 2
Overview of the sensitivity tests^a

Sensitivity test	Impact on MSY and E_{MSY}	Impact on recruitment and depletion
<i>Recruitment pattern</i>		
Earlier by 1 month	Low	Low
Later by 1 month	Low	Low
Overall catchability coefficient	High	Low
Annual efficiency increase	High	High
Within-year availability pattern estimated with a sine function	Better fits, but model does not produce sensible parameter estimates	
<i>Brody growth coefficient</i>		
Shape of the stock–recruitment relationship (Ricker or Beverton–Holt)	Low	Low
Within-year fishing pattern (future)	High	N/A
Transformation of catch in the likelihood function (square root, logarithm or unity)	Low	Medium
Input data uncertainty included ^b	Low	Low
Process error in natural mortality ^b	Low	Low
Process error in weekly recruitment pattern ^b	Low	Low
Process error in catchability ^b	Low	Low
Process error in catch-at-age ^b	Low–medium	Low–medium
Error in species distribution and division ^b	Low	Low

^a Columns 2 and 3 provide a qualitative summary of the impact of the sensitivity test.

^b See Dichmont et al. (2001) for the technical specifications for these sensitivity tests.

such inclusion is beyond the scope of the present assessment. The high steepness values reported by Ye (2000) were estimated in one area only and using survey and commercial logbook data, while the

lower values tended to be based on commercial data only which may suggest that the information in Ye (2000) is insufficient to develop penalty functions or priors.

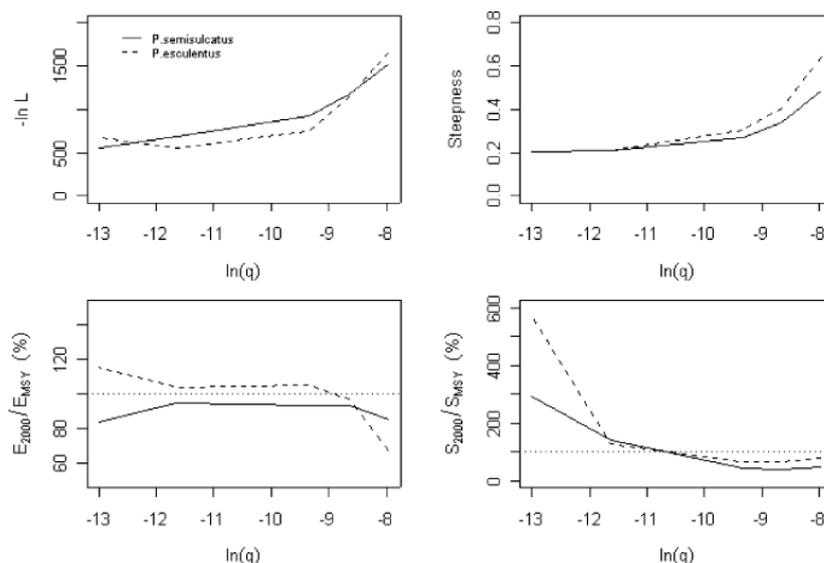


Fig. 7. The negative of the logarithm of the likelihood function, steepness, E_{2000}/E_{MSY} , and S_{2000}/S_{MSY} as a function of the assumed value for the logarithm of the overall catchability coefficient.

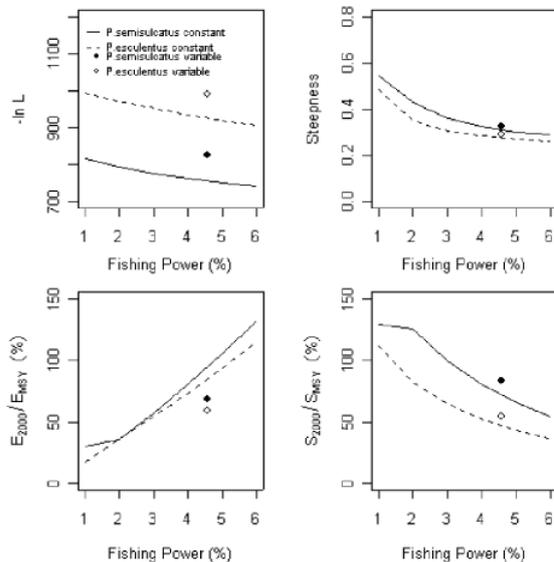


Fig. 8. The negative of the logarithm of the likelihood function, steepness, E_{2000}/E_{MSY} , and S_{2000}/S_{MSY} as a function of the rate of efficiency increase. The solid dots denote the results for the 'variable' option in Fig. 2.

3.3.2. Fishing power

The base-case analysis and all previous assessments have been based on the assumption that fishing power has been increasing at a fixed percentage each year. The base-case percentage is 5% ('constant' in Fig. 2) and sensitivity has been explored in the past to alternative constant rates of fishing power increase (e.g. Wang and Die, 1996). Recently, the assumption of constancy has been questioned given the known history of changes in technology and regulations in the fishery (Northern Prawn Fisheries Assessment Group, pers. commun.), resulting in the creation of an alternative time-sequence of changes in fishing power ('variable' in Fig. 2).

The results are very sensitive to assumptions about changes over time in fishing efficiency (Fig. 8). As expected, the results become more pessimistic (lower values for steepness, S_{2000}/S_{MSY} and higher values for E_{2000}/E_{MSY}) with higher (assumed) values for the constant rate of efficiency increase. The results are also sensitive to how changes in fishing efficiency have occurred (contrast the results for the 'variable' scenario in Fig. 8 (an annual geometric mean increase of about 4.6%) with those for a constant rate of in-

crease of 5%). The reason for the sensitivity in this case is that a major decline in fishing power is assumed to have occurred in 1987 under the 'variable' scenario, and the subsequent low annual fishing power increase over the last 5 years (see Fig. 2) is predicted to have resulted in some resource recovery. The constant 5% and 'variable' scenarios differ to the greatest extent in terms of E_{2000}/E_{MSY} (due to differences in E_{2000} rather than E_{MSY}). It is also noteworthy that the negative log likelihood is appreciably higher for the 'variable' scenario than for the constant 5% scenario suggesting that the catch and effort data supply some information about the time-sequence of changes in fishing efficiency, although not too much about the overall extent of this change.

3.3.3. Within-year effort distribution

Fishing occurred almost throughout the year during the early 1980s. By 1993, the year in which there was a large-scale buy-back of vessel units, there were mid-year as well as December/January closures. The sensitivity of the results to assuming a uniform distribution of effort is explored in Table 3. The differences between within-year effort distribution scenarios in Table 3 are due only to differences in the estimates of quantities related to MSY because the indices of spawning stock size and recruitment and the parameters of the stock–recruitment relationship are based on the historical catch and effort data for which the within-year distribution of effort is known. Table 3 therefore implicitly examines the benefits of the seasonal closures. MSY and E_{MSY} are both higher for the most recent within-year effort pattern. Therefore, the seasonal closures both reduce fishing mortality and simultaneously increase potential yields.

3.4. Future projections

Fig. 9 shows the trade-off between the probability that S_{2010} exceeds S_{MSY} and the average catch over the years 2001–2010 associated with different total levels of fishing effort (expressed in 1993 days) from 0 (closure) to 40,000 days based on the base-case analysis. The total effort is split to targeted effort by species in the ratio of the base-case point estimates of E_{MSY} for the two species. The within-year fishing effort pattern for these projections is assumed either to be uniform or the average pattern during 1993–2000.

Table 3

Management-related quantities (point estimates and 90% intervals) for variants of the base-case assessment, which modify the assumption regarding the within-year distribution of future fishing effort

Quantity	1993–2000 average		Uniform	
	<i>P. semisulcatus</i>	<i>P. esculentus</i>	<i>P. semisulcatus</i>	<i>P. esculentus</i>
S_{1999}/S_{MSY} (%)	66 (54–81)	43 (31–58)	68 (55–83)	43 (31–58)
MSY (t)	1709 (1449–2022)	1418 (1078–2040)	1496 (1505–1789)	1343 (1020–1932)
E_{MSY} (1993 days)	11041 (8623–14744)	6588 (4709–11388)	6986 (5609–8963)	5527 (4002–9239)

As expected, the probability of being below S_{MSY} in 2010 increases as a function of effort. The results for the best estimate of E_{MSY} are highlighted in Fig. 9 because the present constant effort policy applied to manage tiger prawns in the NPF is based on E_{MSY} . The average catch also increases as a function of effort. However, unlike S_{2010}/S_{MSY} , 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. The difference in the risk-reward curves between the uniform and 1993–2000 average effort patterns is much smaller for *P. esculentus* than for *P. semisulcatus*.

There is a distinct difference between the results for *P. semisulcatus* and those for *P. esculentus* in terms of risk and reward. For *P. semisulcatus*, risk rises sharply after an effort of 5000 standardised days. Conversely,

for a small decrease in average catch, the risk can be reduced substantially. This is not the case for *P. esculentus*. The risk is already substantially higher at 5000 days than for *P. semisulcatus*. A small reduction in risk results in a similar decrease in catch. This difference may reflect the lower productivity of *P. esculentus*.

There appear to be substantial benefits to be gained by appropriately chosen seasonal closures, especially for *P. semisulcatus*. For this species, there is a large difference between the results for a uniform fishing pattern and those for an effort distribution pattern equal to the average during 1993–2000. The major differences between the two 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 part of the year imply that little effort is applied to *P. semisulcatus* prior to spawning. However, this is not the case for *P. esculentus* and

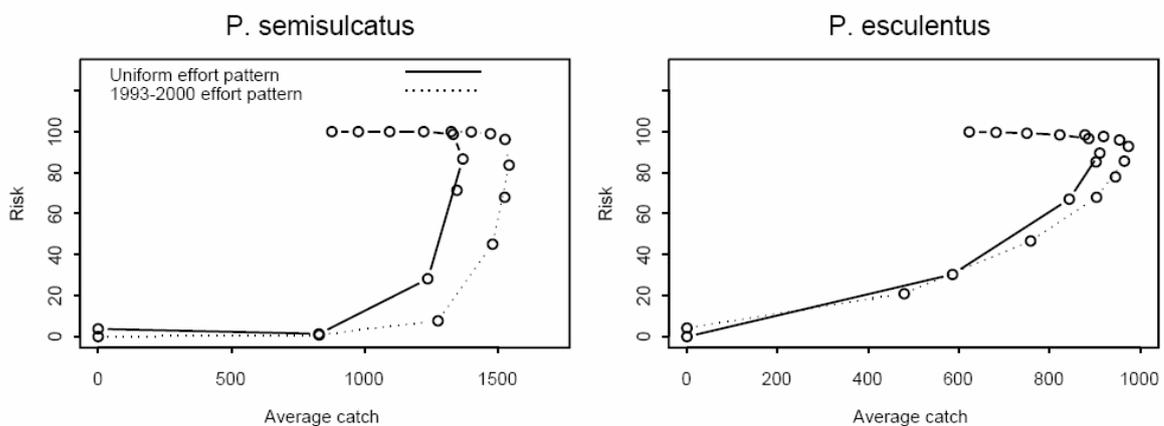


Fig. 9. The probability that S_{2010} exceeds S_{MSY} (“risk”) versus the average catch during 2001–2010. Results are shown for *P. semisulcatus* and *P. esculentus* and for two assumptions regarding the within-year distribution of future fishing effort. The open symbols denote the results corresponding to setting future fishing effort to the current best estimate of E_{MSY} .

therefore much of the effort on *P. esculentus* occurs prior to spawning even with the recent within-year effort pattern.

3.5. General discussion

The approach used to provide management advice for tiger prawns in Australia's Northern Prawn Fishery is based on fitting a population dynamics model to weekly catch and effort data. Assessment approaches based on fitting population dynamics models have formed the basis for management advice for tiger prawns in the NPF for several years (e.g. Wang and Die, 1996; Haddon, 1997). A few prawn resources elsewhere in the world are assessed using fishery-independent as well as commercial catch and effort data (e.g. Quinn et al., 1998), while Caputi et al. (1998) illustrate how it is possible to estimate the stock–recruitment relationship directly from data collected from a fishery. The population dynamics model that underlies the analyses of this paper has been tailored to the specifics of NPF tiger prawns by allowing for week-specificity in recruitment, spawning and availability. The weekly nature of the population dynamics model also enables changes over time in season length to be considered. Table 3 suggests that the results are highly sensitive to the within-year effort distribution pattern and ignoring this when conducting assessments would have led to considerable bias.

The modelling approach adopted for tiger prawns is, however, not without its problems. For example,

it is clear from Fig. 7 that catchability, availability, recruitment and fishing-induced mortality cannot be distinguished given catch and effort data alone. These factors could be distinguished, in principle at least, had time-series of catch-at-age data been available. However, this was not the case. The solution adopted in this paper to pre-specify catchability and availability using auxiliary information is therefore necessary but certainly not ideal. The use of time-invariant recruitment, availability and spawning patterns (Fig. 3) is less-than-ideal but is unavoidable in the absence of additional data. The last five sensitivity tests in Table 2 involve assessing the likely impact of uncertainty about the values for parameters assumed known from auxiliary information. These sensitivity tests involved generating values for the fixed parameters of the assessment from subjective priors and re-running the assessment. Replicating this process leads to a distribution of outcomes. However, the widths of these distributions were relatively narrower than those based solely on the uncertainty associated with fitting the model to the data. Although the square root transform improves the normality of the residuals (Fig. 4), within-year patterns in the residuals remain (Fig. 10). Attempts to remove this by postulating different within-year patterns in availability failed as this led to further confounding.

By-catch catchability is included when estimating the annual recruitment and spawning stock indices and when calculating E_{MSY} . The former is relatively standard as it simply reflects accounting for

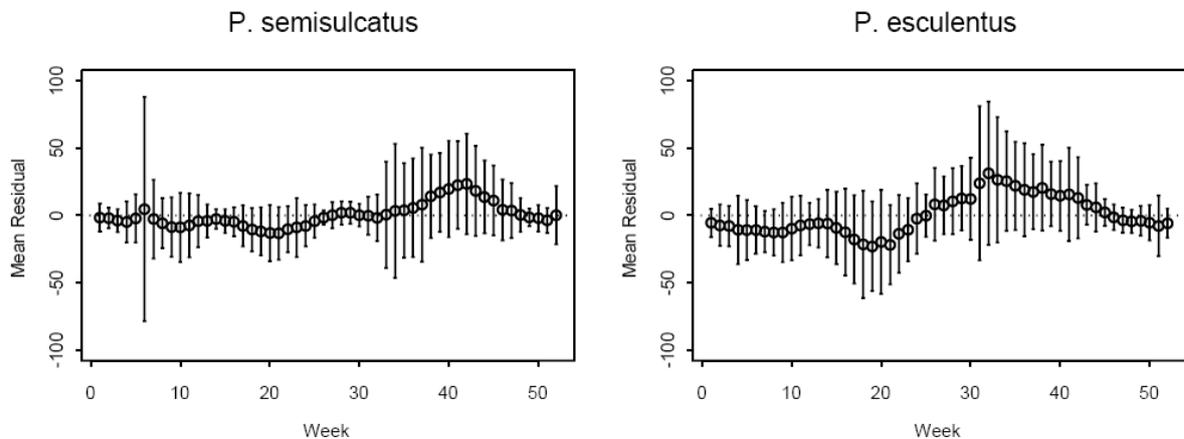


Fig. 10. Within-year residual patterns about the fit to the catch-in-weight data for the base-case analysis.

all known catches. In contrast, the latter is novel, even for assessments of teleosts. Including by-catch catchability when computing E_{MSY} is, however, an important factor for this assessment—ignoring the by-catch catchability when computing E_{MSY} would lead to an over-estimation of the target effort by roughly 10%.

The estimates of the management-related quantities were found to be sensitive to the assumptions about the distribution of effort across the season. The uniform fishing year led to lower estimates for MSY and E_{MSY} than using the average of the pattern during 1993–2000. This result highlights the benefits of reducing effort during key periods in the life cycle of the animal (e.g. spawning and recruitment).

As is often the case, some of the results are robust to uncertainty while others are not. The result which is common to all analyses is that recruitment (and the spawning stock) in recent years is substantially smaller than at the start of the fishery. Unfortunately, the steepness of the stock–recruitment relationship is not well determined by the data, being close to implausibly low when compared with estimates of this parameter for teleosts. Unfortunately, the values for the key management reference points MSY and E_{MSY} , and hence whether the resource should be considered to be over-exploited, are highly sensitive to the shape of the stock–recruitment relationship. Although the bulk of the results point to the qualitative conclusion that both tiger prawn species, particularly *P. esculentus*, are currently over-exploited, the sensitivity of the stock–recruitment relationship to the assumptions underlying the assessments questions the use of MSY-related management quantities and indeed any reference points that rely on the use of a stock–recruitment relationship. One way to identify more appropriate reference points would be through the use of the management strategy evaluation approach (Smith, 1994; Punt et al., 2001).

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References

- Bishop, J., Die, D., Wang, Y.-G., 2000. A generalized estimating equations approach for analysis of the impact of new technology on a trawl fishery. *Aust. NZ J. Stat.* 42, 159–177.
- Buckworth, R.C., 1985. Preliminary results of a study of commercial catches, spawning and recruitment of *Penaeus esculentus* and *P. semisulcatus* in the western Gulf of Carpentaria. In: Rothlisberg, P.C., Hill, B.J., Staples, D.J. (Eds.), *Proceedings of the Second Australian National Prawn Seminar (NPS2)*, Cleveland, Australia, pp. 213–225.
- Butterworth, D.S., Hughes, G.S., Strumpfer, F., 1990. VPA with ad hoc tuning: implementation for disaggregated fleet data, variance estimation, and application to the horse mackerel stock in ICSEAF Divisions 1.3 + 1.4 + 1.5. *S. Afr. J. Mar. Sci.* 9, 327–357.
- Caputi, N., Penn, J.W., Joll, L.M., Chubb, C.F., 1998. Stock–recruitment–environment relationships for invertebrate species of Western Australia. In: *Proceedings of the North Pacific Symposium on Invertebrate Stock Assessment and Management*. Canadian Special Publications, Fish. Aquat. Sci. 125, 247–255.
- Deriso, R.B., 1980. Harvesting strategies and parameter estimation for an age-structured model. *Can. J. Fish. Aquat. Sci.* 37, 268–282.
- Dichmont, C.M., Die, D., Punt, A.E., Venables, W., Bishop, J., Deng, A., Dell, Q., 2001. Risk analysis and sustainability indicators for prawn stocks in the Northern Prawn Fishery. Report of FRDC 98/109. CSIRO Marine Research, Cleveland, 187 pp.
- Die, D.J., Ellis, N., 1999. Aggregation dynamics in penaeid fisheries: banana prawns (*Penaeus merguensis*) in the Australian Northern Prawn Fishery. *Mar. Freshw. Res.* 70, 667–675.
- Die, D., Loneragan, N., Haywood, M., Vance, D., Manson, F., Taylor, B., Bishop, J., 2000. Indices of recruitment and effective spawning for tiger prawn stocks in the Northern Prawn Fishery. Report of FRDC 95/014. CSIRO Marine Research, Cleveland, 180 pp.
- Francis, R.I.C.C., 1992. Use of risk analysis to assess fishery management strategies: a case study using orange roughy (*Hoplostethus atlanticus*) on the Chatham Rise, New Zealand. *Can. J. Fish. Aquat. Sci.* 49, 922–930.
- Haddon, M., 1997. A biomass-dynamic model of the northern tiger prawn fishery: an alternative estimate of potential long-term yields. NPFAG document 1996/4. Available from the Australian Fisheries Management Authority, Canberra, 25 pp.
- Hill, B.J., Wassenberg, T.J., 1985. A laboratory study of the effect of streamer tags on mortality, growth, moulting and duration of nocturnal emergence of the tiger prawn *Penaeus esculentus* (Haswell). *Fish. Res.* 3, 223–235.
- Kirkwood, G.P., Somers, I.F., 1984. Growth of two species of tiger prawn, *Penaeus esculentus* and *P. semisulcatus* in the western Gulf of Carpentaria. *Aust. J. Mar. Freshw. Res.* 35, 703–712.

- Myers, R.A., Bowen, K.G., Barrowman, N.J., 1999. Maximum reproductive rate of fish at low population size. *Can. J. Fish. Aquat. Sci.* 56, 2404–2419.
- Patterson, K., Cook, R., Darby, C., Gavaris, S., Kell, L., Lewy, P., Mesnil, B., Punt, A., Restrepo, V., Skagen, D.W., Stefansson, G., 2001. Estimating uncertainty in fish stock assessment and forecasting. *Fish. Fish.* 2, 125–157.
- Punt, A.E., Smith, A.D.M., Cui, G., 2001. Review of progress in the introduction of management strategy evaluation (MSE) approaches in Australia's South East Fishery. *Mar. Freshw. Res.* 52, 719–726.
- Quinn II, T.J., Turnbull, C.T., Caihong, F., 1998. A length-based population model for hard-to-age invertebrate populations. In: Funk, F., Quinn II, T.J., Heifetz, J., Ianelli, J.N., Powers, J.E., Schweigert, J.F., Sullivan, P.J., Zhang, C.I. (Eds.), *Fishery Stock Assessment Models*. University of Alaska Sea Grant AK-SG-98-01, Fairbanks, pp. 531–536.
- Ricker, W.E., 1975. *Handbook of Computations for Biological Statistics of Fish Populations*. Bulletin of Fisheries Research Board of Canada, vol. 191, p. 382.
- Robins, C.M., Wang, Y.-G., Die, D., 1998. The impact of global positioning system and plotters on fishing power in the northern prawn fishery, Australia. *Can. J. Fish. Aquat. Sci.* 55, 1645–1651.
- Schnute, J.T., 1985. A general theory for analysis of catch and effort data. *Can. J. Fish. Aquat. Sci.* 42, 414–429.
- Smith, A.D.M., 1994. Management strategy evaluation—the light on the hill. In: Hancock, D.A. (Ed.), *Population Dynamics for Fisheries Management*. Australian Society for Fish Biology Workshop Proceedings, Perth, August 24–25, 1993. Australian Society for Fish Biology, Perth, pp. 249–253.
- Somers, I.F., 1990. Manipulation of fishing effort in Australia's penaeid prawn fisheries. *Aust. J. Mar. Freshw. Res.* 41, 1–12.
- Somers, I.F., 1994. Species composition and distribution of commercial penaeid prawn catches in the Gulf of Carpentaria, Australia, in relation to depth and sediment type. *Aust. J. Mar. Freshw. Res.* 45, 317–335.
- Somers, I.F., Kirkwood, G.P., 1991. Population ecology of the grooved tiger prawn, *Penaeus semisulcatus*, in the north-western Gulf of Carpentaria, Australia: growth, movement age structure and infestation by the bopyrid parasite *Epipenaeon ingens*. *Aust. J. Mar. Freshw. Res.* 42, 349–367.
- Somers, I., Wang, Y., 1997. A simulation model for evaluating seasonal closures in Australia's multispecies Northern Prawn Fishery. *N. Am. J. Fish. Manage.* 17, 114–130.
- Vance, D.J., Staples, D.J., Kerr, J.D., 1985. Factors affecting year-to-year variation in the catch of banana prawns (*Penaeus merguensis*) in the Gulf of Carpentaria, Australia. *J. Conserv. Int. Explor. Mer.* 42, 83–97.
- Walters, C.J., 1985. Bias in the estimation of functional relationships from time series data. *Can. J. Fish. Aquat. Sci.* 42, 147–149.
- Wang, Y.-G., 1999. A maximum-likelihood method for estimating natural mortality and catchability coefficient from catch-and-effort data. *Aust. J. Mar. Freshw. Res.* 50, 307–311.
- Wang, Y.-G., Die, D., 1996. Stock–recruitment relationships of the tiger prawns (*Penaeus esculentus* and *Penaeus semisulcatus*) in the Australian Northern Prawn Fishery. *Mar. Freshw. Res.* 47, 87–95.
- Ye, Y., 2000. Is recruitment related to spawning stock in penaeid shrimp fisheries? *ICES J. Mar. Sci.* 57, 1103–1109.

APPENDIX 2 - HOW MANY SIMULATIONS SHOULD BE DONE?

The author of this section is Bill Venables and the section is provided for information only.

A key question when developing this project was the minimum number of simulations for each scenario given the large number of scenarios and the computer time requirements for each. Assume a number of simulations have been run and a sorted sequence of results is generated, say $X_{(1)} < X_{(2)} < \dots < X_{(n-1)} < X_{(n)}$, and assumed further that the objective is to determine how much of the complete distribution of possible simulations lies between the limits $X_{(1)}$ and $X_{(n)}$, which are all it is planned to report in addition to, say, the median. To be more specific, let p be a specified central chunk of the distribution, say 0.90, and let $\xi_{(1-p)/2}$ and $\xi_{1-(1-p)/2}$ be the lower and upper percentiles after excluding $(1-p)/2$ in either tail. If the objective is to estimate the probability of the event that the range contains a chunk p of the distribution, symmetrically, that is:

$$\Pr\left[\left(X_{(1)} < \xi_{(1-p)/2}\right) \cap \left(X_{(n)} > \xi_{1-(1-p)/2}\right)\right]$$

This event guarantees that not only does the range covers a specified chunk, p , but that no more than $(1-p)/2$ lies outside either end. Figure App.2.1 shows the coverage probabilities for chunks of size 0.90 (dashed curve) and 0.95 (solid curve) corresponding to a number of simulations.

Hence, for example, 58 simulations would guarantee that the range contains a 90% chunk of the distribution, symmetrically, with guarantee probability of 0.90. The guarantee probability that in fact it contains 95% of the distribution is still about 60%. From this graph, it was deduced that 120 simulations would provide slightly more than 90% certainty that 95% of the distribution is covered.

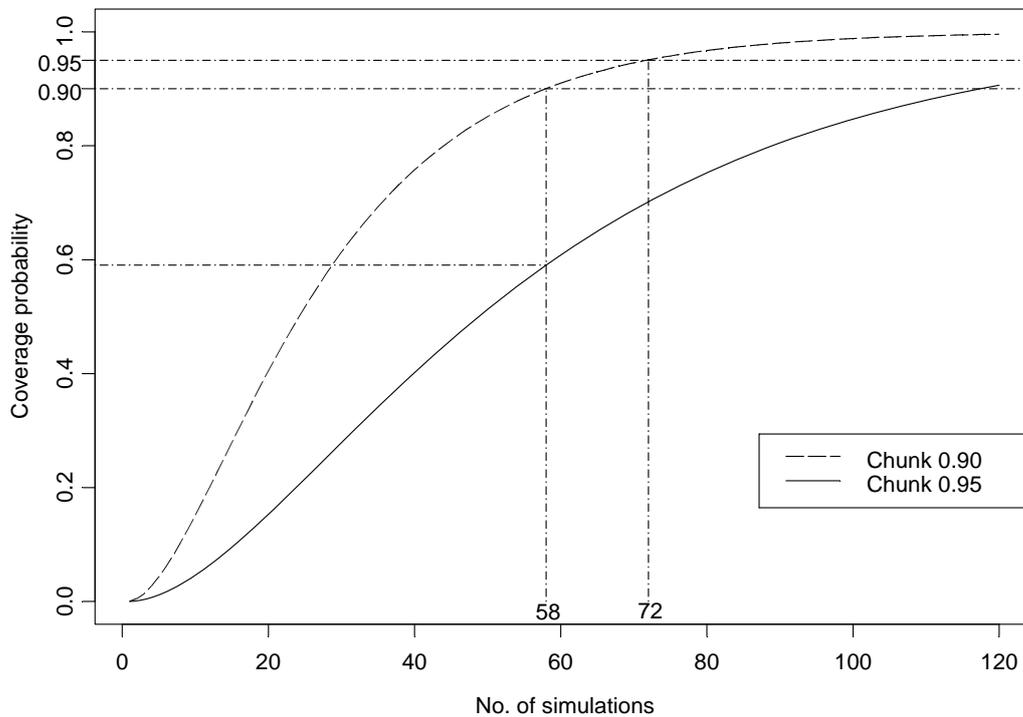


Figure App.2.1: The coverage probability that a given number of simulations would contain the central 90% or 95% of the distribution

This suggested protocol is conservative in two ways. Firstly, it is conservative when compared with the usual sample size selection rule in a standard power analysis, for example, which usually sets the design specification to guarantee that the chance of rejecting a false null hypothesis be at least 80%, using a 5% test. In our case we require the probability that it contains a 95% chunk of the distribution with a specified probability of at least 90%.

Secondly it is conservative in that it requires that the range of the simulations cover the **central** 0.95 chunk of the distribution, and not just an arbitrary 0.95 chunk. This ensures that not only is the spread likely to be adequate for an accurate interpretation of the result, but the location, using the median as an index, is also likely to be more accurate than it would otherwise be.

In confirmation of this, we simulated a run of 120 draws from a normal distribution 10000 times and found the following:

- The lower limit to the range was less than the 0.025 point of the distribution and the upper limit was greater than the 0.975 point in 91.8% of cases, in close agreement with the general contention from the graph above, but
- The actual size of the chunk of the distribution covered by the range of the run exceeded 0.95 in 98.3% of cases.
- The chunk of the distribution covered by the range of the run ranged from 0.8973071 to 0.9998933, but was very skewed to the left and the mean chunk size was in fact 0.9833432. A histogram of the 10000 chunk sizes is shown below.

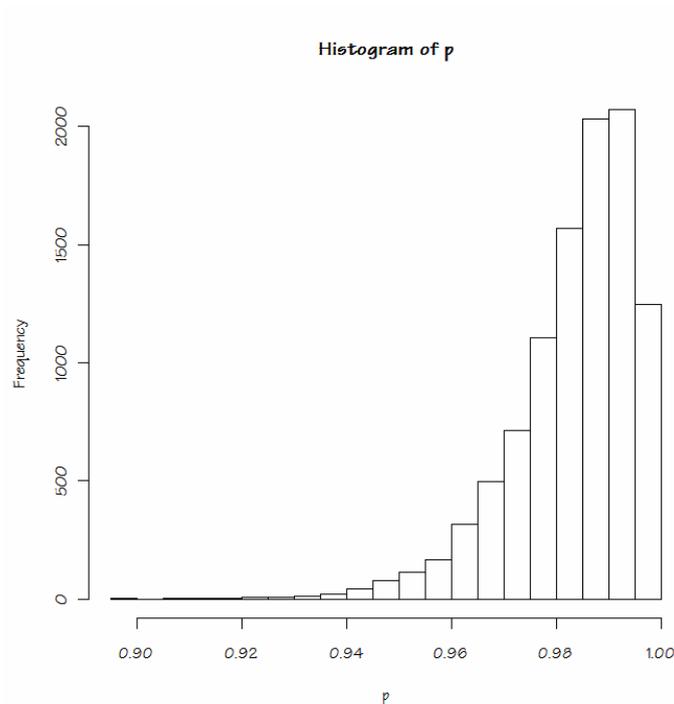


Figure App2.2: Frequency histogram of p.

This seems to suggest that, with 120 simulation runs, the range of the results is likely to be a very thorough representation of both the location and spread of the output quantity.