A new approach to assessment in the NPF: spatial models in a management strategy environment that includes uncertainty

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1 SUMMARY AND INTRODUCTION

2001/002	A new approach to assessment in the NPF: spatial models in a management strategy environment that includes uncertainty

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1.1 Outcomes

The project outcomes have contributed to:

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

These have been achieved by the following outputs:

1. The development of a framework that explicitly models the harvest strategies (assessment, decision rules to set effort and season) being applied within the NPF,
2. Performance measures by which to assess different harvest strategies,
3. Recommendations on the scale and model complexity needed to best manage the fishery, and
4. A series of different harvest strategies and sensitivity tests that highlight key research directions and strengths and weaknesses of the present assessment and management approach.

1.2 Project objectives

a. Develop a new multi-stock operating model for the Northern Prawn Fishery

b. Use the model from (a), to develop alternative Management Targets and Reference Points appropriate for species-group, single-stock management that nevertheless explicitly accounts for variability and uncertainty.

c. Evaluate the performance of management strategies that relate to these new management targets and indicators.

d. Communicate the advantages and disadvantages of the alternative options (model, target and strategy) to Industry and NORMAC.

1.3 Non-technical Summary

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.

Uncertainty and error are explicitly included in the evaluations of this study, again based on past experience. These 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 (see Section 6.3) 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 mode - see Section 4.2 for details).

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 (see Section 7 for details). 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[1]. 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 commn*), 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 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 *Penaeus esculentus* (brown tiger prawns) below the target level of S_{MSY} in median terms. A case therefore could be made for choosing one

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[1] In actual 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} as the LRP (i.e. 50%).

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* (grooved tiger prawns) above S_{MSY}. 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. 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, 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 S_{MEY}, rather than on effort, catch or spawning stock size in absolute terms[2].

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 20%.

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 in Section 9. 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 report 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 Manage-

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[2] S_{MEY} is the spawning stock size that would achieve Maximum Economic Yield.

ment 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. 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} when the target spawning stock size used in the management strategy is 1.6 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.

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 is consistent with the notion that it is the inability of management to influence the spatial distribution of effort that is 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. One way to implement spatial management without a spatially-structured stock assessment would be to determine the effort level using a single-stock assessment and to “allocate” the effort spatially (perhaps based on relative catch rates or the results of surveys). The only way to ensure that the spawning stock size is at or above S_{MSY} is to increase the target spawning stock size in the decision rule if spatial management is impossible to implement. However, as is clear from Section 9.6, this will only be possible with some loss in yield.

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 assessments are conducted every few (2-3) years and the cpue regression approach used to provide scientific 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 through, for example clear written decision rules, is an essential ingredient of this process.

1.4 Acknowledgements

Janet Bishop is thanked for providing the raw logbook data. These data were kindly provided by the Industry to AFMA, and subsequently to Ms Bishop. The Northern Prawn Fishery Assessment Group are also thanked for their comments on a presentation of this work.

1.5 Background

The NPF is one of the Commonwealth's most valuable fisheries. The species groups targeted include tiger, banana and endeavour prawns. The fishery was managed from 2001 until 2004 using input controls with the aim that the fishing effort expended would lead to a 70% chance 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 the fishery is that the efficiency of fishing effort is continually increasing so that past effort reductions have been fully offset by improved efficiencies, and some past effort reductions did not 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, and 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*. 2003). 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 below the biomass that could produce MSY. Both models assume a single homogenous stock of tiger prawns in the NPF, although the catch and effort data are standardized with respect to geographical location and week in the season to allow for spatial heterogeneity to some extent before being used when fitting the biomass dynamic model.

Spatial stock assessments would appear to be essential for a resource that tends to aggregate, or that has distinct geographical trends. 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 are highly depleted with spawning stock sizes much lower than suggested by the single-stock models.

Dichmont *et al*. (2001) 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, 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 MSY-related 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.

1.6 Need

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

The MSY may give a false expectation of stability in species such as prawns, whose dynamics are dominated by yearly recruitment variation. Management targets that relate to present rather than to equilibrium conditions (e.g. a target fishing mortality rate) may be more achievable with intrinsically variable fisheries, such as prawns. However, reference points developed worldwide have concentrated on fisheries based on output controls. 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 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.

1.7 Benefits and adoption

The methods and results have direct benefit to the management of the fishery:

a) a wide array of different management options have been tested in this report that clearly highlights both strengths and weaknesses of the whole management chain from assessment to decision to implementation,

b) the MSE framework is now available for further scenario runs, often with few coding changes, and

c) the results have clarified the key future research directions.

A presentation to the Northern Prawn Fishery Assessment Group has explained the method and key results.

1.8 Planned outcomes

The MSE framework tests the existing assessment and decision-making system within the NPF and highlights the strengths and weaknesses thereof. To build on the conclusions of this report will mean that ecological and economic sustainability of this fishery will be enhanced. This will be through better control of the management process through developing an acceptable form of spatial management, developing clear and described decision rules with which to set harvest strategies and fully describe the trade-offs between reducing resource risk and increasing profit.

1.9 Intellectual property

None

1.10 Staff

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2 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. Analysis of these data would then either be by fitting 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). 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 1) generally consists of an operating model that can be considered as a "virtual" resource and is seen as a representation of the "true" 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 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.

In this report, 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.

2.1 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 types 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 does not necessarily require the use of an operating model.

It is necessary to simulate the dynamics of the fishery and the stock(s) it fishes 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.

The description of the relative performance of different management strategies is another stock 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_{curr}/S_{MSY}; Dichmont *et al* 2003) 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 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.

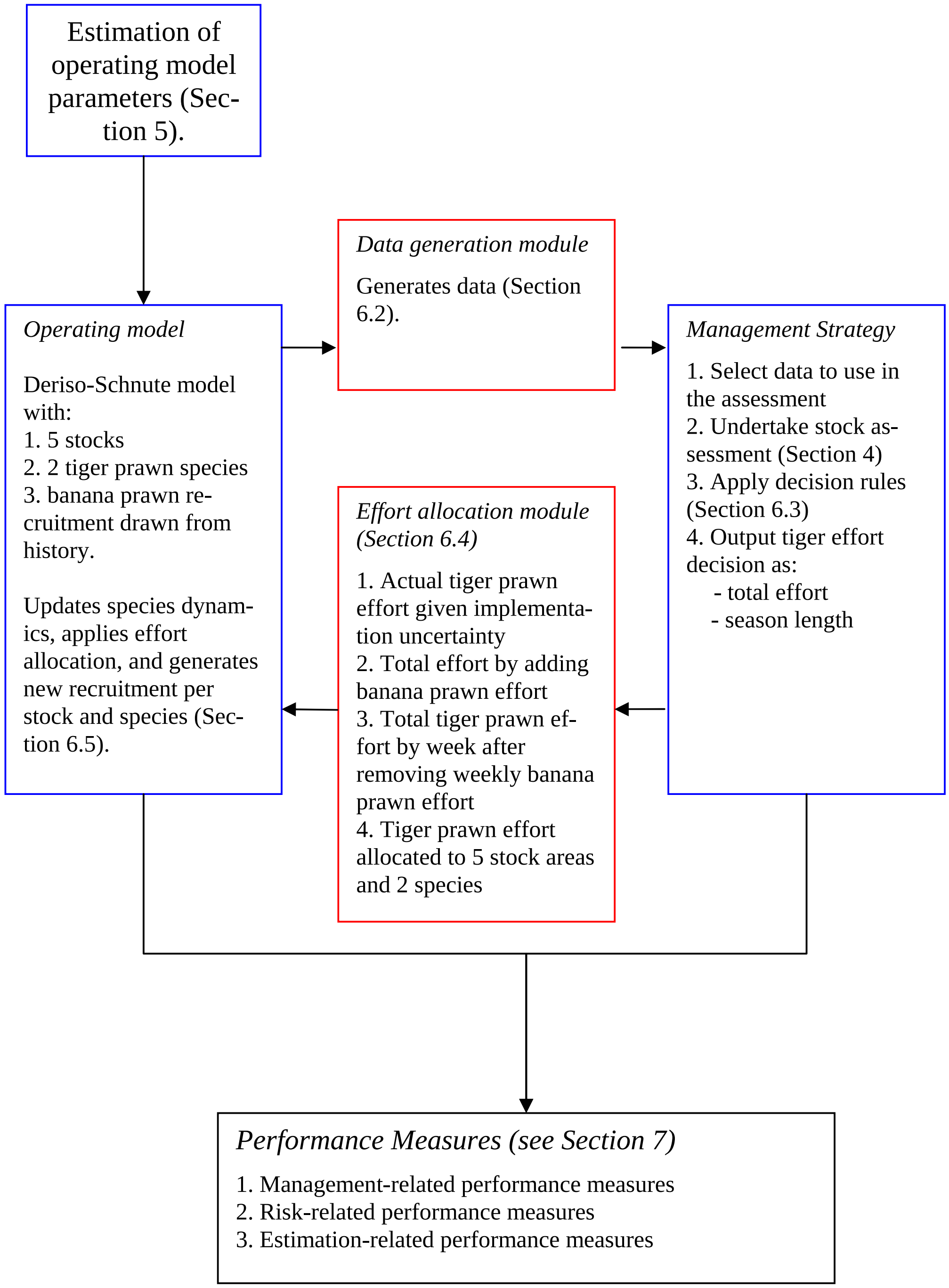

Figure 1: Diagrammatic representation of the NPF Management Strategy Evaluation framework.

3 DESCRIPTION OF THE FISHERY AND ITS MANAGEMENT

3.1 Discovering the fishery

The first exploratory fishing surveys in the Gulf of Carpentaria (Figure 2) during the 1950s discovered banana prawns. However, the densities encountered during these surveys were too low to justify a fishery (Pownall 1994, Cartwright 2004). It was, in fact, surveys undertaken by Commonwealth Scientific and Industrial Research Organisation (CSIRO) researchers in 1964 on the *Rama* and in 1965 on the *M.V. Munroe* that discovered what led to the start of the commercial prawn fishery in the Gulf during the late 1960s (Pownall, 1994).

The fishery initially only targeted a single banana prawn species (*Penaeus merguiensis)* in the Gulf of Carpentaria. This species is characterised by forming dense aggregations that stir the sediment making visible ‘boils’. Catches of *P. merguiensis* increased substantially to a peak of more than 12,000t in 1974 (Figure 3). These large catches, the open access nature of the fishery (which included very large foreign vessels in the 1960s and 70s), and Government boat building subsidies, lead to a substantial increase in the size of the fleet. Furthermore, the fact that *P. merguiensis* is short-lived and aggregates, meant that the fishery was characterised by a substantial investment in processing and targeting equipment. The banana prawn fishery shrank from being year-round during the 1960s, to being a few months during the 1970s, and finally to being just a few weeks during the 1980s.

The Joseph Bonaparte Gulf is a two to three day steam west of the Gulf of Carpentaria. Some exploratory surveys and fishing took place in this stock area during the 1960s. However, the fishery only expanded to the Joseph Bonaparte Gulf (where a different banana prawn species, *P. indicus*, occurs) during the early 1980s.

The fishery expanded spatially, and also in terms of the species assemblages caught, as the banana prawn fishery began to decline, especially in terms of catch per vessel. The additional species were two valuable tiger prawn species (*Penaeus esculentus* and *P. semisulcatus*), the less valuable endeavour prawns (*Metapenaeus endeavouri* and *P. ensis*), and a minor fishery for blue-legged king prawns (*Melicertus plebejus*). The tiger prawn fishery rapidly expanded, until it too began to suffer from excessive capacity and declining catches during the late 1980s.

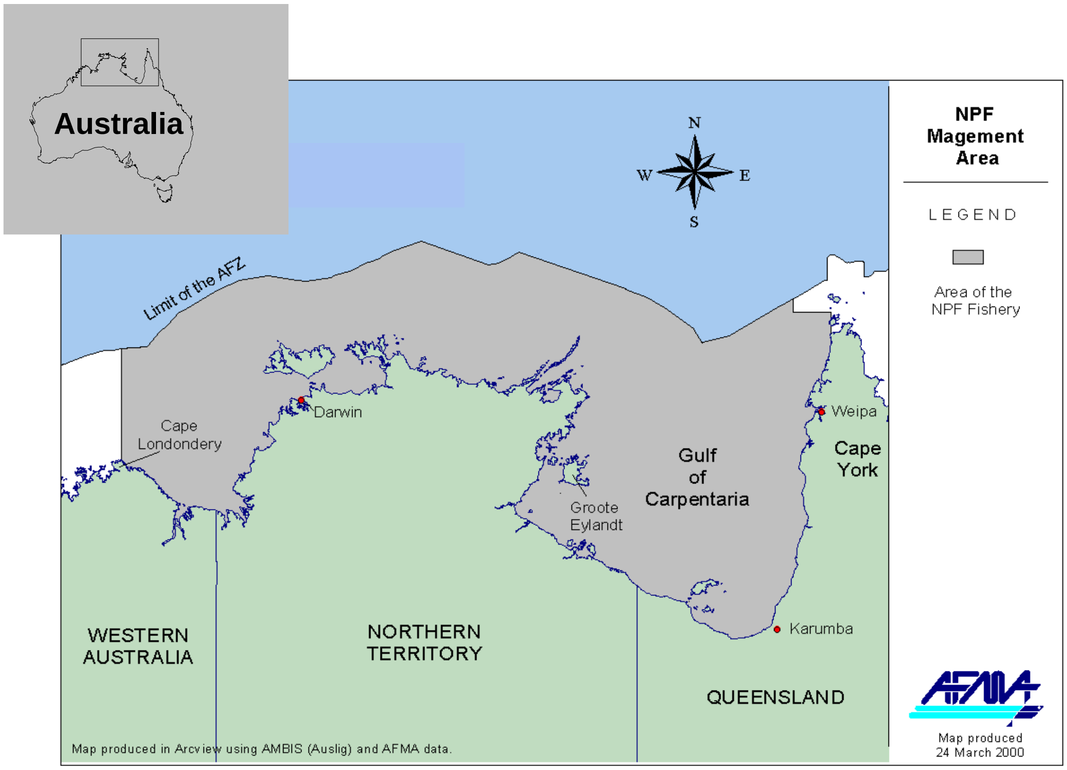

Figure 2: Map showing the extent of the Northern Prawn Fishery. Insert shows its position in the Northern tropics of Australia. Source: AFMA, 2000.

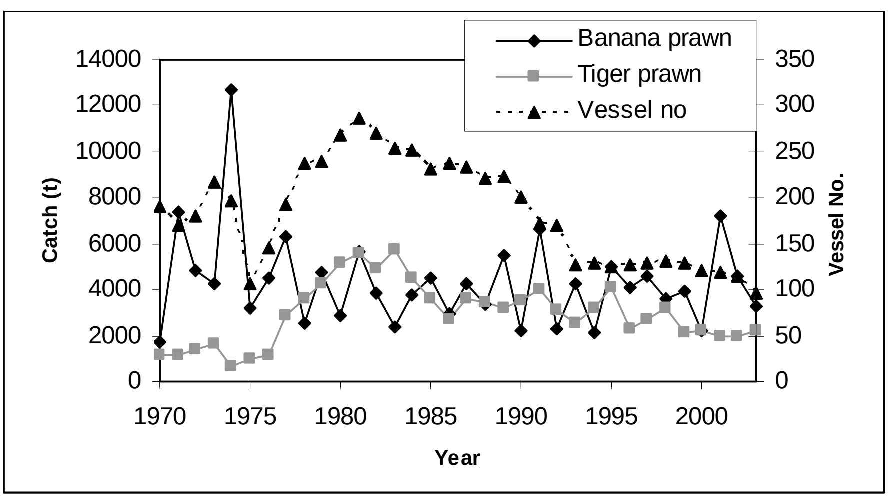

Figure 3: Annual banana and tiger prawn landings (tonnes) and the number of vessels fishing in the Northern Prawn Fishery.

3.2 Management

The original vessels in the fishery were small wooden quad rig otter trawlers with brine storage tanks. In contrast, the vessels in use today are large steel prawn trawlers with computers, GPS and plotters that use spotter planes during the banana prawn season. The fleet was reduced from more than 280 vessels in the 1980s to the present fleet of 97 vessels after many changes to management arrangements. The fishery now lands between 6–8,000 tonnes of prawns annually. Over the period 1992/93 to 2001/02, real revenue for operators in the NPF 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 fishery.

Input controls rather than output controls (e.g. catch quotas) have formed the basis for management of the NPF. Initially, the fishery was managed by the three States whose waters include the NPF (Taylor and Die 1999). This meant that there was little possibility of a unified management response for resources that occur within more than one State. Even so, excellent research was undertaken by the different science agencies and, as early as 1987, substantial increases in vessel fishing power were quantified (Buckworth 1987). 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 which led to management of many of the resources in the NPF that straddle State or International boundaries falling under the jurisdiction of the Australian Federal Government. The Australian Fisheries Service was the agency initially responsible for the management of the NPF following the signing of the OCS. This agency was restructured in 1992 to form the present-day Australian Fisheries Management Authority (AFMA).

The AFMA is responsible for the day-to-day management of fisheries that fall under the jurisdiction of the Australian Federal Government (henceforth referred to as "the Commonwealth"). The Fisheries Management Act of 1991 includes five specific legislative objectives:

1. Implementing efficient and cost-effective management on behalf of the Commonwealth
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 has several important characteristics: it is a body corporate 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).

3.3 The partnership approach

The Fisheries Management Act of 1991 emphasises a "partnership approach" among fishery managers, scientists, industry, 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 relevant to decision making.

Various committees exist to facilitate this process, two of which are fundamental to the successful management of the NPF: a) the Northern Prawn Fishery Assessment Group (NPFAG), and b) the Northern Prawn Management Advisory Committee (NORMAC). Both of these committees report directly to the Board of AFMA thereby maintaining the independence of scientific and management advice. The NPFAG consists mainly of stock assessment, biological and economic scientists and industry members. It is the technical committee that provides scientific advice on the status of stocks, bycatch and the ecosystem. The NORMAC consists of eight members and an independent chair. There are five members from industry, a member from a conservation group, a scientist and a representative from AFMA. Additionally, there are two permanent observers: one representing the Northern Territory and the State of Queensland and, recently, one from the Department of Environment and Heritage.

The *Environment Protection and Biodiversity Conservation Act 1999* requires 5-yearly certification of the Ecological Sustainability of a fishery to obtain an export licence from Australia. The two major principles against which the sustainability of a fishery is assessed are:

> PRINCIPLE 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.
>
> PRINCIPLE 2 Fishing operations should be managed to minimise their impact on the structure, productivity, function and biological diversity of the ecosystem.

Certification of the NPF occurred in 2004 (Anon 2003).

3.4 Assessment advice

Simulation modelling techniques based on biological information and fishery-dependent and field data were used from the 1970s to determine season opening dates for the banana prawn fishery to maximise the value-per recruit (e.g. Lucas *et. al.* 1979, Somers, 1985, Somers 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 consequently not have been possible without extensive co-operation from industry (Somers and Taylor 1990). Stock assessment of the tiger prawn resource during the 1990 and 2000's showed the resource to be overexploited (see Table 1 for references and management details). The assessments of the tiger prawn resource changed from being based on an equilibrium surplus production model (Somers 1992), to an age-based model (Wang and Die 1997), and ultimately to a delay-difference model (Dichmont *et al*. 2003).

Perhaps the most influential scientific discovery from the viewpoint of the management of the fishery was that there appears to be strong stock-recruitment effect for tiger prawns (i.e. the expected level of recruitment declines with declining spawning stock size) (Wang and Die 1997). This was unexpected given the then prevailing scientific view that prawn fishing, no matter how intense, is unable to affect the future productivity of the resource. However, the idea of a stock-recruitment effect became more accepted within the scientific committee (if not industry) following the collapse of the tiger prawn resource in Exmouth Gulf in 1982–83 (Anon 2003).

3.5 History of effort reductions

The management of the NPF since the 1980s has been characterised by attempts to reduce effort and restructure the fishery. Several approaches were used to reduce the size of the fleet (Table 1) and these did indeed lead to a marked drop in the number of vessels in the fishery (Figure 3). However, a reduction in the number of vessels does not equate to a reduction in fishing mortality (Bishop *et al*, 2000, Cartwright 2004) because all vessels are not equally efficient and because the fishing power of individual vessels increases over time (Buckworth 1987, Robins *et al.* 1998, Dichmont *et al.* 2003).

In 1985, each vessel was initially assigned a number of "A-units" (a transferable Statuary Fishing Right based on vessel volume and engine horse power) and effort reductions were based on these units. However, this system was inflexible and actually impeded restructures to the fleet. Eventually, both industry and management agreed that the A-unit management system had to be changed. Consequently, NORMAC and AFMA embarked on an extensive consultation process in 1993 to determine the form of a new management system.

There was general agreement within industry, and unanimous agreement at NORMAC in November 1996, that the system of management should change to a system based on tradeable gear units (this system defines the amount of headrope a vessel can use based on the number of gear units it has). However, the consensus among industry disappeared once the formula for converting A-units to gear units was determined; those operators who considered that they would be disadvantaged by the formula opposed the change (Cartwright 2003, Stone 2005). This group, which was composed of smaller SFR holders, also disputed the results of the stock assessment, especially that fishing power was increasing and believed instead that changes in the catch-rates were largely attributable to either environmental factors, predation, or the fleet being reduced to too small a size to effectively work all of the prawn grounds (Cartwright 2003). The questions regarding the stock assessment were considered during a review in 2001 (Deriso 2001).

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 each year from 1997, e.g. Die *et al.* 1997), and about the high rate at which fishing power was increasing (Robins *et al.* 1996, Bishop *et al*. 2000). These concerns were raised at the NORMAC meetings from 1995 (Table 1). However, the reductions in fishing effort during this period were less than those advised by the NPFAG based on the results of the stock assessment to achieve NORMAC's management target of setting the level of fishing effort to that corresponding to Maximum Sustainable Yield (MSY), primarily because it was believed that the change from A- to gear-units would occur soon. 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 (NORMAC 45) to have reduced fishing effort by only 15%.

Two major changes to the management of the fishery occurred in the early 2000s: a) the gear unit system was implemented with an immediate 15% reduction, and b) the scientific advice on the need for a substantial reduction in fishing mortality (a 40% reduction for *P. esculentus* and a 25% reduction for *P. semisulcatus*; Dichmont *et al* 2001) was heeded. This reduction in 2001 was implemented by reducing total headrope length by 25% and several season changes particularly centred at reducing brown tiger effort. In addition, management changed its focus from aiming to set the level of fishing effort at that corresponding to MSY to managing so that there is a probability of at least 70% that the spawning stock size is above that corresponding to MSY. Present indications suggest some recovery of the resource has occurred (NPFAG 2004).

Table 1: Major developments and management changes (with intended reduction if stated) in the Northern Prawn Fishery

Year	Scientific advice and management development	Target reduction, if any	Reference
1980	• Introduction of limited entry		• Taylor and Die 1999
1985	• 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 (tends only to reduce latent effort)		• Taylor and Die 1999 • Pownall *et al.* 1994
1987	• Reduction from quad to twin gear, mid-year closure, ban on daylight trawling during the tiger prawn season	30% reduction of effort	• Pownall *et al.* 1994
1988	• Restriction on headrope length of nets		• Pownall *et al.* 1994
1990	• Voluntary industry-funded buyback scheme with loans from the government (unsuccessful at reducing the fleet to the target; actual reduction by target date was 72,000 units (172 trawlers))	50,000 A-units (i.e. less than 130 vessels) by 1 April 1993	• Pownall *et al.* 1994
1993	• Compulsory, industry-funded, buy-back scheme (reduces the fleet to 137 (128 active) vessels) • Removal of net size restrictions (although use of double gear only remains)	Across the board reduction of 30% of the remaining A-units	• Pownall *et al.* 1994
1995	• Start of annual assessments using an age-based model by CSIRO for consideration by the NPFAG • NPFAG declares the effective effort to be too high		• e.g. Wang and Die 1996, Die *et al.* 1997, Die and Wang 1998
1996	• Fishing power estimated to be increasing at 2-5% per annum (the stock assessment		• Robins *et al.* 1998

	used 5% per annum as agreed by NORMAC) • A Gear Units Workshop considers the idea of gear units as a management tool (attended by industry, scientists and managers) • First attempt by the NPFAG to introduce biological reference points deferred by NORMAC 39 to 1997 for further discussion and explanation		• NORMAC 39 Agenda Item 5
1997	• NPFAG advises that both tiger prawn stocks are biologically overexploited and recommends an immediate reduction in effort of at least 10% • Alternative tiger prawn stock assessment confirms the NPFAG advice • NORMAC recommends that the fishery be closed 3 weeks earlier at the end of the year and during the mid-season closure for 1998 and, in 1999 when gear units are to be implemented, an 15% reduction in gear units. • AFMA Board accepts advice	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	• Die *et al.* 1997 • Haddon 1997 • NORMAC 41 and Die and Bishop in NORMAC 42
1998	• Mandatory introduction of VMS 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 refute the advice • The end of the season closure reverts to the end of November and a large area closure starting 1 November is implemented • E_{MSY} becomes the target reference point when gear units are introduced		• NORMAC 43 • Die and Wang 1998
1999	• NPFAG advises that effort in 1998 was 35% greater than E_{MSY}, that both tiger prawn species remain overexploited, and that effort needs to reduced by 35% • NORMAC recommends replacing the spatial closure recommended in 1998 by larger mid-year and end-of-year closures • Allocation Advisory Panel investigates the gear unit system in terms of the translation formula • Bycatch Action Plan released	15% reduction	• Die and Bishop 1999 • NORMAC 45
2000	• Australian Senate Inquiry endorses gear-based management • Gear based management enters into force	10% reduction in effort	

	in July with an associated 15% reduction in gear • NPFAG report that seasonal closures have been successful in reducing the effort, but that stocks are still over-exploited and declining • AFMA Board and Minister write to NORMAC insisting on reductions in effort • TEDs compulsory in the tiger prawn fishery		
2001	• CSIRO develops a new model for tiger prawns • Technical review of the stock assessment • NPFAG still considers the tiger prawn stocks to be over-exploited (brown tiger prawns are less than 50% of their target level) • Minister calls meeting of fishers and local politicians to demand action • NORMAC sets a rebuilding target for tiger prawns of 2006 • NORMAC agrees to a large reduction in effort through a 25% reduction in gear units and seasonal changes to take place in July 2002. • TEDs compulsory	40% reduction on brown tiger prawns and 25% on grooved tiger prawns	• Dichmont *et al.* 2001, Dichmont *et al.* 2003 • Deriso 2001 • NORMAC 51
2004	• Both grooved and brown tiger are declared recovered although with precaution as survey results do not necessarily support this optimism		• NPFAG 2004

4 STOCK ASSESSMENT MODELS

4.1 Model descriptions

Three different stock assessment methods have been developed for comparison: a simple regression of catch rates through time, a biomass dynamic model, and a Deriso-Schnute delay-difference model. Some of these can be further refined 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").

Table 2 describes the model types, the data they use, and the species and spatial scale at which they can be applied. The details of the biomass dynamic and Deriso-Schnute models as applied to the NPF are already published (Haddon and Hodgson 2000, Dichmont *et al*. 2003) so these are not provided here. The modified Wang and Die model (Dichmont *et al*. 2001) is not considered in this study because it leads to very similar results to the Deriso-Schnute model, but is extremely time-consuming to apply.

The simple 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 to evaluate the relative utility of applying management strategies based on the two stock assessment models (biomass dynamic and Deriso-Schnute). 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 tiger prawn fishery. One of the unusual aspects of this model is that "bycatch effort" (the effort applied to the second tiger prawn species when assessing the status of the first tiger prawn species and *vice versa*) is accounted for because there are very few stock areas in the fishery where only one species of tiger prawn is caught.

Table 2: The specifications of the stock assessment methods

Model	Overview	Data used	Species	Number of stocks
Simple linear	The slope of a linear regression for the past five years $\ln\left(\frac{C_y^s}{E_y^s}\right) = m \times y + c$	*Unstandardised* catch rate over five years	Tiger prawn species combined	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	Tiger prawn species combined	Single stock (catch rate data standardized by stock area)
Deriso-Schnute	A weekly two-species model that uses catch, effort and fishing power changes over time to estimate annual recruitment and subsequently, a stock-recruitment relationship.	1. Catch, effort, fishing power 2. Catch, effort, fishing power, and survey index	Brown and Grooved tiger prawns separately.	1. Single stock 2. Multiple stock areas

4.2 Modification to the Deriso model: inclusion of a Survey Recruitment Index

The objective function of the Deriso model can be modified to be able to make use of a fishery-independent index of recruitment. Assuming that the recruitment index for year y is a lognormally distributed relative index of the recruitment for year y, the contribution of the recruitment index information to the objective function is:

$$\sum_s \sum_A \sum_y \tfrac{1}{2(CV_{y,A}^s)^2} \left(\ell n I_{y,A}^s - \ell n(\tilde{q}_A^s \, \hat{R}_{y,A}^s) \right)^2 \tag{1}$$

where $I_{y,A}^s$ is the recruitment index for species s, in assessment stock area A, and year y;

$CV_{y,A}^s$ is the coefficient of variation of the recruitment index for species s, in assessment stock area A, and year y;

$\hat{R}_{y,A}^s$ is the model-estimate of the recruitment for species s, in assessment stock area A, and year y; and

$\tilde{q}_A^s$ is the model-estimate of the constant of proportionality that relates the recruitment index and the annual recruitment for species s and assessment stock area A.

4.3 The surplus production model

It is possible to construct a non-equilibrium surplus production model that attempts to represent the dynamics of the stock based on just summary catch and catch rate data. The results of this model can be used to estimate the time-trajectory of stock size (B_y), MSY, the stock biomass corresponding to MSY (B_{MSY}), and the effort corresponding to MSY (E_{MSY}). These estimates can then be used to determine future management action, in terms of allowable effort levels. The model used is described by Haddon (2001) and consists of three equations with six parameters:

$$B_{y+1} = B_y + \frac{r}{p} B_y \left(1 - \left(\frac{B_y}{K} \right)^p \right) - C_y \tag{2}$$

and

$$\hat{I}_y = \frac{C_y}{E_y} = q_y\, B_y \tag{3}$$

where B_y is the stock biomass at the start of year y;
r is the intrinsic growth rate parameter;
K is the long-term average maximum population size;
p is the parameter that controls the degree of asymmetry of the surplus production function (production vs stock biomass);
C_y is the catch during year y;
E_y is the nominal effort for year y;
q_y is the catchability during year y (related to fishing power); and
B_0 is the stock biomass at start of the time-series of catches.

The catchability in each year is a combination of an initial catchability, q_0 , and an annual incremental multiplier to account for changes over time in fishing power:

$$q_y = q_0 \times q_{inc}^{y} \tag{4}$$

In this way, increases in fishing power can be represented by numbers for q_{inc} greater than 1 (1.05 is a 5% increase per annum), while decreases in fishing power are represented by numbers less than 1. q_{inc} is set to 1.05 for every year from 1970 to 2002, with q_{inc} being set at 1 for 2003 and later (i.e. catchability is assumed to be constant from 2003). q_{inc} is pre-specified rather than being estimated because the fishery data have lost contrast since the mid-1990s and no longer estimate the biomass and catchability together well.

The biomass dynamic model operates at the scale of the whole Northern Prawn Fishery with an annual time step. As a result, data from the operating model representing all tiger prawn catches and tiger prawn-directed effort by week, stock area, and year are summarized into total catch and effort by week and stock area (summed across species). Annual indices of relative abundance are obtained by standardizing the catch rates by week and stock area. The statistical model fitted is $\ell\mathrm{n}(C/E)_{y,w,r} = \mu + \alpha_w + \beta_r + \gamma_y$.

The six parameters of the biomass dynamic model are r, K, B_0, p, q_0, and q_{inc}, although q_{inc} is pre-specified as noted above. The values for these parameters are estimated using the simplex method (Nelder and Mead 1965).

MSY can be estimated using the formula $rK/(p+1)^{\frac{(p+1)}{p}}$. There is, however, no simple way to calculate B_{MSY} and E_{MSY} because catchability is changing over time. Instead, the estimates of these parameters are found using an iterative process. First, the B_{MSY} that corresponds to MSY is calculated, and then the effort that needs to be applied to the B_{MSY} to give the MSY (i.e. the E_{MSY}) is determined. Figure 4 shows an example of a fit of the biomass dynamic model to simulated data. This fit appears acceptable both during the known history (prior to 2002) and during the projection period (2003–2009)

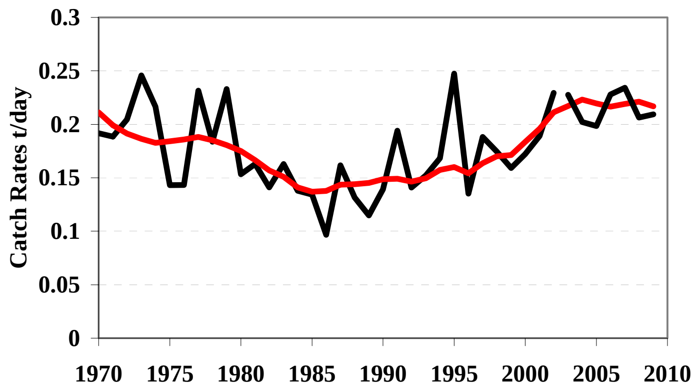

Figure 4: Comparison of observed catch rates (derived from operating model values of catch and effort) with the predicted catch rates from the surplus production model (the relatively smooth line). The results in this Figure assume a q_{inc} of 1.05 from 1970 to 2002 and of 1.0 from 2003. The break in the observed data in 2003 separates the actual data from those generated by the operating model.

The estimates of the parameters of the biomass dynamic model vary markedly during the projection period, partly because of the high levels of recruitment variability. This lack of stability in the parameter estimates influences the apparent productivity of the stock so that the estimates of E_{MSY} and B_{MSY} are also unstable. Nevertheless, stable catches and catch rates appear to be possible.

5 THE OPERATING MODEL AND HOW IT IS CONDITIONED

5.1 Calculating the catch and effort by week and species

The algorithm developed by Venables and Dichmont (2004) was used to split the tiger group catch in the logbook database into catch by tiger prawn species.

5.2 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 equations of this section.

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

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

and (5)

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

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:

$$Z_{y,w} = M + F_{y,w} \tag{6}$$

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_y is the recruitment during 'biological year' y;

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

ρ is the Brody growth coefficient;

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

$$\tilde{y}(y,w) = \begin{cases} y & w < 40 \\ y+1 & \text{otherwise} \end{cases} \tag{7}$$

Equation (7) 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.

$$F_{y,w} = \tilde{q}' A_w \, q_{y,w} \, (E^T_{y,w} + E^B_{y,w} / q_b) \tag{8}$$

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

$E^B_{y,w}$ is the 'by-catch' effort during week w of year y (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 fishing stock area of which the stock area under consideration consists - based on historical logbook data (Table 3);

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:

$$q_{y,w} = (\omega_y)^{(w-1)/52} \prod_{y'<y} \omega_{y'} \Big/ \prod_{y''<1993} \omega_{y''} \tag{9}$$

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 (9) is defined so that fishing efficiency is 1 at the start of 1993 (hence the division by the term $\prod_{y''<1993} \omega_{y''}$).

Table 3: The fraction of the total NPF fishing stock area of which the stock area under consideration consists using logbook data. See Figure 6 for an explanation of the stock regions.

	Outside GOC	Groote	Vanderlins	Karumba	Weipa
P. semisulcatus	0.396	0.140	0.319	N/A	0.145
P. esculentus	0.301	0.090	0.288	0.321	N/A

Specification of the values for the ω_y's is difficult. It is clear to all participants in the fishery than one day's fishing during 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 one day's fishing in 1970. The 5% increase per annum in efficiency used in stock assessments before 2000 was 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 1988–92 (about 2.5% per annum) based on analyses of catch-rate data (Haddon 2000, Robins *et al.* 1998, Bishop *et al.* 2000). However, the exact nature (and to some extent magnitude) of the change in efficiency is uncertain. Therefore, two alternative scenarios for how fishing efficiency (also referred to as "fishing power") may have changed over time ("Base Case High" and "Base Case Low"; Dichmont *et al*. 2003a) are considered in the analyses of this report[3] (Figure 5).

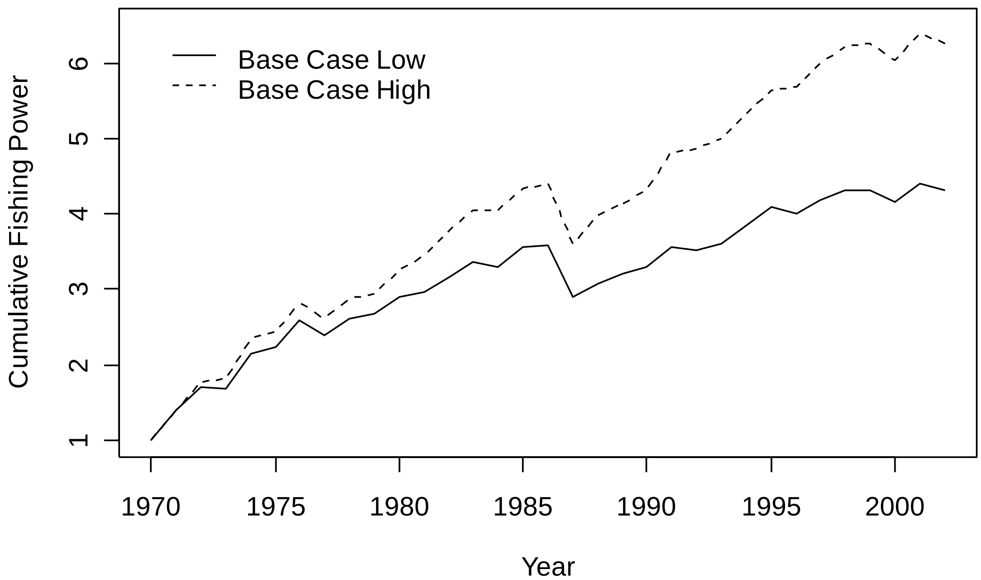

Figure 5: The two fishing power scenarios considered in the analyses of this report.

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

$$S_y = \sum_w \beta_w \frac{1-e^{-Z_{y,w}}}{Z_{y,w}} \tilde{N}_{y,w} \tag{10}$$

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

5.3 Estimating annual recruitment

The values for the bulk of the parameters of the operating model are assumed known based on auxiliary information. The values for the parameters that are not pre-specified (i.e. the annual recruitments for 1970 to 2001) are obtained by minimizing an objective function involving the catch-in-weight data. Assuming that some function of observed catch-in-weight is normally distributed, a simplified version of the objective function is:

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[3] A third time-series of efficiencies ("Spatial High") is available (Dichmont *et al*., 2003b) but this series was not considered in the analyses of this report owing to computational time constraints.

$$L = \sum_y \sum_w \{\log \sigma_c + \frac{1}{2\sigma_c^2}[k(Y_{y,w}^{obs}) - k(Y_{y,w})]^2\} \tag{11}$$

where σ_c is the residual standard deviation;

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

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

$$Y_{y,w} = \tfrac{F_{y,w}}{Z_{y,w}} B_{y,w} (1 - e^{-Z_{y,w}}) \tag{12}$$

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

The summations in Equation (11) are restricted to the weeks for which the catch is non-zero. Sensitivity to the choice of transformation function *Y* was examined by Dichmont *et al.* (2001), because different transformation functions give different emphasis to small and large catches-in-weight. A square-root transformation was used for the analyses reported on here based on the results in Dichmont *et al.* (2001).

No catches were reported for 1969 so the 1969 recruitment is essentially non-estimable. The recruitment in the first year (1969/70) is therefore assumed to be the same as that in the second year (1970/71). The 1969 recruitment is needed so that the population age-structure for 1970 can be initialised. Given the high natural mortality rate, the results are insensitive to assumptions regarding the 1969/70 recruitment.

In addition, the 2002/03 recruitment parameter cannot be estimated because the data for 2002 provide very little information about the magnitude of this recruitment since only a small fraction of the 2002 fishery occurred after October (when the 2002/03 year-class first recruited to the fishery). However, once the model if projected forward, the value for this quantity can be determined (see Section 6.5).

5.4 Fitting the stock-recruitment relationship

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 10), according to a Ricker stock-recruitment relationship:

$$\hat{R}_{y+1} = \tilde{\alpha} S_y \, e^{-\tilde{\beta} S_y} \tag{13}$$

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 was based on the serially correlated stock-recruitment relationship given by:

$$R_y = \hat{R}_y \, e^{\eta_y} \qquad \eta_{y+1} = \rho_r \eta_y + \sqrt{1-\rho_r^2}\,\xi_{y+1} \qquad \xi_{y+1} \sim N(0;\sigma_r^2) \tag{14}$$

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.

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:

$$L = \log\left(\sqrt{\det(\Omega + V)}\right) + \tfrac{1}{2}\sum_{y_1}\sum_{y_2}\left(\log R_{y_1} - \log\hat{R}_{y_1}\right)([V+\Omega]^{-1})_{y_1,y_2}\left(\log R_{y_2} - \log\hat{R}_{y_2}\right) \quad (15)$$

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 14) 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 (Equations 5 to 12) 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).

5.5 Results

Dichmont *et al*. (2001) identified seven potential stocks of tiger prawns in the NPF. These were 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. Since the numbers of tiger prawns in two of the three potential stock areas outside the Gulf of Carpentaria are so small, the areas “JB Gulf”, “Melville” and “N. Arnhem” (Figure 6) had to be combined into a stock area denoted “Outside GOC” so that a usable stock-recruitment relationship could be estimated. This leads to a total of five stock areas, four of which are in the Gulf of Carpentaria. Historical catches by species group and the two tiger prawn species are given in.

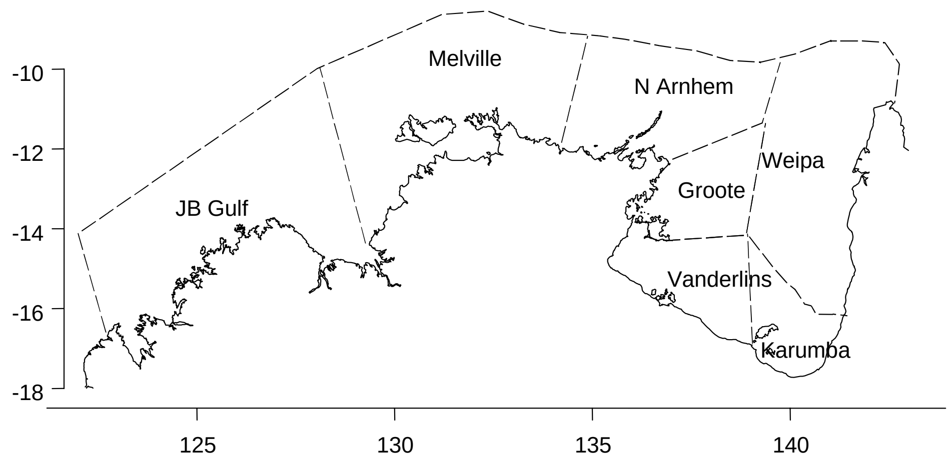

Figure 6: The stock boundaries identified by Dichmont *et al*. (2001).

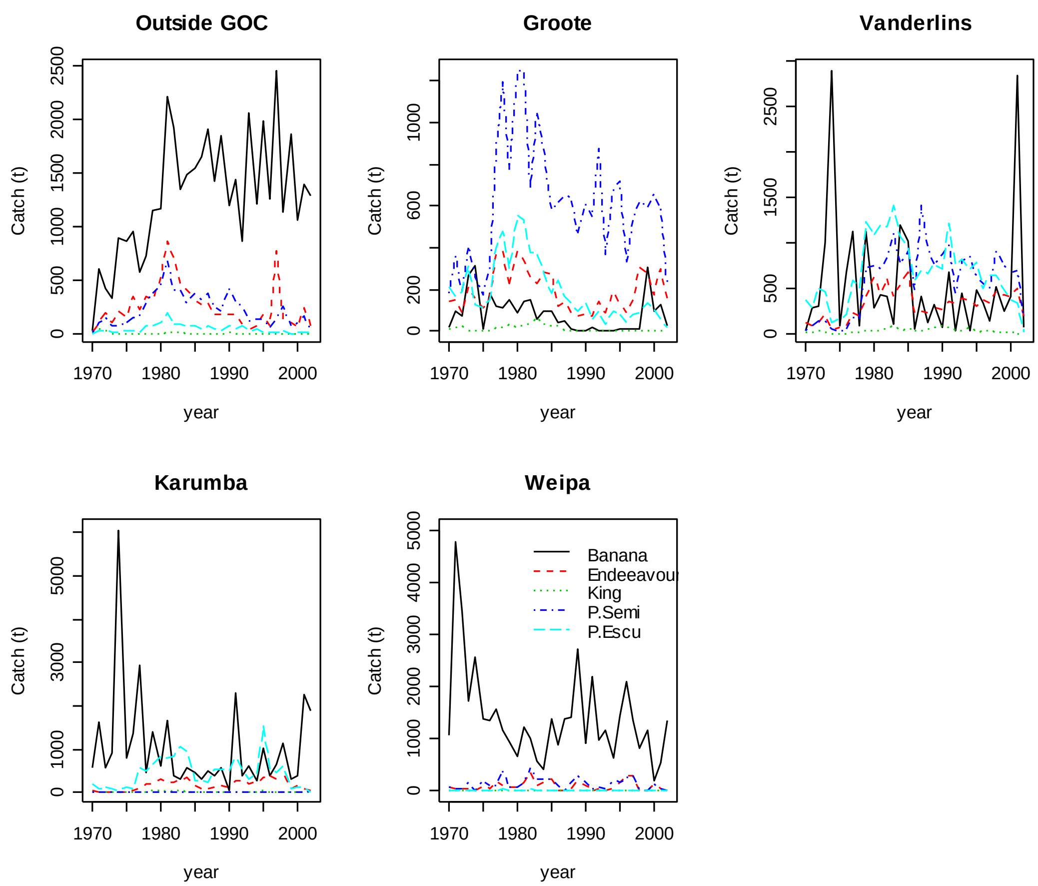

Figure 7: Annual catches by stock region for the banana, endeavour and king prawn group, and grooved (*P. semisulcatus*) and brown (*P. esculentus*) tiger prawns.

The operating model assumes the worst case scenario, which is that the stocks in each stock area are independent of each other. Recruitment estimates with standard errors for *P. semisulcatus* and *P. esculentus* are given in Figures 8 and 9 for the "Base Case

High" fishing power scenario and the value of $\tilde{q}$ obtained by Wang (1999). Some stock areas (e.g. Groote, Vanderlins, and Karumba) contain reasonable biomass of both species, while only one species is found in other stock areas (Weipa is mainly a grooved tiger prawn area and Karumba a brown tiger prawn area). In those areas where numbers of a species are so small that they are inestimable, their biomass was assumed to be zero. In the case of brown tiger prawns caught in Weipa, these catches and effort were allocated to the adjacent area of Karumba. For grooved tiger prawns in Karumba, they were allocated to the adjacent stock area of Vanderlins as the catches of grooved tiger prawns in the Karumba stock area were taken very close to the boundary with the Vanderlins stock area. This means that Karumba is assumed to consist exclusively of brown tiger prawns and Weipa exclusively of grooved tiger prawns. This is reasonable given that the grooved tiger prawn catch was ~84%[4] and ~3% of the total catch in Weipa and Karumba respectively during 2003 (Venables, pers. commn). The vast majority of these Weipa stock area brown tiger prawns are caught well south of Weipa itself towards the Karumba stock area.

[4] The catch within the Albatross Bay region is almost entirely grooved tiger prawns and most of the brown tiger prawn catch comes from the southern part of the Weipa stock area and have therefore been added to the Karumba stock area.

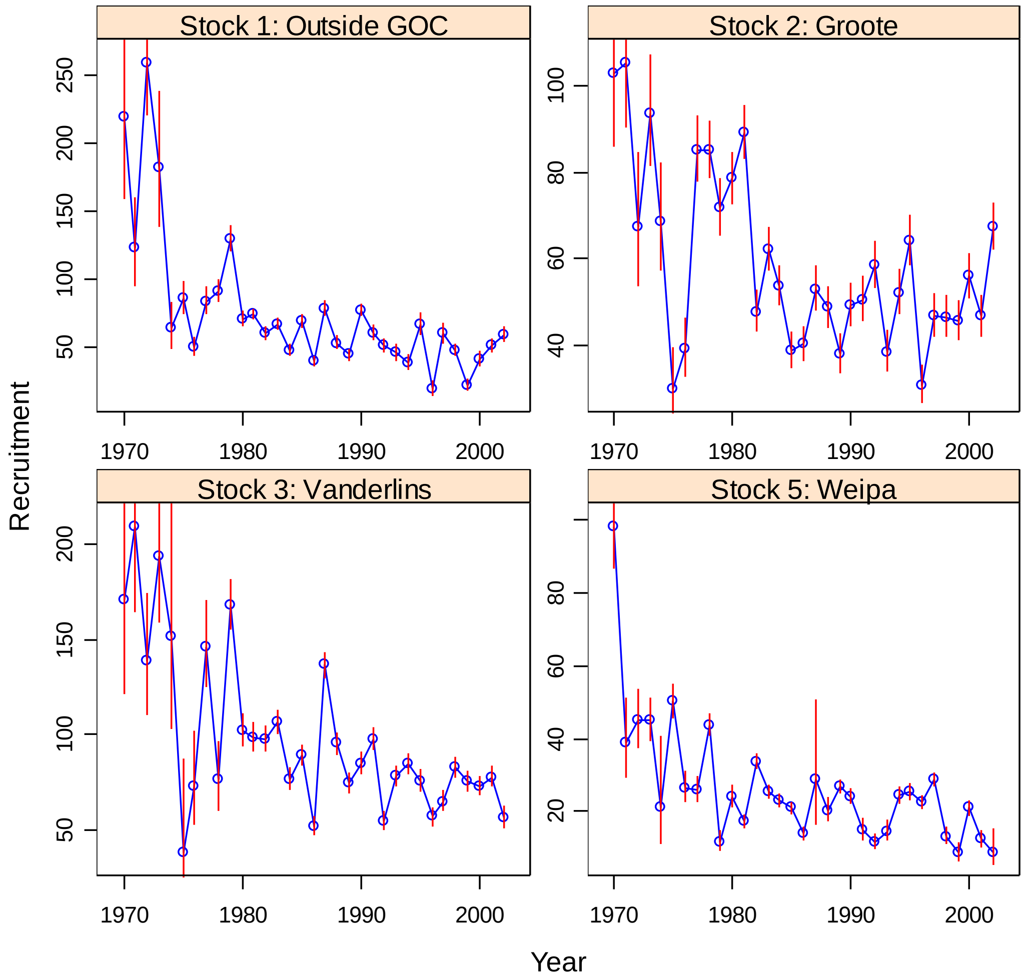

Figure 8: Recruitment indices (± 1 std dev) for *Penaeus semisulcatus* for four stock areas (results for the Karumba area are omitted because of the assumed absence of *P. semisulcatus*). These estimates are based on the "Base Case High" fishing power scenario and the estimate of catchability obtained by Wang (1999).

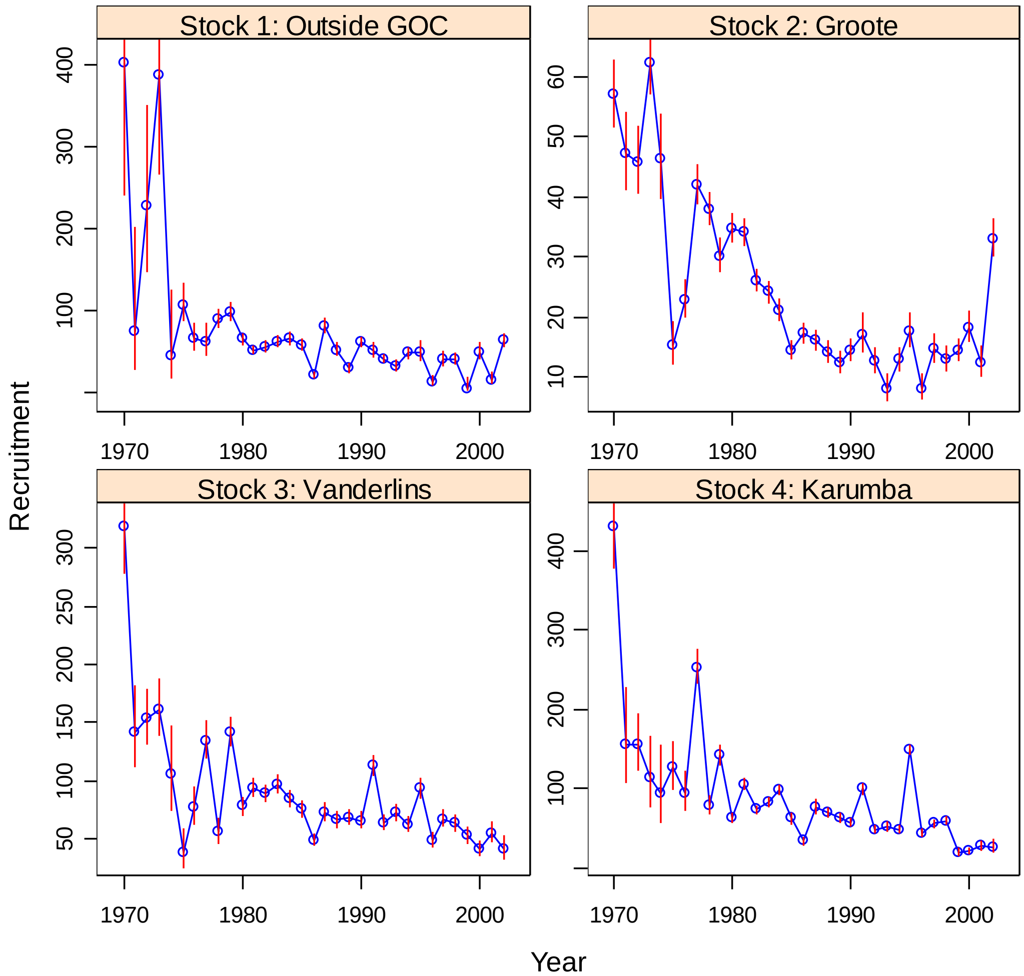

Figure 9: Recruitment indices (± 1 std dev) for *P. esculentus* for four stock areas (results for the Weipa area are omitted because of the assumed absence of *P. esculentus*). These estimates are based on the "Base Case High" fishing power scenario and the estimate of catchability obtained by Wang (1999).

The stock-recruitment relationship for each species is shown for each stock area in Figures 10 and 11. The differences among stock areas are quite remarkable. This may, of course, be due to there being too little information to estimate the parameters of the stock-recruitment relationship precisely.

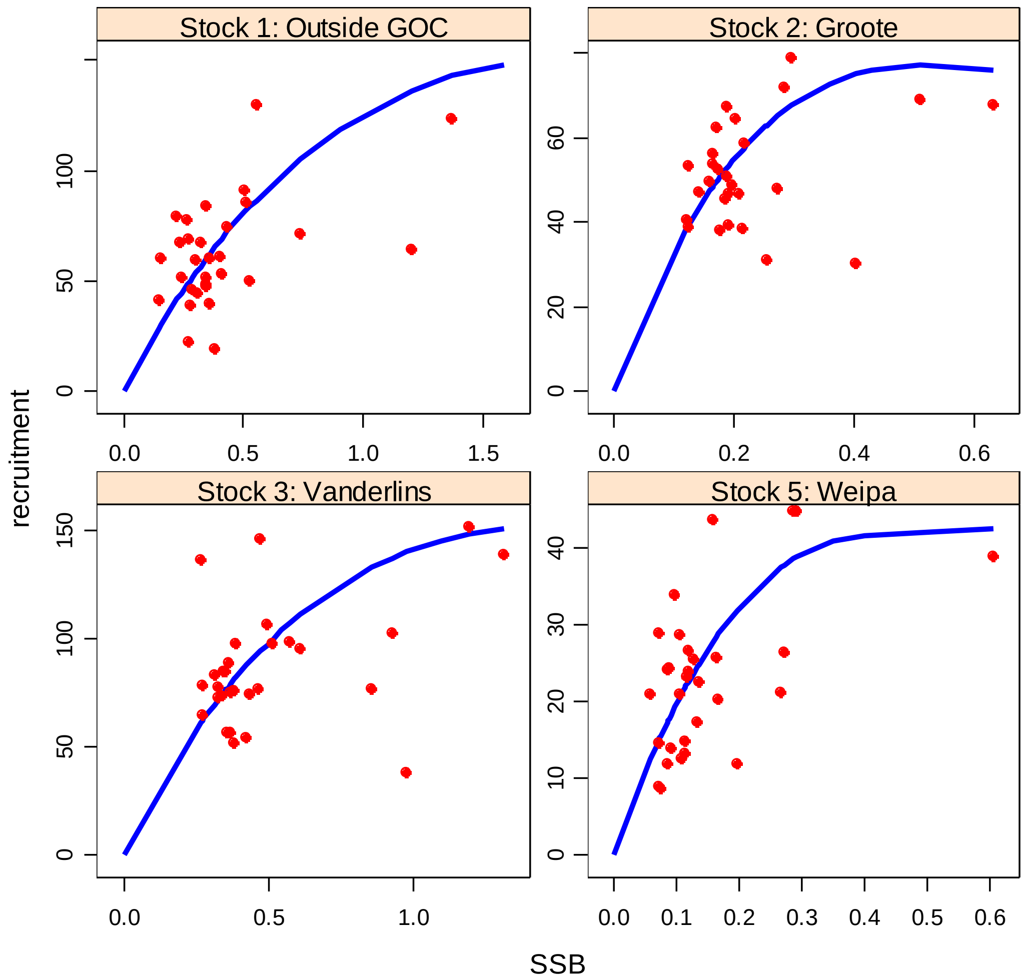

Figure 10: Stock-recruitment relationships for *P. semisulcatus* for four of the five stock areas. The dots are estimates of recruitment and the solid lines are the estimated stock-recruitment relationships. The results in this figure are based on the “Base Case High” fishing power scenario and the estimate of catchability obtained by Wang (1999).

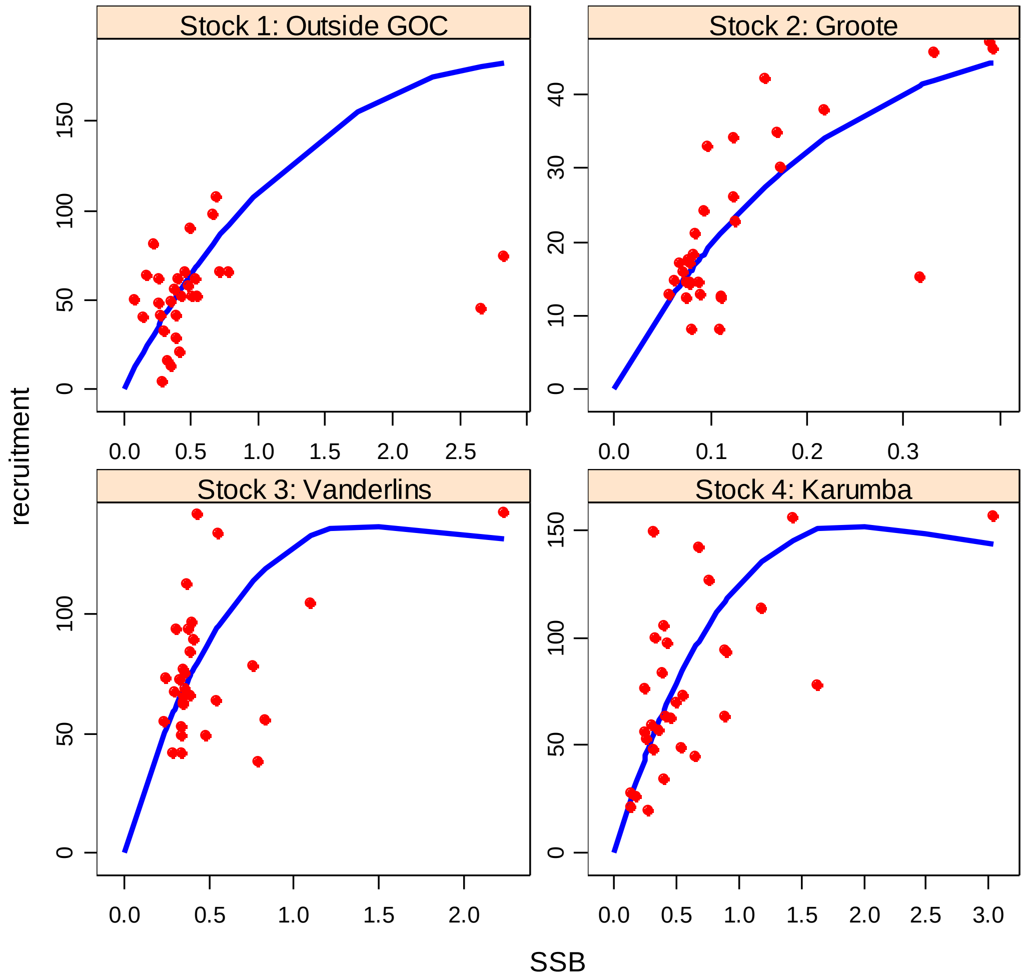

Figure 11: Stock-recruitment relationships for *P. esculentus* for four of the five stock areas. The dots are estimates of recruitment and the solid lines are the estimated stock-recruitment relationships. The results in this figure are based on the “Base Case High” fishing power scenario and the estimate of catchability obtained by Wang (1999).

6 THE MSE MODEL

6.1 The operating model

Parameter uncertainty is captured by conducting simulations for different sets of parameter values. Two approaches are used to generate these sets of parameters: a) they are generated parametrically from the asymptotic variance-covariance matrix obtained from the fit of the operating model to the actual data, and b) they are sampled from a numerical representation of a Bayesian posterior based on placing "non-informative" priors on the values for all of the estimable parameters (i.e. uniform priors on the logarithms of the annual recruitments).

The samples from the Bayesian posterior distribution were obtained using the Markov Chain Monte Carlo (MCMC) algorithm (Hastings 1970, Gelman *et al*. 1995). Descriptive statistics and tests based on the program *coda* (Smith *et al.* 2004) were used to evaluate convergence. In most cases, convergence was achieved fairly rapidly, but more than 20 million cycles were necessary for all of the parameters to pass the Raftery and Lewis, Geweke, and Heidelberger and Welch tests. Particular emphasis was placed on the Heidelberger and Welch (1983) test for stationarity. Failure to pass this test was used to indicate that further cycles were needed to achieve convergence. Every 5,000th value was saved and the first 2,000 samples were treated as a "burn-in" period. The parameters that were least likely to converge were the recruitments for the early years or those estimated to be very low. In the latter case, the chain either showed high autocorrelation or periods of high autocorrelation followed by long periods of no autocorrelation.

6.2 Generating the data

6.2.a Catch and effort data

The effort data are assumed to be known without error. The catch data are either assumed to be measured without error or subject to log-normally distributed observation error. The data provided to the assessment procedures are aggregated as appropriate for the method considered (see Table 2). No allowance is made for errors between the boundaries used for stock assessment and the true boundaries between the stock areas, although this could have been examined relatively straightforwardly (e.g. Punt *et al*. 1995, Punt 2003).

6.2.b Survey data

The recruitment index from the survey data for species *s*, year *y*, and stock area *a*, $I^s_{y,a}$, is generated from a log-normal distribution with median given by the actual recruitment in the operating model for year *y* and stock area *a*, and coefficient of variation, CV_I, i.e.:

$$I^s_{y,a} = R^s_{y,a}\, e^{\varsigma^s_{y,a} - (CV_I)^2/2}; \qquad \varsigma^s_{y,a} \sim N(0;(CV_I)^2) \tag{16}$$

The information on recruitment for year y passed to the assessment procedure for assessment area A is the index $\tilde{I}^s_{y,A}$ and its coefficient of variation $CV^s_{y,A}$. These quantities are calculated using the equations:

$$\tilde{I}^s_{y,A} = \sum_a P_{a,A}\, I^s_{y,a}; \qquad\qquad CV^s_{y,A} = CV_I \sqrt{\sum_a P_{a,A} (I^s_{y,a})^2} \,/\, \tilde{I}^s_{y,A} \tag{17}$$

where $P_{a,A}$ is one if stock area a is in assessment area A and zero otherwise.

6.3 The management strategies

Management strategies usually consist of two parts: a) an assessment procedure which provides estimates using the available data, and b) decision rules which determine the target level of effort and the season length using the estimates obtained from the assessment procedure. Four assessment procedures (the linear regression method, the biomass dynamic model, the Deriso model, and the modified Wang and Die model) were available on which to base management strategies. 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). However, the modified Wang and Die model is very time consuming to run and has been shown to provide similar results to the Deriso model. For these reasons, the modified Wang and Die model is not considered further in this report.

6.3.a Estimation Phase

The outputs obtained from the three assessment procedures differ widely:

1) Linear regression – the slope and intercept of a straight line regression of the logarithms of the catch rates over the previous five years on year.
2) Biomass dynamic model – the intrinsic growth rate, biomass time-trajectory, carrying capacity, the Pella-Tomlinson shape parameter, and the initial catchability coefficient.
3) The Deriso model – the time-series of recruitments, and the parameters of the stock-recruitment relationship (steepness, virgin stock size, stock-recruitment variance and autocorrelation) by species.

In the bulk of the simulations, a single stock variant of the Deriso model was used, although three- and five-stock variants were also examined. The stock areas for the three-stock variant of the Deriso model are: “Outside Gulf” (JBG-Melville-Arnhem), “western Gulf” (Groote and Vanderlines), and “eastern Gulf” (Weipa and Karuma). The five-stock version corresponds to the stocks in the operating model. Any improvement in performance moving from the single- to the three- and then to the five-stock variant of the management strategies based on the Deriso assessment procedure reflect the impact of better understanding stock structure.

6.3.b Reference Points

The values for MSY, S_{MSY} and E_{MSY} are calculated for the biomass dynamic model as outlined in Section 4.3. The method for calculating these quantities for the Deriso model are outlined in Dichmont *et al*. (2001). No MSY-type reference points can be calculated using the regression model, and effort decisions are consequently based on the slope of the regression line.

6.3.c Decision rules to calculate tiger prawn target effort

The tiger prawn effort (aggregated over stock area and season) given a specified closure regime is calculated according to one of the following options:

1) $E^{\text{int}}_{\text{target}} = \sum_{s,a} \mathrm{E}^{s}_{a,y-1}(1.0+\tfrac{1}{2}\text{Slope})$ (straight line regression model), or

2) S_{MSY}-based effort decisions (biomass dynamic and Deriso models)

   The target effort is the minimum of E_{MSY} and the effort that would allow recovery by a pre-specified year, i.e.:

$$E = \min(E^{PS}_{\text{MSY}} + E^{PE}_{\text{MSY}}, E^{PS}_{rec} + E^{PE}_{rec}) \tag{18}$$

where E^{s}_{MSY} is the effort corresponding to MSY for species *s*, and

E^{s}_{rec} is the effort targeted at species *s* corresponding to recovery to S_{MSY} by 2006 with a probability of 0.7, i.e. the effort so that:

$$P\left(\frac{S^{PS}_{2006}}{S^{PS}_{\text{MSY}}} > 1\right) = 0.7 \quad \text{and} \quad P\left(\frac{S^{PE}_{2006}}{S^{PE}_{\text{MSY}}} > 1\right) = 0.7 \tag{19}$$

Calculating effort levels to satisfy Equation (19) requires quantifying uncertainty using, for example, a bootstrap or Bayesian analysis each time the assessment procedure is applied and conducting a sequence of projections to find the effort level that satisfies Equation (19). This would have been extremely time consuming and would have severely limited the number of scenarios and management strategy variants that could have been examined. Instead of basing the effort corresponding to recovery on Equation (19), two alternative decision rules which still remain within the spirit of the S_{MSY} concept were developed to set the target tiger prawn effort, although only one of these formed the basis for the calculations reported here[5]. Figure 12 illustrates the decision rule used for calculations of this report. Three input settings determine how precautionary the effort target should be: a) the maximum proportion of E_{MSY} 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. This decision rule can be tuned to leave the spawning stock size at, below, or above S_{MSY}.

[5] The second method uses a confidence interval for the estimate of E_{MSY} from the assessment based on the Fieller method (Fieller 1940) to establish the intended effort.

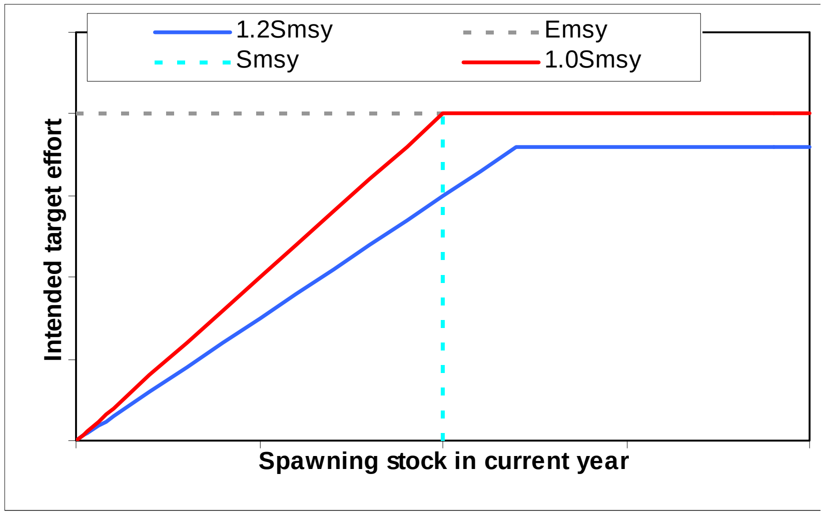

Figure 12: The tiger prawn effort decision rule. Two example decision rules are given; one with the S_{MSY} as the target and another that is more precautionary.

6.3.d The season length

Devising a decision rule based on the results of the assessment to determine the season length is not straightforward because there is little historical precedent on which to base such a decision rule. However, the decision table in Figure 13, which uses the estimate of the ratio of the spawning stock size for the most recent year to S_{MSY} perhaps best describes past decisions. This Figure captures the past behaviour of the managers that 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 was the start date of the fishery for many years[6]. A season length is calculated separately for each species using Figure 13 and the weeks of overlap selected as the season to be implemented – this can be interpreted as a conservative, but realistic, way of using Figure 13.

In most cases, including the Base Case, a season change based on the management strategies is implemented with a 100% probability (see Section 9.1 for a description of the Base Case operating model). However, for the experiment described in Section 8, there are scenarios in which this implementation probability is set at 1/3.

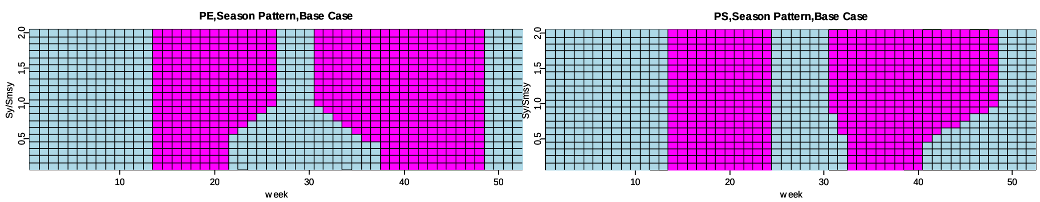

Figure 13: Decision rule to determine the season length (dark grey is open to fishing and light grey is closed) based on the status of the stock (S_y/S_{MSY} i.e. the spawning stock size for the most recent year to S_{MSY}) for each species. "PS" is *P, semisulcatus* and "PE" is *P. esculentus*,

6.4 The effort allocation module

The effort allocation module provides the link between the management strategy and the biological component of the operating model. The management strategy is used in each year of the projection period to undertake an assessment using all of the available catch and effort data to determine:

- the total allowable effort, $E_{\text{target}}^{\text{int}}$, to be targeted at tiger prawns, and
- the season length i.e. which weeks during the season are to be open to fishing so that the management objectives related to the status of the tiger prawn stocks relative to their target levels are satisfied.

In contrast, the biological component of the operating model projects the spatially- and species-structured tiger prawn population dynamics model forward based on effort by week, stock area, and (tiger prawn) target species, $E_{y,w}^{s,a}$. The steps involved in converting from the NPF-wide species-aggregated tiger prawn effort level ($E_{\text{target}}^{\text{int}}$) with the

[6] Except for 2004 when a mid-April start date was implemented.

selected season length, to the effort for each tiger prawn species by stock area and week ($E_{y,w}^{s,a}$) are as follows:

1. Generate the total tiger prawn effort that *actually* occurs, E_y^{act} (i.e. by accounting for four difficulties a) for whether the scientific recommendation for a change in effort is accepted by the decision makers, b) for the inability to accurately implement management decisions owing to variability in participation rates, c) for the difficulty associated with using input controls to place restrictions on fishing mortality when multiple species and stocks are being managed, and d) for inadequacies in correcting for changes over time in fishing power, etc. (Figure 5),
2. Generate a banana prawn season and convert the actual effort targeted towards tiger prawns to the total allowable effort for all prawn species (including banana prawns), E_y^{tot}.
3. Split the total effort into effort by week, $E_{y,a}^{act}$.
4. Reduce the effort by week by the amount of weekly effort directed towards banana prawns, leaving the weekly tiger prawn effort ($\tilde{E}_{y,w}^{\text{act}}$).
5. Split the effort by week into effort by week and stock area, $\tilde{E}_{y,w}^{\text{act},a}$.
6. Split the effort by week and stock area $\tilde{E}_{y,w}^{\text{act},a}$ into effort by week, stock-area and (tiger prawn) target species, $E_{y,w}^{s,a}$.

Each of these steps is outlined in more detail below. In many of these steps, a random year is used to describe the amount of effort during the banana prawn season, the weekly banana and tiger prawn effort patterns, and the areas in which the fleet fishes during a given week. The same random year is used for all these cases as the size of the banana prawn catch seems to influence the temporal and spatial pattern of the fishery. Of course, a different random year is used for each year of the projection period.

6.4.a Generate the actual tiger prawn effort

The actual number of days targeted at tiger prawns is related only fairly coarsely to the number of days that NORMAC had intended to be targeted towards tiger prawns (Figure 14). The slope of the straight line in Figure 14 is not significantly greater than zero if allowance is made for a non-zero intercept. However, a straight line through the origin is more biologically reasonable (if NORMAC closes the fishery, no effort will occur) and is not inconsistent with the data. There is, however, considerable variability about the fitted line. This high variance presumably arises from the inability to accurately predict:

1. the effect of input controls such as restrictions on gear or A-units;
2. unquantified, or incorrectly estimated changes in fishing power (effort creep); and
3. the number of vessels leaving the fleet during a restructure.

The difference between the actual and intended number of fishing days targeted towards tiger prawns can be summarized by the following model with an implementation error standard deviation of 0.20 (corresponding to a ~30% CV):

$$\ell\text{n}E_y^{\text{act}} = \ell\text{n}E_{\text{target}}^{\text{int}} + \varepsilon_y \quad \varepsilon_y \sim N\left(0, 0.20^2\right) \tag{20}$$

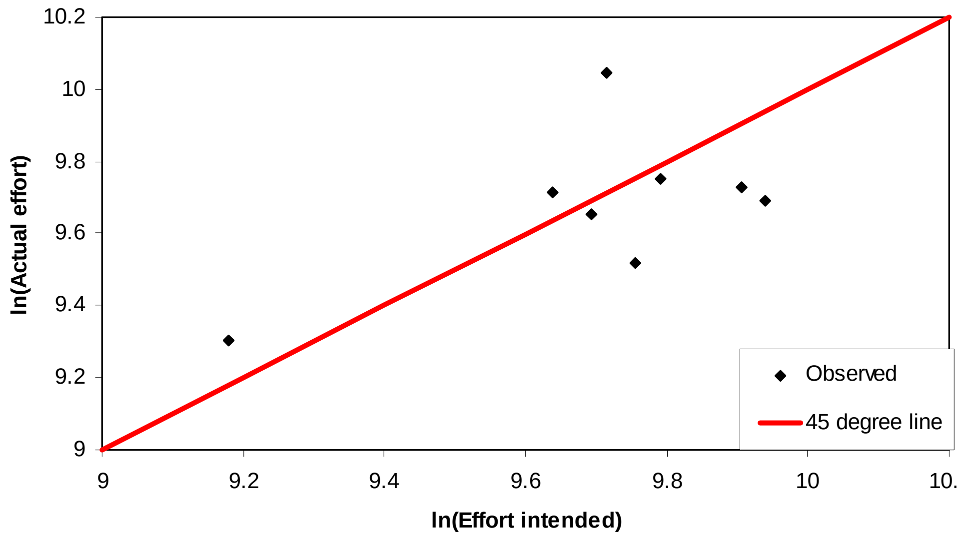

Figure 14: Log-log plot of the desired total standardised effort (tiger prawn days) based on past management decisions by AFMA versus the actual total standardised effort (tiger prawn days) that resulted. The line is a straight line fit with a unit slope.

Table 4 summarizes the implementation error associated with the effort reductions from 1987 to 2002 in terms of the intended reduction in effort by species and how much actually occurred. Data are included in Table 4 (but not Figure 14) for years for which there was no intention to change the amount of effort targeted at tiger prawns. The percentage reduction in effort by species was assumed to be same for cases where the NORMAC minutes do not clearly state which species a reduction in effort was intended to pertain to.

Table 4: Comparison of the percentage change in effort by tiger prawn species and year intended by NORMAC and the actual change in effort that actually occurred.

Year	Management change	Effort on PS		Effort on PE	
		Intended Change (%)	Actual Change (%)	Intended Change (%)	Actual Change (%)
1987	Quad to twin, mid season closure etc.	-25	-22	-25	-49
1993	Compulsory buyback of A-units	-30	-22	-30	+49
1994	No change	0	+26	0	+19
1995	No change	0	-19	0	-10
1996	No change	0	+19	0	+4
1997	Seasonal closure	-10	-13	-10	+7
1998	Spatial closure	-05	+44	-5	-23
1999	Seasonal closure	-15	-17	-15	+15
2000	Gear units	-10	-6	-10	-12
2001	Seasonal closure	-5	-6	-5	+12
2002	Gear unit and season	-25	-1	-40	-10

A further aspect that needs to be considered in relation to implementation error is whether a recommendation by the NPFAG for a change to the amount of effort directed towards tiger prawns is accepted by the decision makers or not. Table 1 shows that recommendations for changes in effort by the NPFAG are often not accepted. This feature of the management system is mimicked in the simulations by only implementing changes in effort based on the management strategies with probability 1/3 (assumed independent among years and independent of the size of the recommended change).

6.4.b Generating a banana prawn season

No attempt is made in this study to model the population dynamics of banana prawns and hence how much effort will be directed towards banana prawns (and away from tiger prawns) during any given year. Instead, an empirical approach to modelling the impact of fishing for banana prawns is adopted. This involves selecting a year, *y'*, from 1990–2002 (excluding 1994 which was anomalous due to its very early first season opening date) at random and assuming that the fraction of the weekly effort "lost" to banana fishing is equal to that for the randomly selected year.

6.4.c Convert to total effort

The effort supplied by the management strategy is the effort to be directed towards the two tiger prawn species combined (E_y^{act}). Therefore, the total level of effort directed towards both banana and tiger prawns is:

$$E_y^{tot} = \frac{E_y^{act} E_{y'}^{tot}}{E_{y'}^{tiger}} \tag{21}$$

where $E_{y'}^{tiger}$ is the total actual tiger prawn effort for the random year *y'*;

$E_{y'}^{tot}$ is the total prawn effort for the random year *y'* ; and

E_y^{tot} is the total actual effort directed towards all prawn species.

6.4.d Allocating effort to week and allowing for fishing for banana prawns

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 (see Section 6.3d). Effort is allocated equally to weeks open to fishing i.e.:

$$E_{y,w}^{\text{act}} = O_{y,w}\, E_y^{\text{act}} / \sum_{w'} O_{y,w'} \tag{22}$$

Equation (22) 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 generally true. To calculate the effort directed towards tiger prawns during week *w* of (future) year *y*, $\tilde{E}_{y,w}^{\text{act}}$, we apply:

$$\tilde{E}_{y,w}^{\text{act}} = E_{y,w}^{\text{act}} (1 - \lambda_{y',w}) \tag{23}$$

where $\lambda_{y',w}$ is the fraction of the effort during week *w* of random year *y*' that was targeted at banana prawns (see Table 5).

6.4.e Splitting the effort to stock area

Although models exist for how vessel effort in the NPF is distributed spatially (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, $\tilde{E}^{\text{act}}_{y,w}$, to the effort by week and stock area, $\tilde{E}^{\text{act},a}_{y,w}$, an empirical approach is used instead for this purpose. The algorithm to split the effort for year *y* and week *w* to stock area is as follows.

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:

   $$p^{a}_{y,w} = \frac{\exp\left(\mathbf{x}^{\mathrm{T}}\boldsymbol{\beta}_a\right)}{\sum_{a=1}^{5}\exp\left(\mathbf{x}^{\mathrm{T}}\boldsymbol{\beta}_a\right)}, \qquad \text{where, for identification, we set } \boldsymbol{\beta}_1 = \mathbf{0} \qquad (24)$$

   For calibration purposes, only weeks where the total tiger effort exceeded 50 boat days were used.

2. The predictors used for the model for each area were:
   a. A separate constant for each combination of year and season (season 1 is defined as weeks 1-27 and season 2 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(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 boat 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 value for the previous week were used. The linear components, $\mathbf{x}^{\mathbf{T}}\beta_a$, 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 the allocation uses, in principle, only predictions from the second stage model. This indirect approach allows greater stability to the process than is achieved 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 and this became a factor to consider in the designed experiments (see Section 8).

4. The multinomial model is unrealistic, although the estimates and predictions that come from it are reasonable (Figure 15). The scatter about the line in Figure 16 is an indication of the kind of spread that the operating model should achieve in simulations (or even a lower bound to allow for the calibration effect). The real effort allocation in the fishery is clearly overdispersed relative to the multinomial and this effect can be achieved in the operating model by allowing for a second component of variation added to the linear predictor. Thus the operating model uses a conditional multinomial allocation of effort that can be described as:

$$\{\tilde{E}_{y,w}^{\text{act},a}, a=1,\ldots,5\} \mid \varepsilon_{y,q}^{a} \sim \text{Multinomial}\left(\tilde{E}_{y,w}^{\text{act}};\, p_{y,w}^{a} = \frac{\exp(\mathbf{x}_{y,w}^{\mathrm{T}}\boldsymbol{\beta}_a + \varepsilon_{y,w}^{a})}{\sum_{a=1}^{5}\exp(\mathbf{x}_{y,w}^{\mathrm{T}}\boldsymbol{\beta}_a + \varepsilon_{y,w}^{a})}\right) \quad (25)$$

where $\varepsilon_{y,w}^{a} \sim \mathrm{N}(0,\sigma^2)$. Experiments suggest that $\sigma^2 = 0.275$ conveys an appropriate amount of overdispersion (see Figure 16 below).

Note that the effort allocation for any particular week in the operating model, other than the initial week of the first and second 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 module is "self-sustaining".

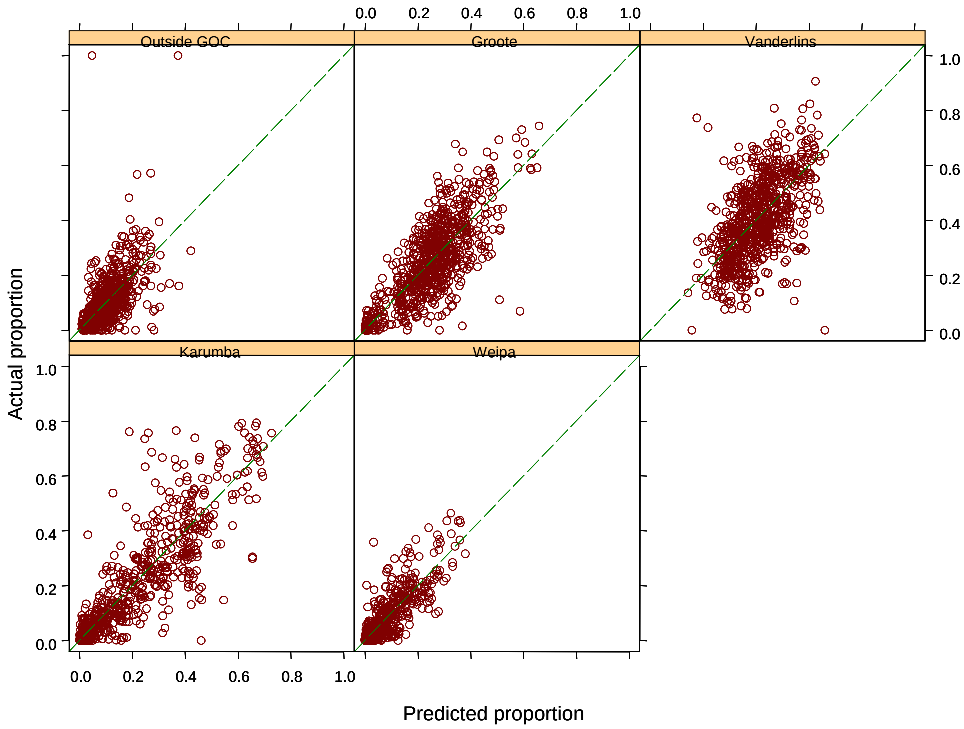

Figure 15: Observed and predicted weekly proportions for each stock area, combined over the calibration years 1980–2003.

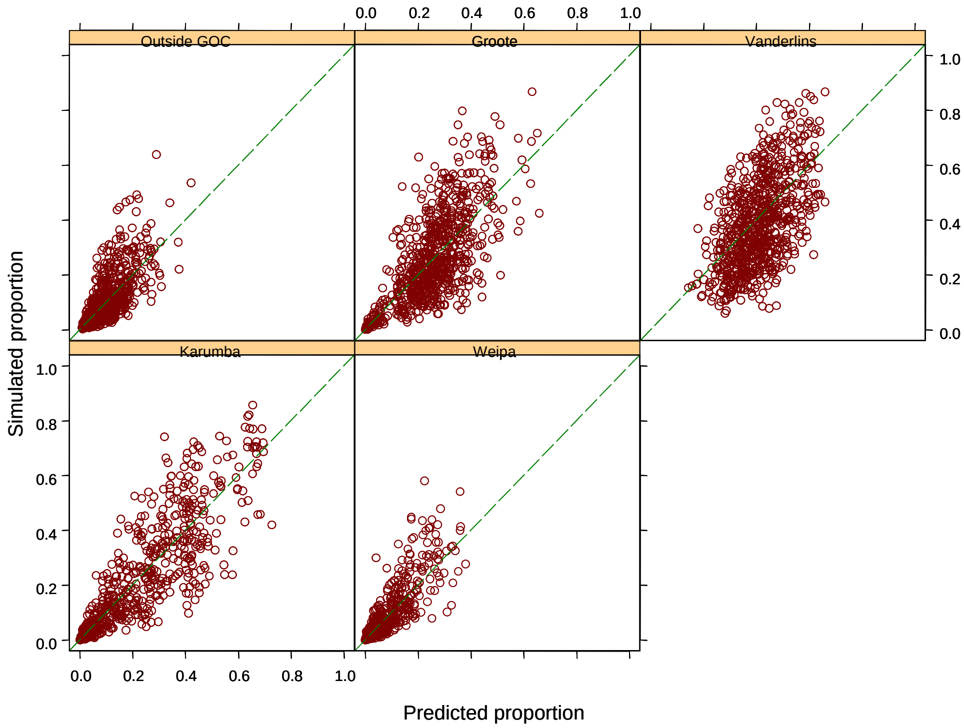

Figure 16: Simulated effort proportions versus predicted proportions. The simulated effort proportion is obtained by adding a random perturbation, $\varepsilon \sim N(0,\sigma^2 = 0.275)$, to the linear predictor before exponentiation and normalisation.

6.4.f Split of the effort to tiger species

The final step of the effort allocation module is to allocate the effort by week and stock-area to tiger species. This is achieved using the formula:

$$E^{1,a}_{y,w} = \pi^a_w \, E^a_{y,w}; \qquad E^{2,a}_{y,w} = (1-\pi^a_w)E^a_{y,w} \tag{26}$$

where π^a_w is the average proportion of the effort during week *w* in stock area *a* that is targeted at *P. semisulcatus*.

Note that this generation process is regarded as having no error associated with it (a feature it shares with the population dynamics model itself), as Dichmont *et al.* (2001) showed this to be small. The split proportions, π^a_w, are based on a statistical model that relates the proportion to geographical and physical predictors and is calibrated using a long series of survey data from the NPF. The model is a generalized linear model using a quasi-likelihood family very similar to the binomial family. More precisely the predictors used are (a) the relative east-west position along the coastline, (b) the distance from the coastline, (c) depth, (d) a harmonic term in time of year and (e) an interaction term between distance from the coastline and the harmonic term in time of year. Full details are given in Venables and Dichmont (2004). Further experimental work and enhancements to this model are currently the subject of a research project (AFMA R01/1149: Species Distribution and Catch Allocation: Data and Methods for the NPF).

6.5 Generating future recruitment

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 with in Dichmont *et al*. (2001) by:

a) generating a recruitment residual for biological year *y*+1, η_{y+1} (see Equation 13); 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, 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 module. 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}.

The operating model described in Section 5 only includes within-stock temporal (i.e. inter-annual) correlation in recruitment (see Equation 14). 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 stock area concerned. 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 (Figure 17) and this was used in some tests when generating recruitment in the future (see Equations (13), (14) and (15)). 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.

Figure 17: 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*

Table 5: Proportion of effort by week targeted at banana prawns.

Year	**Week**																
	1-13	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
1990	1.00	1.00	0.99	0.96	0.50	0.36	0.29	0.29	0.30	0.30	0.24	0.30	0.31	0.30	0.37	0.84	0.05	0.04
1991	1.00	1.00	0.99	0.92	0.73	0.47	0.49	0.33	0.42	0.32	0.47	0.65	0.79	0.45	0.36	0.19	0.00	0.00
1992	1.00	0.98	0.79	0.38	0.37	0.35	0.30	0.22	0.27	0.21	0.19	0.18	0.05	0.00	0.09	0.29	1.00	0.00
1993	1.00	1.00	0.82	0.59	0.72	0.57	0.45	0.51	0.41	0.43	0.35	0.29	0.21	0.00	0.00	0.00	0.00	0.00
1995	1.00	1.00	1.00	0.83	0.50	0.23	0.15	0.16	0.22	0.20	0.25	0.16	0.00	0.00	0.00	0.00	0.00	0.00
1996	1.00	1.00	1.00	0.92	0.63	0.42	0.37	0.30	0.34	0.28	0.24	0.23	0.00	0.00	1.00	0.00	0.00	0.00
1997	1.00	1.00	0.91	0.68	0.46	0.48	0.41	0.46	0.41	0.41	0.36	0.43	0.00	0.14	0.00	0.12	0.08	0.00
1998	1.00	1.00	0.91	0.69	0.63	0.49	0.41	0.43	0.40	0.37	0.31	0.31	0.00	0.00	0.00	0.00	0.00	0.00
1999	1.00	1.00	0.98	0.87	0.76	0.74	0.69	0.66	0.57	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2000	1.00	0.99	0.79	0.48	0.38	0.33	0.73	0.29	0.31	0.76	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2001	1.00	1.00	1.00	1.00	0.96	0.53	0.49	0.50	0.52	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.32	0.00
2002	1.00	1.00	0.95	0.71	0.58	0.67	0.66	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Year	Week(continued)																		
	31	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**	**49-52**
1990	0.06	0.03	0.05	0.02	0.07	0.03	0.05	0.06	0.09	0.03	0.07	0.02	0.04	0.02	0.03	0.02	0.06	0.10	0.00
1991	0.04	0.02	0.04	0.01	0.01	0.02	0.01	0.02	0.03	0.08	0.05	0.05	0.04	0.10	0.03	0.07	0.03	0.10	0.00
1992	0.01	0.02	0.03	0.03	0.03	0.03	0.04	0.05	0.02	0.08	0.03	0.03	0.05	0.06	0.07	0.05	0.08	0.02	0.00
1993	0.04	0.06	0.04	0.04	0.03	0.06	0.13	0.08	0.09	0.03	0.11	0.05	0.07	0.02	0.09	0.02	0.10	0.01	0.00
1995	0.09	0.04	0.06	0.04	0.05	0.05	0.05	0.09	0.07	0.10	0.09	0.17	0.09	0.16	0.05	0.15	0.09	0.12	0.00
1996	0.11	0.10	0.07	0.11	0.07	0.15	0.08	0.10	0.08	0.10	0.10	0.11	0.11	0.10	0.09	0.10	0.09	0.04	0.00
1997	0.14	0.14	0.10	0.09	0.12	0.10	0.12	0.04	0.07	0.03	0.04	0.07	0.08	0.10	0.16	0.50	0.38	0.80	0.00
1998	0.28	0.07	0.10	0.10	0.08	0.02	0.01	0.00	0.02	0.03	0.02	0.03	0.03	0.07	0.01	0.02	0.02	0.04	0.00
1999	0.30	0.41	0.33	0.15	0.10	0.06	0.05	0.04	0.01	0.03	0.01	0.02	0.00	0.03	0.03	0.02	0.00	0.00	0.00
2000	0.31	0.28	0.14	0.16	0.09	0.06	0.02	0.02	0.02	0.03	0.02	0.00	0.01	0.02	0.05	0.00	0.00	0.00	0.00
2001	0.72	0.70	0.34	0.09	0.09	0.16	0.13	0.11	0.15	0.05	0.11	0.05	0.04	0.05	0.07	0.33	0.00	0.00	0.00
2002	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

7 PERFORMANCE MEASURES

7.1 Introduction

An evaluation of alternative management strategies is conducted by developing an operating model of the fishery (to generate the data available for assessment purposes in each simulated year) and a set of management strategies which analyse the data from the operating model using an assessment procedure and then use the results from the assessment procedure to determine management actions. The results from the assessment procedure may include output quantities (such as E_{MSY}, MSY and S_{MSY}) that are of interest to management. Clearly, the amount of information generated by an MSE can be enormous. It is most efficient to summarize the results of the simulations using a relatively small number of performance measures to identify the best-performing management strategies and, conversely, those which fail to perform adequately (Sainsbury *et al* 2000). In the context of an MSE, there are two types of performance measures: 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 fishery stock assessment methods are able to estimate quantities (such as *MSY*, E_{MSY}, current spawning stock biomass, etc.) that are of interest to the decision makers.

In relation to the performance measures that rely on estimates of output quantities, it should be noted that not all assessment procedures estimate all output quantities and that it is by no means the case that a management strategy that estimates output quantities adequately will perform well in terms of satisfying the management objectives for the Northern Prawn Fishery.

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). That is, the management strategy comparisons are not made by comparing the output quantities from each assessment with the "true" values for these quantities in the operating model. Rather, it is by considering performance measures derived from the operating model that makes it possible to compare management strategies based on the Deriso-Schnute delay difference model with the empirical regression approach.

Estimation-related performance measures must, obviously, be based on a comparison of estimates of output quantities from the assessment procedures with the "true" values from the operating model.

7.2 Management-related performance measures

Ultimately, the performances of the different management strategies need to be considered relative to the five legislative objectives of the Australian Fisheries Management Authority (AFMA) (Anon 1998) and the management objectives for the NPF defined in the most recent Strategic Plan (Anon 2001). AFMA's five legislative objectives are:

- implementing efficient and cost-effective fisheries management on behalf of the Commonwealth;
- 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 and the exercise of the precautionary principle, in particular the need to have regard to the impact of fishing activities on non-target species and the long-term sustainability of the marine environment;
- maximising economic efficiency in the exploitation of fisheries resources;
- ensuring accountability to the fishing industry and to the Australian community in the Authority's management of fisheries resources; and
- achieving government targets in relation to the recovery of the costs of the Authority.

The five objectives identified in the 2001-2006 NPF Strategic Plan are:

- ensure the utilization of the fishery resources within the North Prawn Fishery is consistent with the principles of ecologically sustainable development and the exercise of the precautionary principle;
- maximize economic efficiency in the utilization of the fisheries resources within the Northern Prawn Fishery;
- implement efficient and cost-effective management of the Fishery;
- effectively communicate and consult with AFMA, the fishing industry, other marine resource users and the broader community; and
- ensure that the incidental catch of non-target commercial and other species in the NPF is reduced to a minimum.

Management-related performance measures are therefore statistics (such as the average over simulations of the total catch over the 15-year period 2003–17) that summarize how successfully a management strategy is able to satisfy the AFMA's legislative objectives and the objectives identified specifically for the NPF. The objectives in the NPF Strategic Plan are essentially the same as AFMA's legislative objectives, except that avoidance of incidental catch is emphasized in the fishery objectives and there is no mention of AFMA's cost recovery objective.

In common with previous Management Strategy Evaluation exercises in Australia (e.g. Polacheck *et al*. 1999, Punt *et al.* 2001a, 2001b, Campbell and Dowling 2003), only the first three of AFMA's legislative objectives (cost-effective management, economic efficiency and ecologically sustainable development, ESD) are considered in this study. The emphasis is therefore on the sustainability of the stocks and of the fishery. The other two objectives relate to social management policies and ecosystem management issues that are beyond the scope of the current modelling project.

It has been argued (Kaufmann *et al*. 1999, pg. 88) that the second objective (economic efficiency) can be satisfied for the target species of a fishery if the fishery is managed by means of Total Allowable Catches implemented as Individual Transferable Quotas. This is because, if quota trading worked as predicted, the fishery will move over time to a situation in which the catch is taken with a minimum of inputs (Punt *et al*. 2001b). The NPF is managed by means of Individual Transferable Gear Units. The arguments made by Kaufmann *et al*. (1999) could therefore also apply in the case of the NPF. Dealing with the ‘cost effective management’ objective is complicated. However, it should be possible to deal with this objective adequately by determining the ‘financial’ cost associated with alternative management strategies as the costs associated with: a) monitoring, b) conducting assessments, c) holding meetings to discuss the outcomes of assessments and their implications for management, and d) implementing and enforcing the resultant management regulations. It would be possible, in principle, to quantify these costs, but this is beyond the scope of the present study.

Ideally, the objectives for management should be expressed as “operational management objectives”, i.e. clearly defined objectives that can be quantified by data collected from the fishery or outputs from assessment models. For example, the last of the NPF objectives could be represented by the operational management objective “reduce the catch of all turtles by 80% between 2001 and 2005”. The performance measures used when performing the Management Strategy Evaluation would then be based on these operational management objectives (Sainsbury *et al*. 2000).

Unfortunately, prior to the commencement of this project, the management goals were incompletely articulated as “set the fishing effort to that corresponding to *MSY*”. However, during 2001, the management goal was revised to relate to recovering the spawning stock to the level at which, in expectation, *MSY* is achieved (S_{MSY}). Specifically, NORMAC 51 commented that “In determining milestones and performance measures for the fishery, NORMAC agreed that from 2002 and thereafter (annually) NORMAC will use the NPFAG accepted assessment model to estimate the performance of the previous years stock relative to spawner target levels. The agreed target is a 70+% chance that the spawner population at the end of 2006 will be above or at spawner target levels. NORMAC will utilise the advice of the NPFAG (majority) to provide the advice to assess performance against the target” (NORMAC 51). The risk-related performance measures considered in this study are therefore based primarily on the size of the spawning stock relative to S_{MSY} (which is treated as a limit reference point, i.e. success is defined as leaving the spawning stock above S_{MSY}). The decision by NORMAC 51 defined a limit reference point but did not provide any guidance regarding target reference points. In developing the performance measures therefore, the ‘target’ for the fishery was for it to produce the “highest stable average” yield consistent with leaving the spawning stock above S_{MSY}.

The performance measures related to the Ecologically Sustainable Development objective should consider two key aspects when evaluating a management strategy: a) the impact of the management strategy on the viability of the target species and perhaps also its associated ecosystem, and b) the impact of the management strategy on the profitability of the fishery. Each of these aspects is discussed in turn and relevant performance measures identified.

7.2.a Risk-related performance measures

It could be argued that the ideal risk-related performance measure is the probability that the resource drops below the level at which it is unable to play its appropriate role in the ecosystem (the ‘biological bottom line’). However, there is no clear objective basis for specifying such a level for any species, and certainly not for tiger prawns in the Northern Prawn Fishery. Instead, it is conventional to choose a variety of alternative ‘biological bottom lines’ and to assess the probability of the population dropping below each. The performance measures are therefore designed to reflect concern about the possible consequences of low biomass. Such consequences include fishery collapse due to recruitment failure, species replacement, or depensatory processes (Hilborn 1997), and impacts on the rest of the ecosystem (Corten 1986). The following represent the set of possible ‘biological bottom lines’ examined in this study.

a) S_{MSY} the spawning stock size at which *MSY* is achieved – this level is conventional in fisheries management, has been included in several international agreements (e.g. United Nations (1995)), and has been selected as a limit reference point by NORMAC. However, there is no evidence that depleting a resource to below S_{MSY} will necessarily lead to severe biological problems.

b) $0.2\ S_0$ this level has been used in many previous studies (e.g. Beddington and Cooke 1983, Francis 1992, Punt 1995, 1997, Punt *et al*. 2001b). However, Hilborn (1997) criticises the use of 20% of B_0 as a performance measure because (a) it is arbitrary, (b) some stocks have recovered from lower levels, and (c) stocks below 20% of the virgin biomass may be capable of producing high sustainable yields.

c) S_{low} this level is the lowest spawning stock size ever encountered prior to the application of the management strategy; avoiding dropping the spawning stock size below the lowest level ever encountered considers the question “does the application of the management strategy ‘make things worse’”?; as for the two previous ‘biological bottom lines’, there is no evidence that dropping the spawning stock below S_{low} will *necessarily* lead to highly undesirable biological outcomes.

Performance measures based on the probability of dropping below these three ‘biological bottom lines’ only consider the impact of fishing on the target species. In principle, the health of the ecosystem should be related fairly closely to the size of the prawn biomass, but the exact relationship is unclear. The FRDC project (“Bringing economic analysis and stock assessment together in the NPF: a framework for a biological and economically sustainable fishery"[7]) will address the question of the ecosystem impacts of different management strategies more explicitly.

The following performance measures are considered for each of the two species. Note that the probability measures are computed across multiple simulations so the probability statement $P(S_y^a > 0.2S_0^a)$ should be interpreted as the probability, across simulations, that the spawning stock size in stock area a during year y is greater than 20% of the average unfished spawning stock size in stock area a.

a) The probability that the spawning stock size exceeds the limit reference point agreed to by NORMAC. This probability can be a) calculated by stock, b) calculated over all stocks, and c) triggered only when all stocks are above S_{MSY}, i.e.

$$P(S_y^a > S_{MSY}^a) \tag{27}$$

$$P(\sum_a S_y^a > \sum_a S_{MSY}^a) \tag{28}$$

$$P(\forall a : S_y^a > S_{MSY}^a) \tag{29}$$

It is necessary to specify the year(s) for which equations (27–29) are to be evaluated. For the purposes of this study, three years are examined: a) 2006 (in line with the decision by NORMAC 51 that recovery to S_{MSY} should have occurred by 2006), b) 8 years after the management strategies are first applied (i.e. 2010), and c) the end of the projection period (2015).

b) The probability that the spawning stock size exceeds $0.2S_0$. As for the previous set of performance measures, this probability can be a) calculated by stock, b) calculated over all stocks, and c) triggered only when all stocks are above $0.2S_0$, i.e.:

$$P(\min_{y>2002} S_y^a > 0.2\, S_0^a) \tag{30}$$

$$P(\min_{y>2002} \sum_a S_y^a > 0.2 \sum_a S_0^a) \tag{31}$$

$$P(\forall a : \min_{y>2002} S_y^a > 0.2 S_0^a) \tag{32}$$

Unlike the previous set of performance measures these performance measures are based on 20% of the average unfished spawning stock size. This is because these (and the following) performance measures capture the possibility that the population is depleted to levels at which tiger prawns may be unable to continue to play their appropriate role in the ecosystem.

c) The probability that spawning stock size exceeds the lowest spawning size from 1969–2002. These performance measures capture the probability that the spawning

[7] Proposal available on request from C. Dichmont.

stock size will be reduced (unintentionally) below the lowest level observed since the fishery started. Dropping the spawning stock size below the lowest level encountered for 30 years could be considered to be a form of ‘management failure’

$$P\left(\min_{y>2002} S_y^a > S_{low}^a\right) \tag{33}$$

$$P\left(\min_{y>2002} \sum_a S_y^a > \sum_a S_{low}^a\right) \tag{34}$$

$$P\left(\forall a : \min_{y>2002} S_y^a > S_y^a\right) \tag{35}$$

d) the total spawning stock size by stock area in 2010 and 2105 relative to the true total spawning stock size that would achieve the Maximum Sustainable Yield (S_Y/S_{MSY} (%)).

7.2.b ‘Economic’ performance measures

There are two approaches to developing performance measures that capture the economic aspects of the outcomes 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 is to assess economic performance using simple proxies. Development of a detailed economic model is beyond the scope of this project although the development of such a model is envisaged as part of the FRDC project “Bringing economic analysis and stock assessment together in the NPF: a framework for a biological and economically sustainable fishery”. The proxies used in this project for the economic performance of the management strategies were:

a) discounted total (across stocks and tiger prawn species) catch, i.e.:

$$C^T = \sum_y C_y e^{-\delta(y-2003)} \tag{36}$$

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

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

The median and the lower 5th percentile of the discounted total catch across simulations are reported; the median represents the expected catch of the management strategy while the lower 5th percentile represents the “guaranteed” performance of the management strategy.

b) probability 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.

c) probability that the catch is less than the lowest catch taken over the historical (1969–2002) period, C_{low}, $P(C_y < C_{low})$.

d) stability of catches. The stability of the catches is measured by the average absolute (percentage) change in landed catches, *AAV*:

$$AAV = \frac{100 \sum_{y=2003}^{2015} \left| C_y - C_{y-1} \right| e^{-\delta(y-2003)}}{\sum_{y=2003}^{2015} C_y e^{-\delta(y-2003)}} \tag{37}$$

Equation (37) is based on the total catch of all tiger prawn species over all weeks and stock areas. This equation implicitly assumes that the value of the catch is independent of week, stock area, and species. In principle, allowance could be made for week-, species- and area- specific prices and costs but evaluation of these is beyond the scope of the present study.

7.2.c Estimated-related performance measures

Performance, in terms of estimating a output quantity, is defined by the magnitude of the relative error:

$$E_y^{i,j} = 100 \frac{\hat{Q}_y^{i,j} - Q_y^{i,j}}{Q_y^{i,j}} \tag{38}$$

where $E_y^{i,j}$ is the relative error for quantity *i* for simulation *j* based on an assessment conducted during year *y*,

$Q_y^{i,j}$ is the true (i.e. operating model) value for quantity *i* for simulation *j* during year *y*, and

$\hat{Q}_y^{i,j}$ is the estimate (based on some method of stock assessment) for quantity *i* for simulation *j* based on an assessment conducted during year *y*.

The relative errors for a given quantity, stock assessment method, and year of assessment are summarised by a variety of statistics. These include the median and 90% intervals of the relative errors, and the median of the absolute values for the relative errors (abbreviation MARE). The median relative error captures the “bias” of the estimates of a output quantity while the MARE captures the impact of both bias and variability. The median relative error and MARE are preferred in this study to the expected relative error (the bias) and the root mean square error (RMSE) because they capture the intent of the bias and RMSE but are more robust to the impact on the summary statistics of occasional outlying estimates. These particular summary statistics have been used in several previous evaluations of the performance of methods of stock assessment (e.g. Punt *et al.* 2002).

The output quantities considered in the study are:

- the spawning stock size for each year and stock area, S_y^a;
- the total annual spawning stock size, $\sum_a S_y^a$;
- the spawning stock size corresponding to *MSY*, by stock area, S_{MSY}^a;
- the spawning stock size corresponding to *MSY* summed across stock areas, $\sum_a S_{MSY}^a$;
- the ratio of the spawning stock size for each year and stock area, relative to that corresponding to *MSY*, S_y^a / S_{MSY}^a;
- the total spawning size for each year relative to that corresponding to *MSY*, $\sum_a S_y^a / \sum_a S_{MSY}^a$
- the steepness of the stock-recruitment relationship by stock area, h^a;
- the fishing effort (in 1993 units) corresponding to *MSY*, by stock area, E_{MSY}^a;
- the fishing effort (in 1993 units) corresponding to *MSY* summed across stock areas, $\sum_a E_{MSY}^a$;
- the Maximum Sustainable Yield, *MSY*, for each stock area, MSY^a; and
- the Maximum Sustainable Yield summed across stock areas, $\sum_a MSY^a$.

The spawning stock in absolute terms and relative to S_{MSY} are considered because the management objectives for the fishery are measured in terms of the latter ratio but the absolute size of the spawning stock is nevertheless of interest to several stakeholder groups. The results of several previous studies that have evaluated the performance of stock assessment methods suggest that the ratio of spawning stock size to a reference level will be determined more accurately and precisely than the absolute spawning stock size (e.g. Punt 1995, 1997, Punt *et al.* 2002). E_{MSY} is included in the list of output quantities because it formed the basis for the previous (target) reference point for the fishery while *MSY* is included in the list because the long-term average yield at S_{MSY} is of interest to fishers and managers.

The estimates of the above quantities are compared with the “true” values from the operating model at the start of the first projection year (2003), after seven years (2010) and at the end of the projection period (2015). Not all of the stock assessment methods considered in this study provide estimates for all of the above quantities. For example, the surplus production model provides estimates aggregated across stock area and species.

8 FACTORS AFFECTING PERFORMANCE MEASURES

8.1 Methods

A set of simulations is undertaken to identify the key factors affecting the different performance measures. Viewed as an experimental design, this set is unbalanced, but is nevertheless able to achieve adequate resolution for the main problem. Complete balance would have been computationally infeasible, and in a practical sense unnecessary.

8.2 The scenarios

The factors considered in the simulations relate to the specifications for the operating model and those for the management strategies. Table 6 lists the 16 factors, combinations of which lead to a total of 60 scenarios. 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. The scenarios for the catch rate and biomass dynamic model are summarized in Appendix A while those for the Deriso model are summarized in Appendix B.

Table 6: The factors (and their levels) considered in the scenarios.

Factor	Equation / Section number	Operating model	Management strategy
1. Model type	Sec 4.2	Deriso	1. Deriso, 2. Biomass dynamic 3. Simple regression
2&3. Efficiency factor	Sec 5.2	1. Base Case High (BCH) 2. Base Case Low (BCL)	1. Base Case High (BCH), 2. Base Case Low (BCL)
4&5. Catchability coefficient, $\tilde{q}$	Eqn (9)	1. From Wang (1999) – q 2. Twice Wang (1999) – 2q	1. From Wang (1999) – q 2. Twice Wang (1999) – 2q
6. Observation error on catch (%CV)	Sec 6.2a	1. None 2. 10%	
7. Stock-species correlation in recruitment for future years	Sec 6.5 (Figure 17, Sec 6.5)	1. None 2. Based on the historical correlations of the residuals about the fit of the stock-recruitment relationship for each area and species	None
8. Include survey	Sec 4.2	N/A	1. No

index			2. Yes (Deriso model only)
9. Implementation error	Eqn (20)	N/A	1. No (CV=0) 2. Yes (CV = 15%) 3. Yes (CV= 30%)
10. Area allocation weight to current catch rates relative to historical pattern in effort area allocation module	Sec 6.4e	N/A	1, or 1.5
11. Method of generating parameter vectors	Sec 6.1 and Appendix C	1. Variance-covariance matrix 2. Bayesian posterior	N/A
12. Target spawning stock size and effort level	Sec 6.3c (Figure 12)	N/A	1. 1.0S_{MSY} and 1.0E_{MSY} 2. 1.2S_{MSY} and 0.8E_{MSY}
13. Number of stocks	Sec 4.2	5	1. 1 stock 2. 3 stocks 3. 5 stocks
14. Range of years to calculate E_{MSY}	Dichmont *et al.* 2003[8]	1993–2002	1. 1993–2002 2. Recent 10 year running window
15. Chance that the season changes	Sec 6.3d	N/A	1. Each year 2. Random chance of 1 in 3 that a change will be decided upon
16. Chance the effort level changes	Sec 6.4a	N/A	1. Each year 2. Random chance of 1 in 3 that a change will be decided upon

[8] The calculation of E_{MSY} and the other MSY-related management quantities require a within-year pattern of effort. This pattern can either be based on the average pattern during 1993-2002, or the average pattern over the 10 years prior to the year in which the assessment occurs.

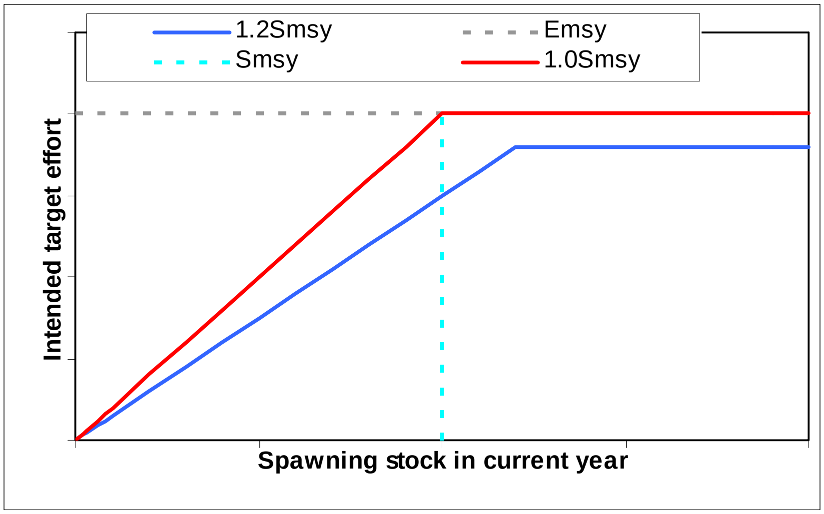

Figure 18: The two decision rules on which the experiment is based.

The results of the scenarios are, where applicable, analysed by species and "assessment model" type. The following stepwise process is used to analyse the various performance measures:

1. a linear model with all possible main effects is fit (using the *aov* function in *R*);
2. the most parsimonious main effects model is selected according to the 'Bayesian Information Criterion' (BIC) using the *stepAIC* function from the MASS library in *R*;
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 supplied by the most parsimonious main effect 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 full main effects generalised linear models (using the mnemonic notation in Table 7 below) for the cpue regression, Deriso and biomass dynamics management strategies are given by Equations 39-41 respectively.

$$PM_{C,NPF} \sim OE + SCR + DE + qOp + CWt + Rval + RefPt + NoStock + PSeason + PEffort \quad (39)$$

$$\begin{aligned} PM_{D,NPF} \sim\ & FpOp + FpAss + OE + SCR + Survey + DE + qOp + qAss + CWt + Rval \\ & + Refpt + NoStock + Refyr + PSeason + PEffort \end{aligned} \quad (40)$$

$$PM_{B,NPF} \sim OE + SCR + DE + qOp + CWt + Rval + RefPt + PSeason + PEffort \quad (41)$$

where $PM_{D(orC\ or\ B),\ NPF}$ is the NPF-wide performance measures for the Deriso assessment (D), the cpue regression approach (C) or the biomass dynamic model (B). In all cases, the median values of each factor were used.

It should be noted that:

1. The results for the three assessment procedures were analysed separately because some factors do not apply to some assessment procedures. For example, fishing power and catchability are inputs for the Deriso model-based assessment procedure whereas catchability is an estimated parameter in the biomass dynamic model and is not used by the cpue regression approach.
2. Many of the economic-related performance measures are for both species combined.
3. All the risk- and economic-related performance measures are for the operating model (i.e. the "true" resource that is being managed).

Table 7: Description of factors (other than assessment model type) examined in main experiment and their abbreviations (see Table 6 for the levels for each factor).

Abbreviation	Description
FpOp	Efficiency factor for the operating model
FpAss	Efficiency factor for the assessment method
OE	Observation error on catch (%CV)
SCR	Is recruitment spatially correlated?
Survey	Does the assessment use the survey indices of recruitment?
DE	The level of implementation error
qOp	The catchability coefficient in the operating model
qAss	The catchability coefficient in the assessment model
CWt	Area allocation weight to past cpue
Rval	Whether the parameters sets for the operating model are based on the variance-covariance matrix or the Bayesian posterior distribution.
RefPt	The target value of S_{MSY} in the decision rule
NoStock	The number of stock areas in the assessment
RefYear	The range of years used when determining E_{MSY}
PSeason	Is the season length changed annually?
PEffort	Is the effort level changed annually?

8.3 Results

8.3.a Risk-related performance measures

The risk-related performance measures are calculated for each year, but are only analysed for 2010 and 2015. Three groups of performance measures (see Section 7) are considered:

- the probabilities that the "true" spawning stock sizes in 2010 and 2015 are above S_{MSY} (e.g. $P(S_{2010} > S_{MSY})$;
- the probabilities that the "true" spawning stock sizes in those years are above 20% of the virgin spawning biomass (e.g. $P(S_{2010} > 0.2S_0)$; and
- the probability that the "true" spawning stock size is above the lowest "true" spawning stock size in known history (e.g. $P(S_{2010} > S_{low})$).

Since the risk-related performance measures relate to the "true" resource being managed, there are spawning stock sizes and MSY-type reference points for each of the eight species$\times$stock combinations. All the above statistics can be produced for each stock and species. Alternatively, the spawning stock sizes can be added together and NPF-wide statistics produced or probabilities can be defined so that a simulation "succeeds" for a given threshold stock size if all eight stocks are above their respective thresholds. Considering all of these possibilities would lead to an overwhelming volume of results to analyse. These results are summarised briefly in Tables 8-10.

Table 8: Summary of results across all scenarios, years and species for the risk-related performance measure the probability of being above S_{MSY}.

	NPF-wide	Out-side GOC	Groote	Vanderlins	Karumba	Weipa	All
Minimum	0.00	0.00	0.03	0.00	0.00	0.00	0.00
1st Quartile	0.20	0.48	0.68	0.25	0.05	0.34	0.00
Median	0.45	0.63	0.77	0.48	1.00	1.00	0.02
Mean	0.48	0.61	0.77	0.49	0.56	0.68	0.12
3rd Quartile	0.78	0.83	0.89	0.71	1.00	1.00	0.11
Maximum	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 9: Summary of results across all scenarios, years and species for the risk-related performance measure the probability of being above S_{LOW} (the lowest spawning stock size from 1970–2002)

	NPF-wide	Out-side GOC	Groote	Vanderlins	Karumba	Weipa	All
Minimum	0.82	0.76	0.91	0.76	0.64	0.83	0.48
1st Quartile	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Median	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Mean	1.00	0.99	1.00	1.00	0.99	1.00	0.97
3rd Quartile	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Maximum	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 10: Summary of results across all scenarios, years and species for the risk-related performance measure the probability of being above $0.2S_0$

	NPF-wide	Out-side GOC	Groote	Vanderlins	Karumba	Weipa	All
Minimum	0.88	0.73	0.93	0.83	0.00	0.00	0.00
1st Quartile	1.00	0.98	1.00	1.00	0.71	0.95	0.55
Median	1.00	1.00	1.00	1.00	1.00	1.00	0.78
Mean	1.00	0.98	1.00	1.00	0.85	0.88	0.71
3rd Quartile	1.00	1.00	1.00	1.00	1.00	1.00	0.96
Maximum	1.00	1.00	1.00	1.00	1.00	1.00	1.00

There are cases where none (or all) of the scenarios are above S_{MSY} (Table 8). On the other hand, there is generally a low chance that any of the scenario runs lead to the spawning stock size falling below the historically lowest spawning stock size (Table 9), although there was a much higher chance that the spawning stock size in a year is below 20% of the virgin stock size (Table 10).

With reference to the performance measure $P(Sy > S_{MSY})$, all three “assessment procedures” consistently under-perform outside the Gulf (stock area “Outside GOC”) and in the western Gulf (stock areas Groote and Vanderlins) compared to the stock areas in the eastern Gulf (Figure 19). Performance, in terms of keeping the spawning stock size above S_{MSY}, is poorest for the Vanderlins stock area (Figure 19).

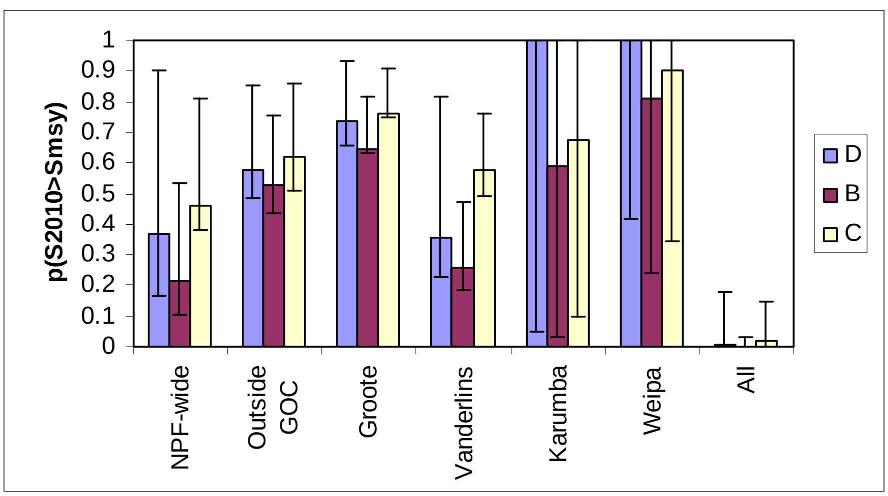

Figure 19: Median values (with 1st and 3rd quartiles) for $P(Sy>S_{MSY})$ for all scenarios for the Deriso (D), biomass dynamic (B) and cpue regression (C) management strategies.

The greatest contrast in the values for a performance measure in Tables 8 - 10 occurs for $P(Sy > S_{MSY})$. Little is gained by analysing each stock area individually or by excluding some of the stock areas in terms of analysing the factors that are most influential in the experiment. The analyses therefore focus on the performance measure $P(S_{2010} > S_{MSY})$ by species for the entire NPF. A summary of the highly significant terms is given in Table 11. Since the risk-related performance measures are binomial 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.

The following factors are ignored, either because they are redundant for the assessment procedure underlying the management strategy or because they lead to a singular model:

a) *from cpue regression analyses*: fishing power and catchability (neither of these values are relevant);
b) *from both the cpue regression and the Deriso assessment*: number of stocks in the assessment (this resulted in singularity and was never included formally in the experiment because it would have required an unrealistic amount of computer time); and
c) *from the Deriso assessment*: including a survey index in the assessment (this resulted in singularity and was also never included formally in the experiment).

Note that we are only interested in uncovering the factors that have an important influence on the results at this stage. It is a screening step and the effects of these factors are explored more thoroughly later using a more balanced experiment.

Table 11 demonstrates that, where relevant, the most significant factors are fishing power, catchability (and various combinations thereof), whether recruitment is correlated spatially among stocks, the extent of implementation error, and the target spawning stock size used in the decision rule.

Table 11: Summary of the regression results for the performance measure $P(S_{2010} > S_{MSY})$ (PS=*P. semisulcatus*, PE=*P. esculentus*, Significance codes: 0 '***', 0.001 '**', 0.01 '*', 0.05 '.', 0.1 'blank'). The shaded factors are included in the final model.

Factor	PS Deriso	PE Deriso	PS biomass dynamic	PE biomass dynamic	PS cpue regression	PE cpue regression
FpOP	***	***				
FpASS	***	***				
DE					***	***
SCR			***	***	***	***
qOp	***	***				
qAss						
Rval	*		***		***	
RefPt	***	***	***	***		
RefYear	*					
FpOP:FpASS	***					
FpASS:DE	**					
FpASS:SCR	*	***				

FpASS:qOp						
FpAss:qAss	***					
FpAss:Rval	***					
FpAss:RefYear	***					
FpOp:qOp		***				
DE:qOp	***					
SCR:DE			***	***	***	***

8.3.b Economic related Performance Measures

The method used to analyse the risk-related performance measures is also used to analyse the economic-related performance measures (on the log scale). A crude summary of the median values over all scenarios (Table 12) shows that there is a large range over all scenarios in the values of the economic performance measures discounted catch, catch variability, and the lowest catch. On the other hand, the annual median catches fall below 2000t in only a few scenarios.

Table 12: Summary of the median values across all scenarios for the different assessment procedures of some of the economic-related performance measures (“D”=Deriso, “B”=biomass dynamic, “C”=cpue regression).

	Discounted catch			AAV			Lowest catch (t)			Percentage of years in which the catch fell below 2000t		
	D	C	B	D	C	B	D	C	B	D	C	B
Minimum	13180	20760	22940	6.43	4.07	12.60	904	1317	1230	0.00	0.01	0.01
1st quartile	23120	21950	23750	12.84	10.37	17.24	1574	1685	1454	0.01	0.01	0.02
Median	24400	22840	24180	15.21	11.00	21.07	1801	1794	1643	0.01	0.02	0.03
Mean	23390	22710	24090	15.94	12.91	22.76	1710	1734	1618	0.02	0.02	0.02
3rd quartile	25350	23200	24520	17.78	14.80	27.88	1920	1874	1783	0.02	0.03	0.03
Maximum	27270	24690	25110	25.83	21.82	38.15	2073	1959	1933	0.11	0.05	0.04

The results of the final linear models for each of the economic-related performance measures are given in Table 13. Table 13 identifies more factors than Table 11 and there are quite noteworthy differences among the various performance measures in terms of the factors that are most significant. Even so, implementation error, the fishing power for the operating and assessment models and their possible interactions (in the case of the Deriso assessment), the target spawning stock size used in the decision rule, and whether the parameter sets are simulated from a distribution based on the asymptotic variance-covariance matrix or the Bayesian posterior are significant factors. As was the case for the risk-related performance measures whether recruitment is correlated spatially was also an important factor.

Table 13: Summary of the final models for some of the economic-related performance measures; Discounted catch, (Dcatch), AAV, Lowest catch.(CLow) and the percentage of the years the catch falls below 2000t (Significance codes: 0 ‘***’, 0.001 ‘**’, 0.01 ‘*’, 0.05 ‘.’, 0.1 ‘blank’). The shaded factors are included in the final models.

Factor	DCatch			AAV			Clow			% yrs catch falls below 2000t		
	D	C	B	D	C	B	D	C	B	D	C	B
FpOP	***						***					
FpASS	***			***			**					
qOP	***						***					
Rval	***	***	***					***	***	* * *	***	***
RefPt	***		***			***			***			
FpOP:FpA	***											
FpOP:qO	***						***					
FpOP:Ref	***											
FpASS:Re	***											
FpASS:D				***								
SCR		***	***	***	***	***						***
DE		***		***	***	***	***	***	***	* * *	***	***
SCR:DE		***		***	***	**		*				
SCR:qAss				***								
OE			***			***			***			
OE:CSR												
qAss				***								
PEffort						***						

8.4 Summary

It is clear that, for the management strategies based on Deriso model-based assessment procedure, the catchability in 1993 and fishing power values chosen for the assessment and operating model (especially when they are mismatched) are important factors that influence the final results in terms of both the risk- and economic-related performance measures. 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. Note that this chapter only screened the factors; assessing how they influence the results is addressed in Sections 9 and 10.

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 some understanding of the underlying mechanisms that may lead to such correlation may be important. At present, little is known of the mechanisms behind the correlations in recruitment evident from the fits of the model to the actual data.

The extent of implementation error, whether the parameters of the operating model are generated from the variance-covariance matrix or the Bayesian posterior, and the interaction between the extent of implementation error and whether recruitment is spatially correlated or not all appear to be important factors.

The following two chapters report the results of a series of balanced simulation experiments to investigate the effects that each of these factors has on the various performance measures. The best methods to demonstrate these differences are graphical (rather than purely numerical) as the graphs highlight the degree of change, permit simple visual appreciation of any trends, and summarise effects across all the performance measures very well.

9 MANAGEMENT PROCEDURE SCALE AND COMPLEXITY

9.1 The Base Case operating model

A Base Case operating model was defined. The specifications of this operating model were chosen to mimic as closely as possible a management strategy (denoted "D1") that is based on the single-stock Deriso assessment method, sets catchability and fishing power to "q" and "Base Case High" respectively, and has a target spawning stock size of S_{MSY} for both species of tiger prawn. The Base Case operating model does not include implementation error on the data provided, but does include a $^2/_3$rds chance that any total effort change recommended would not be implemented.

9.2 The different "assessment" methods

9.2.a Performance measures

The objective of a MSE is to identify an assessment procedure and decision rules that together (as a management strategy) leave each tiger prawn species close to their target reference points (in the case of the Base Case scenario, S_{MSY}). In addion, the management strategy should avoid four possible adverse consequences:

1) it should not sacrifice long-term catch (quantified by the performance measure "DCatch"),
2) it should not sacrifice inter-annual catch stability (quantified by the performance measure "AAV")
3) it should avoid the possibility of occasional very low catches (quantified by the performance measures "P(C_y<2000t)" and "CLOW"), and
4) it should not risk fishery collapse (quantified by the performance measures $P(S_{2015}>S_{LOW})$ and $P(S_{2015}>0.2S_0)$).

An assessment of resource status is undertaken each year, which then determines the total effort level and the season length (see Section 6.3) for the management strategies based on the biomass dynamic (prefix "B") and the Deriso (prefix "D") models. In contrast, no assessment of resource status is made for the cpue regression approach (prefix "C"). Instead, the slope of the logarithms of the catch rates over the most-recent five years is taken as an indication of change in resource status. Since the decision rule based on the cpue regression approach is $E_y = E_{y-1}(1+0.5\text{Slope})$, the annual effort changes are half the size of the slope of the regression. With no way of using the cpue regression approach to change season length, this remains the same as for 2002 for the management strategies based on the cpue regression approach.

It should be borne in mind that there is a gradient in the complexity of the assessment procedures from the cpue regression approach, to the biomass dynamic model and to the Deriso model. The most obvious differences are that the cpue regression approach does not assess the status of the resource and is not species-specific, the biomass dynamic model assesses the status of both tiger prawn species together using an annual model, and the Deriso model assesses the status of each tiger prawn species separately using a weekly model that accounts for inter-annual changes in recruitment.

Figure 20 is an example of a comparison plot, which summarizes the performances of several management strategies for a single operating model or the performance of one management strategy for several operating models. The panels on a comparison plot show the median and 90% intervals for the ratio of the spawning stock size in 2010 and 2015 to S_{MSY} for *P. semisulcatus* and *P. esculentus* (abbreviated as “PS” and “PE”), the median and 90% intervals for four economic-related performance measures (DCatch, AAV, $P(C_y<2000t)$, and CLOW), and the probabilities (by tiger prawn species) of the spawning stock size in 2015 exceeding S_{MSY}, S_{LOW} and $0.2S_0$.

Figure 20 compares the D1 management strategy, which most closely matches the setting for the Base Case operating model, with similarly configured management strategies based on the cpue regression approach and the biomass dynamic model. The target spawning stock size for both species is S_{MSY} (the dotted lines in the first four panels). It is clear that none of the management strategies achieve this target for both species simultaneously. The cpue regression approach stabilises[9] the spawning stock size above S_{MSY} for *P. semisulcatus* and below S_{MSY} for *P. esculentus.* The higher spawning stock sizes achieved by the cpue regression approach come at a cost, however, namely lower total discounted catches. Interestingly, the cpue regression approach performs similarly to management strategy D1 in terms of $P(C_y<2000t)$ and CLOW, and slightly better than management strategy D1 in terms of minimizing inter-annual catch variability. Management strategies D1 and B1 both leave the spawning stock size for *P. semisulcatus* close to the target level, but are unable to do this for *P. esculentus*, the spawning stock size of which is well below $S_{MSY.}$

The management strategy based on the biomass dynamic model (“B1”) leads to the largest inter-simulation variance in the values for the economic-related performances measures although the median values for the performance measures are similar to those for management strategy D1 (Figure 20).

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[9] There is little difference between the S_{2010}/S_{MSY} and S_{2015}/S_{MSY} values

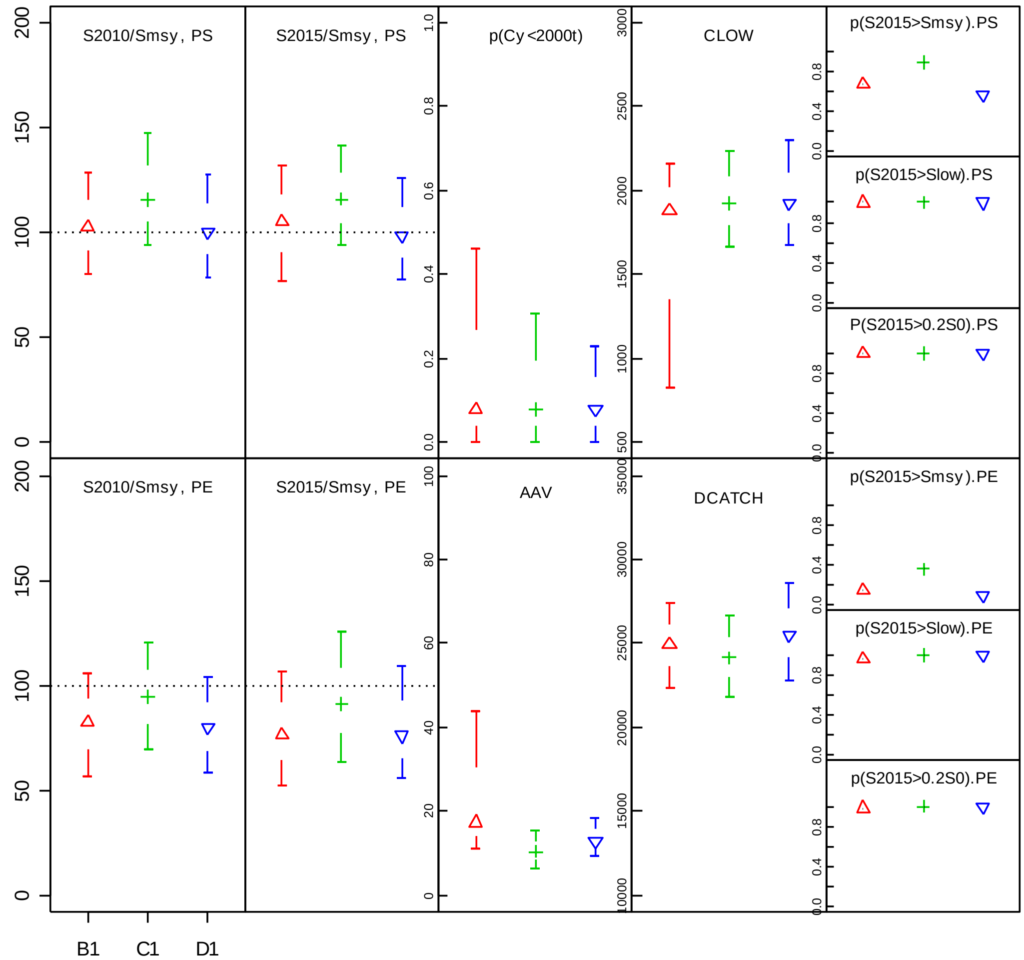

Figure 20: Comparison plot for the D1 (Deriso model), B1 (biomass dynamic model), and C1 (cpue regression approach) management strategies. The results in this figure are based on the Base Case operating model.

The results in Figure 20 are mimicked when expressed by stock area (Figure 21). Figure 21 shows that some stocks are left at S_{MSY} while others are left above or below this level. The poorest performance, in terms of leaving the spawning stock size at or above S_{MSY}, occurs for *P. esculentus* in the Karumba stock area.

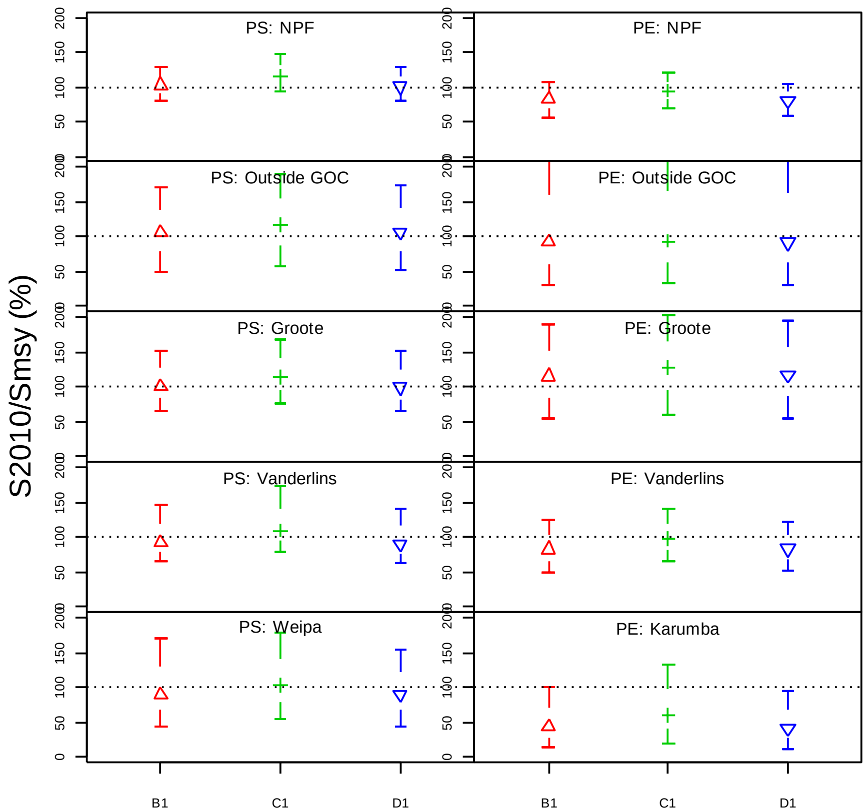

Figure 21: Medians and 90% intervals for the spawning stock size in 2010 relative to S_{MSY}, for each of the stock areas and species in the operating model. Results are shown for the D1 (Deriso model), B1 (biomass dynamic model), and C1 (cpue regression approach) management strategies.

Comparing the results of the cpue regression approach ("C1" in Figures 20 and 21) with those of the Deriso model ("D1" in Figures 20 and 21) demonstrates that the ability to assess the resource by species (as is the case for the Deriso model) does not reduce risk for both species. Several factors, either alone or in combination, could contribute to the failure of the management strategy based on the sophisticated assessment model to outperform the simpler management strategy:

1. 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);
2. the assessment is biased to some extent; and/or

3. the season length set when the spawning stock size is estimated to be at or above the target level (see Figure 13) is such that the capture of pre-spawning individuals is difficult to avoid using only controls on total effort.

The possibility that a multi-stock assessment would better achieve the management targets is investigated in Section 9.3 and the effect of a different baseline season in Section 9.4. The possibility and implications of bias in the stock assessment are considered throughout Sections 9 and 10.

9.2.b The performance of the assessment

Figure 22 shows the relative error distributions for the time-trajectories of spawning stock size and recruitment, as well as those for S_{MSY}, E_{MSY} and stock-recruitment steepness for the Deriso model applied in 2015 to data generated by the Base Case operating model. Relative error distributions for S_{MSY}, E_{MSY} and stock-recruitment steepness based on Deriso model assessments conducted in 2003 and 2006 are also shown in Figure 22. The results in Figure 22 suggest that:

1. 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 biased) and E_{MSY} (negatively bias). Any bias in the ratio S_y/S_{MSY} is therefore due predominantly to bias associated with S_{MSY}.
2. 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 there is often little bias in S_y/S_{MSY} and slight negative bias associated with E_{MSY}, the management strategy is still not able to leave the spawning stock size of *P. esculentus* above S_{MSY}.
3. There is no evidence for learning, because the estimates of S_{MSY}, E_{MSY} and stock-recruitment recruitment steepness are as biased in 2015 as they were in 2003. This is possibly because many parameters are set within the Deriso model rather than being estimated.

It should be noted that Figure 22 probably over-estimates the estimation ability of the Deriso model assessment because this assessment and the operating model are structurally similar in many ways (e.g. catchability, fishing power, seasonal recruitment and spawning patterns). Larger biases are to be expected when the model underlying the assessment differs to a greater extent from the operating model.

The estimates of the parameters of the biomass dynamic model imply a resource that is huge and very unproductive (Table 14). 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 in Figure 20. 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 14: Parameter estimates from the biomass dynamic model in 2010 when the data are generated by the Base Case operating model. *qinc* 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

9.2.c Summary

1. While all the Base Case management strategies are able to attain S_{MSY} for *P. semisulcatus*, none are able, at the same time, to attain S_{MSY} for *P. esculentus*.
2. Basing a management strategy on an assessment method that attempts to estimate stock status by species does not improve the probability of leaving the spawning stock size close to S_{MSY}.
3. The estimates provided by the biomass dynamic model are highly imprecise and this is reflected in the values for the economic-related performance measures though less so for the management-related performance measures.
4. The poor performance of the management strategy based on the Deriso model in terms of protecting the *P. esculentus* resource cannot be attributed to any great extent to bias in the assessment.
5. *P. esculentus* is most depleted in the Karumba stock area (median for S_{2010}/S_{MSY} of 43% (B1), 61% (C1) and 38% (D1)) and this is the primarily reason for the inability to leave the spawning stock size of this species at S_{MSY}.

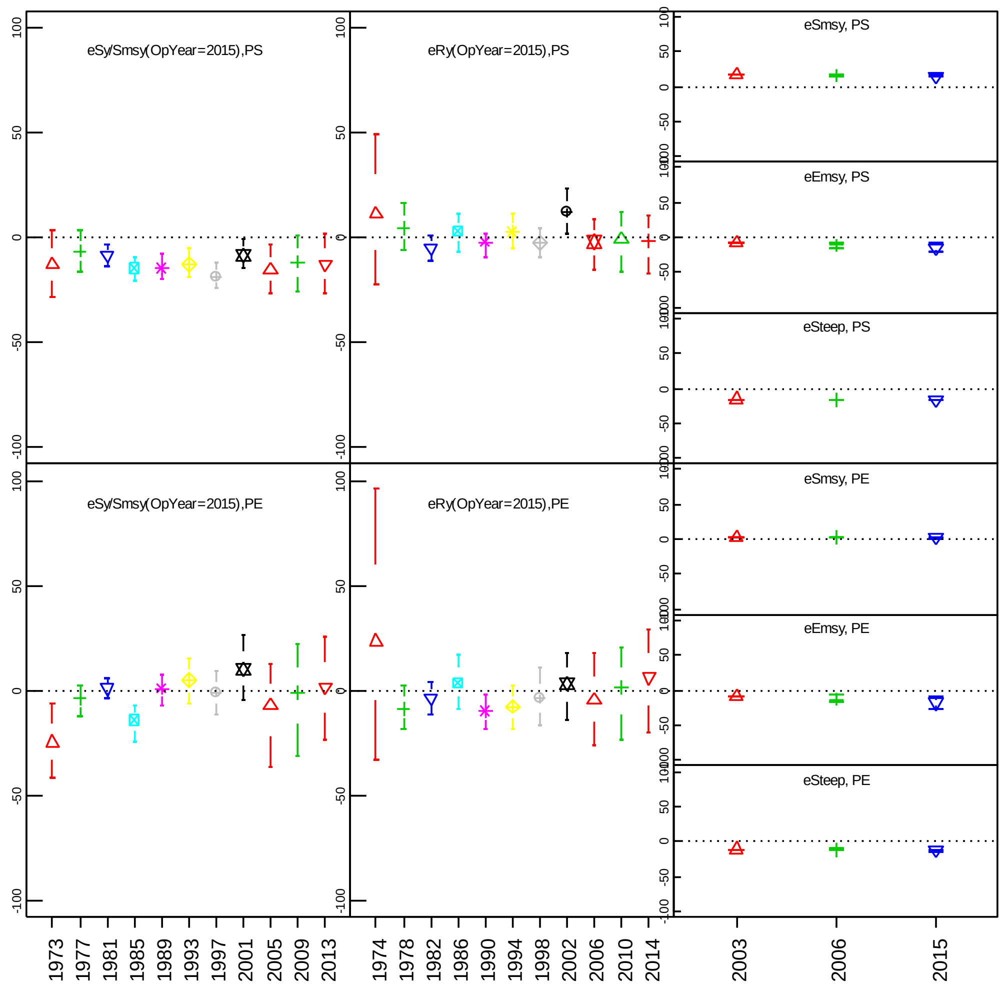

Figure 22: Relative error (%) distributions for the Deriso assessment model when reality is reflected by the Base Case operating model. OpYear is the year in which the assessment took place. The years on the x-axis for S_Y/S_{MSY} and R relate to the assessment year i.e. "eS_Y/S_{MSY} (OpYear=2015)" is the relative error of $S_{(1973,1983,1993,2003,2013)}/S_{MSY}$ as determined by an assessment conducted in 2015. eSteep, eEmsy and eSmy are respectively the relative errors associated the estimates of the steepness parameter, E_{MSY} and S_{MSY}.

9.3 Multi-stock assessment

9.3.a Performance Measures

Management strategies that analyse data at finer spatial scales may be expected to have improved performance (particularly in terms of leaving the spawning stock size of *P. esculentus* close to S_{MSY}). This section therefore examines management strategies based on multi-stock variants (3 and 4 stocks respectively) of management strategies D1 and C1 using the Base Case operating model to determine the benefits (if any) of better capturing the true underlying stock structure when conducting stock assessments.

The variant of the D1 management strategy based on a 3-stock assessment (abbreviation D26) includes an outside Gulf stock ("Outside GOC"), 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 the 4-stock assessment (abbreviation D27) is based on assuming that each of the Outside GOC, Groote, 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 be found in the Weipa stock area in the operating model (see Section 5.5).

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 (Figures 23 and 24) 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 (D26 and D27) than that based on the single stock assessment (D1).

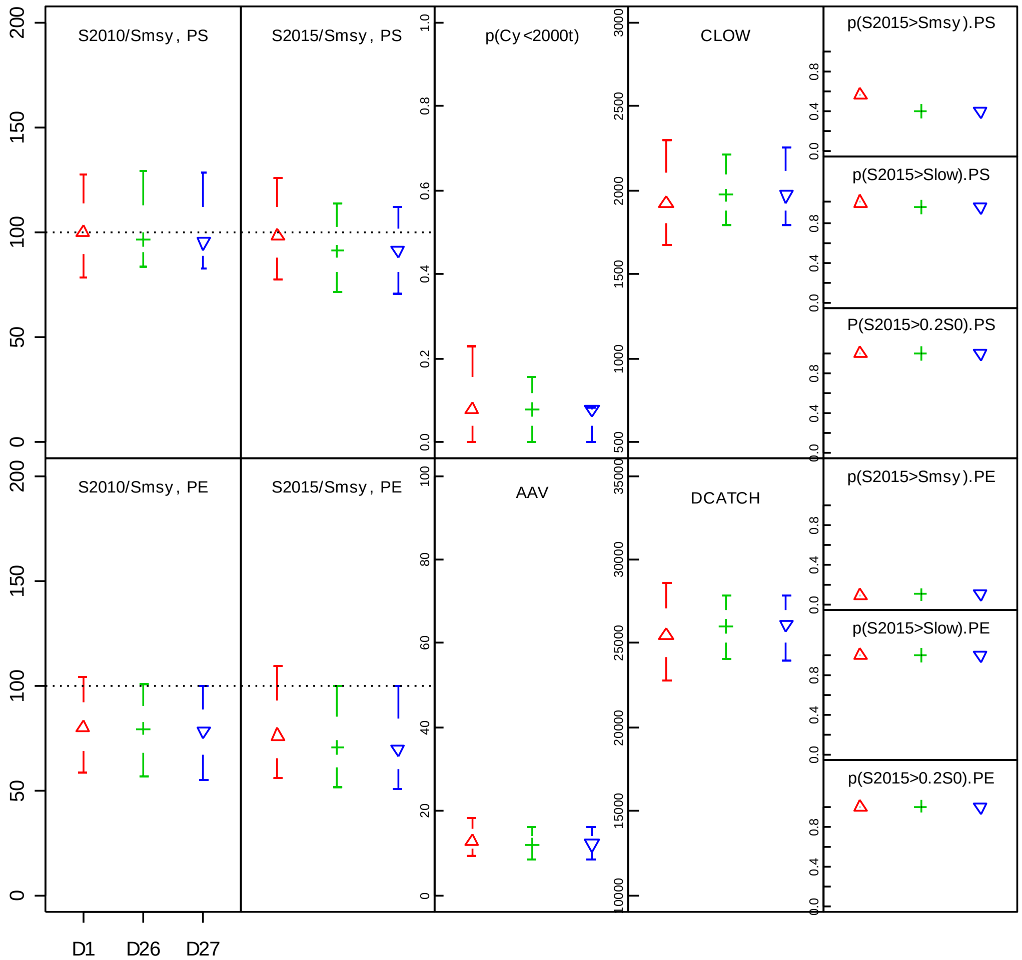

Figure 23: Comparison plot for the Deriso model-based management strategies based on a single stock (D1), 3 stocks (D26), and 4 stocks (D27). The results in this figure are based on the Base Case operating model.

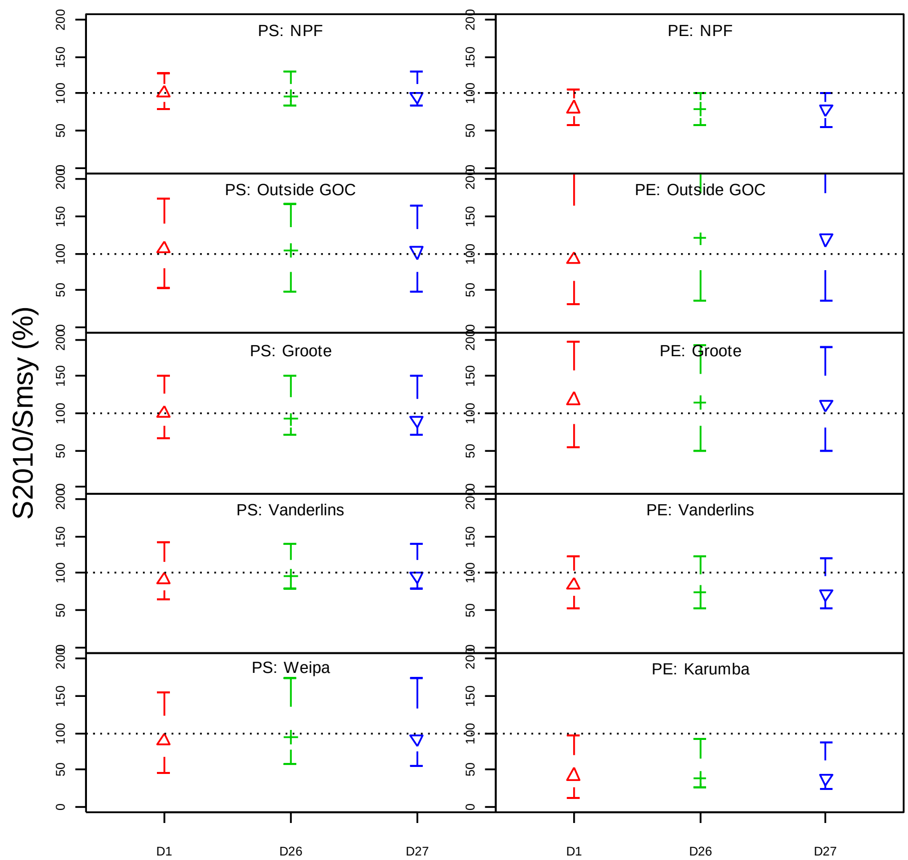

Figure 24: Medians and 90% intervals for the spawning stock size in 2010 relative to S_{MSY}, for each of the stock areas and species in the operating model. Results are shown for the Deriso model-based management strategies based on a single stock (D1), 3 stocks (D26), and 4 stocks (D27).

There is also little benefit in applying the management strategy based on the cpue regression approach at a finer spatial scale (Figure 25). In fact, the cpue regression approach is even less sensitive to specifications regarding spatial structure than the management strategy based on the Deriso model.

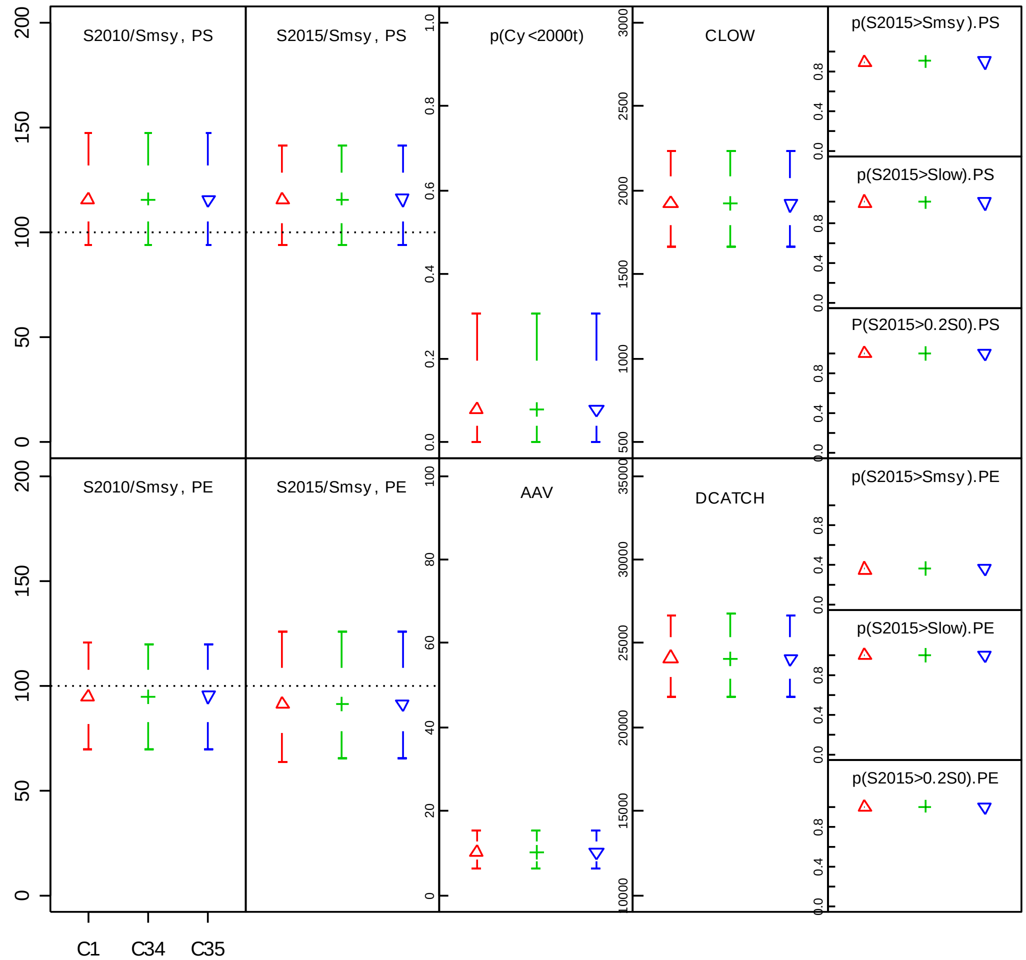

Figure 25: Comparison plot for the cpue regression approach-based management strategies based on a single stock (C1), 3 stocks (C34), and 4 stocks (C35). The results in this figure are based on the Base Case operating model.

9.3.b Estimation Performance

Figures 26 and 27 summarize the estimation performance of the 3- and 4- stock Deriso assessments when applied in 2015. There are some noteworthy differences between Figures 26 and 27 and Figure 22, which summarises the estimation-related performance measures for the single-stock Deriso assessment. Specifically, the bias of S_y/S_{MSY} for *P. semisulcatus* becomes increasingly negative over time in the eastern Gulf (region 3 in Figure 26 and region 4 in Figure 27). *P. semisulcatus* is not found in the Karumba stock area so this trend in bias pertains to *P. semisulcatus* in the Weipa stock area. The widths of the intervals in Figure 26 and (particularly) Figure 27 tend to be wider than those in

Figure 22 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 in Figure 22, the estimates of E_{MSY}, steepness and S_{MSY} are quite markedly biased for some of the putative stocks (e.g. *P. esculentus* in the Outside GOC stock area (region 1 in Figures 26 and 27). What is perhaps somewhat disturbing in this example is that the bias associated with S_{MSY} and E_{MSY} actually get larger (more negative) as time progresses; the reasons for this remain unclear.

9.3.c Summary

The lack of improvement in the performance measures between the management strategies based on single- and multi-stock assessments may be due to model bias for certain stocks especially *P. semisulcatus* in the eastern Gulf. However, this cannot be the only reason because the performance of the cpue regression approach, which is not based on a stock assessment, is also not improved by better accounting for spatial structure. A more plausible reason for the lack of improvement may be that effort is not allocated directly to a specific stock area, thereby negating some of the possible benefits of a multi-stock assessment. The Groote, Vanderlins and Karumba stock areas are likely to get 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 (Figure 7). Section 9.5 examines the benefits of being able to allocate effort directly to stock areas.

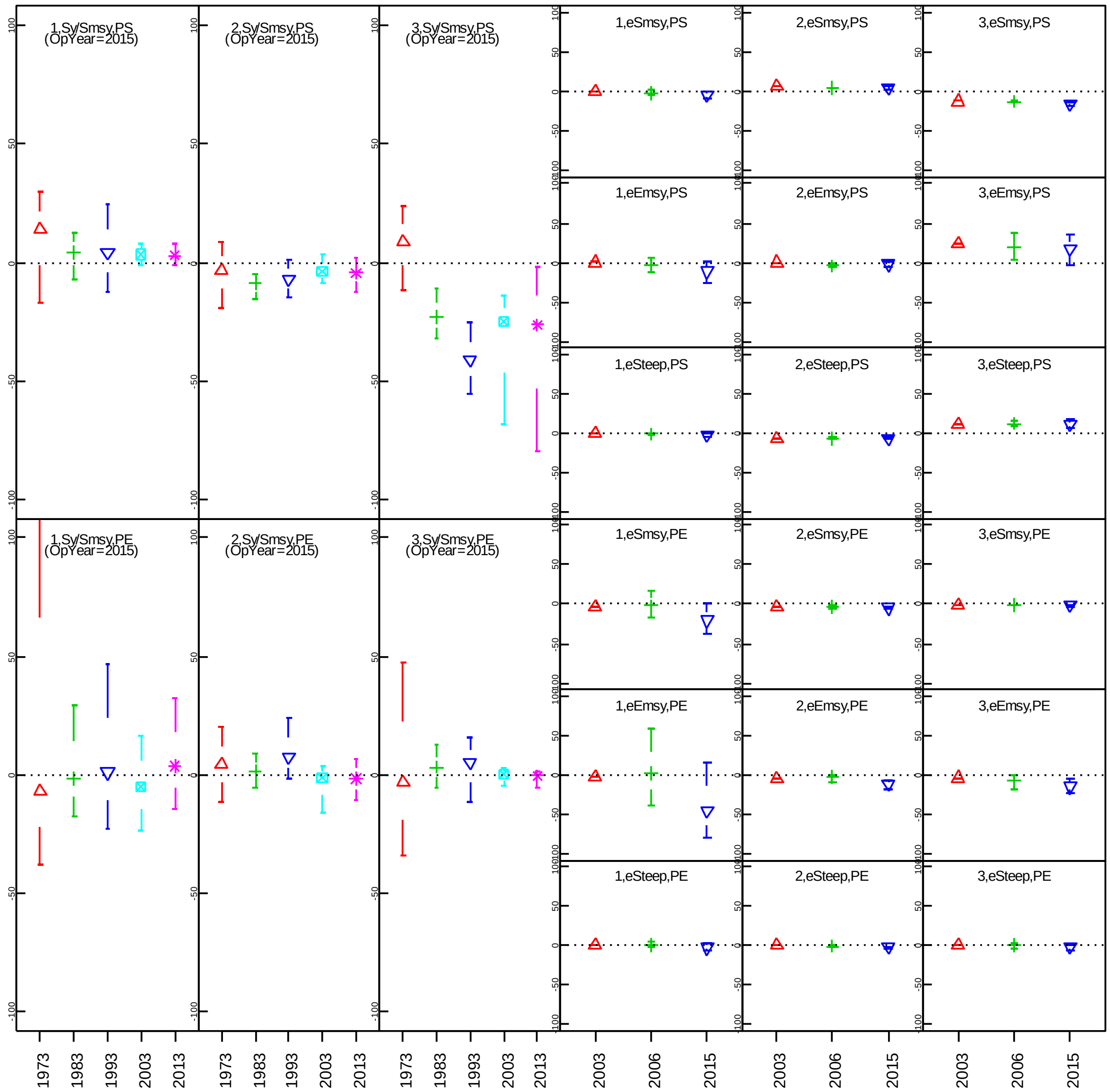

Figure 26: Relative error (%) distributions for the 3-stock Deriso assessment model (D26) when reality is reflected by the Base Case operating model. The prefixed number in each label relates to the stock involved (1 – Outside GOC, 2 – Groote & Vanderlins, and 3 – Karumba & Weipa). OpYear is the year in which the assessment took place. The years on the x-axis for S_Y/S_{MSY} relate to the assessment year i.e. "1 S_Y/S_{MSY} (OpYear=2015)" is the relative error of $S_{(1973,1983,1993,2003,2013)}/S_{MSY}$ for stock 1 as determined by an assessment conducted in 2015. eSteep, eEmsy and eSmy are respectively the relative errors associated the estimates of the steepness parameter, E_{MSY} and S_{MSY}.

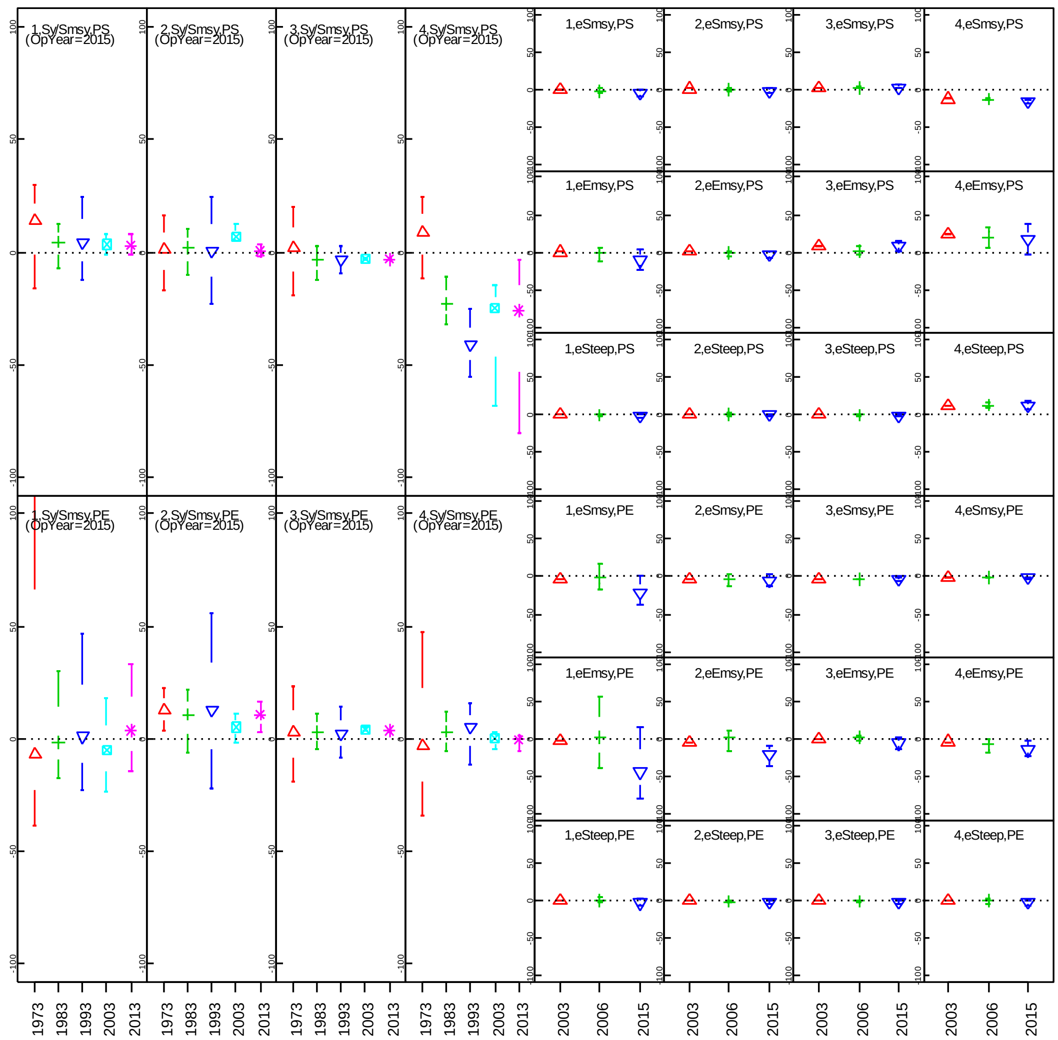

Figure 27: Relative error (%) distributions for the 4-stock Deriso assessment model (D26) when reality is reflected by the Base Case operating model. The prefixed number in each label relates to the stock involved (1 – Outside GOC, 2 – Groote, 3 – Vanderlins, and 4 – Karumba & Weipa). OpYear is the year in which the assessment took place. The years on the x-axis for S_Y/S_{MSY} relate to the assessment year i.e. “1 S_Y/S_{MSY} (OpYear=2015)” is the relative error of $S_{(1973,1983,1993,2003,2013)}/S_{MSY}$ for stock 1 as determined by an assessment conducted in 2015. eSteep, eEmsy and eSmy are respectively the relative errors associated the estimates of the steepness parameter, E_{MSY} and S_{MSY}.

9.4 Changing the target season

Since the season dates are changed 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; see 6.4.a), the specifications for season length may be an important factor determining whether the spawning stock size is left at or above S_{MSY}. Furthermore, which weeks are open and which are closed to fishing 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 due to its migration patterns. Two additional ways of changing the season in response to changes in the estimates of S_y/S_{MSY} by species (Figure 28) were explored in the light of management strategy D1's poor performance at leaving the spawning stock size of *P. esculentus* at or above S_{MSY}. The D67 management strategy is the same as the D1 management strategy, except that it opens the season in week 14 and always closes it in week 22. Closing the fishery after week 21 is a means of eliminating the catch of tiger prawns during the first season (although an unintended – and unquantified – consequence of this change may be underutilization of the banana prawn resource). The D68 management strategy is based on the D67 management strategy except that the opening date for the second season is moved from week 31 to week 32 to reduce the effort directed towards *P. esculentus* (Figure 28).

The results of using management strategies D1, D67 and D68 are contrasted in Figure 29[10] while the resulting effort distributions between 2003 and 2015 for each management strategy are shown for a single simulation in Figure 30[11]. A more restrictive first season seems to move the effort directed onto *P. esculentus* by management strategy D1 to being directed at *P. semisulcatus* as the effort gets concentrated into the second season (Figure 30). A consequence of this is that although there is some increase in the spawning stock size of *P. esculentus* towards S_{MSY}, the spawning stock size of *P. semisulcatus* is now below S_{MSY}. Overall, therefore, changing how season length is modified in response to changes in abundance does not achieve the outcome desired. Concentrating effort into the second half of the year (Figure 30), but keeping the total effort the same, benefits *P. esculentus* at the expense of *P. semisulcatus* and may lead to lower catches of banana prawns (only in years in which the catch of banana prawns is very low does the length of the first season approach that for management strategies D67 and D68).

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[10] Changing how the season length is modified given the results of the assessment does not impact estimation performance (results not shown).

[11] It should be borne in mind that the results for a single simulation may not be reflective of those for the entire set of simulations, except in broad detail.

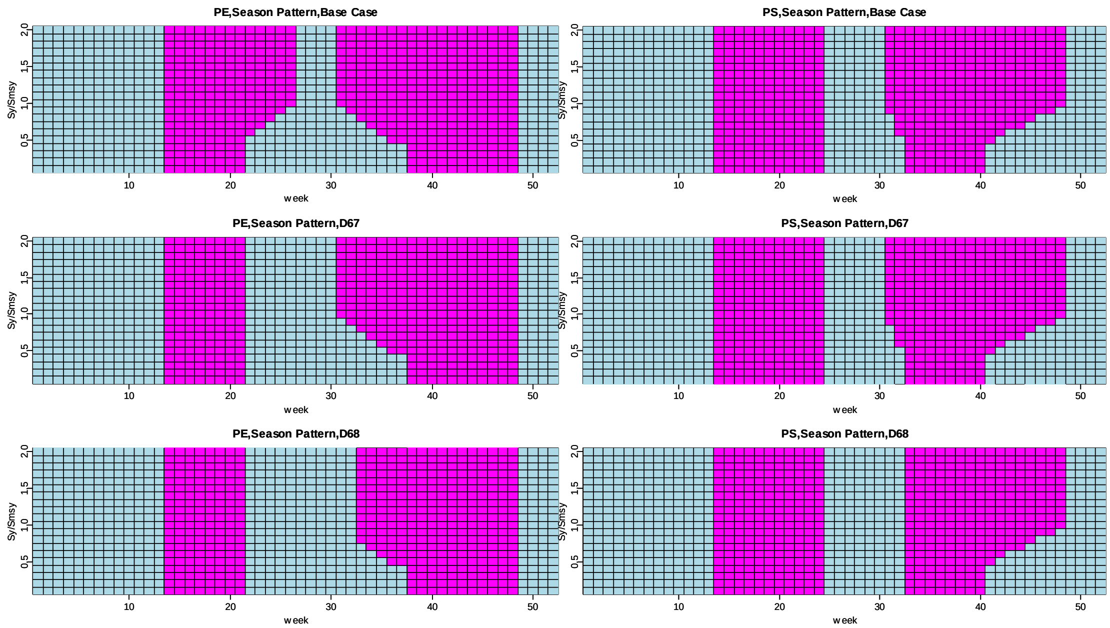

Figure 28: The season set for *Penaeus esculentus* (PE) and *P. semisulcatus* (PS) as a function of the estimate of S_y/S_{MSY} from the assessment for the D1, D67 and D68 management strategies involving the illustrated changes to the opening dates. The light shaded cells denote the weeks closed to fishing.

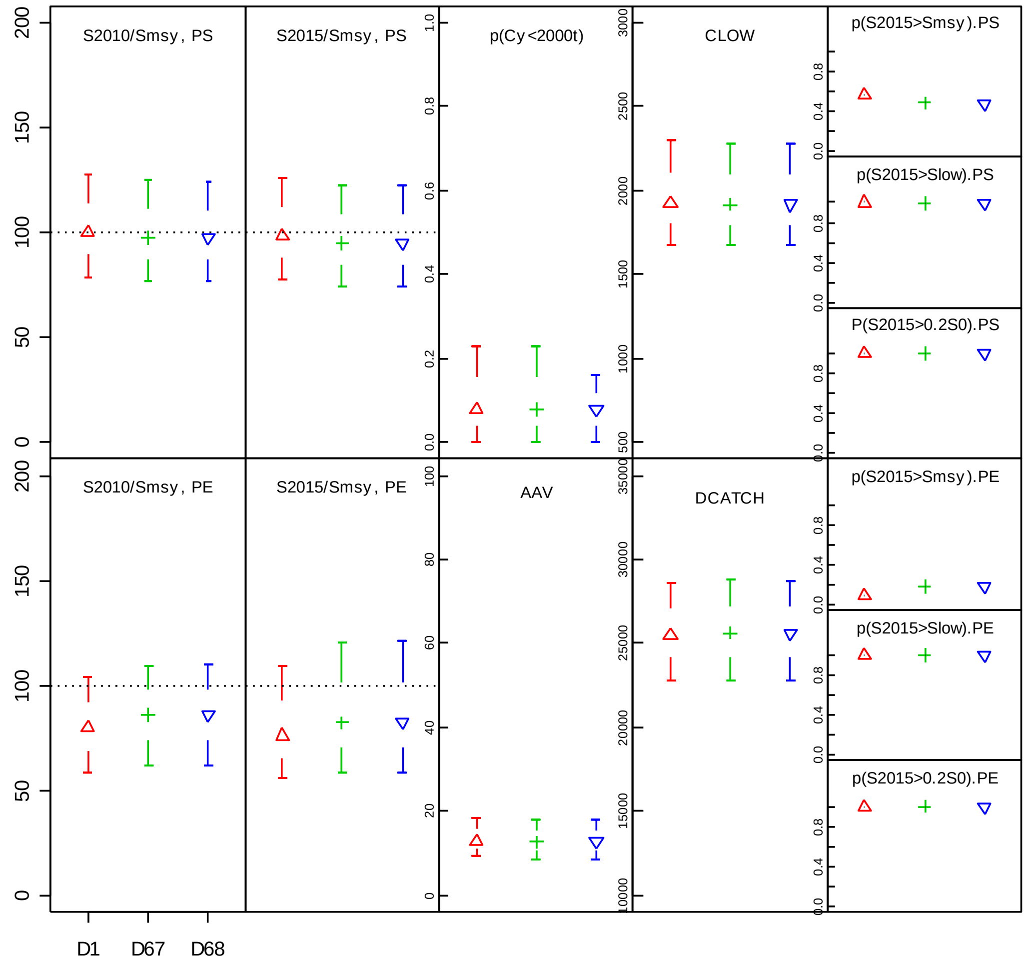

Figure 29: Comparison plot for the D1, D67 and D68 management strategies (see Figure 28). The results in this figure are based on the Base Case operating model.

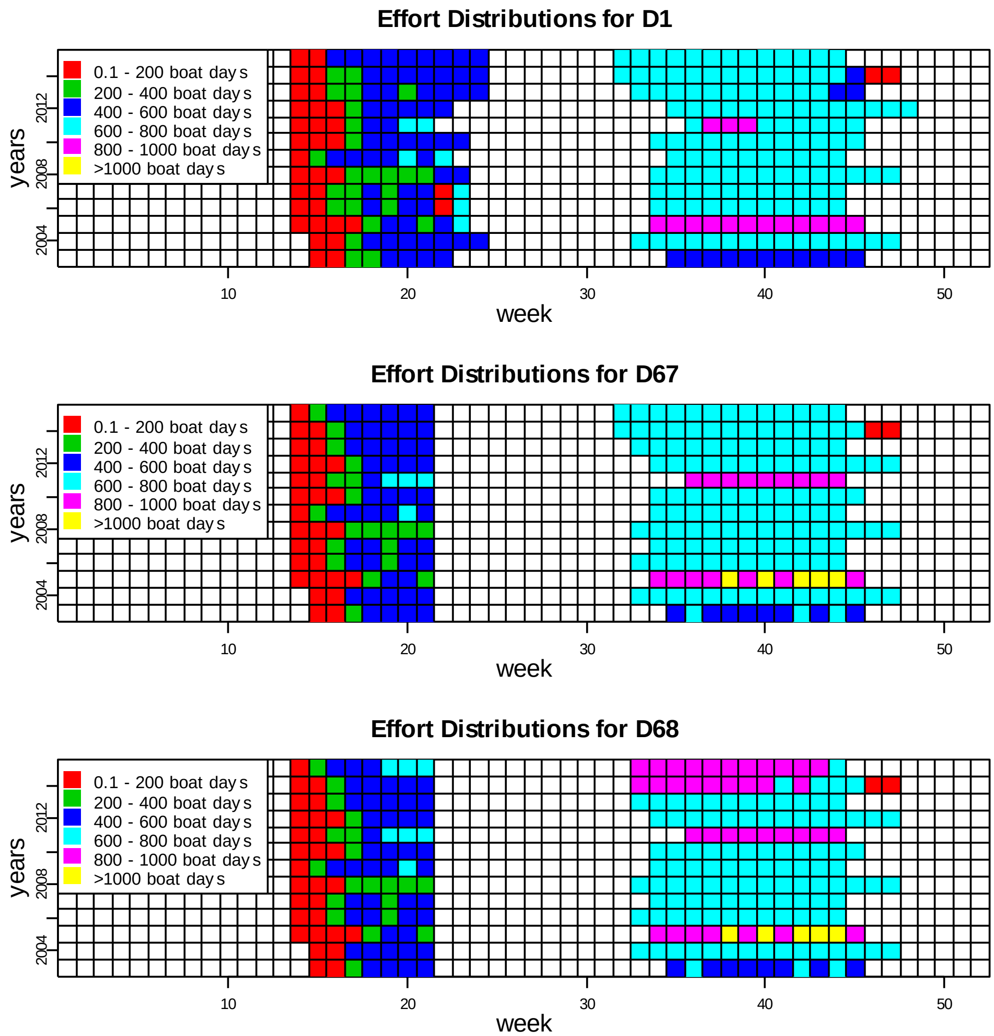

Figure 30: Effort directed towards tiger prawns by week (2003-2015) for the D1, D67 and D68 management strategies (see Figure 28) for a single simulation. The results in this figure are based on the Base Case operating model.

9.5 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 (see Section 6.4.a). 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 based 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 (Figures 31 and 32). 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 31). 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 32) 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.

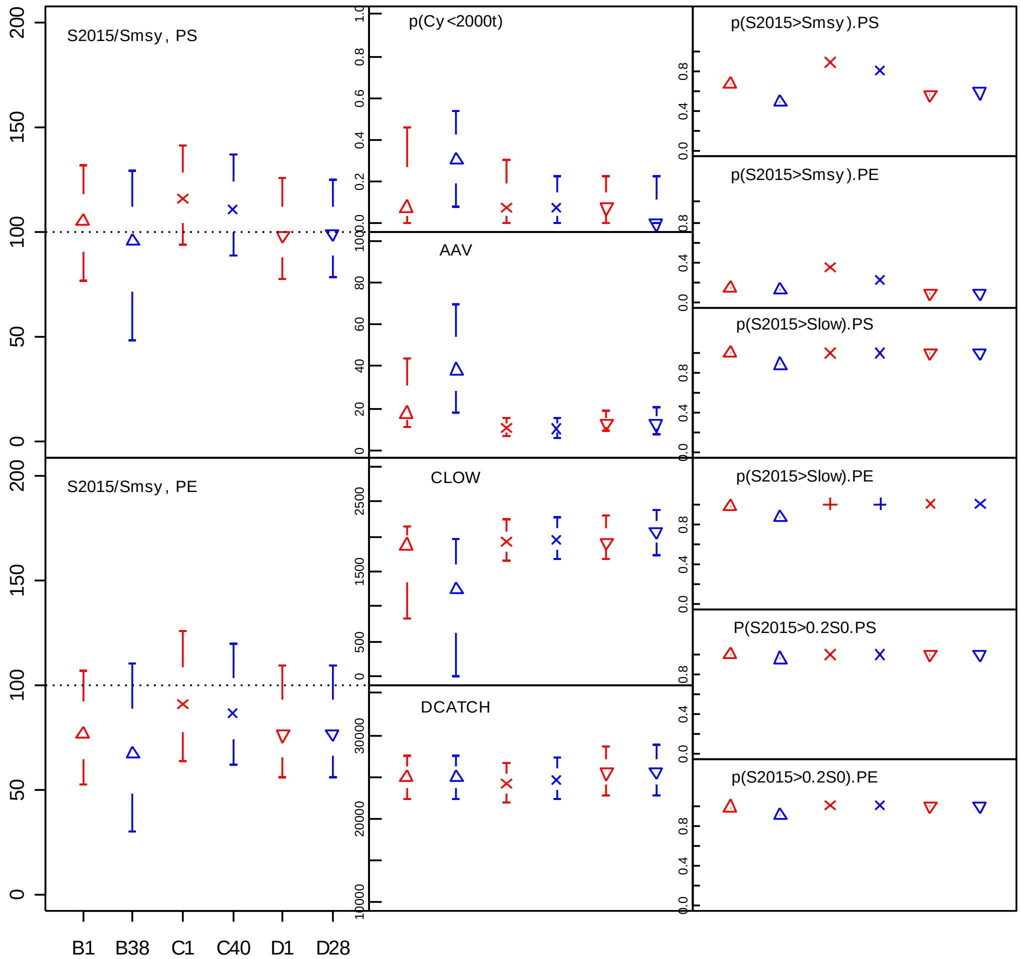

Figure 31: Comparison of the performances of management strategies for which the probability of adopting recommendations for changes in effort levels is one-in-three (management strategies B1, C1 and D1) and for which such recommendations are always adopted (management strategies B38, C40 and D28). The results in this figure are based on the Base Case operating model.

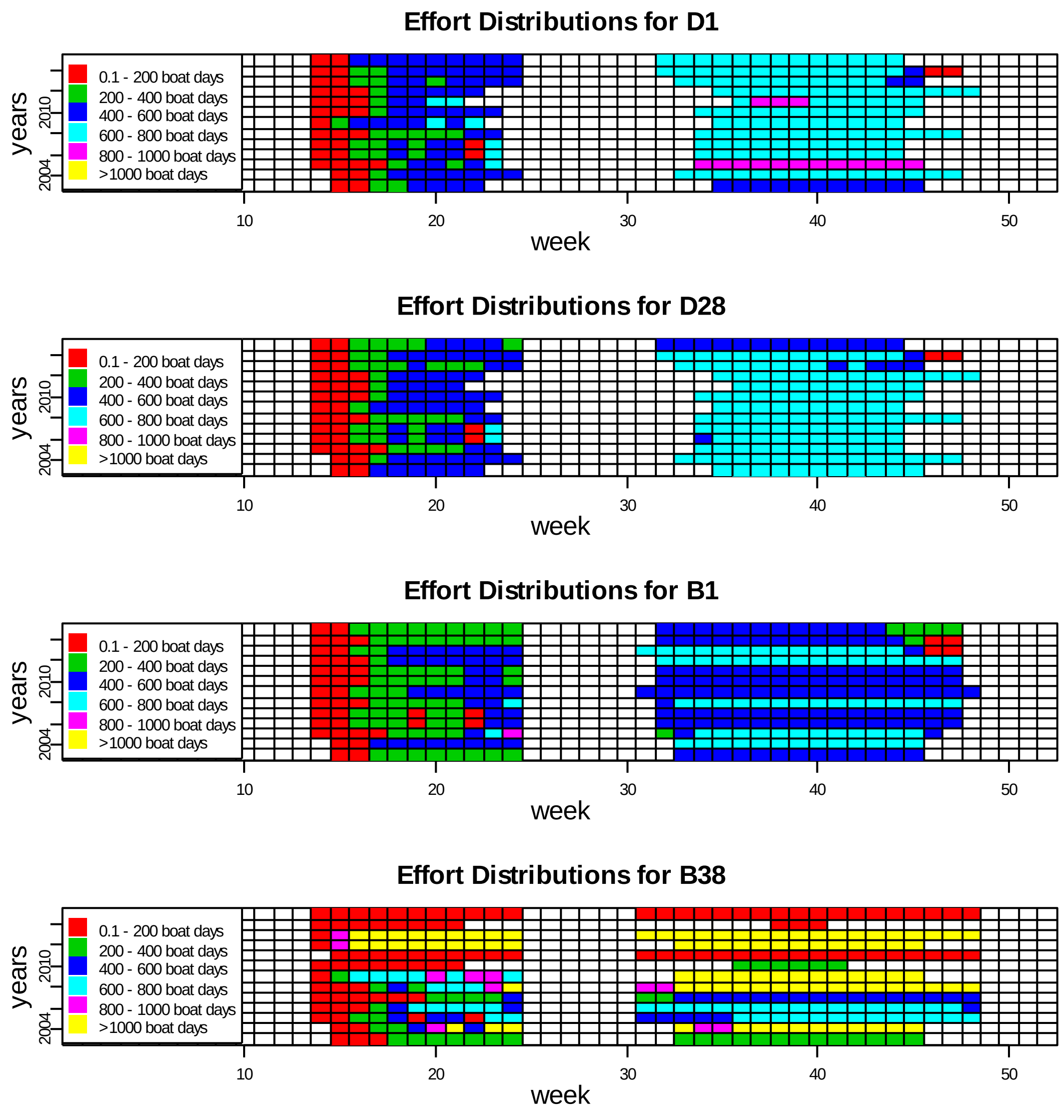

Figure 32: Effort directed towards tiger prawns by week (2003–2015) for the D1, D28, B1 and B38 management strategies for a single simulation. The results in this figure are based on the Base Case operating model.

9.6 Increasing the target spawning stock size in the decision rule

A balance needs to be struck between the level of the spawning stock size and the size of the catch when selecting a management strategy and, particularly, when selecting the target spawning stock size level in the decision rule (see Section 6.3c for details). Figure 33 explores the sensitivity of the performance measures for the Deriso model-based management strategies to changing the target spawning stock size level (and therefore also the target effort level) used when determining the annual effort level.

As expected, both risk (e.g. S_{2010}/S_{MSY} and $P(S_{2015}>S_{MSY})$) and reward (e.g. DCatch and C_{low}) are reduced as the target spawning stock size is increased from S_{MSY} to $1.6S_{MSY}$. The spawning biomass of *both* species exceeds S_{MSY} in 2010 and 2015 with greater than 50% probability only when the target spawning stock size is $1.4S_{MSY}$or higher.

There is a greater than 70% probability that the spawning stock size will exceed S_{MSY} in 2010 and 2015 when the target spawning stock size level in the decision rule is between S_{MSY} and 1.2 S_{MSY} (*P. semisulcatus*) and 1.4 S_{MSY} and 1.6 S_{MSY} (*P. esculentus*). This conclusion remains generally valid even when the results are analysed by stock area (Figure 34). However, *P. esculentus* in the Karumba stock area does not quite recover to S_{MSY} even when the target spawning stock size level in the decision rule is set to 1.6 $S_{MSY.}$

The values for the economic- and risk-related performance measures change in different ways as the target spawning stock size level in the decision rule is increased from S_{MSY} to $1.2S_{MSY}$. Specifically, the proportional increase in spawning stock size is much greater than the proportional reduction in catch (Figure 33). However, large reductions in the economic-related performance measures occur once the spawning stock size level in the decision rule increases beyond 1.2 S_{MSY}. This suggests that although there is a large reduction in risk by increasing the target level of spawning stock size in the decision rule from S_{MSY} to $1.2S_{MSY}$, there is relatively little loss in reward.

The estimation performance of the Deriso model-based stock assessment appears to be independent of the target spawning stock size level in the decision rule (Figure 35).

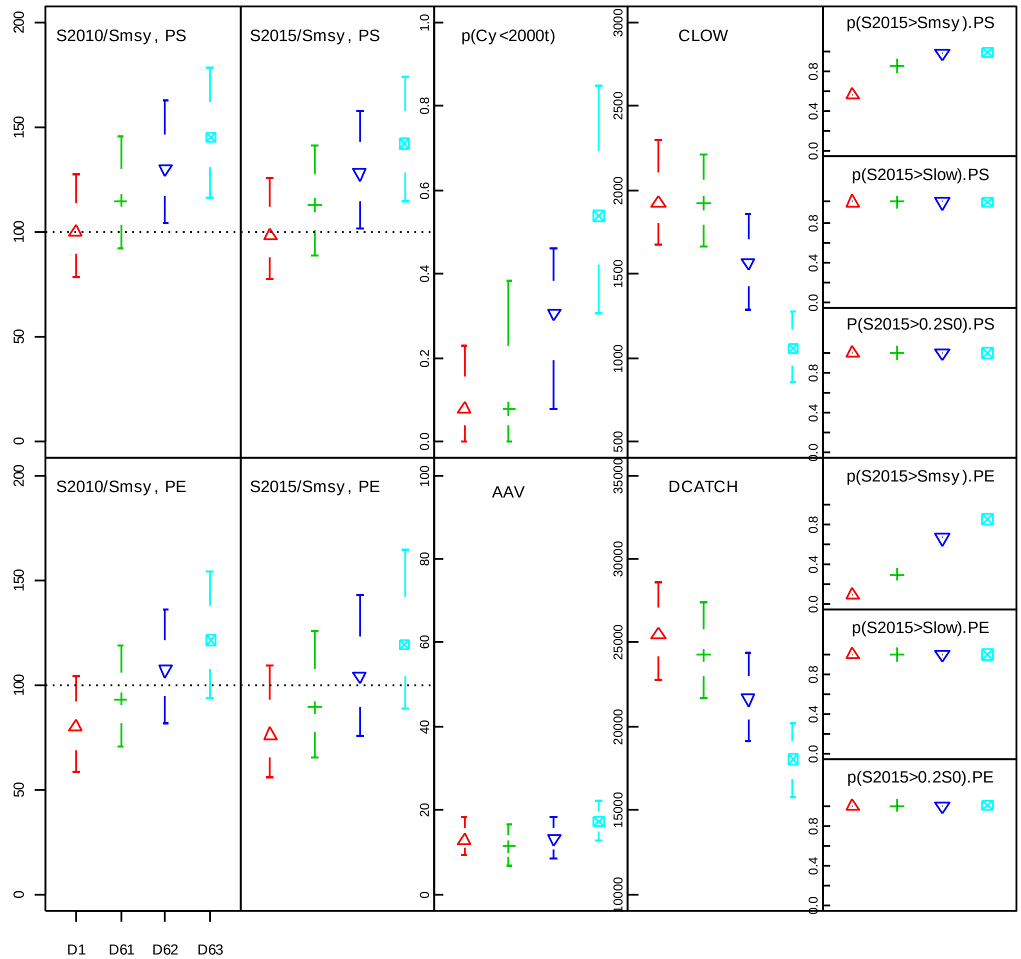

Figure 33: Comparison of the management-related performance of Deriso model-based management strategies which differ in terms of the target spawning stock size level in the decision rule: D1 (S_{MSY}), D61 ($1.2S_{MSY}$), D62 ($1.4S_{MSY}$), and D63 ($1.6S_{MSY}$). The results in this figure are based on the Base Case operating model.

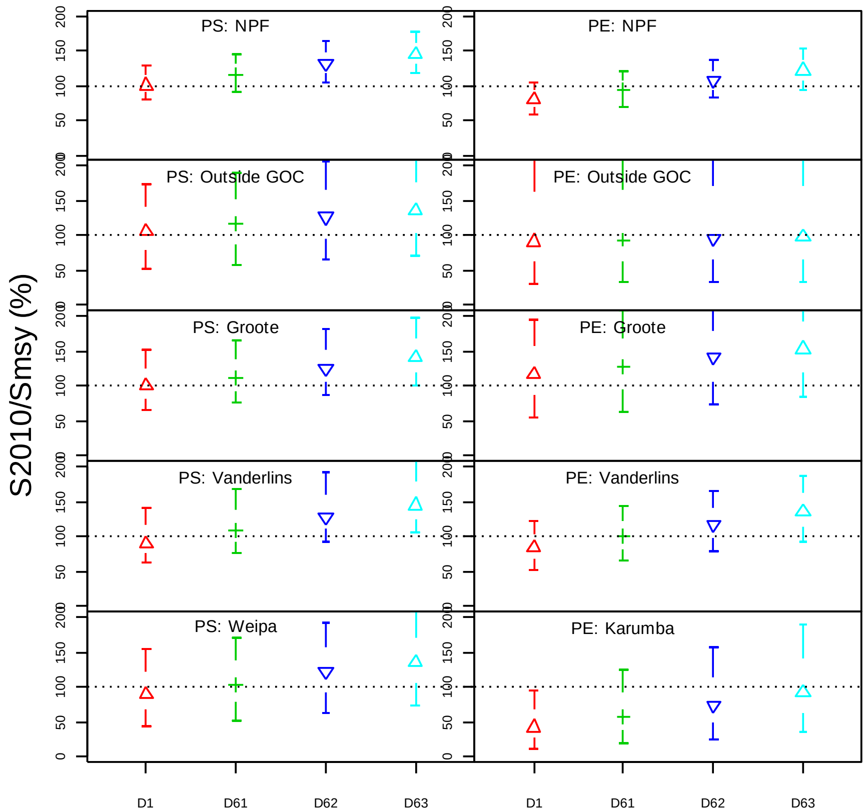

Figure 34: Medians and 90% intervals for the spawning stock size in 2010 relative to S_{MSY}, for each of the stock areas and species in the operating model. Results are shown for Deriso model-based management strategies which differ in terms of the target spawning stock size level in the decision rule: D1 (S_{MSY}), D61 ($1.2S_{MSY}$), D62 ($1.4S_{MSY}$), and D63 ($1.6S_{MSY}$). The results in this figure are based on the Base Case operating model.

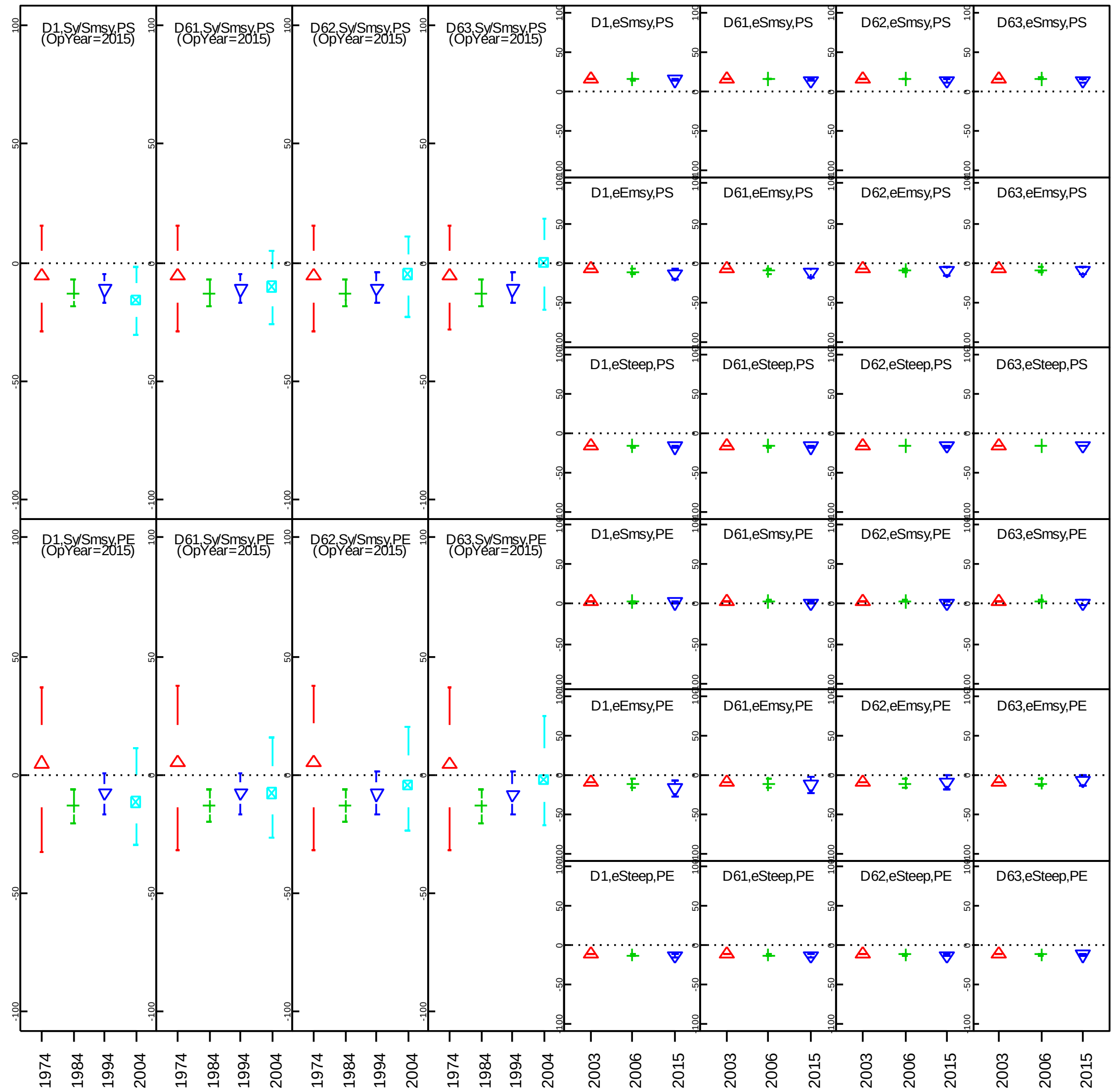

Figure 35: Relative error (%) distributions for the Deriso model-based stock assessment when the target spawning stock size level in the decision rule is S_{MSY} (D1), 1.2S_{MSY} (D61), 1.4S_{MSY} (D62), and 1.6S_{MSY} (D63), and reality is reflected by the Base Case operating model. OpYear is the year 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 $S_{(1974,1984,1994,2004)}/S_{MSY}$ for the D1 management strategy as determined by an assessment conducted in 2015. eSteep, eEmsy and eSmy are respectively the relative errors associated the estimates of the steepness parameter, E_{MSY} and S_{MSY}.

9.7 Summary

The ideal is to be able to use a simple assessment model and decision rule that is nevertheless able to achieve the objectives for the fishery without compromising catch stability or catch itself. In this section, the effects on the various performance measures of the temporal scale, the spatial scale, and the overall complexity of the assessment were investigated. Since the NPF uses S_{MSY} as a limit reference point when making management decisions, many of the risk-related performance measures are defined relative to S_{MSY}. Fishery stability is quantified through economic-related performance measures such as catch variability (Average Annual Variability), long term catch (discounted at 5% per annum based on suggestions by economists, Kompas *pers commn*), the lowest catch during the projection period, and the probability of the catch dropping below 2000t (seen as a very poor year).

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 the biomass back towards the TRP. In the case of the NPF, the fishery moved in 2004 to using the Maximum Economic Yield as its TRP. However, this TRP is not considered in this report because it is undefined at the species level. 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) and lower catches (less reward). However, there is some non-linearity in the relationship between risk and reward as the target spawning stock size used in the management strategy to define effort levels is increased from S_{MSY} to $1.2S_{MSY}$. Given this non-linearity, the benefits of increasing the target spawning stock size used in the management strategy to slightly above S_{MSY} seem to exceed the costs. However, costs, in terms of reduced catch, increase as the target stock size is increased and, for example, if the target becomes 1.6 S_{MSY} then 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 target spawning stock size in the decision rule of S_{MSY}. Catch rates would be higher if the stock size is higher (i.e. the profit per vessel may increase) and this will tend to offset the economic cost of the lower catches to some extent. However, in the absence of detailed information about costs, the size of the offset cannot be quantified.

None of the management strategies were 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 was based on the most of the same assumptions as the operating model. Trying to account for stock structure by applying the assessment to parts of the NPF (i.e. 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 in absolute terms, and are consequently almost always fished; effort remains in those stock areas irrespective of the stock 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 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.

Another reason for the inability to leave the spawning stock at S_{MSY} on average include 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 in the management strategies was examined, but, unless the method used to specify the total effort is also changed, modifying this algorithm to avoid catching *P. esculentus* did lead to a slight improvement in attain the S_{MSY} for *P. esculentus* but also led to a greater reduction in spawning stock of *P. semisulcatus*.

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 reinforces the likelihood 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 that some form of spatial management may be required to ensure that all stocks of both species are at or above S_{MSY}. This may necessitate spatially-structured stock assessments. If it becomes necessary to undertake such assessments, it seems appropriate to select a spatial-structure which 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 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 and because 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 putative stocks. One way to implement spatial management without a spatially-structured stock assessment would be to determine the effort level using a single-stock assessment and to "allocate" the effort spatially (perhaps based on previous relative catch rates or the results of surveys). The only way to ensure that the spawning stock size is at or above S_{MSY} if spatial management is impossible to implement is to increase the target spawning stock size in the decision rule. However, as is clear from Figure 33, this will only be possible with some loss in yield.

It seems likely that management will continue to want estimates of management-related quantities such as spawning stock size relative to S_{MSY}. Therefore, future management recommendations would have to be based, to some extent, on an management strategy which involves 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 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. In principle, a reduction in resources could be possible if formal assessments are conducted every few (2-3 years) and the cpue regression approach is used to provide scientific management advice for the intervening years. This option has yet to be evaluated using the MSE framework and the benefits of going this route may be minor anyway because assembling the data and estimating fishing power tends to be most time consuming task when conducting an assessment.

In conclusion therefore, a mixture of model scale and complexity is required. It would seem that movement towards spatially-structured assessments and management is appropriate. However, essential in this process is that the *ad hoc* nature of how this fishery is currently managed and how management changes are implemented should be changed so that the approaches used to determine and implement effort levels and season length are clear to all.

10 SENSITIVITY TESTS

This chapter investigates the key factors that affect the management-related and estimation-related performance measures (see Section 7). The key factors affecting performance identified in the unbalanced experiment detailed in Section 8 were:

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

Factors 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.

The following sections explore the impact of each of these seven factors using a balanced design approach.

10.1 Fishing power

There is considerable uncertainty regarding changes over time in fishing power in the NPF (Dichmont *et al.* 2003). Furthermore, it has been demonstrated that assumptions regarding changes in fishing power can impact the results of stock assessments of tiger prawns substantially (Dichmont *et al*. 2001, 2003a). It is therefore not surprising that the management-related performance measures in this study are also very sensitive to assumptions about changes in fishing power. The two fishing power series ("Base Case High" (BCH) and "Base Case Low" (BCL), Figure 5; Dichmont *et al.* 2003), selected by the Northern Prawn Fishery Assessment Group, are used to bound the possible changes in fishing power in the analyses in this report.

Figures 36 and 37 illustrate the effects of assumptions regarding changes over time in fishing power by showing performance measures for two management strategies and two operating models constructed from the D1 management strategy and the Base Case operating model by varying the fishing power series:

- D1 – both the operating model and the management strategy are based on BCH;
- D34 – both the operating model and the management strategy are based on BCL;
- D64 – the operating model is based on BCH and the management strategy on BCL; and
- D65 – the operating model is based on BCL and the management strategy on BCH.

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 (case D65 in Figures 36 and 37) and is below S_{MSY}

(substantially so for *P. esculentus*) when the management strategy is based on BCL but "reality" is BCH. (case D64 in Figures 36 and 37). Somewhat surprisingly, the lowest catch and the total discounted catch for cases D64 and D65 are fairly similar. This comparison should be interpreted with some caution because changing the fishing power scenario in the operating model changes the current status and productivity of the "true" population.

Figure 38 explores the impact of assumptions regarding changes in fishing power on estimation ability. The biases are relatively small when the assessment method is based on correct fishing power scenario (cases D1 and D34 in Figure 38). In contrast, the estimate of E_{MSY} is positively biased when the assessment is based on BCL but reality is BCH (case D64 in Figure 38) 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 (case D65 in Figure 38).

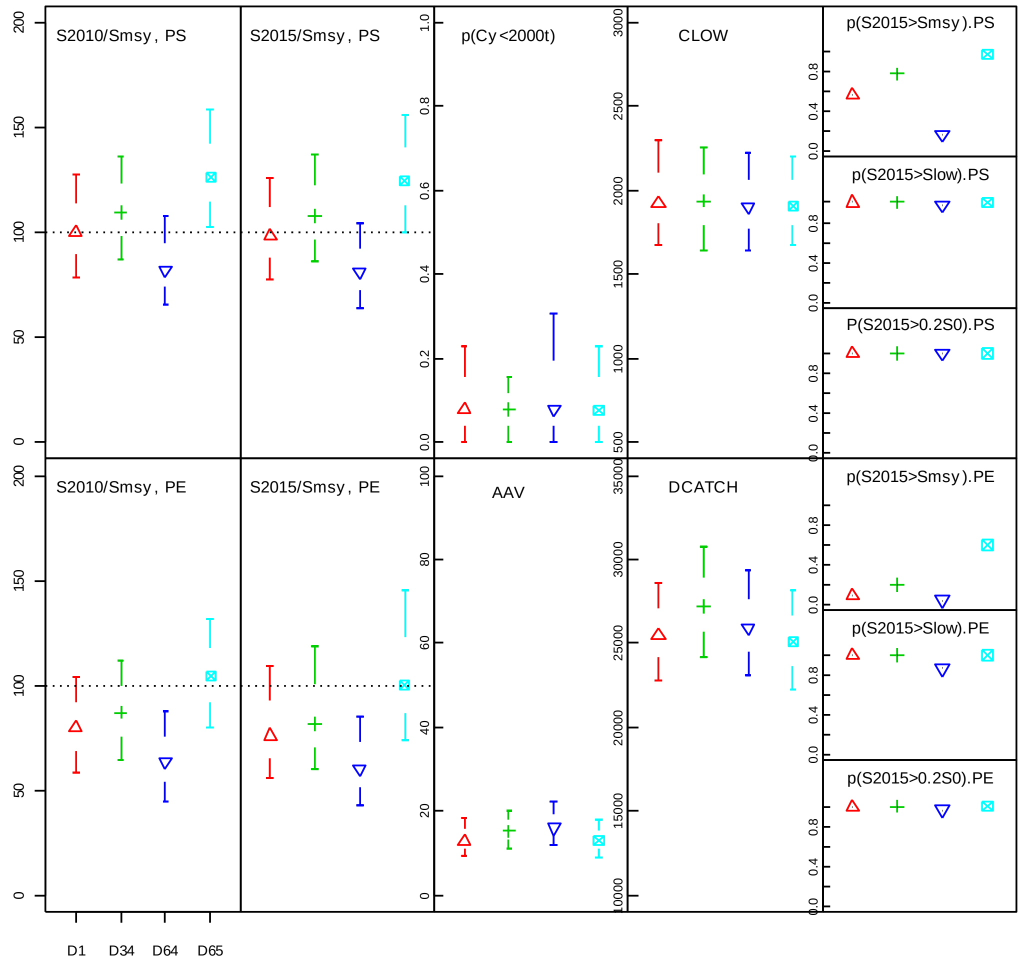

Figure 36: Sensitivity of the management-related performance measures to the fishing power series in the operating model and that underlying the management strategy: D1 – both the management strategy and the operating model are based on BCH; D34 – both the management strategy and the operating model are based on BCL; D64 – the management strategy is based on BCL and the operating model on BCH; and D65 – the management strategy is based on BCH and the operating model on BCL.

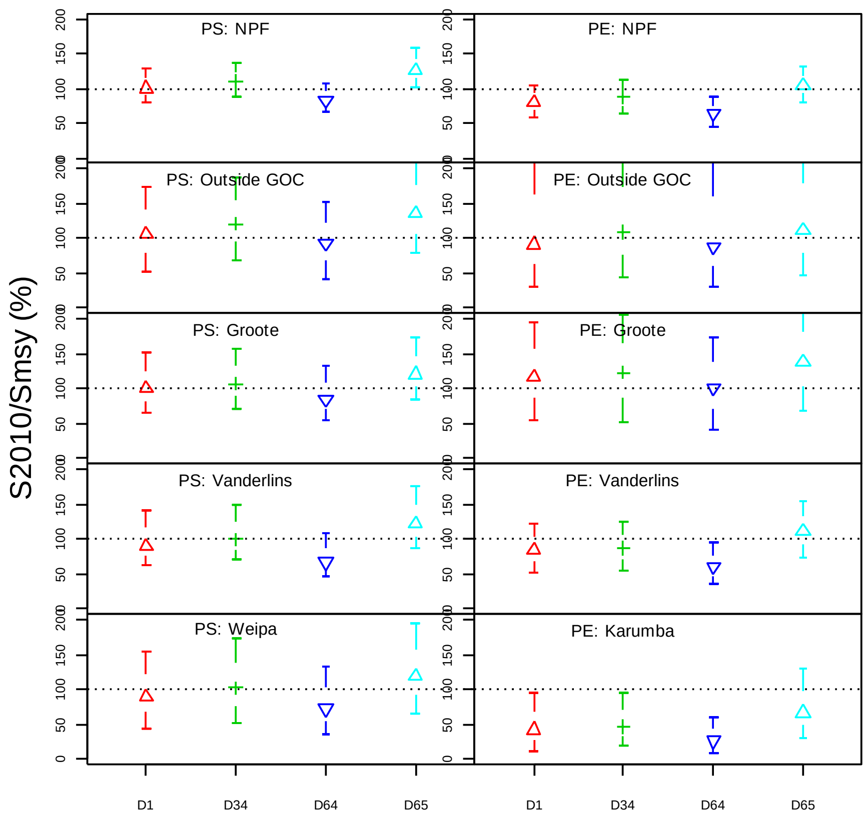

Figure 37: Sensitivity of the medians and 90% intervals for the spawning stock size in 2010 relative to S_{MSY}, for each of the stock areas and species in the operating model to the fishing power series in the operating model and that underlying the management strategy: D1 – both the operating model and the management strategy are based on BCH; D34 – both the operating model and the management strategy are based on BCL; D64 – the operating model is based on BCH and the management strategy on BCL; and D65 – the operating model is based on BCL and the management strategy on BCH .

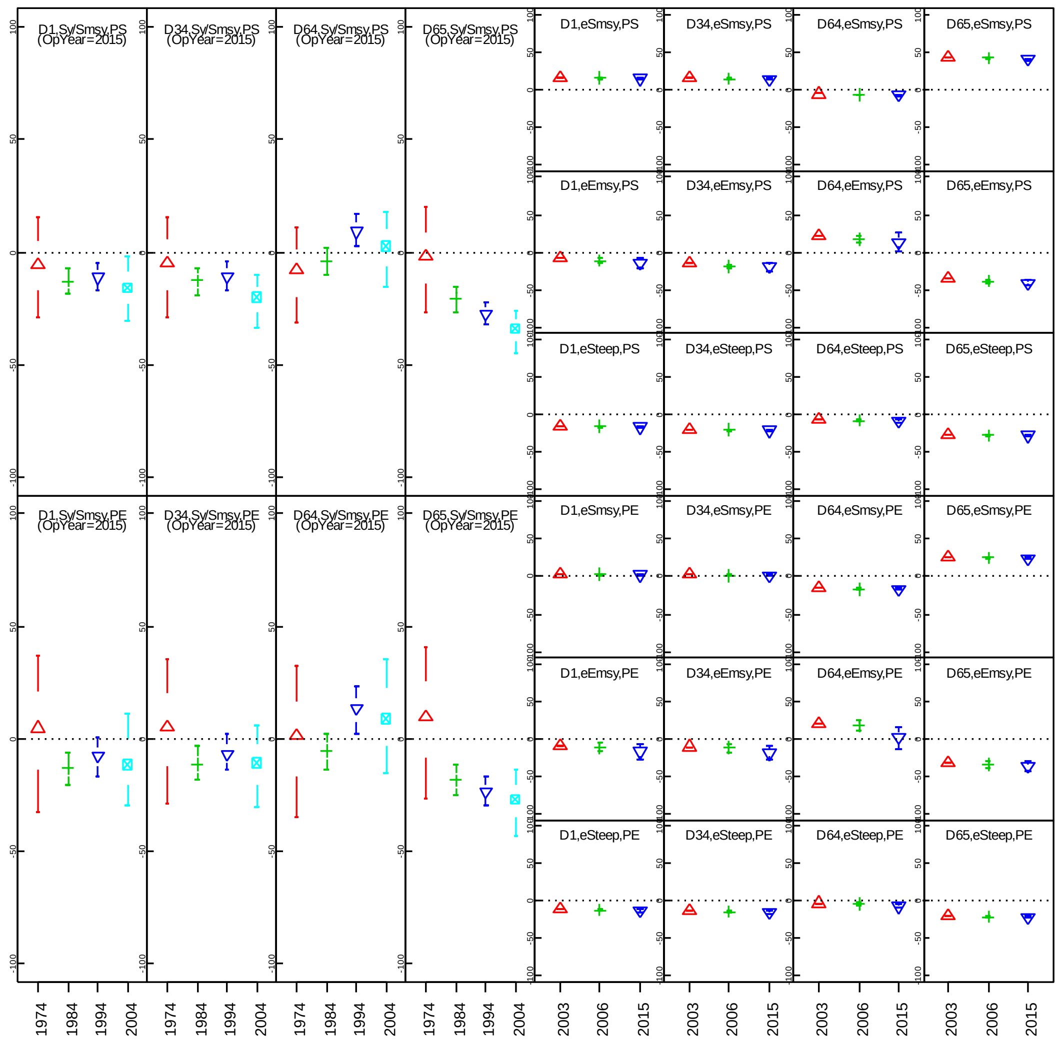

Figure 38: Sensitivity of the relative error (%) distributions to the fishing power series in the operating model and that underlying the management strategy: D1 – both the operating model and the management strategy are based on BCH; D34 – both the operating model and the management strategy are based on BCL; D64 – the operating model is based on BCH and the management strategy on BCL; and D65 – the operating model is based on BCL and the management strategy on BCH. 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, eEmsy and eSmy are respectively the relative errors associated the estimates of the steepness parameter, E_{MSY} and S_{MSY}.

10.2 Catchability

10.2.a Deriso assessment

The value of the catchability coefficient for the start of 1993 is another factor that has been shown to influence the results of the assessment of tiger prawns in the NPF substantially (Dichmont *et al*. 2003a). The estimate of $\tilde{q}$ obtained by Wang (1999) is negatively biased because its calculation is based on the assumption that there is no recruitment during a period when recruitment is, in fact, increasing. Current practice when developing scientific management advice (e.g. NPFAG 2002, 2003) is to conduct assessments for the value of $\tilde{q}$ obtained by Wang (1999) and twice this value (the "q" and "2q" scenarios).

Figures 39 and 40 illustrate the impact of assumptions regarding the value of $\tilde{q}$ by showing performance measures for two management strategies and two operating models constructed from the D1 management strategy and the Base Case operating model by varying $\tilde{q}$:

- D1 – both the operating model and the management strategy are based on "q";
- D37 – both the operating model and the management strategy are based on "2q";
- D36 – the operating model is based on "q" and the management strategy on "2q"; and
- D38 – the operating model is based on "2q" and the management strategy on "q".

The management-related performance measures are, somewhat surprisingly given the results of Dichmont e*t al*. (2003a), rather insensitive to how $\tilde{q}$ is treated in the operating model relative to how it is treated in the assessment procedure (Figure 39). This may be because quantities such as S_y/S_{MSY} (which determine the level of effort and season length) are affected almost equally by whatever value is assumed for $\tilde{q}$.

Although how $\tilde{q}$ is treated has only a minor effect on the management-related performance measures, this choice clearly impacts estimation ability (Figure 40). As expected, the estimates are more conservative when the assessment procedure is based on "2q" rather than on "q". The biases are lowest for the earliest assessment year (1974) with "q" in the assessment procedure (cases D1 and D36 in Figure 40), irrespective of how $\tilde{q}$ is set in the operating model. The estimates of S_y/S_{MSY} become increasing negatively biased with time for these cases, and particularly for case D36. There is a very large positive bias for S_{MSY} for both species for case D38.

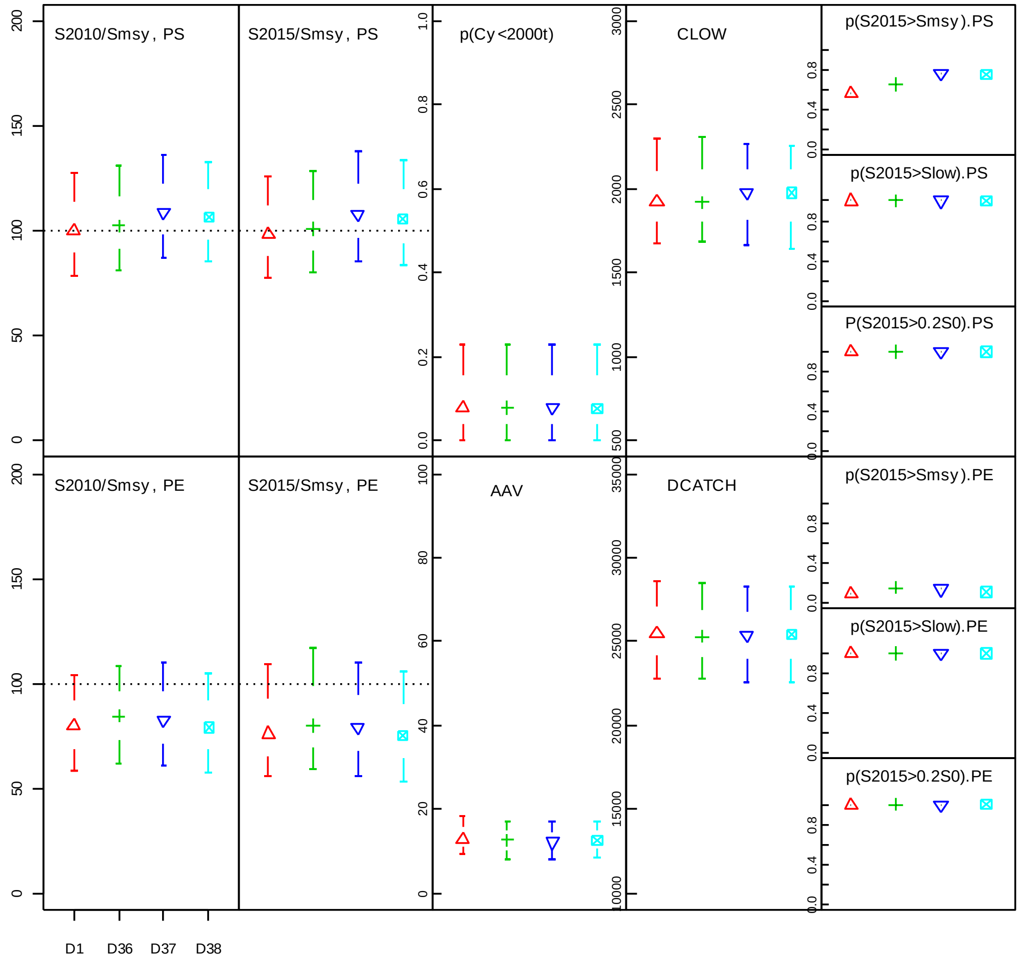

Figure 39: Sensitivity of the management-related performance measures to the value of the catchability coefficient for 1993 in the operating model and that in the assessment underlying the management strategy: D1 – both the operating model and the management strategy are based on "q"; D37 – both the operating model and the management strategy are based on "2q"; D36 – the operating model is based on "q" and the management strategy on "2q"; and D38 – the operating model is based on "2q" and the management strategy on "q".

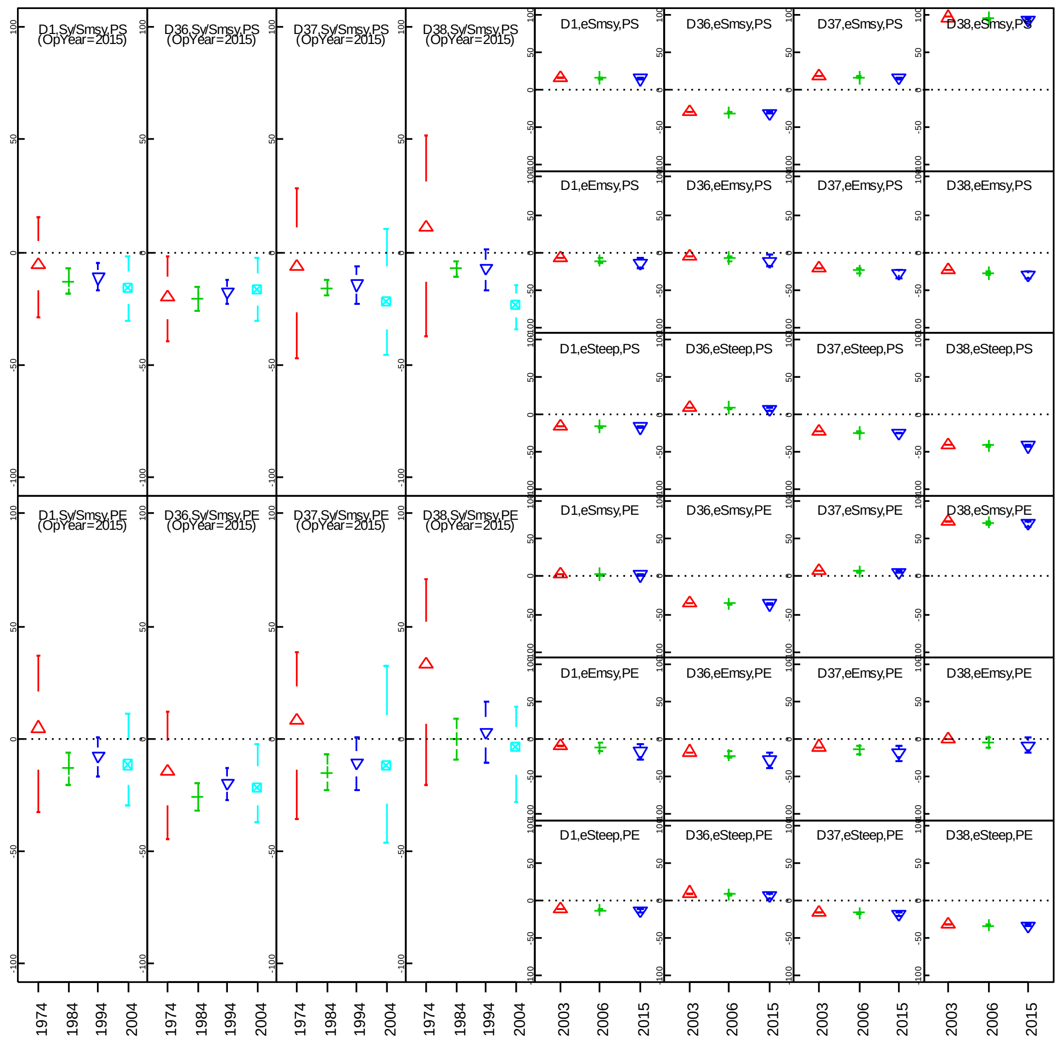

Figure 40: Sensitivity of the relative error (%) distributions to the value of the catchability coefficient for 1993 in the operating model and that in the assessment underlying the management strategy: D1 – both the operating model and the management strategy are based on “q”; D37 – both the operating model and the management strategy are based on “2q”; D36 – the operating model is based on “q” and the management strategy on “2q” ; and D38 – the operating model is based on “2q” and the management strategy on “q”. 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, eEmsy and eSmy are respectively the relative errors associated the estimates of the steepness parameter, E_{MSY} and S_{MSY}.

10.2.b 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 (Figure 41). 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 ("q" is $8.8e^{-5}$ in the operating model) (case B1 in Figure 42), and there is no large increase in the estimate of catchability from the biomass dynamic model when catchability in the operating model is "2q" (case B42 in Figure 42). Although it would be ideal to estimate catchability within the assessment, there seems little ability to do so given the available logbook data. In principle, catchability should be estimated more reliably within the assessment if survey data were included in the likelihood function, but this has not been evaluated quantitatively.

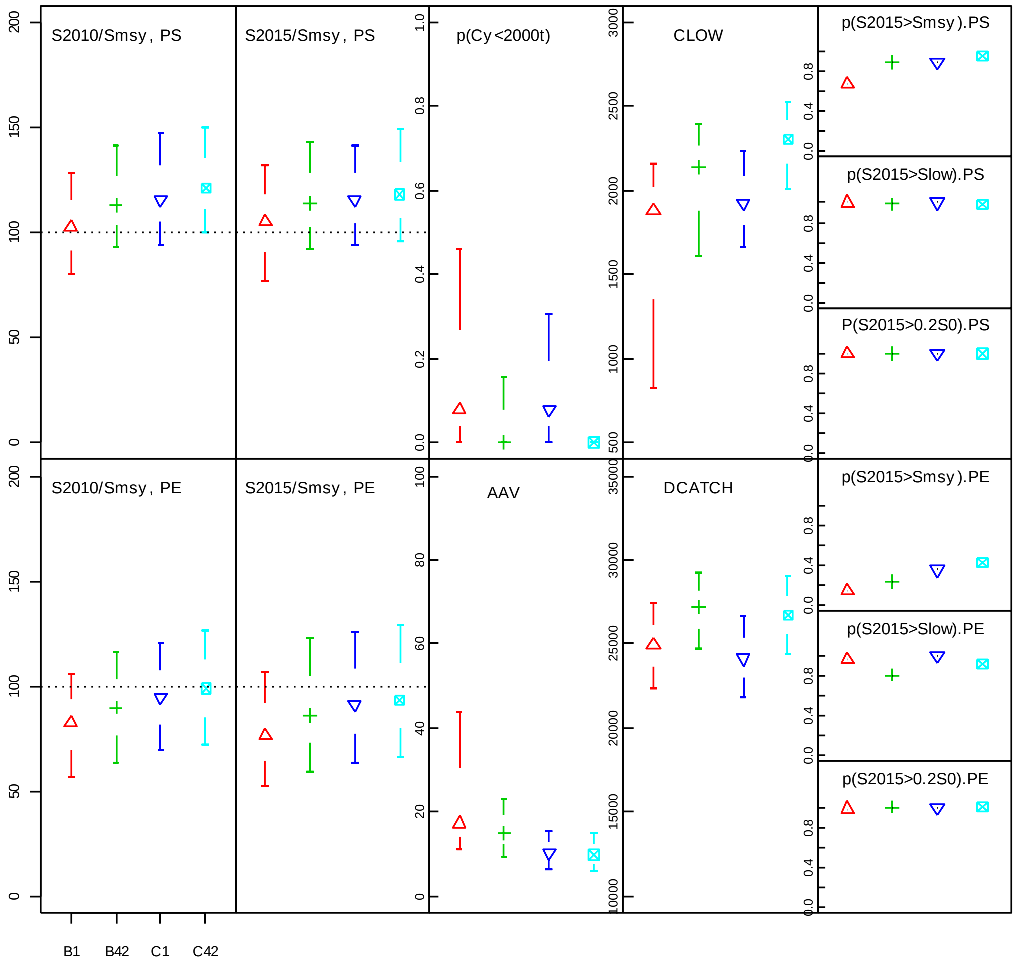

Figure 41: Sensitivity of the management-related performance measures to the value of the catchability coefficient for 1993 in the operating model for management strategies based on biomass dynamic (B) and cpue regression (C) approaches: B1 and C1 - “q”; B42 and C42 - “2q”.

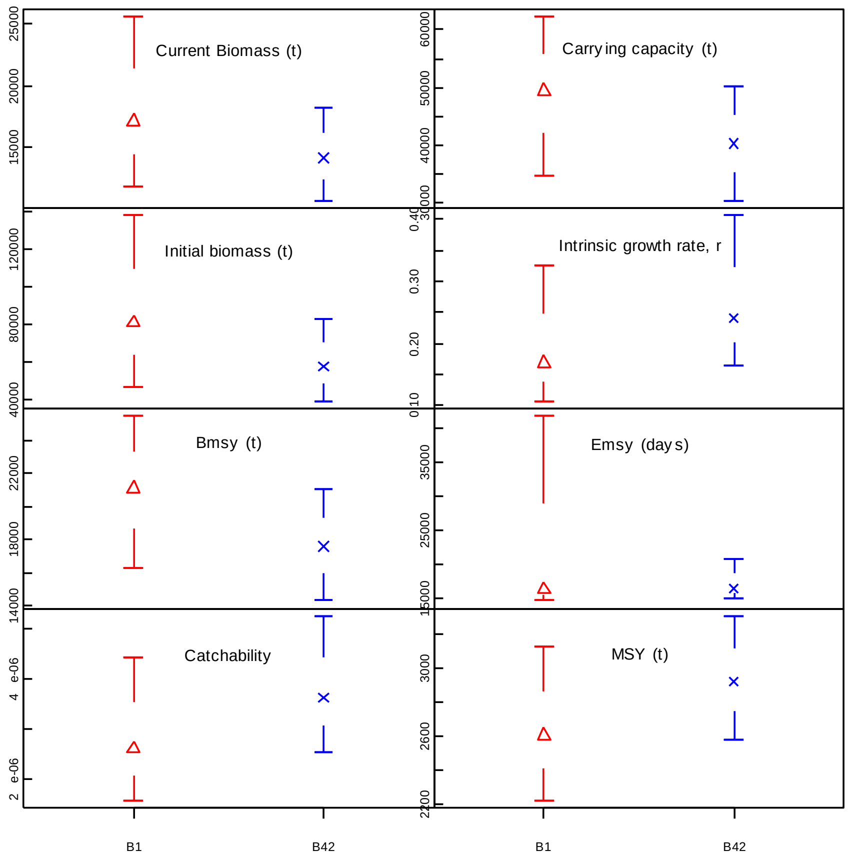

Figure 42: Medians and 90% intervals for the estimates (in 2015) of current biomass, initial biomass, B_{MSY} and catchability from the biomass dynamic model for two values for the catchability coefficient for 1993 in the operating model: B1 – "q"; B42 – "2q".

10.3 Fishing power and catchability

Section 8 highlights the importance 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 across the operating model and assessment procedure is undertaken for management strategies based on the single-stock Deriso model (see Table App.E.1 for these combinations and Figures App.E.1 to App.E.7 for detailed graphical representation of the management-related and estimation-related performance measures).

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 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 ("DCatch") for each management strategy (Figure 43). Results are grouped by operating model in Figure 43:

- the operating model based on "q" and BCH ("qH" in Figure 43),
- the operating model based on "2q" and BCH ("2qH" in Figure 43),
- the operating model based on "q" and BCL ("qL" in Figure 43), and
- the operating model based on "2q" and BCL ("2qL" in Figure 43).

It should be noted that the results in Figure 43 range from the assessment model being based on the correct assumptions about catchability ($\tilde{q}$) and fishing power to it being based on completely incorrect assumptions. The ideal management strategy would that which performs best for all the operating models (because the real situation is not, in reality, known).

A few general patterns emerge (Figure 43):

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 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 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.

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, 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}. Point 2 above implies that, irrespective of reality (the specifications of the operating model), assuming the Base Case High fishing power series leads to a higher probability of leaving the spawning stock size at (or above) S_{MSY} for both tiger prawn species than assuming the Base Case Low fishing power series (Figure 43). Of the management strategies based on the "Base Case High" fishing power series, that based on setting $\tilde{q}$ to "2q" 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 44 explores the performance of the estimation procedure associated with 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 44) 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 44) 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}.

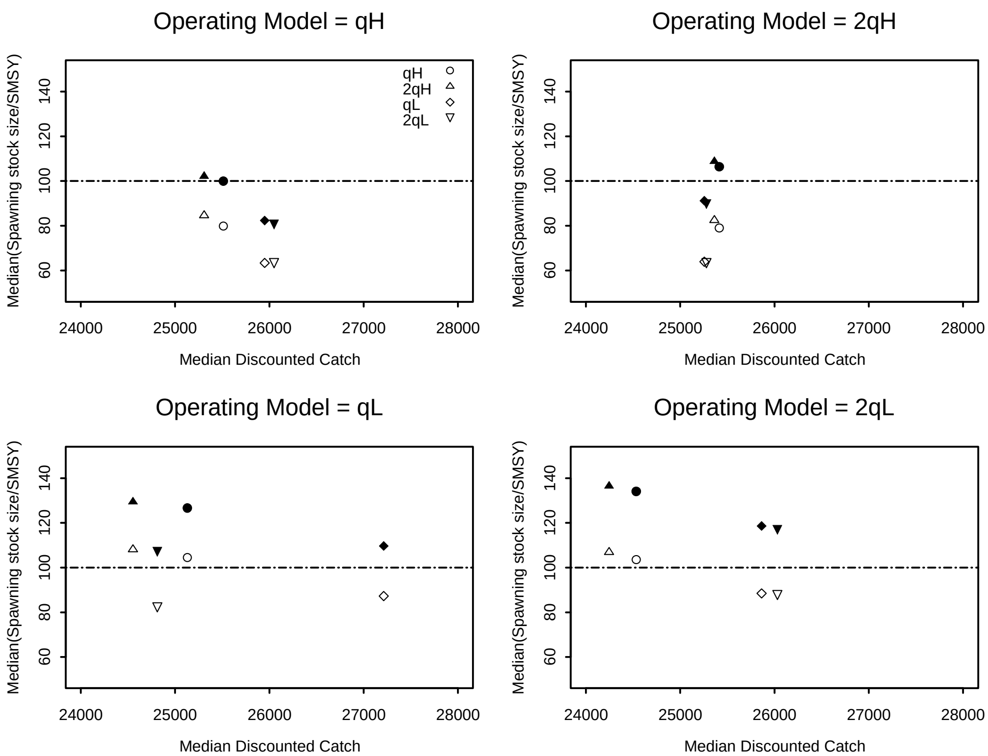

Figure 43: Median values for S_{2010}/S_{MSY} versus median discounted catches for four management strategies based on the Deriso model-based assessment procedure for each of four operating models. The specifications for the operating models / management strategies depend on the value assumed for $\tilde{q}$ ("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.

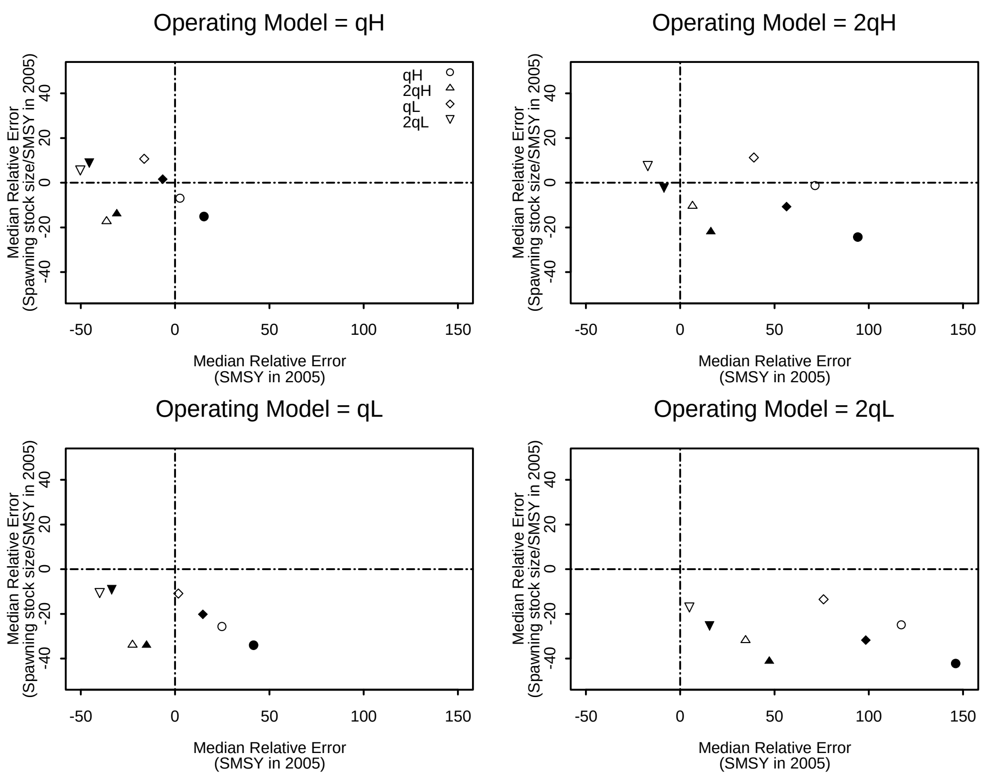

Figure 44: Median relative errors for S_{2005}/S_{MSY} and S_{MSY} based on the Deriso model-based assessment procedure applied in 2010. Results are shown for four variants of the assessment procedure and for four operating models. The specifications for the operating models / management strategies depend on the value assumed 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.

10.4 Implementation error

Implementation error relates to the difference between the actual effort expended in the fishery and that intended from the outcomes of the management strategy (see Section 6.4.a). The results in Figure 14 suggest that the coefficient of variation of the amount of implementation error could be 20% 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 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.

Figure 45 contrasts the values for the management-related performance measures for management strategies based on the Deriso model assessment procedure for three scenarios regarding the extent of implementation error (0, 15% and 30%) while Figure 46 shows results for levels of implementation error of 0 and 30% for management strategies based on the Deriso model, the biomass dynamic model, and the cpue regression approach.

There is relatively little impact of different levels of implementation error on the management-related performance measures based on $S_{2010}/S_{MSY}$and S_{2015} /S_{MSY} and the total discounted catch for the Deriso model-based management strategy (Figures 45 and 46). In contrast, implementation error has a marked impact on the values for some of the risk-related performance measures. Specifically, larger amounts of implementation error lead to higher inter-annual variation in catches, a high probability of a catch less than 2000t in some future years, and a lower lowest catch. These results are perhaps not unexpected because there is no “bias” caused by implementation error; rather the average effort level will be imposed as anticipated, but with larger inter-annual variation for larger amounts of implementation error.

It would have been anticipated that results in Figure 45 would also have been apparent in Figure 46, but this does not appear to be the case. While the changes to the economic-related performance measures are as expected in Figure 46, there are also changes to the distributions for the ratios of the spawning stock sizes in 2015 to S_{MSY} for the biomass dynamic and cpue regression approach-based harvest strategies and to the total discounted catch (cpue regression approach). The exact reasons for the responses of the biomass dynamic and cpue regression methods to implementation error are not clear. However, it is possible to speculate. For example, there is no evidence for a change to the estimation performance of the Deriso model assessment in the presence of implementation error (results not shown). However, the estimates from the biomass dynamic model are somewhat less precise when there is implementation error (Figure 47). This effect is small for most of the quantities in Figure 47 other than E_{MSY} which is much less precise when there is implementation error. It may be this imprecision in the estimates of E_{MSY} that lead to the wider intervals for S_y/S_{MSY} in Figure 46.

In summary, and as expected, improved performance results from less implementation error so, self-evidently, the amount of implementation error should be minimised to the extent possible.

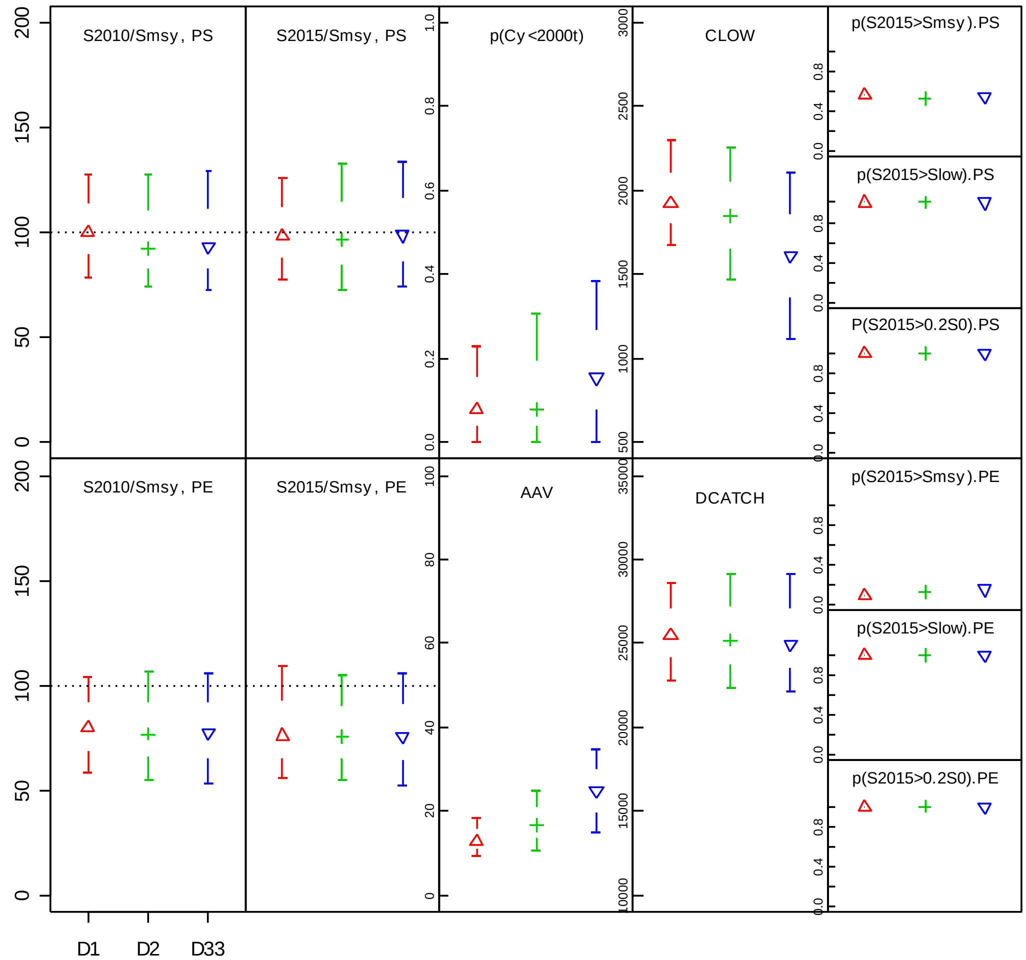

Figure 45: Comparison of the management-related performance of the Base Case Deriso model-based management strategy for operating models with no implementation error (D1), 15% implementation error (D2), and 30% implementation error (D33).

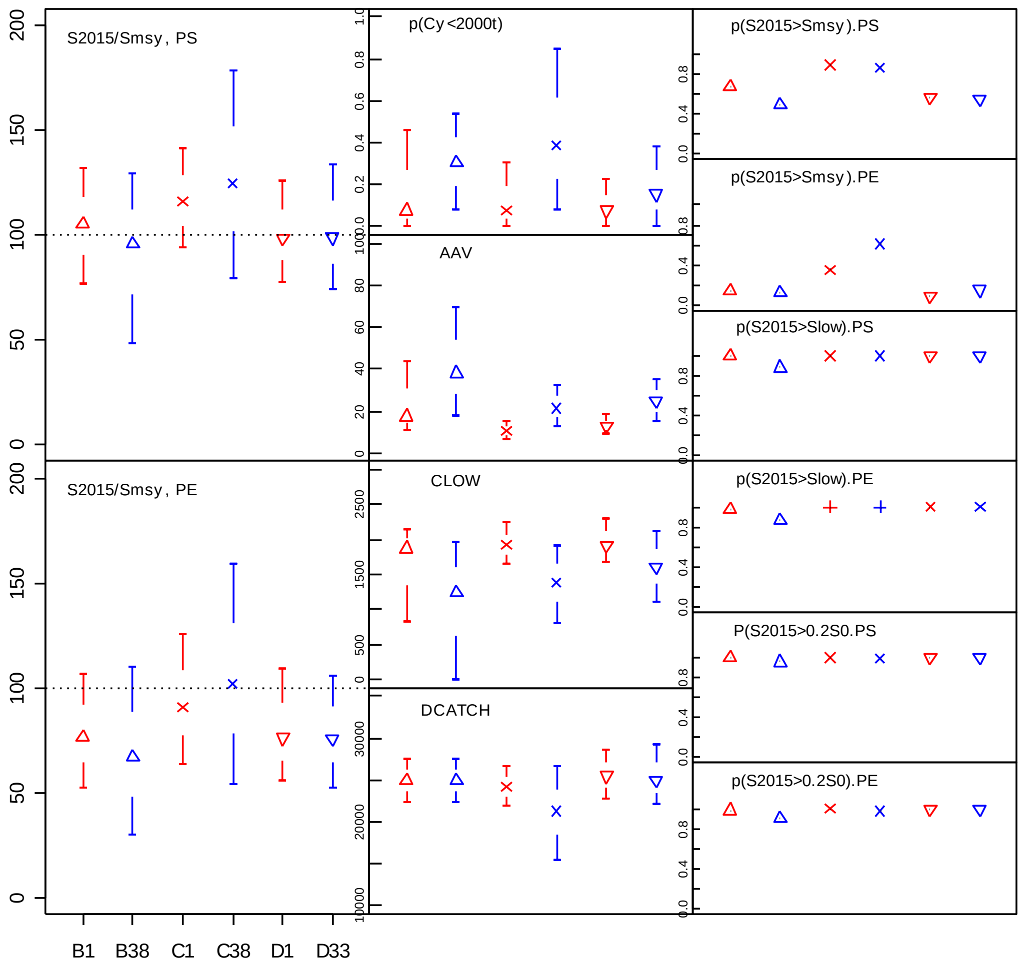

Figure 46: Comparison of the management-related performance of three management strategies for two operating models: (B1, C1 and D1 – no implementation error; B38, C38 and D33 – 30% implementation error).

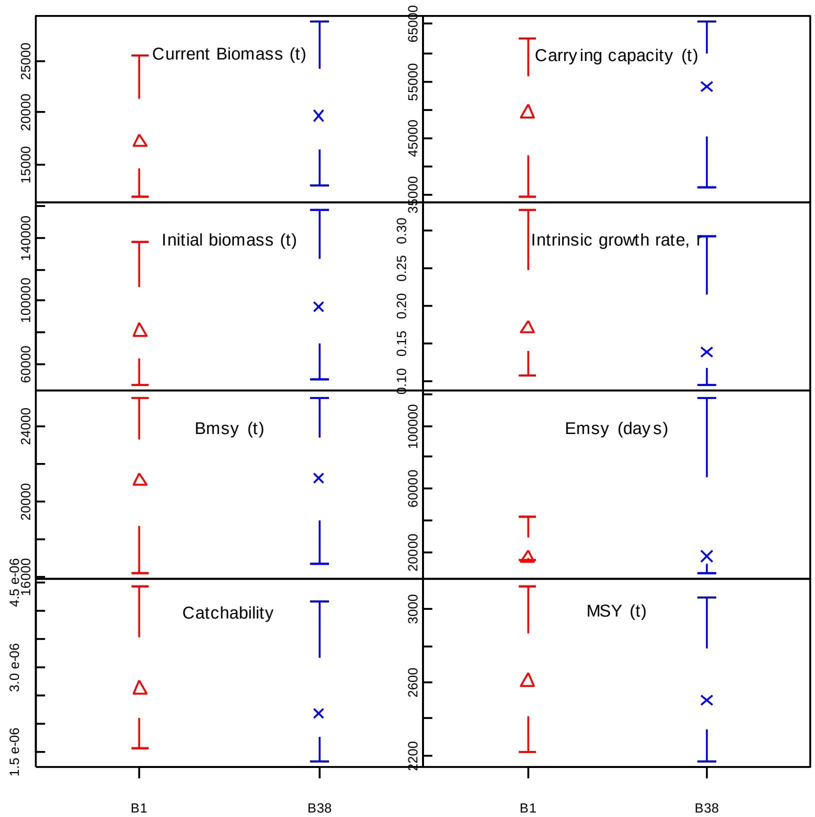

Figure 47: Medians and 90% intervals for some management related quantities based on the biomass dynamic model for operating models with: B1 – no implementation error; B38 – 30% implementation error.

10.5 Spatial correlation in recruitment among stocks

The Base Case operating model only includes within-stock temporal (i.e. inter-annual) correlation in recruitment (see Equation 14). 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 stock area concerned. 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 (Figure 17) and this was used when generating recruitment in the future (see Equations (13), (14) and (15)). 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 for all management strategies when allowance is made for spatial correlation in recruitment (Figures 48 and 49). The estimation performance of the Deriso model assessment method is not affected substantially by allowing for spatial correlation in recruitment (Figure 50) although 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, whereas this is not the case when this correlation is not included in the operating model.

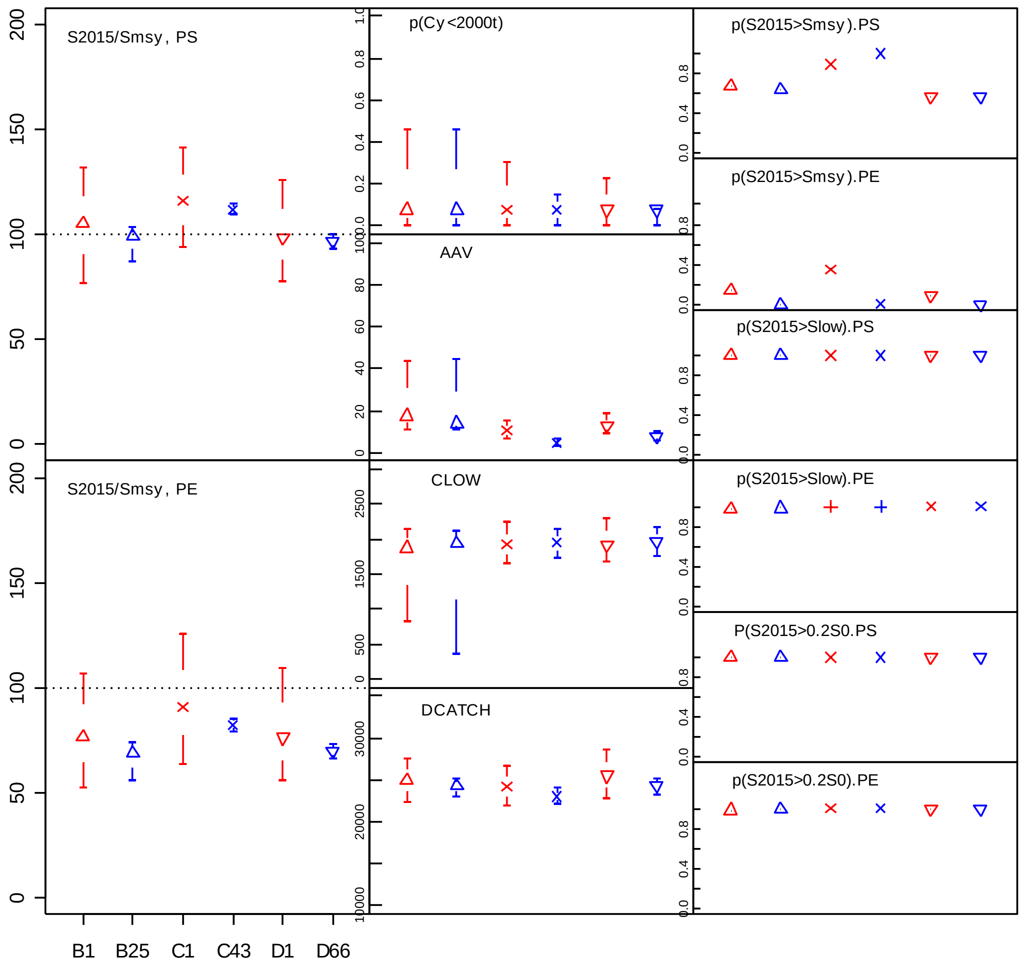

Figure 48: Comparison of the management-related performance of three management strategies for two operating models: (B1, C1 and D1 – Base Case operating model; B25, C43 and D66 – with spatially-correlated recruitment; B – biomass dynamic, C – CPUE regression, D – Deriso).

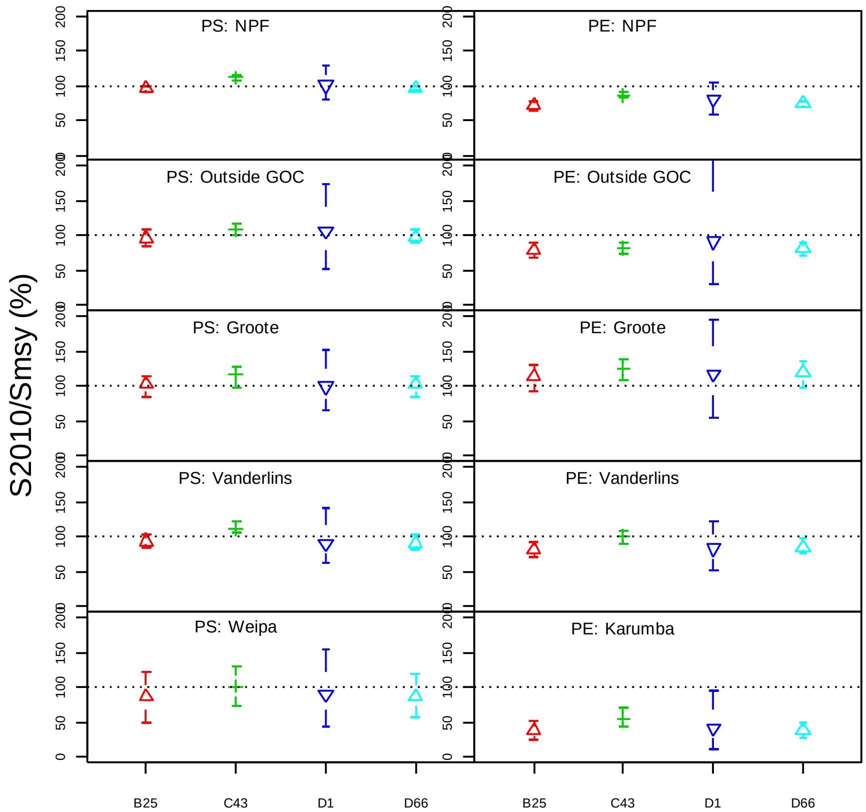

Figure 49: Sensitivity of the medians and 90% intervals for the spawning stock size in 2010 relative to S_{MSY}, for each of the stock areas and species in the operating model. Results are shown for management strategies based on the biomass dynamic (prefix B), cpue regression (prefix C), and Deriso (prefix D) methods. Spatial correlation in recruitment is included in the operating model for cases B25, C43 and D66 but not for case D1.

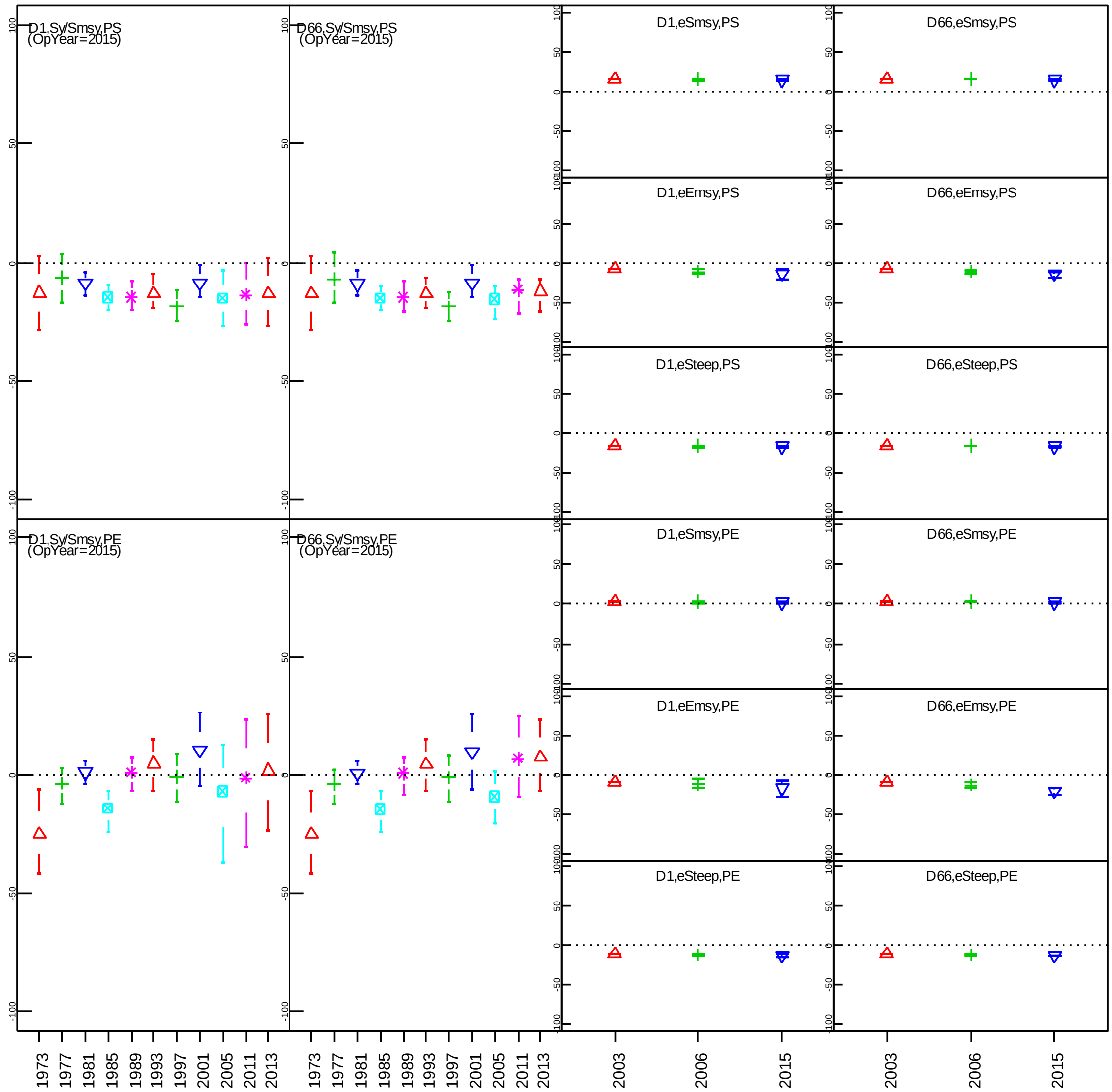

Figure 50: Relative error (%) distributions for the Deriso model assessment method applied to two operating models: D1 – Base Case; D66 – Base Case, but with spatial correlation in recruitment. OpYear is the year in which the assessment took place. The years on the x-axis for S_Y/S_{MSY} relate to the assessment year, i.e. "D1 S_Y/S_{MSY} (OpYear=2015)" is the relative error of $S_{(1973,1985,1993,2005)}/S_{MSY}$ 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}.

10.6 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 matrix[12] corresponding to the minimum of the negative log-likelihood function (see Equation 11), 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. The two approaches differ in that one is based on frequentist considerations and other on the Bayesian paradigm.

Appendix C contrasts the distributions for the recruitment parameters for 1970, 1980, 1990 and 2000 for each of the eight stocks included in the operating model from the two methods. There is generally little difference between the distributions based on the variance-covariance matrix and those from the Bayesian method, with most distributions being close to 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 Fig 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 performance of stock assessment methods and this is borne out by the results in Figure 51 (management-related performance measures) and Figure 52 (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.

[12] The Hessian matrix is the matrix of second derivatives of a multivariate function. That is, the gradient of the gradient of the function.

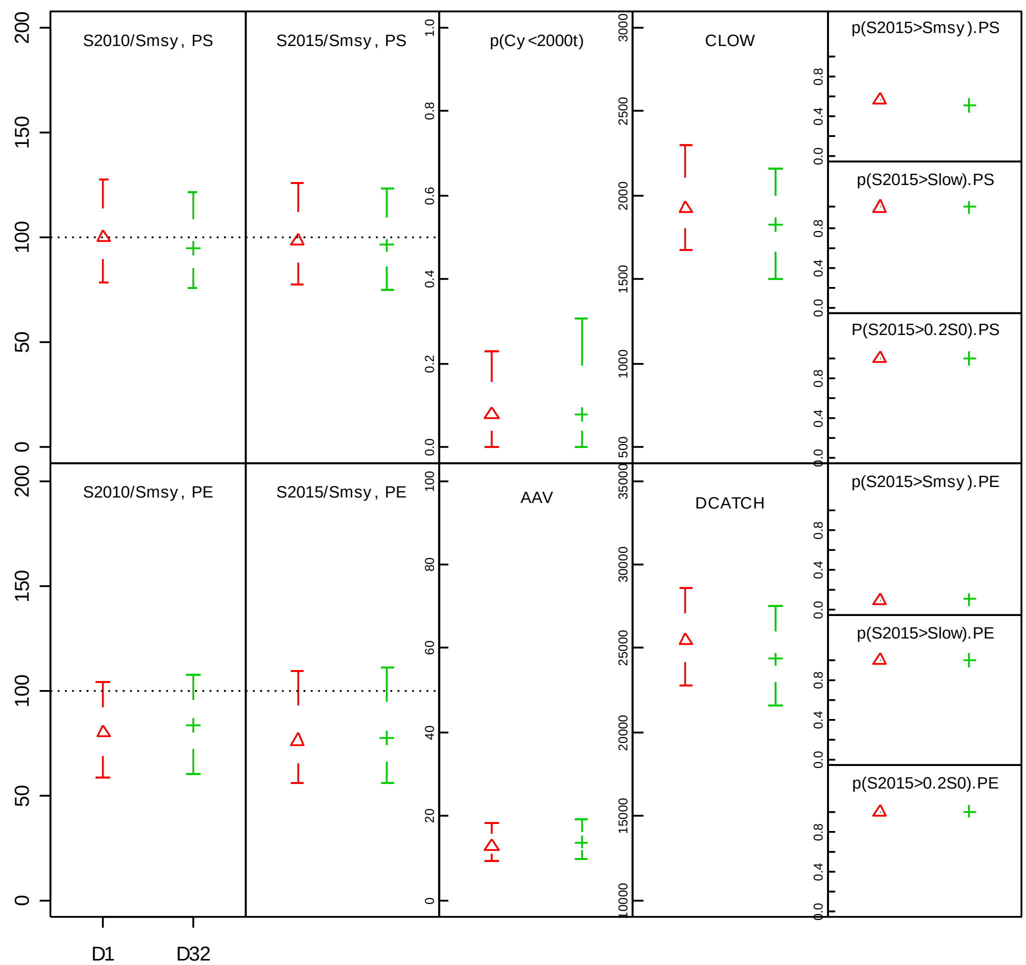

Figure 51: Comparison of the management-related performance of the Deriso model-based management strategy for two variants of the Base Case operating model: D1 – parameters sets generated from the variance-covariance matrix; D32 – parameter sets generated from a Bayesian posterior distribution.

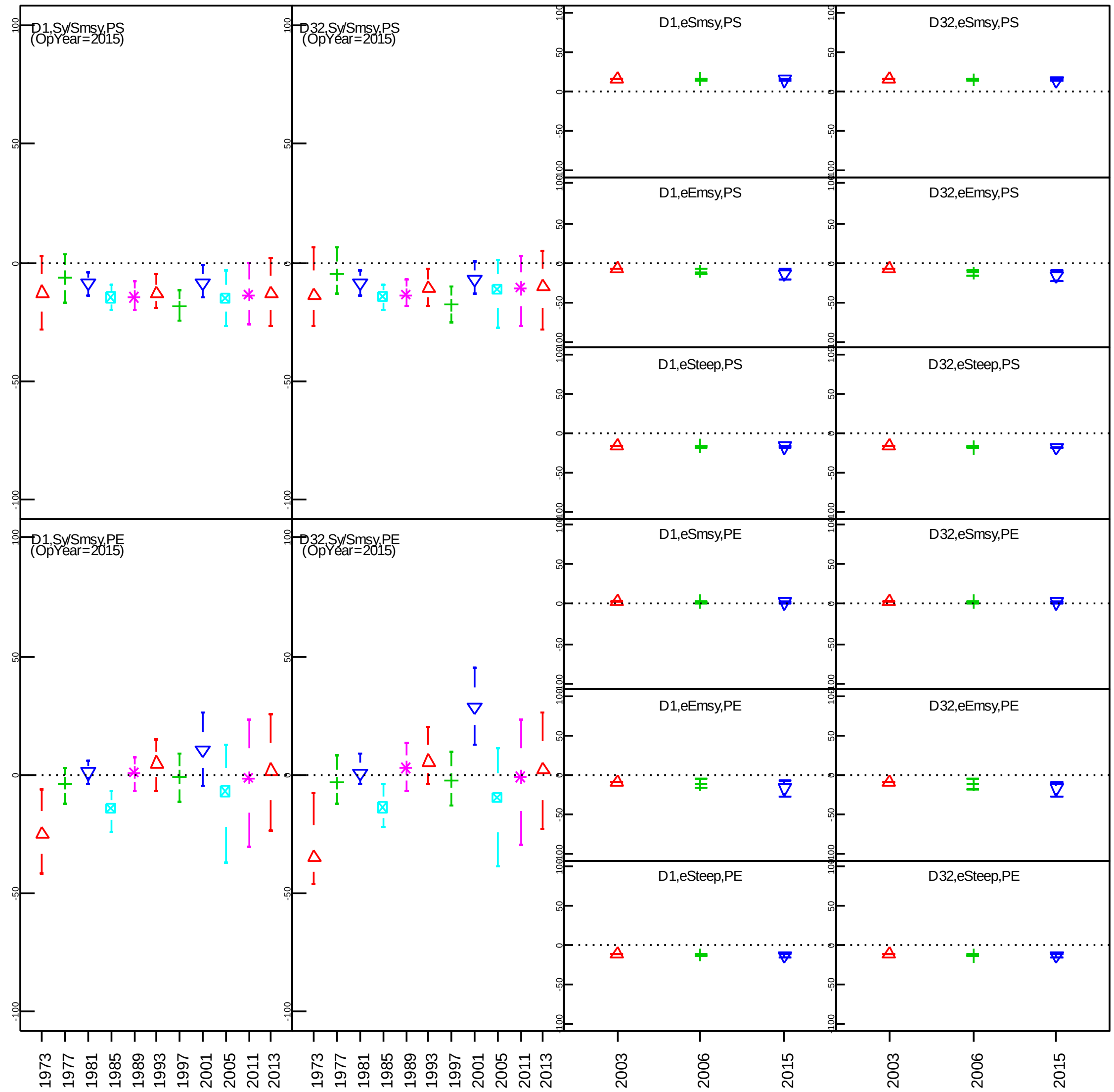

Figure 52: Sensitivity of the relative error (%) distributions for the Deriso assessment method to whether the parameter sets are generated from the variance-covariance matrix (D1) or from a Bayesian posterior (D32). OpYear is the year in which the assessment took place. The years on the x-axis for S_Y/S_{MSY} 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, eEmsy and eSmy are respectively the relative errors associated the estimates of the steepness parameter, E_{MSY} and S_{MSY}.

10.7 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 approximately 10%. Adding observation error with a coefficient of variation of 10% to the catch data has almost no impact of the management-related performance measures (Figure 53) while it results in a slight decrease in the estimates from the Deriso stock assessment method (Figure 54).

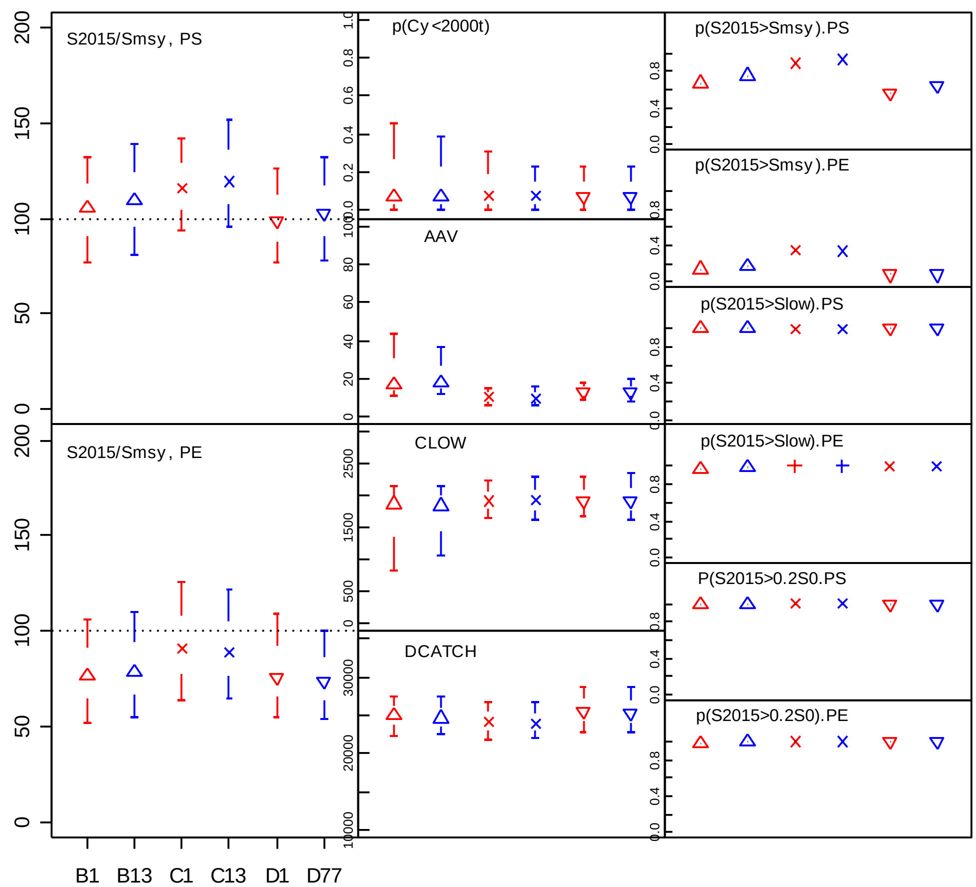

Figure 53: Management-related performance measures for management strategies based on the biomass dynamic model (prefix “B”), the cpue regression approach (prefix “C”) and the Deriso model (prefix “D”) when the operating model includes (cases B13, C13 and D77) and ignores (case B1, C1 and D1) observation error on the catch data with a coefficient of variation of 10%.

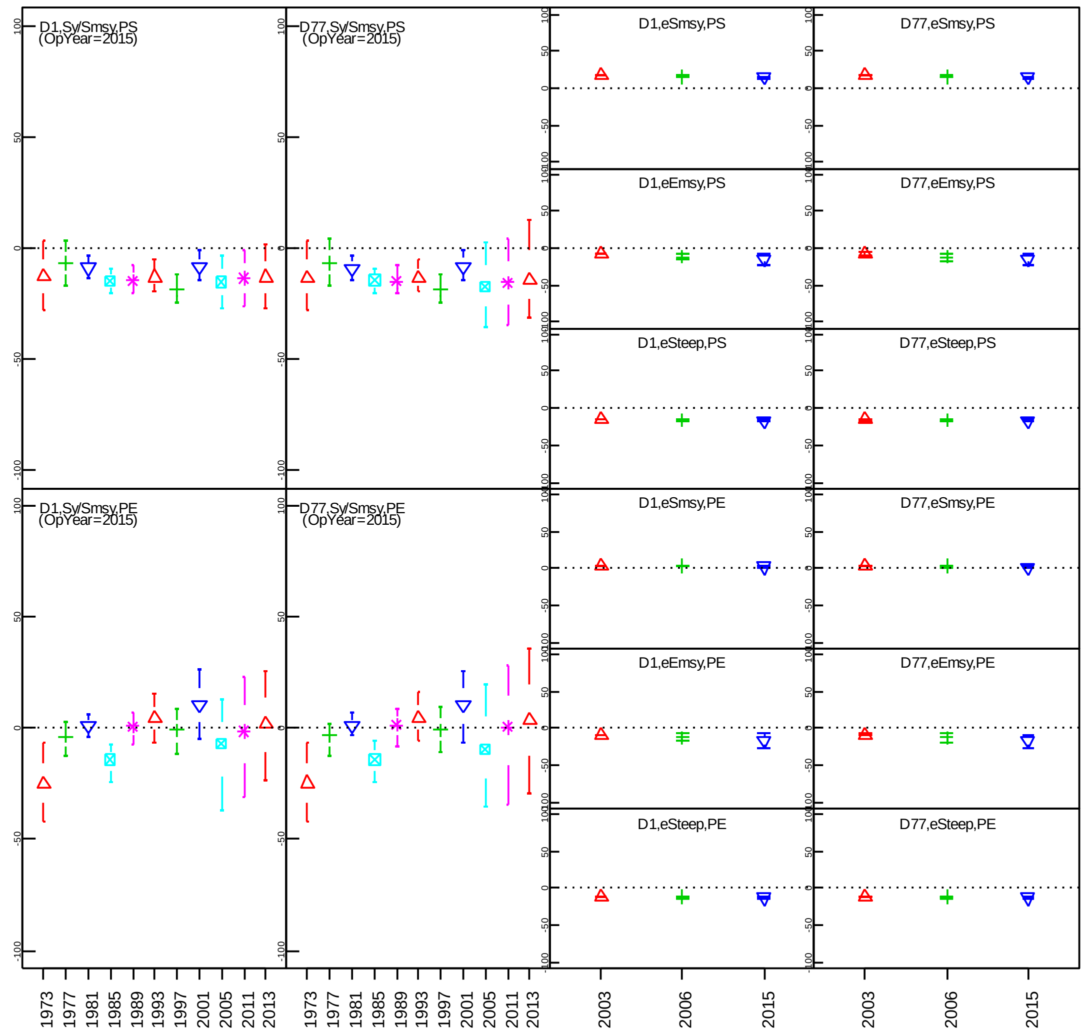

Figure 54: Sensitivity of the relative error (%) distributions for the Deriso assessment method to whether (case D77) or not (case D1) observation error with a coefficient of variation of 10% is added to the catch data used for assessment purposes. OpYear is the year in which the assessment took place. 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}.

10.8 Summary

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.

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 developed that is better able to leave the spawning stock size of *P. esculentus* above S_{MSY}. 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. Of the management strategies based on the "Base Case High" fishing power series, that based on setting $\tilde{q}$ to "2q" 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.

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, 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 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 20%.

11 ADDITIONAL SCENARIO RUNS

11.1 Setting and allocating effort by area

A full evaluation of the implications of spatially allocating the management strategy estimated effort would involve:

a) applying a management strategy to data aggregated over the entire NPF to determine the total level of effort, but allocating this level of effort to each stock area proportional to the estimate of E_{MSY} by stock area are based on a multi-stock assessment of the NPF undertaken in 2003.
b) as for a), except that the total level of effort is allocated based on the results of surveys (it should be noted that the annual recruitment surveys cannot be used for this purpose because they are only conducted in the Gulf); and
c) conducting a 4-stock assessment and applying the decision rules by stock area to determine stock area-specific effort levels.

It was only possible to examine case a) in this project given time constraints and the currently limited extent and number of annual recruitment surveys. However, Figure 55 shows that there is little change to the values for the management-related performance measures for *P. esculentus,* while there a slight decrease in the median for S_{2010}/S_{MSY} for *P. semisulcatus*.

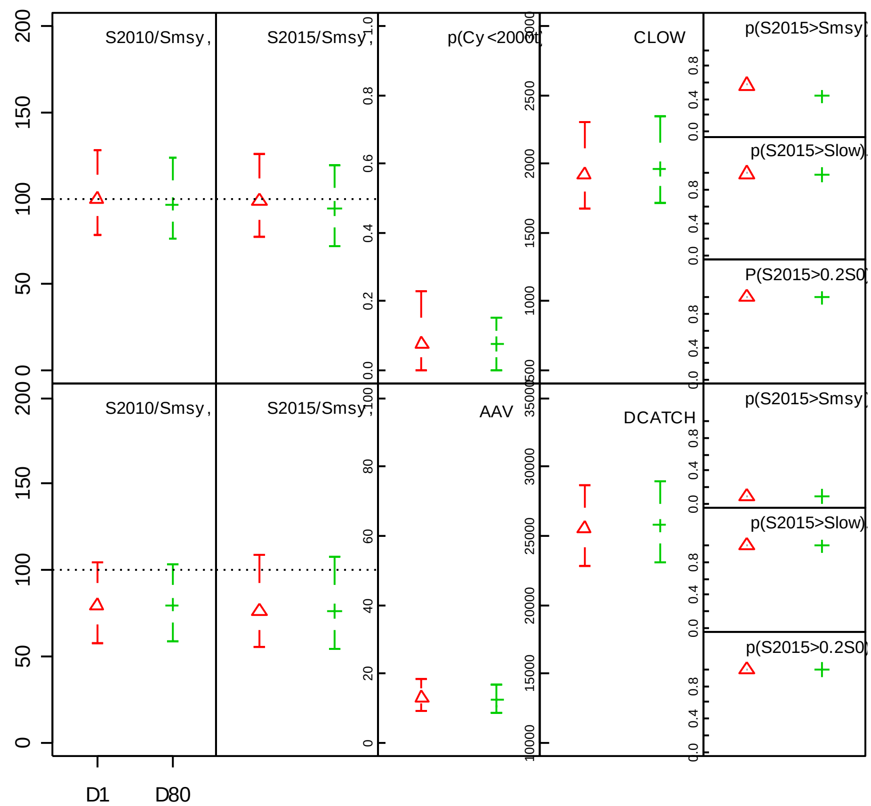

Figure 55: Comparison of the management-related performance of the Deriso model-based management strategies which differ in terms of how effort is allocated spatially (throughout the fishery - D1; in proportion to the estimate of E_{MSY} by stock area – D80).

11.2 Setting different spawning stock targets for each species

Figure 56 compares the management-related performance measures for two variants of the Deriso model-based management strategy obtained by varying the target spawning stock size level in the decision rule:

- D1 - S_{MSY} for both species; and
- D79 - S_{MSY} for *P. semisulcatus* and $1.3S_{MSY}$ for *P.esculentus*.

The specifications for management strategy D79 are based on the results in Section 9.6, which suggest that the probability of leaving the spawning stock size of *P. esculentus* at or above S_{MSY} is improved by increasing the target spawning stock size level in the decision rule.

The probability of being above S_{MSY} is higher for both species for management strategy D79, 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 species combined, so that S_{2010} and S_{2015} for *P. semisulcatus* are also increased even though the higher target level in the decision rule was aimed at *P. esculentus*. This results in further evidence that the overlapping geographical distributions of the two tiger prawn species, combined with their differing biology, makes attempting to manage them separately towards the same target reference points very difficult.

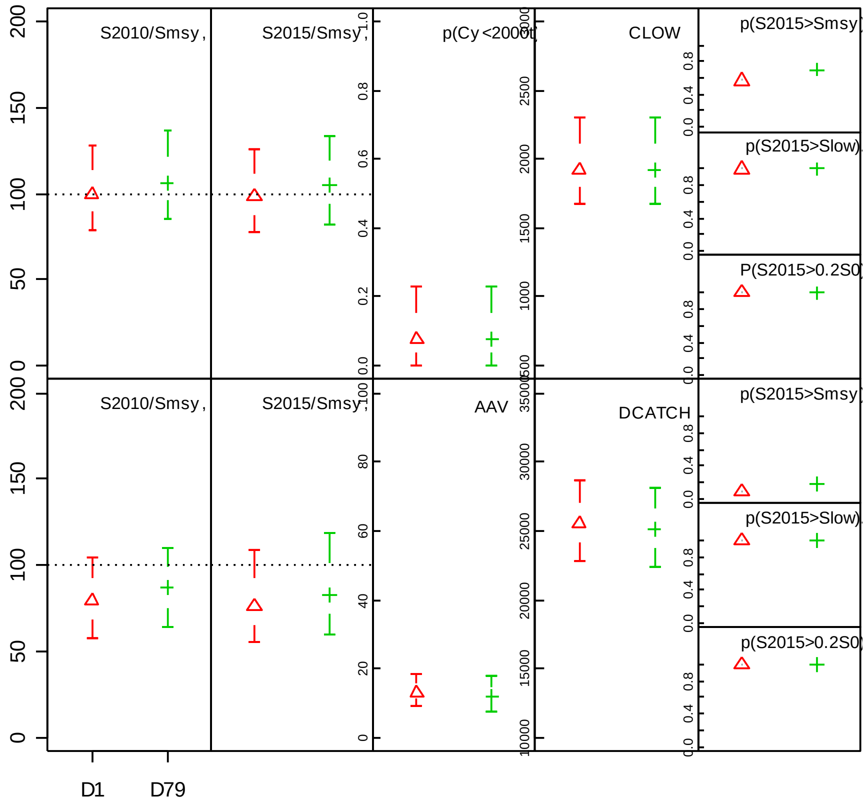

Figure 56: Comparison of the management-related performance of the Deriso model-based management strategies which differ in terms of the target spawning stock level in the decision rule: D1 (S_{MSY} for both tiger prawn species), D79 (S_{MSY} for *P. semisulcatus* and $1.3S_{MSY}$ for *P. esculentus*). The results in this figure are based on the Base Case operating model.

11.3 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 ½ 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 57, 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 < 2000*t* 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.

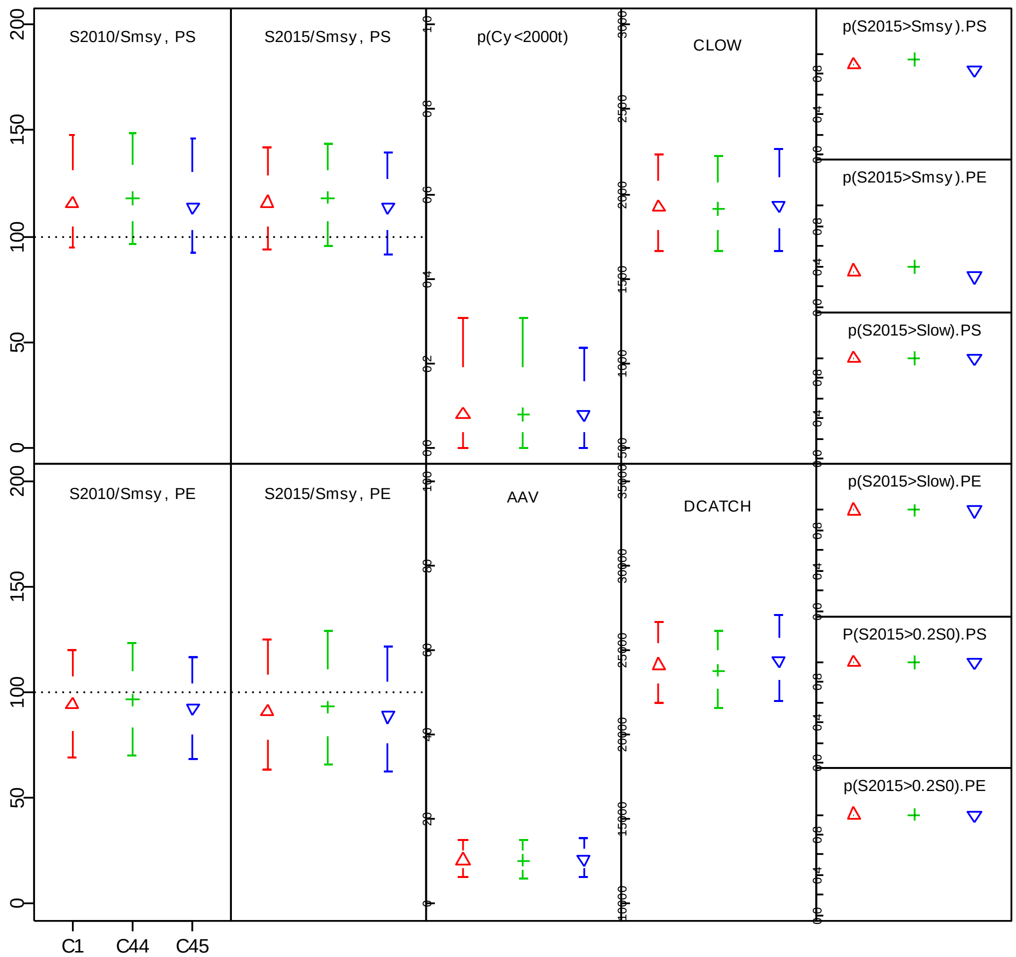

Figure 57: Management-related performance measures for variants of the cpue regression approach in which the slope of the logarithms of the catch rates are multiplied by 0.5 (C1), 0.25 (C44) and 0.75 (C45). The results in this figure are based on the Base Case operating model.

11.4 Summary

This chapter examined two ways to improve the poor performance of the single- and multi-stock Deriso-model-based management strategies in terms of attempting to leave the stocks of *P. esculentus*, particularly that in the Karumba stock area, above S_{MSY}. Neither allocating the effort level spatially, based on stock area-specific estimates of E_{MSY}, nor increasing the target spawning stock size level in the decision rule for *P. esculentus*, achieved the desired outcome. This suggests that the alternative of regular multi-stock assessments to determine stock area-specific effort levels should be examined (see Section 13), and raises the possibility that it may be necessary to develop methods of allocating effort by area.

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13 FUTURE RESEARCH

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_{SMY}. 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 (see Section 9.3) 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. Section 11.1 examines one possible way to implement such an approach. However, its performance was not particularly successful. Two additional 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 the results from surveys[13]; 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.
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 (Section 9.3.b). 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 report 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

[13] 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.

behaviour of the fishing fleet. This requires expanding the operating model to include ecosystem and economic components[14].

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) (Section 4.3). 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 are 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, the assessment should be updated to include these data and to also estimate catchability.

[14] 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”).

APPENDIX A - SCENARIOS FOR THE CPUE AND BIOMASS DYNAMIC-BASED HARVEST STRATEGIES FROM SECTION 8

Run no.	Observation error CV (%)	Spatially correlated recruitment	Implementation Error	Catchability and fishing power (operating model)	Area allocation weight to past cpue	Recruitment Monte Carlo values	Target	No of stocks	Reference years for E_{MSY}	p(seasons)	p(effort)
1	0	No	0	q/BCH	1	Varco Matrix	1.0 S_{MSY}	1	last 10 years	1	3
2	0	No	15%	q/BCH	1	Varco Matrix	1.0 S_{MSY}	1	last 10 years	1	3
3	10%	Yes	0	q/BCH	1.5	Bayesian	1.0 S_{MSY}	1	last 10 years	1	3
4	10%	Yes	15%	q/BCH	1.5	Bayesian	1.0 S_{MSY}	1	last 10 years	1	3
5	0	Yes	15%	q/BCH	1	Varco Matrix	1.2 S_{MSY}	1	last 10 years	1	3
6	0	Yes	30%	q/BCH	1	Varco Matrix	1.2 S_{MSY}	1	last 10 years	1	3
7	10%	No	15%	q/BCH	1.5	Varco Matrix	1.2 S_{MSY}	1	last 10 years	1	3
8	10%	No	30%	q/BCH	1.5	Varco Matrix	1.2 S_{MSY}	1	last 10 years	1	3
9	10%	Yes	15%	q/BCH	1	Varco Matrix	1.2 S_{MSY}	1	last 10 years	1	3
10	10%	Yes	30%	q/BCH	1	Varco Matrix	1.2 S_{MSY}	1	last 10 years	1	3
11	0	Yes	15%	q/BCH	1.5	Bayesian	1.2 S_{MSY}	1	last 10 years	1	3
12	0	Yes	30%	q/BCH	1.5	Bayesian	1.2 S_{MSY}	1	last 10 years	1	3
13	10%	No	0	q/BCH	1	Varco Matrix	1.0 S_{MSY}	1	last 10 years	1	3
14	10%	No	15%	q/BCH	1	Varco Matrix	1.0 S_{MSY}	1	last 10 years	1	3
15	0	Yes	0	q/BCH	1.5	Bayesian	1.0 S_{MSY}	1	last 10 years	1	3
16	0	Yes	15%	q/BCH	1.5	Bayesian	1.0 S_{MSY}	1	last 10 years	1	3

Run no.	Observation error CV (%)	Spatially correlated recruitment	Implementation Error	Catchability and fishing power (operating model)	Area allocation weight to past cpue	Recruitment Monte Carlo values	Target	No of stocks	Reference years for E_{MSY}	p(seasons)	p(effort)
17	10%	No	15%	q/BCH	1	Varco Matrix	1.2 S_{MSY}	1	1993-2003	1	3
18	10%	No	30%	q/BCH	1	Varco Matrix	1.2 S_{MSY}	1	1993-2003	1	3
19	0	Yes	15%	q/BCH	1.5	Bayesian	1.2 S_{MSY}	1	1993-2003	1	3
20	0	Yes	30%	q/BCH	1.5	Bayesian	1.2 S_{MSY}	1	1993-2003	1	3
21	10%	Yes	0	q/BCH	1	Varco Matrix	1.0 S_{MSY}	1	1993-2003	1	3
22	10%	Yes	15%	q/BCH	1	Varco Matrix	1.0 S_{MSY}	1	1993-2003	1	3
23	0	No	0	q/BCH	1.5	Bayesian	1.0 S_{MSY}	1	1993-2003	1	3
24	0	No	15%	q/BCH	1.5	Bayesian	1.0 S_{MSY}	1	1993-2003	1	3
25	0	Yes	0	q/BCH	1	Varco Matrix	1.0 S_{MSY}	1	1993-2003	1	3
26	0	Yes	15%	q/BCH	1	Varco Matrix	1.0 S_{MSY}	1	1993-2003	1	3
27	10%	No	0	q/BCH	1.5	Bayesian	1.0 S_{MSY}	1	1993-2003	1	3
28	10%	No	15%	q/BCH	1.5	Bayesian	1.0 S_{MSY}	1	1993-2003	1	3
29	0	No	15%	q/BCH	1	Varco Matrix	1.2 S_{MSY}	1	1993-2003	1	3
30	0	No	30%	q/BCH	1	Varco Matrix	1.2 S_{MSY}	1	1993-2003	1	3
31	10%	Yes	15%	q/BCH	1.5	Bayesian	1.2 S_{MSY}	1	1993-2003	1	3
32	10%	Yes	30%	q/BCH	1.5	Bayesian	1.2 S_{MSY}	1	1993-2003	1	3
33	0	No	0	q/BCH	1	Varco Matrix	1.0 S_{MSY}	1	last 10 years	3	3
36	0	No	0	q/BCH	1	Varco Matrix	1.2 S_{MSY}	1	last 10 years	1	3

Run no.	Observation error CV (%)	Spatially correlated recruitment	Implementation Error	Catchability and fishing power (operating model)	Area allocation weight to past cpue	Recruitment Monte Carlo values	Target	No of stocks	Reference years for E_{MSY}	p(seasons)	p(effort)
37	0	No	0	q/BCH	1	Bayesian	1.0 S_{MSY}	1	last 10 years	1	3
38	0	No	30%	q/BCH	1	Varco Matrix	1.0 S_{MSY}	1	last 10 years	1	3
39	0	No	0	q/BCH	1	Varco Matrix	1.0 S_{MSY}	1	1993-2003	1	3
40	0	No	0	q/BCH	1	Varco Matrix	1.0 S_{MSY}	1	last 10 years	1	1

APPENDIX B - SCENARIOS FOR THE DERISO MODEL - BASED HARVEST STRATEGIES FROM SECTION 8

Run no.	Catchability and fishing power (Operating model)	Catchability and fishing power (Management model)	Observation error CV (%)	Spatially correlated Rec	Include survey catch	Implementation Error	Area allocation weight to past cpue	Recruitment Monte Carlo values	Target	No of stocks	Reference years for E_{MSY}	p(seasons)	p(Effort)
1	q/BCH	q/BCH	0	No	No	0	1	Varco Matrix	1.0 S_{MSY}	1	last 10 years	1	3
2	q/BCH	q/BCH	0	No	No	15%	1	Varco Matrix	1.0 S_{MSY}	1	last 10 years	1	3
3	q/BCH	q/BCH	10%	Yes	24%CV	0	1.5	Bayesian	1.0 S_{MSY}	1	last 10 years	1	3
4	q/BCH	q/BCH	10%	Yes	24%CV	15%	1.5	Bayesian	1.0 S_{MSY}	1	last 10 years	1	3
5	2q/BCL	q/BCL	0	Yes	No	15%	1	Varco Matrix	1.2 S_{MSY}	1	last 10 years	1	3
6	2q/BCL	q/BCL	0	Yes	No	30%	1	Varco Matrix	1.2 S_{MSY}	1	last 10 years	1	3
7	2q/BCH	2q/BCH	10%	Yes	24%CV	15%	1	Varco Matrix	1.2 S_{MSY}	1	last 10 years	1	3
8	2q/BCH	2q/BCH	10%	Yes	24%CV	30%	1	Varco Matrix	1.2 S_{MSY}	1	last 10 years	1	3
9	q/BCH	2q/BCH	0	No	No	15%	1	Bayesian	1.2 S_{MSY}	1	last 10 years	1	3
10	q/BCH	2q/BCH	0	No	No	30%	1	Bayesian	1.2 S_{MSY}	1	last 10 years	1	3
11	q/BCL	2q/BCL	10%	No	24%CV	0	1	Varco Matrix	1.0 S_{MSY}	1	last 10 years	1	3
12	q/BCL	2q/BCL	10%	No	24%CV	15%	1	Varco Matrix	1.0 S_{MSY}	1	last 10 years	1	3
13	q/BCH	q/BCH	10%	No	24%CV	15%	1	Varco Matrix	1.2 S_{MSY}	1	1993-2002	1	3
14	q/BCH	q/BCH	10%	No	24%CV	30%	1	Varco Matrix	1.2 S_{MSY}	1	1993-2002	1	3
15	q/BCH	q/BCH	0	Yes	No	15%	1.5	Bayesian	1.2 S_{MSY}	1	1993-2002	1	3
16	q/BCH	q/BCH	0	Yes	No	30%	1.5	Bayesian	1.2 S_{MSY}	1	1993-2002	1	3
17	2q/BCL	q/BCL	10%	Yes	24%CV	0	1	Varco Matrix	1.0 S_{MSY}	1	1993-2002	1	3
18	2q/BCL	q/BCL	10%	Yes	24%CV	15%	1	Varco Matrix	1.0 S_{MSY}	1	1993-2002	1	3
19	2q/BCH	2q/BCH	0	Yes	No	0	1	Varco Matrix	1.0 S_{MSY}	1	1993-2002	1	3
20	2q/BCH	2q/BCH	0	Yes	No	15%	1	Varco Matrix	1.0 S_{MSY}	1	1993-2002	1	3

Run no.	Catchability and fishing power (Operating model)	Catchability and fishing power (Management model)	Observation error CV (%)	Spatially correlated Rec	Include survey catch	Implementation Error	Area allocation weight to past cpue	Recruitment Monte Carlo values	Target	No of stocks	Reference years for E_{MSY}	p(seasons)	p(Effort)
21	q/BCH	2q/BCH	10%	No	24%CV	0	1.5	Bayesian	1.0 S_{MSY}	1	1993-2002	1	3
22	q/BCH	2q/BCH	10%	No	24%CV	15%	1.5	Bayesian	1.0 S_{MSY}	1	1993-2002	1	3
23	q/BCL	2q/BCL	0	No	No	15%	1	Varco Matrix	1.2 S_{MSY}	1	1993-2002	1	3
24	q/BCL	2q/BCL	0	No	No	30%	1	Varco Matrix	1.2 S_{MSY}	1	1993-2002	1	3
25	q/BCH	q/BCH	0	No	No	0	1	Varco Matrix	1.2 S_{MSY}	1	last 10 years	1	3
26	q/BCH	q/BCH	0	No	No	0	1	Varco Matrix	1.0 S_{MSY}	3	last 10 years	1	3
27	q/BCH	q/BCH	0	No	No	0	1	Varco Matrix	1.0 S_{MSY}	5	last 10 years	1	3
28	q/BCH	q/BCH	0	No	No	0	1	Varco Matrix	1.0 S_{MSY}	1	last 10 years	1	1
29	q/BCH	q/BCH	0	No	No	0	1	Varco Matrix	1.0 S_{MSY}	1	last 10 years	3	3
30	q/BCH	q/BCH	0	No	No	0	1	Varco Matrix	1.2 S_{MSY}	1	last 10 years	1	1
31	q/BCH	q/BCH	0	No	No	0	1	Varco Matrix	1.0 S_{MSY}	1	1993-2002	1	3
32	q/BCH	q/BCH	0	No	No	0	1	Bayesian	1.0 S_{MSY}	1	last 10 years	1	3
33	q/BCH	q/BCH	0	No	No	30%	1	Varco Matrix	1.0 S_{MSY}	1	last 10 years	1	3
34	q/BCL	q/BCL	0	No	No	0	1	Varco Matrix	1.0 S_{MSY}	1	last 10 years	1	3
35	q/BCH	q/BCH	0	No	No	0	1.5	Varco Matrix	1.0 S_{MSY}	1	last 10 years	1	3
36	q/BCH	2q/BCH	0	No	No	0	1	Varco Matrix	1.0 S_{MSY}	1	last 10 years	1	3
37	2q/BCH	2q/BCH	0	No	No	0	1	Varco Matrix	1.0 S_{MSY}	1	last 10 years	1	3
38	2q/BCH	q/BCH	0	No	No	0	1	Varco Matrix	1.0 S_{MSY}	1	last 10 years	1	3
39	2q/BCL	q/BCL	0	No	No	0	1	Varco Matrix	1.0 S_{MSY}	1	last 10 years	1	3
40	2q/BCL	2q/BCL	0	No	No	0	1	Varco Matrix	1.0 S_{MSY}	1	last 10 years	1	3

Run no.	Catchability and fishing power (Operating model)	Catchability and fishing power (Management model)	Observation error CV (%)	Spatially correlated Rec	Include survey catch	Implementation Error	Area allocation weight to past cpue	Recruitment Monte Carlo values	Target	No of stocks	Reference years for E_{MSY}	p(seasons)	p(Effort)
41	q/BCH	q/BCL	0	No	No	0	1	Varco Matrix	1.0 S_{MSY}	1	last 10 years	1	3
42	q/BCH	q/BCL	0	No	No	15%	1	Varco Matrix	1.0 S_{MSY}	1	last 10 years	1	3
43	q/BCH	q/BCL	10%	Yes	24%CV	0	1.5	Bayesian	1.0 S_{MSY}	1	last 10 years	1	3
44	q/BCH	q/BCL	10%	Yes	24%CV	15%	1.5	Bayesian	1.0 S_{MSY}	1	last 10 years	1	3
45	2q/BCL	q/BCH	0	Yes	No	15%	1	Varco Matrix	1.2 S_{MSY}	1	last 10 years	1	3
46	2q/BCL	q/BCH	0	Yes	No	30%	1	Varco Matrix	1.2 S_{MSY}	1	last 10 years	1	3
47	2q/BCH	2q/BCL	10%	Yes	24%CV	15%	1	Varco Matrix	1.2 S_{MSY}	1	last 10 years	1	3
48	2q/BCH	2q/BCL	10%	Yes	24%CV	30%	1	Varco Matrix	1.2 S_{MSY}	1	last 10 years	1	3
49	q/BCH	2q/BCL	0	No	No	15%	1	Bayesian	1.2 S_{MSY}	1	last 10 years	1	3
50	q/BCH	2q/BCL	0	No	No	30%	1	Bayesian	1.2 S_{MSY}	1	last 10 years	1	3
51	q/BCL	2q/BCH	10%	No	24%CV	0	1	Varco Matrix	1.0 S_{MSY}	1	last 10 years	1	3
52	q/BCL	2q/BCH	10%	No	24%CV	15%	1	Varco Matrix	1.0 S_{MSY}	1	last 10 years	1	3
53	q/BCH	q/BCL	10%	No	24%CV	15%	1	Varco Matrix	1.2 S_{MSY}	1	1993-2002	1	3
54	q/BCH	q/BCL	10%	No	24%CV	30%	1	Varco Matrix	1.2 S_{MSY}	1	1993-2002	1	3
55	q/BCH	q/BCL	0	Yes	No	15%	1.5	Bayesian	1.2 S_{MSY}	1	1993-2002	1	3
56	q/BCH	q/BCL	0	Yes	No	30%	1.5	Bayesian	1.2 S_{MSY}	1	1993-2002	1	3
57	2q/BCL	q/BCH	10%	Yes	24%CV	0	1	Varco Matrix	1.0 S_{MSY}	1	1993-2002	1	3
58	2q/BCL	q/BCH	10%	Yes	24%CV	15%	1	Varco Matrix	1.0 S_{MSY}	1	1993-2002	1	3
59	2q/BCH	2q/BCL	0	Yes	No	0	1	Varco Matrix	1.0 S_{MSY}	1	1993-2002	1	3
60	2q/BCH	2q/BCL	0	Yes	No	15%	1	Varco Matrix	1.0 S_{MSY}	1	1993-2002	1	3

APPENDIX C – COMPARISON OF THE RESULTS OF BAYESIAN AND LIKELIHOOD METHODS TO GENERATE PARAMETER VECTORS

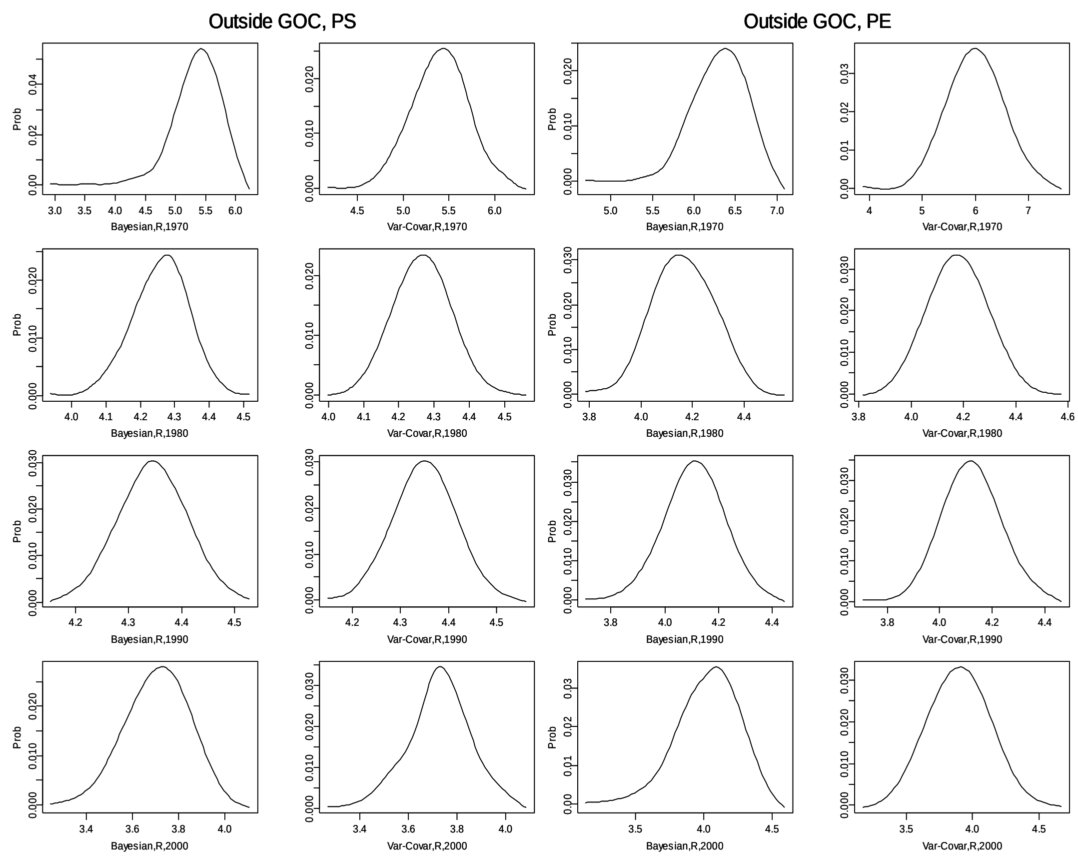

Fig App.C.1: Probability distributions for the estimates of recruitment for 1970, 1980, 1990 and 2000 for the "Outside Gulf" stock area based on the variance-covariance matrix and the Bayesian posterior. "PS" is *P. semisulcatus* and "PE" is *P.esculentus*.

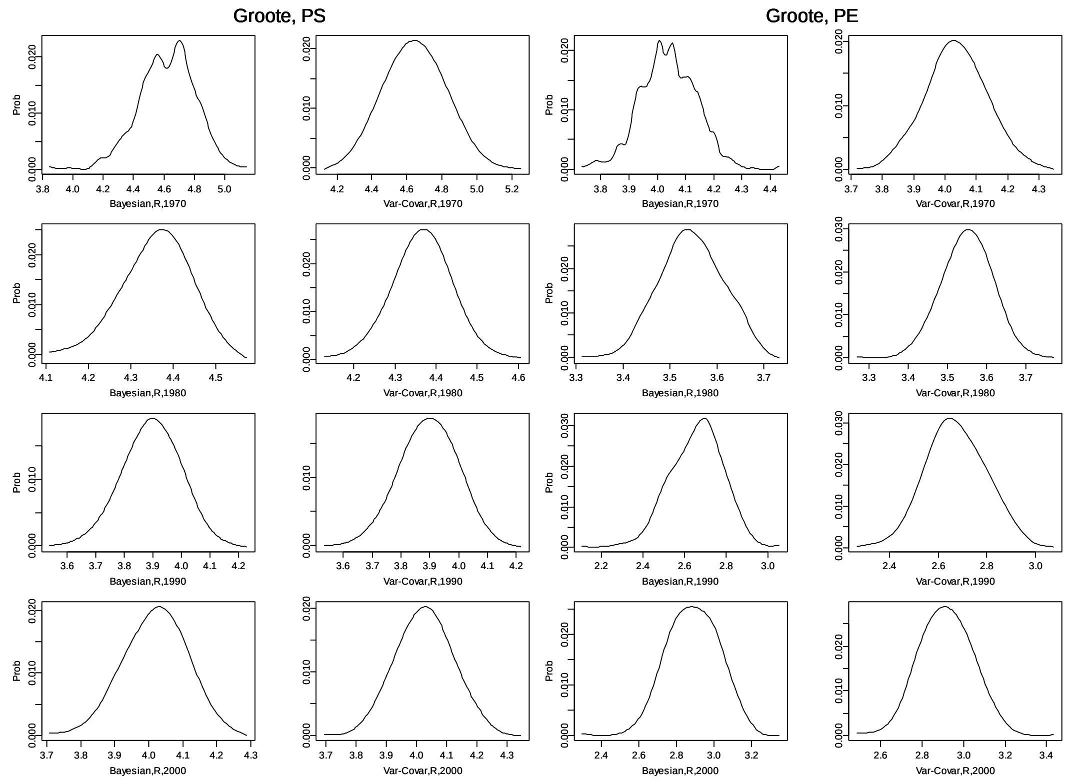

Fig App.C.2: Probability distributions for the estimates of recruitment for 1970, 1980, 1990 and 2000 for the Groote stock area based on the variance-covariance matrix and the Bayesian posterior. “PS” is *P. semisulcatus* and “PE” is *P.esculentus*.

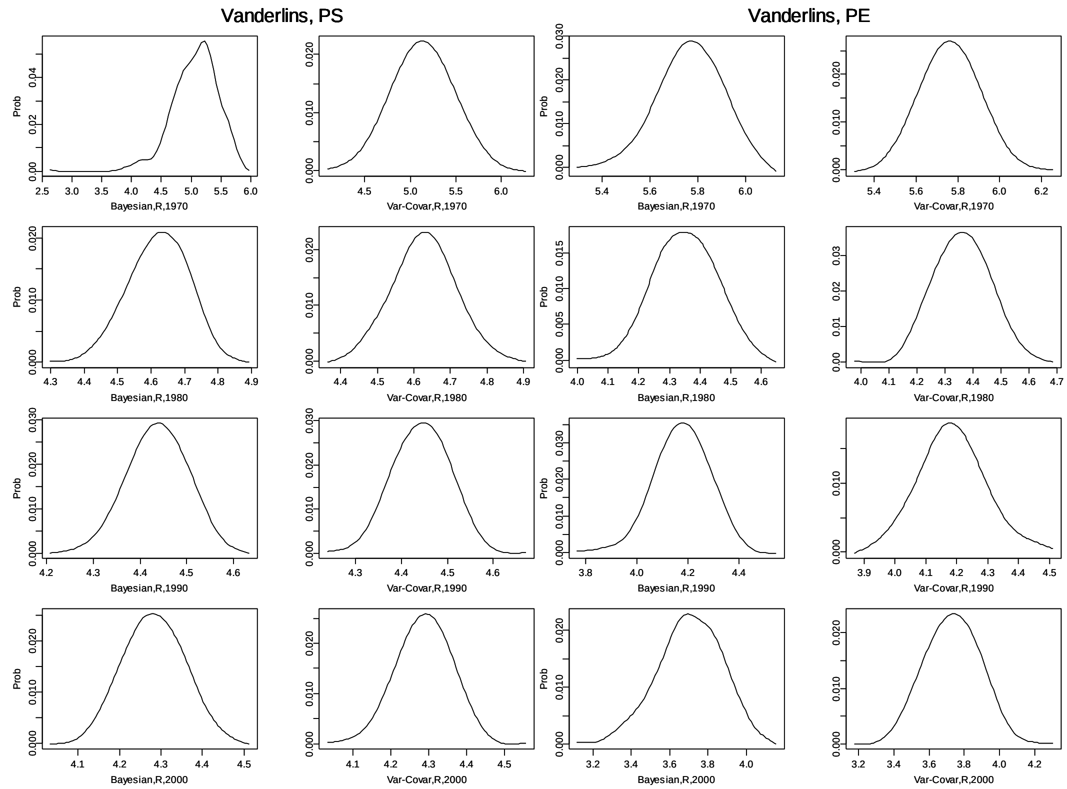

Fig App.C.3: Probability distributions for the estimates of recruitment for 1970, 1980, 1990 and 2000 for the Vanderlins stock area based on the variance-covariance matrix and the Bayesian posterior. "PS" is *P. semisulcatus* and "PE" is *P.esculentus*.

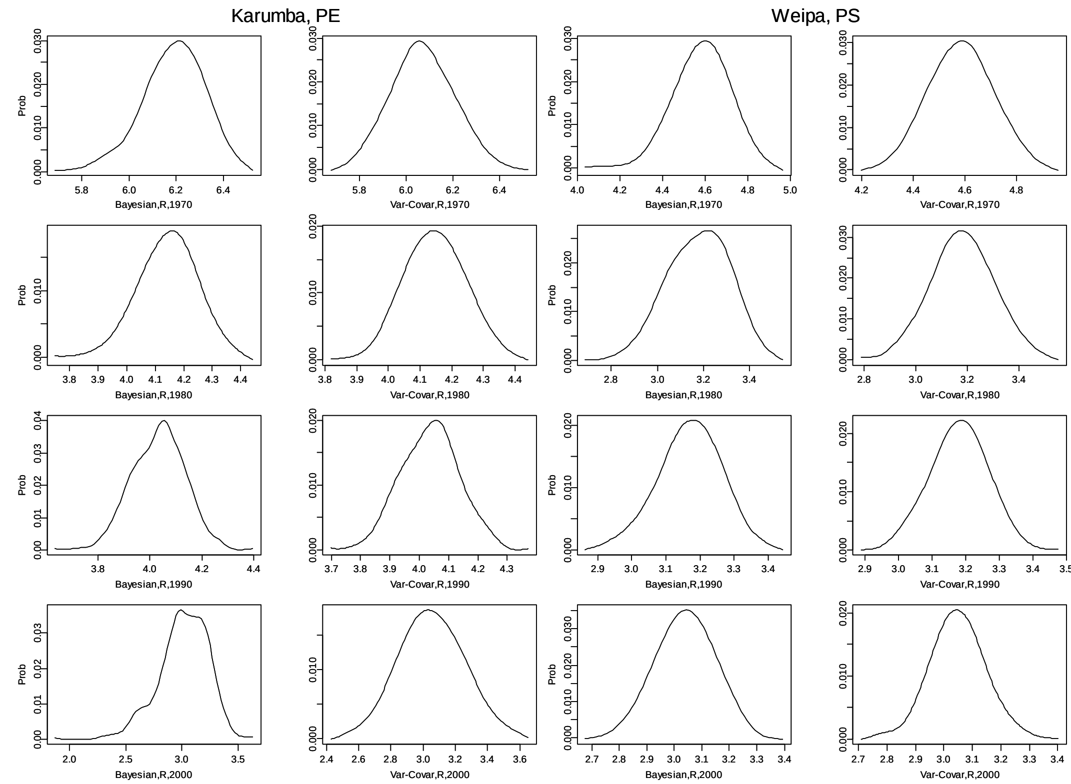

Fig App.C.4: Probability distributions for the estimates of recruitment for 1970, 1980, 1990 and 2000 for the Karumba stock area (*P. esculentus*) and the Weipa stock area (*P. semisculcatus*) based on the variance-covariance matrix and the Bayesian posterior. "PS" is *P. semisulcatus* and "PE" is *P.esculentus*.

APPENDIX D - HOW MANY SIMULATIONS SHOULD BE DONE?

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 $X_{(1)} < X_{(2)} < \cdots < X_{(n-1)} < X_{(n)}$, 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.D.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 greater than 95% certainty that 95% of the distribution is covered.

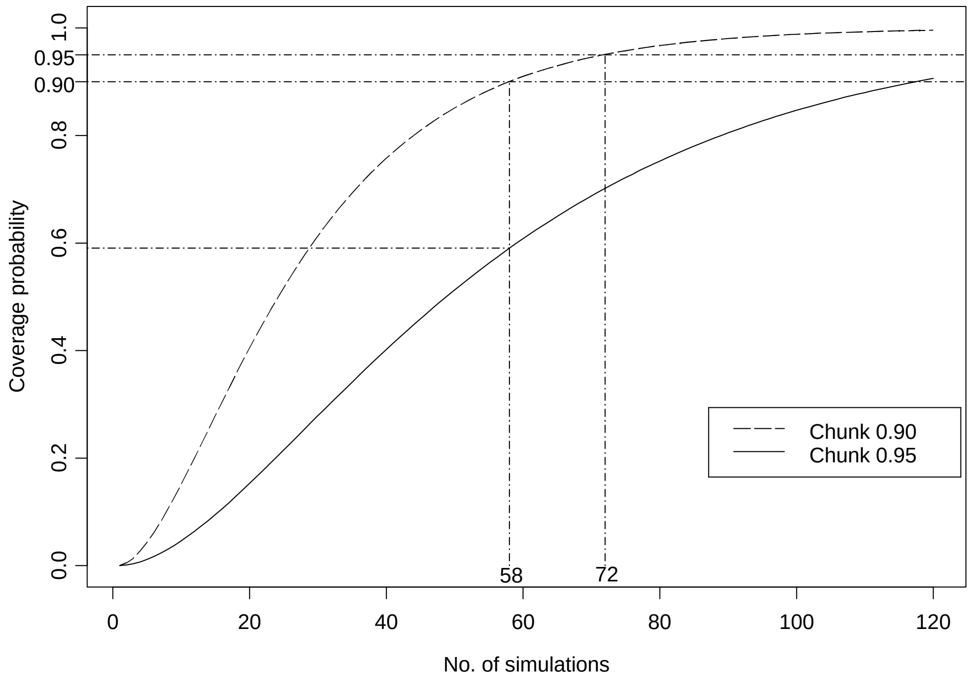

Figure App.D.1: The coverage probability that a given number of simulations would contain the central 90% or 95% of the distribution

APPENDIX E: FISHING POWER AND CATCHABILITY COMBINATION GRAPHS

Table App.E.1: Codes used for fishing power and catchability graphs.

	Operating model		Management Strategy	
Run ID	Fishing power	Catchability in 1993	Fishing power	Catchability in 1993
D1	q	BCH	q	BCH
D34	q	BCL	q	BCL
D36	q	BCH	2q	BCH
D37	2q	BCH	2q	BCH
D38	2q	BCH	q	BCH
D39	2q	BCL	q	BCL
D40	2q	BCL	2q	BCL
D64	q	BCH	q	BCL
D65	q	BCL	q	BCH
D69	q	BCL	2q	BCL
D70	q	BCH	2q	BCL
D71	q	BCL	2q	BCH
D72	2q	BCH	q	BCL
D73	2q	BCL	q	BCH
D74	2q	BCH	2q	BCL
D75	2q	BCL	2q	BCH

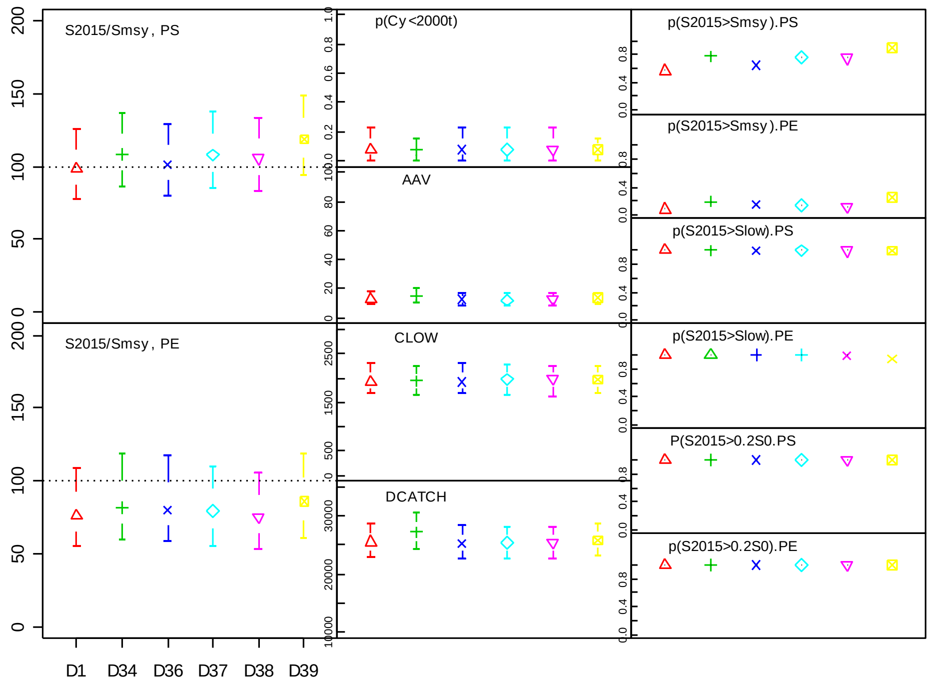

Figure App.E.1: Sensitivity of the management-related performance measures to the value of catchability for 1993 and fishing power: D1 - operating model is “q”, BCH and assessment model is “q”, BCH; D34 - operating model is “q”, BCL and assessment model is “q”, BCL; D36 - operating model is “q”, BCH and assessment model is “2q”, BCH; D37 - operating model is “2q”, BCH and assessment model is “2q”, BCH; D38 - operating model is “2q”, BCH and assessment model is “q”, BCH; D39 - operating model is “2q”, BCL and assessment model is “q”, BCL.

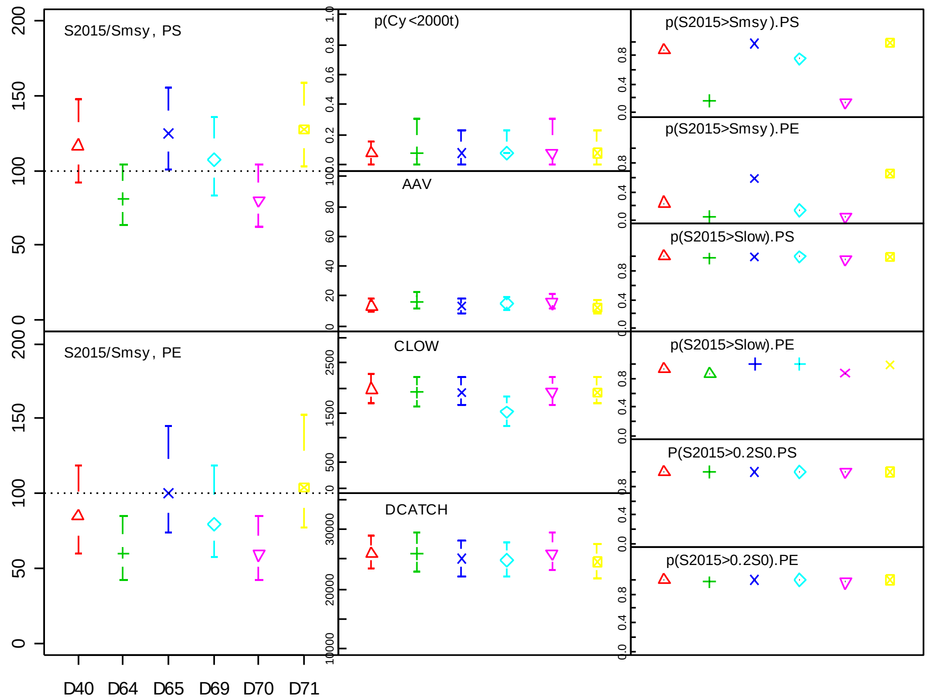

Figure App.E.2: Sensitivity of the management-related performance measures to the value of catchability for 1993 and fishing power: D40 - operating model is “2q”, BCL and assessment model is “2q”, BCL; D64 - operating model is “q”, BCH and assessment model is “q”, BCL; D65 - operating model is “q”, BCL and assessment model is “q”, BCH; D69 - operating model is “q”, BCL and assessment model is “q”, BCL; D70 - operating model is “q”, BCH and assessment model is “2q”, BCL; D71 - operating model is “q”, BCL and assessment model is “2q”, BCH.

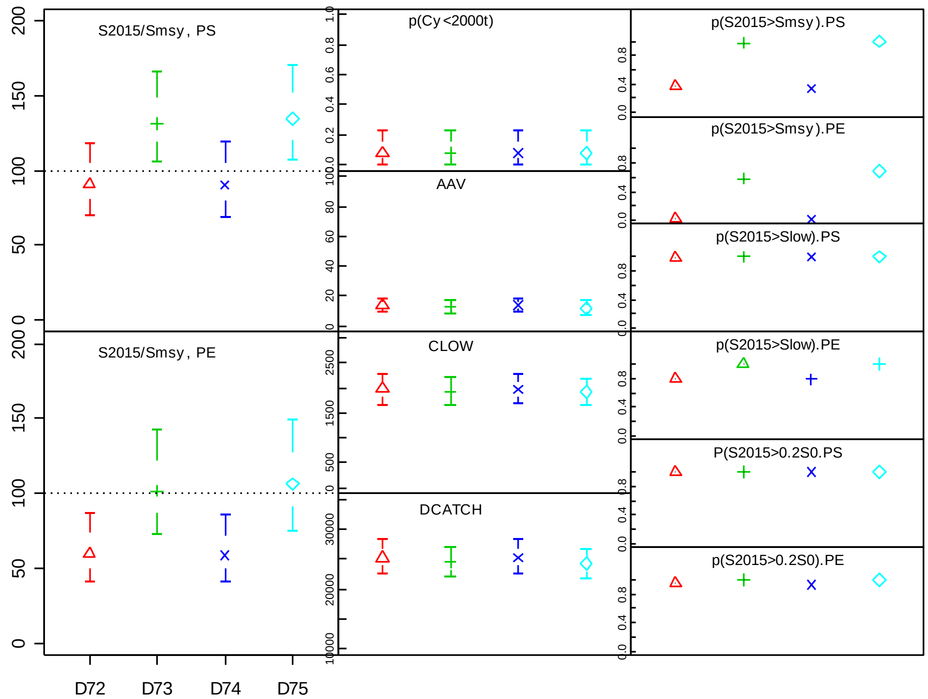

Figure App.E.3: Sensitivity of the management-related performance measures to the value of catchability for 1993 and fishing power: D72 - operating model is "2q", BCH and assessment model is "q", BCL; D73 - operating model is "2q", BCL and assessment model is "q", BCH; D74 - operating model is "2q", BCH and assessment model is "2q", BCL; D75 - operating model is "2q", BCL and assessment model is "2q", BCH.

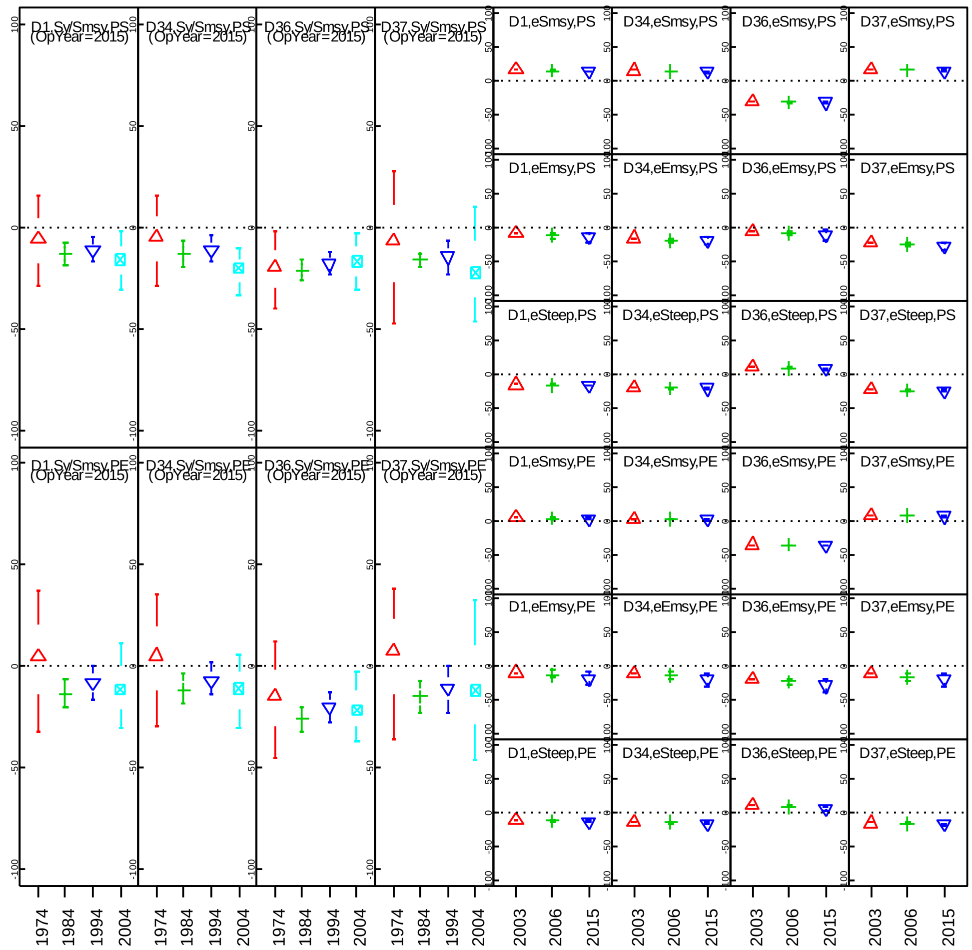

Figure App.E.4: Sensitivity of the relative error distributions (%) to the fishing power series and catchability in 1993 in the operating model and the that underlying the management strategy: D1 - operating model is “q”, BCH and assessment model is “q”, BCH; D34 - operating model is “q”, BCL and assessment model is “q”, BCL; D36 - operating model is “q”, BCH and assessment model is “2q”, BCH; D37 - operating model is “2q”, BCH and assessment model is “2q”, BCH.

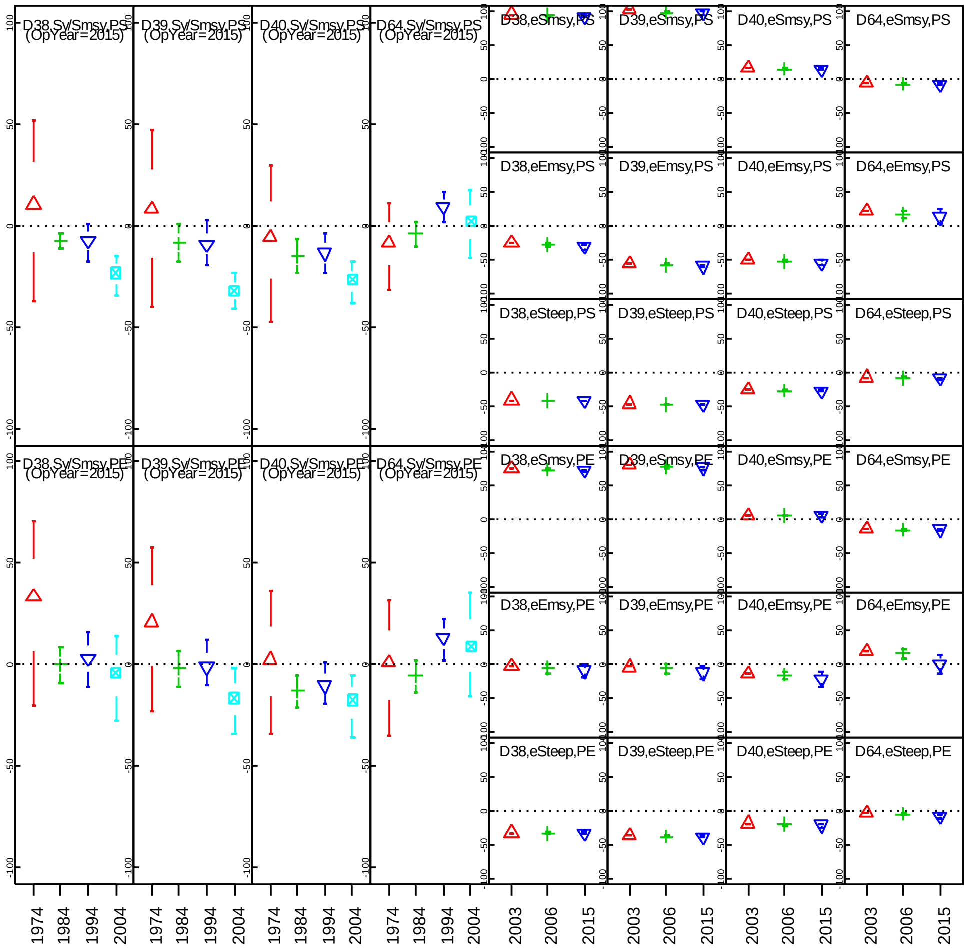

Figure App.E.5: Sensitivity of the relative error distributions (%) to the fishing power series and catchability in 1993 in the operating model and the that underlying the management strategy: D38 - operating model is “2q”, BCH and assessment model is “q”, BCH; D39 - operating model is “2q”, BCL and assessment model is “q”, BCL; D40 - operating model is “2q”, BCL and assessment model is “2q”, BCL; D64 - operating model is “q”, BCH and assessment model is “q”, BCL.

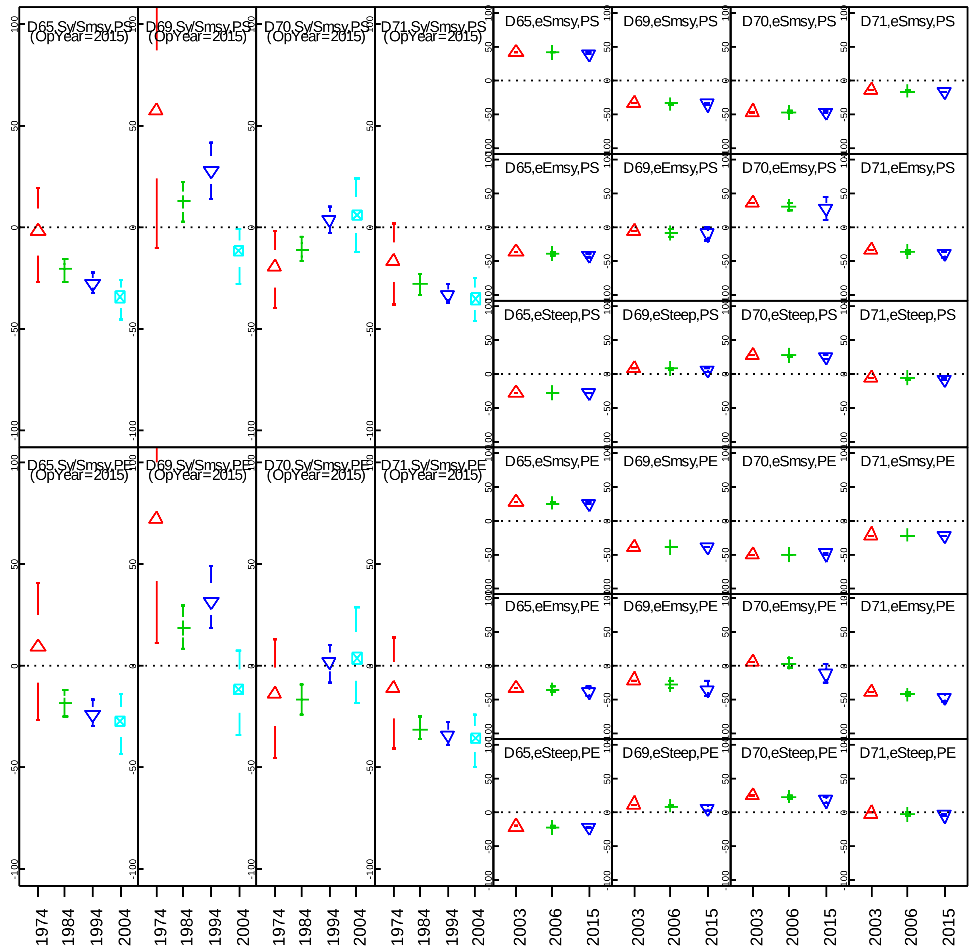

Figure App.E.6: Sensitivity of the relative error distributions (%) to the fishing power series and catchability in 1993 in the operating model and the that underlying the management strategy: D65 - operating model is “q”, BCL and assessment model is “q”, BCH; D69 - operating model is “q”, BCL and assessment model is “q”, BCL; D70 - operating model is “q”, BCH and assessment model is “2q”, BCL; D71 - operating model is “q”, BCL and assessment model is “2q”, BCH

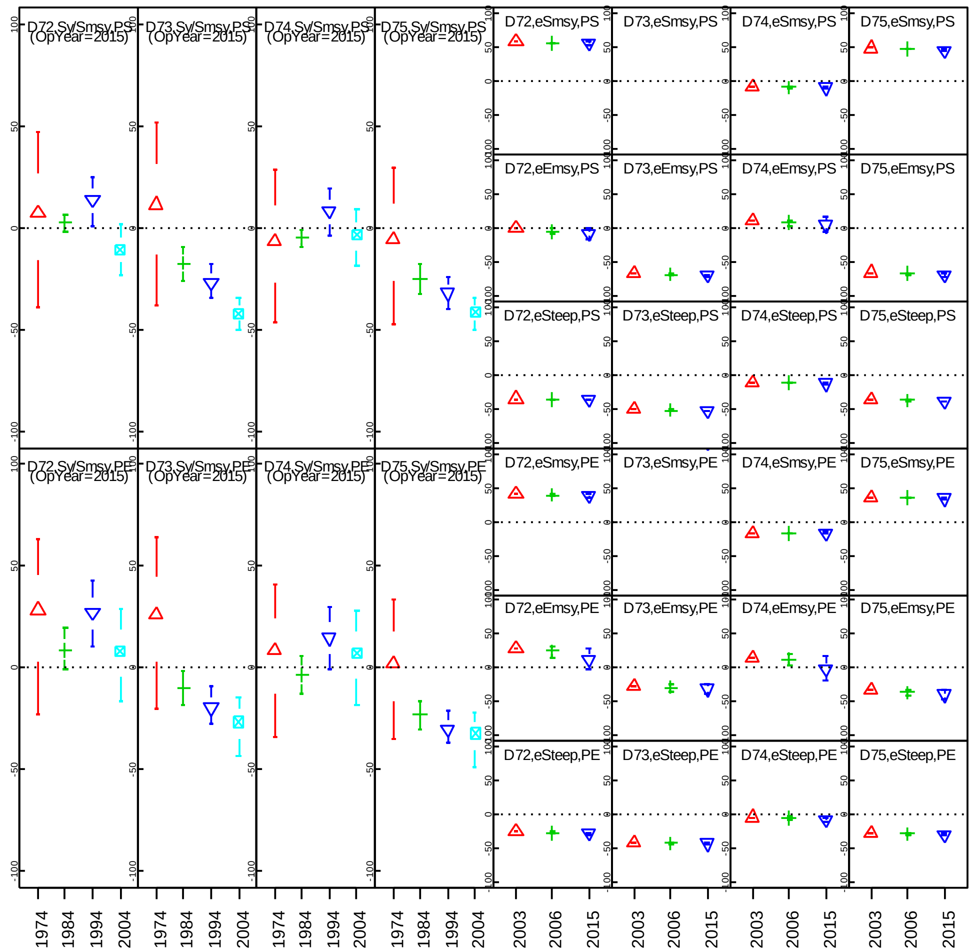

Figure App.E.7: Sensitivity of the relative error distributions (%) to the fishing power series and catchability in 1993 in the operating model and the that underlying the management strategy: D72 - operating model is “2q”, BCH and assessment model is “q”, BCL; D73 - operating model is “2q”, BCL and assessment model is “q”, BCH; D74 - operating model is “2q”, BCH and assessment model is “2q”, BCL; D75 - operating model is “2q”, BCL and assessment model is “2q”, BCH.