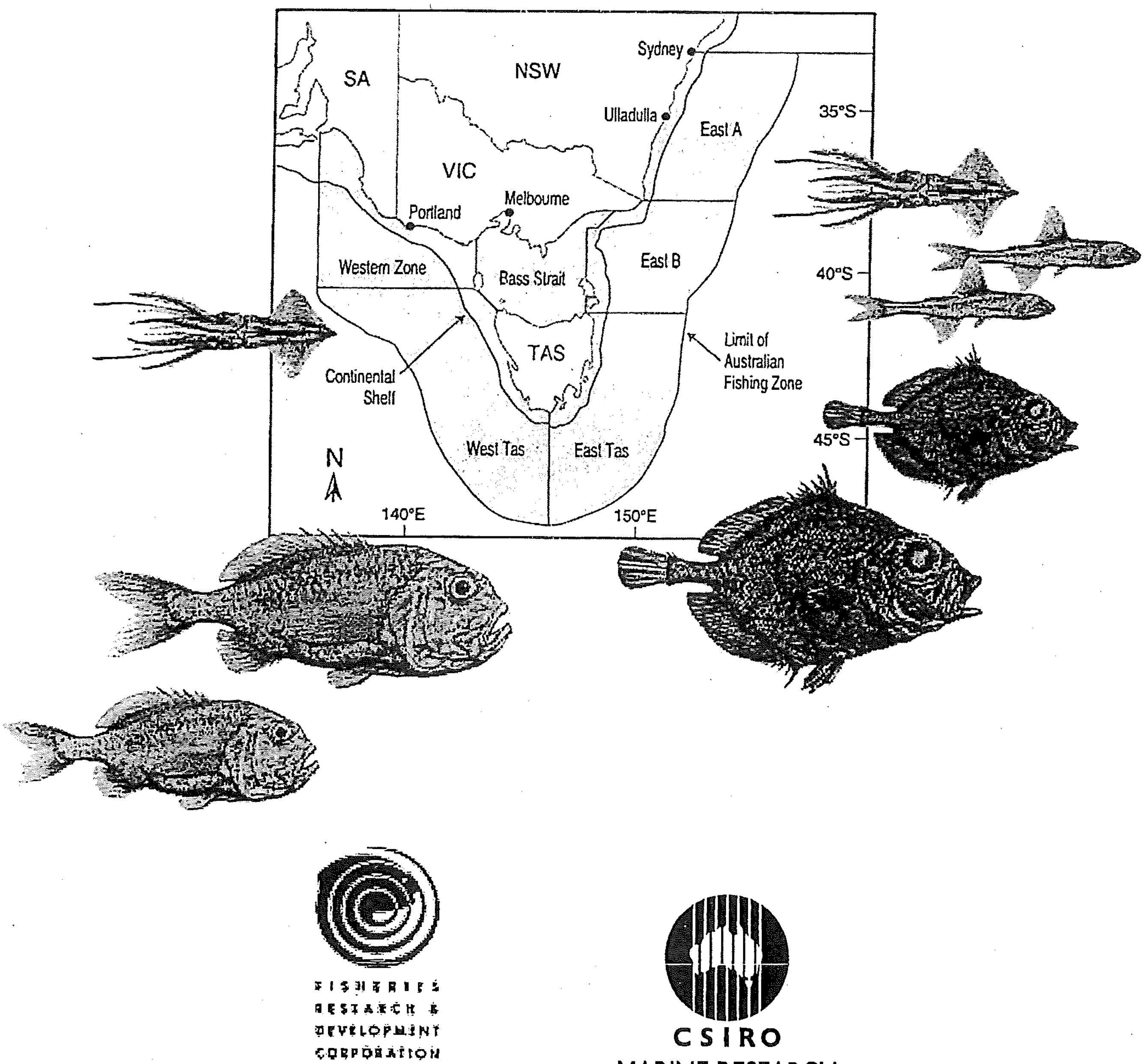
Defining robust harvest strategies, performance indicators and monitoring strategies for the SEF

André E. Punt, Gurong Cui and Anthony D. M. Smith



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CSIRO
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FRDC Project 98/102

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Bibliography
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NON TECHNICAL SUMMARY

1998/ 102	**Defining robust harvest strategies, performance indicators and monitoring strategies for the SEF**

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OBJECTIVES:
1. To evaluate alternative performance indicators in measuring performance against management objectives for the SEF.
2. To select robust assessment methods and harvest strategies for the SEF.
3. To evaluate the costs and benefits associated with different data aquisition strategies for the SEF, with particular reference to different monitoring strategies (fishery-dependent and fishery-independent).
4. To develop the modelling software in a manner which lends itself to tailoring (by CSIRO and other agencies) to suit other Commonwealth or State fisheries.

NON TECHNICAL SUMMARY:

OUTCOMES ACHIEVED

Assessments of SEF species continue to be based on the Integrated Analysis framework as the results of the evaluation of harvest strategies for four SEF species indicate that assessments of, and harvest strategies for, SEF species based on this framework perform best. The results are being used by SEFAG, industry and management to help decide how often assessments should be conducted and the key data collection / research needs. The results of the project have also increased interest by fishers and managers to select harvest strategies for SEF species and have further focused debate on the need for appropriately selected performance indicators.

A harvest strategy is a set of rules that define the data to be collected from a fishery, how those data are to be analysed, and how the results of the data analyses are to be used to determine management actions. One part of a harvest strategy is often a method of fisheries stock assessment. In the context of Australia's South East Fishery, harvest strategies would be used to specify Total Allowable Catches (*TAC*s).

The Management Strategy Evaluation (MSE) approach is used to compare the performances of a variety of commonly applied stock assessment methods and harvest strategies based on these stock assessment methods. The comparison is based on four of the species in Australia's South East Fishery (tiger flathead, *Neoplatycephalus richardsoni*, jackass morwong, *Nemadactylus macropterus,* spotted warehou, *Seriolella puncata*, and pink ling, *Genypterus blacodes*). The data for these four species are relatively sparse and formal stock assessments did not exist for these species when the project was conducted, so the results should be taken primarily as

being representative of species that exhibit behaviours similar to these species. The results should not yet be applied directly to management of the four species selected.

The key steps in the MSE approach are to develop (operating) models that are used to represent the real world in the calculations, to develop performance measures to quantify performance relative to the management objectives for the fishery, and to select appropriate candidate harvest strategies (and stock assessment methods). The operating model for this study is an age-, length- and area-structured population dynamics model tailored (to the extent possible) to Zone 20 of the SEF and that part of Zone 10 south of Bermagui. The operating models include discards that occur for a variety of reasons (small fish, lack of quota and mismatches between the *TAC*s for the different species). The performance measures considered include statistics related to resource conservation (e.g. the probability that the spawner biomass does not drop below commonly-used reference points) and utilization (e.g. the average catch over the next 25 years). The specifics of the operating model (and the performance measures) were chosen based on outcomes from workshops with scientists, managers and fishers in March 1999 and March 2000.

A performance indicator is only useful if a (stock assessment) method can be found that estimates it reliably. Six commonly-used methods of stock assessment (Integrated Analysis, Schaefer and Fox production models, ADAPT-VPA, Age-structured production model, and *ad hoc* tuned VPA) were used to estimate a range of management-related quantities (indicators) for a variety of scenarios. Integrated Analysis, the approach that forms the basis at present for several SEF stock assessments, was found to perform best. Nevertheless it often produced highly inaccurate and imprecise estimates, particularly for spotted warehou. The ability to estimate performance indicators reliably was compromised by several factors. Key amongst these were the use in assessments of an imprecise abundance index or an abundance index that is not related linearly to abundance, error in the assumed value for the rate of natural mortality, and major differences between the model underlying the stock assessment and the real world.

The most reliable performance indicators were found to be based on estimating the ratio of the current spawner (or available) biomass to that when useable information on the catch size- and age-composition first became available. Whether this indicator is actually a useful performance statistic (in the sense that it is a measure of performance against common management objectives) is, however, unclear. In contrast, many commonly-estimated quantities (e.g. absolute spawner biomass, current biomass relative to the pre-exploitation level, and *MSY*) were highly imprecise and inaccurate. Substantially improved estimation performance can be achieved through the occasional collection (and use) of an estimate of absolute abundance and the use in assessments of information on productivity-related parameters such as steepness. Steepness is often difficult to estimate directly, but can be inferred from studies from a range of similar species.

The performances of the harvest strategies depended on many factors. Of particular importance was the impact of the landed catches being restricted by the amount that the market can take. If the *TAC*s for the four species are ‘out of sync’ with each other and the demands of the market, large-scale discarding is predicted to occur. Other factors that impact the performances of the harvest strategies include a poor index of abundance, how depleted the resource is when the harvest strategy is first applied, and the productivity of the resource.

The harvest strategies based on population dynamics models performed noticeably better than those that changed the *TAC* in response to changes in, for example, catch rates, or the difference between the landed catch and the *TAC*. The better-performing harvest strategies were able to allow recovery of highly depleted populations and to encourage utilization of under-utilized populations. However, none of the harvest strategies were able to estimate productivity and depletion particularly successfully, so the performances of all of the harvest strategies were substantially worse than would be expected had the harvest strategy been provided with perfect information.

The best harvest strategies appeared to be those that used an Integrated Analysis method of stock assessment (i.e. one that uses catch, catch rate, length-frequency, age-composition and discard information) and chose *TAC*s based on a target level of spawner biomass. The results suggest that fairly tight limits can be placed on how much the *TAC* can be varied from one year to the next without compromising performance against other objectives, and that any minimum *TAC* levels should be low. There appeared to be little benefit to conducting assessments (and changing *TAC*s) frequently.

The study identified several areas where further development work is necessary. The most important of these is to undertake formal assessments of the four species, and to use these to select parameters for the operating model. This would allow the results of the MSE analyses to be used directly for *TAC* setting purposes.

KEYWORDS: harvest strategy, Integrated Analysis, Monte Carlo simulation, South East Fishery

1. BACKGROUND

The South East Fishery (SEF) is a complex multispecies fishery that is managed by setting Total Allowance Catches (*TAC*s). The level of information differs among species, and information on stock status provided to decision makers varies from sophisticated assessment models evaluating alternative harvest strategies (e.g. Punt and Smith, 1999) to cursory examinations of trends in catch and effort (e.g. Tilzey, 1999). Yet, because *TAC*s are required for each, each species has to have management objectives, management strategies and performances indicators. In the data poor environment that characterises many of the species in the SEF, sustainability indicators have not been based on any quantitative evaluations and may be inappropriate and conflicting. For example, industry and scientists have acknowledged that performance indicators based on trends in catch and catch rate are inadequate because of uncertainty about the relationship between catch rate and abundance (Tilzey, 1999). Punt *et al*. (In press-a) show for broadbill swordfish, *Xiphias gladius*, that if efficiency is changing over time, catch rates can provide a very poor indicator of abundance.

If performance indicators are to be most useful, it is necessary to have harvest strategies for each species, i.e. pre-determined and agreed rules that specify the management actions to be taken when performance indicators are triggered. However, at present, performance indicators are not linked to harvest strategies so it is currently unclear what actions would be appropriate as trigger levels are approached or exceeded. The SEF is a particularly difficult case because it is multispecies, has limited funds for monitoring, and is information poor. This is, of course, not the only such case, as there are many other data poor fisheries around Australia. It is envisaged that the general approach developed for the SEF could be readily modified and applied to other fisheries.

Dealing with uncertainty is one area where modelling of fisheries has expanded significantly in recent years. It is now possible to develop models of fishery processes that allow for typical levels of natural variability, consider multiple species and multiple fleets simultaneously, and take account of spatiality. With such models, it becomes possible to evaluate how robust alternative sustainability indicators and harvest strategies are to mis-specification of biological processes, and uncertainty about values for quantities of interest to management (e.g. stock biomass, productivity).

The opportunity for funding for many of the SEF species is (and will remain) limited. The value of research and monitoring programmes therefore needs to be evaluated carefully through a cost-benefit analysis so that research funds are used to achieve maximum benefits in terms of satisfying the management objectives for the SEF. This project emphasises the utility of data types such as catch age- and length-compositions and therefore compliments the evaluations of FRDC 96/109 (McDonald *et al*., 1998) which examined the value of research on stock structure.

A harvest strategy is a set of rules that specify the data to be collected for management purposes and how those data are to be used to determine management actions. Harvest strategies can potentially be used to deal with many aspects related to management (e.g. minimum sizes, closed seasons). However, to date they have only been used to specify the *TAC*. Harvest strategies often consist of two components: an assessment method and a catch control law (Figure 1). The assessment method is used to analyse the data collected from the fishery to estimate the quantities needed to set the *TAC* (e.g. current biomass, Maximum Sustainable Yield). The catch control law uses the information obtained during the assessment to determine the *TAC*.

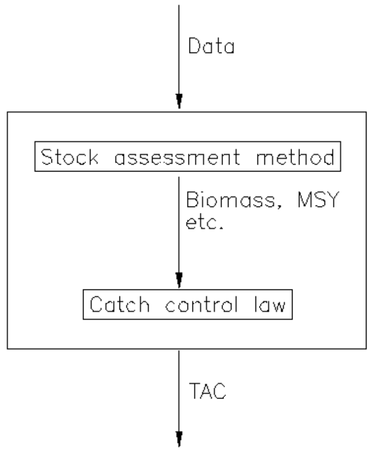

Figure 1 : A harvest strategy illustrating the difference between the assessment and catch control law components.

The evaluations in this report are based on the fishery for four of the species (tiger flathead, *Neoplatycephalus richardsoni*, jackass morwong, *Nemadactylus macropterus,* spotted warehou, *Seriolella puncata*, and pink ling, *Genypterus blacodes*) off southern NSW (defined as Zone 20 of the SEF combined with that part of Zone 10 south of Bermagui – Figure 2). These species and this region were chosen following consultation between the principal investigator and scientists, industry, and managers through SEFAG. Among the reasons for the choice were:

a) assessments had not been conducted for these species for several years at the time that this project was developed;
b) spotted warehou had recently triggered one of AFMAs reference points;
c) the species reflect traditional (tiger flathead and jackass morwong) and recent (spotted warehou and pink ling) targets of the trawl fishery;
d) the species are found in quite different habitats / depths and differ in terms of longevity; and
e) data from a variety of sources are available for these species.

The evaluations are only tailored to these four species to the extent necessary to draw qualitative (generic) conclusions. In particular, a wide range for the depletion of each species at the start of the simulations (1999) is considered rather just than that implied by the current assessment data.

The performance of different harvest strategies should be considered relative to the five legislative objectives of the Australian Fisheries Management Authority (AFMA)(Anon, 1998):

- 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.

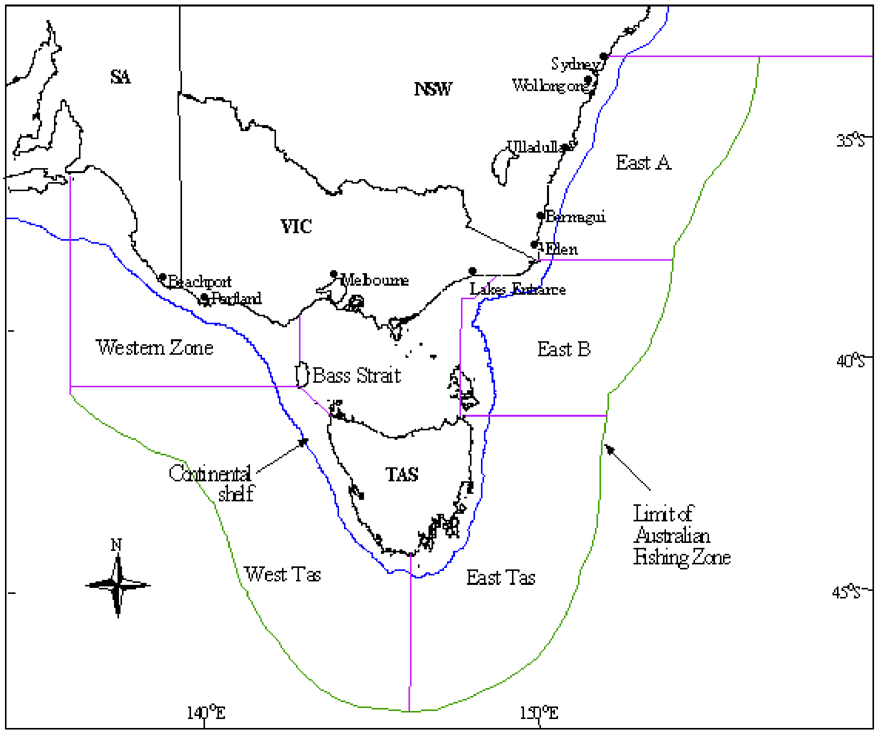

Figure 2 : Map of eastern Australia indicating the region considered in the project.

2. NEED

Given AFMA's need to satisfy its Ecologically Sustainable Development (ESD) objective, there is a need to consider uncertainty and identify performance indicators and harvest strategies that are as robust as possible to incorrect assumptions and misinformed interpretations of data. Use of these indicators and harvest strategies will improve the chances of achieving a reasonable balance between the conflicting objectives of long-term resource sustainability and the maximisation of economic gains. SEFAG's 1997 assessment plan explicitly states the need to "develop harvest strategy evaluation and performance indicators for all SEF species". There is a need to ensure that research and resource monitoring is conducted in a cost-effective manner (e.g. the SEF research priority to develop cost-effective fishery-independent surveys of stock abundance and recruitment indices). The results of this project highlight the research areas most likely to improve management in the SEF.

The project also addresses to some extent two key research areas in subprogram (B) of the Wild Stock Program of the SCFA Research Committee: “Biological and socio-economic evaluation of alternative management scenarios for different species and categories of fishery to provide a framework for management planning” and “The evaluation and provision of harvest strategy models through comparison of management strategies using theory and case studies, establishing objective performance indicators for different jurisdictions and identifying options which are appropriate to the nature of the fishery”.

3. OBJECTIVES

The objectives for the study were:

1) To evaluate alternative performance indicators in measuring performance against management objectives for the SEF.

2) To select robust assessment methods and harvest strategies for the SEF.

3) To evaluate the costs and benefits associated with different data aquisition strategies for the SEF, with particular reference to different monitoring strategies (fishery-dependent and fishery-independent).

4) To develop the modelling software in a manner which lends itself to tailoring (by CSIRO and other agencies) to suit other Commonwealth or State fisheries.

4. METHODS

The scientific approach used to address objectives 1 – 3 is the “Management Strategy Evaluation” (MSE) framework. This framework (Smith, ADM, 1994; Punt *et al*., in press-b) provides a set of tools that allow four key scientific questions to be addressed:

- Evaluation of the extent to which alternative methods of setting future *TAC*s (harvest strategies) can satisfy the management objectives.
- Evaluation of which methods of stock assessment are able to provide sufficiently reliable estimates of quantities of interest to management (such as current biomass and *MSY*).
- Evaluation of whether proposed performance indicators are able to detect the events that they were designed to identify.
- Evaluation of the (management) benefits of research and monitoring programmes.

A key feature of the MSE approach is that it can explicitly take into account uncertainty (in the data available, the values for the parameters of models, the structure of the models upon which advice is based, and the ability to implement management actions). For situations in which there is considerable uncertainty, many alternative models are compatible with the existing data so a more conservative harvest strategy is needed to satisfy the conservation-related ESD objective. As such, the MSE approach is compatible with the principles underlying the precautionary approach to fisheries management (FAO, 1995).

The primary objective of the MSE approach is to identify, in an objective manner, the trade-offs among the management objectives across a range of management actions. This is the information the decision makers need to make an informed decision about management actions, given the importance they assign to each of AFMAs five legislative objectives, given that these objectives may be contradictory. The relative importance of different objectives will, of course, relate to the social, legal, and political context for each management decision. However, by basing the decision on the trade-offs among the management objectives, this context is laid bare. The ideal management action is one that is "robust" to the identified uncertainties rather than one that is "optimal" for any one scenario (but may be poor for several other scenarios).

4.1 Basic overview

In simple terms, the MSE approach involves evaluating the entire management system (including research programmes, stock assessment methods, performance indicators, and harvest strategies) by means of Monte Carlo simulation. This approach to evaluation has a long history in quantitative fisheries science (e.g. Southward, 1968; Hilborn, 1979; Donovan, 1989).

The steps in evaluating alternative harvest strategies (and hence providing answers to the first two key questions identified above) are as follows (Figure 3):

- Identification of the management objectives and representation of these using a set of quantitative performance measures.
- Identification of the alternative harvest strategies.
- Development and parameterization of a set of alternative structural models (called operating models) of the system under consideration.
- Simulation of the future use of each harvest strategy to manage the system (as represented by each operating model). For each year of the projection period (usually 15-25 years; 25 years in the case of this report), the simulations involve the following four steps.
    - Generation of the types of data available for assessment purposes.
    - Application of a method of stock assessment to the generated data set to determine key management related quantities and the inputs to the catch control law.
    - Application of the catch control law element of the harvest strategy to determine the *TAC* based on the results of the stock assessment. The catch control law may include one or more performance indicators.
    - Determination of the (biological) implications of this *TAC* by setting the catch for the "true" population represented in the operating model based on the *TAC*. This step can include the impact of "implementation uncertainty" (e.g. Rosenberg and Brault, 1993).
- Summary of the results of the simulations by means of the performance measures and presentation of the results to the decision makers. Results are often presented as a "decision table" showing the performance of each harvest strategy relative to each management objective.

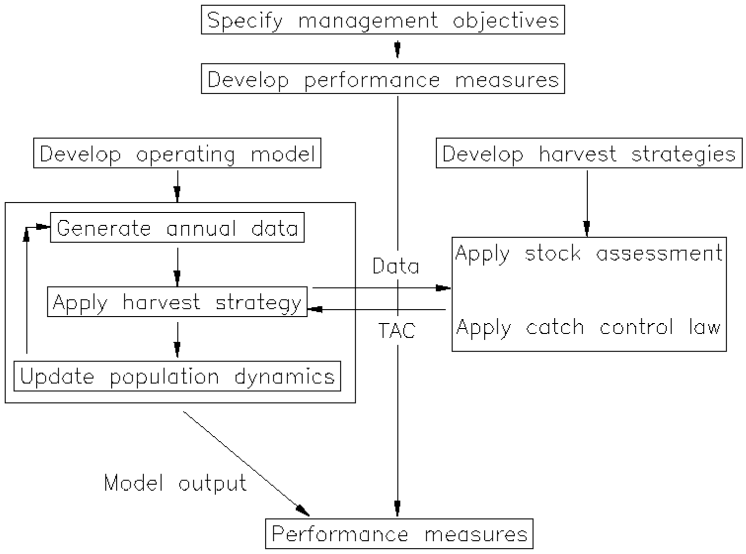

Figure 3 : Outline of the MSE approach.

The steps required to address the other two key questions are also based on the above algorithm.

- The performance measures need to include statistics that measure how well the stock assessment method is able to estimate key quantities of interest to management to evaluate a stock assessment method (e.g. Kirkwood, 1981; de la Mare, 1986; Punt, 1988; Patterson and Kirkwood, 1995). For purposes of this report, the performances of the stock assessment methods are evaluated for an assessment conducted at the start of the first year and of the last year of the simulation period (1999 and 2023). The difference in results between those for 1999 and those for 2023 illustrate the impact of "learning" due to the inclusion of additional data in the assessment.
- Simulations are conducted assuming that the results of the research programme (e.g. survey estimates of absolute abundance) are, and are not, available to evaluate the value of a research programme. The differences in the values for the performance measures then reflect the "value" of the research programme (McDonald and Smith, 1997; McDonald *et al.*, 1997).

4.2 The operating model

The operating model (Appendices D and E) is a general multi-species, multi-area, multi-season model. It explicitly considers the dynamics of the age- and size-structure of each of the four populations and allows for discarding. Reasons for including discarding in the operating model are the capture of small (unmarketable) fish, the inability to market catches of "marketable" fish, and quota-related discarding. The area considered in the operating model is divided into four regions defined in terms of depth (Figure 4) and stochastic movement of fish among depth zones is included in the operating model. The depth zones (25-50m, 50-150m, 150-250m, and 250m+) were chosen mainly because of data availability to estimate movement rates. The operating model allows for density-dependence in growth and recruitment. Stochastic fluctuations in recruitment and selectivity, which may exhibit temporal as well as between species correlation, are also included in the operating model. The operating model attempts to capture the impact of fleet dynamics by capping landed catches of tiger flathead, jackass morwong, and spotted warehou to "that which could be marketed"[1] so landed catches of these species are only constrained by their *TAC* if the *TAC* is set lower than the "market catch". The operating model also considers fleet dynamics (i.e. the amount of effort in each depth zone during summer and winter) by assuming that effort is distributed to maximise the match between the landed catch and the amount required by the market. The operating model is based on the assumption that the fishery consists of a single (trawl) fleet.

The values for the parameters of the operating model are chosen based on information reported in the literature (where available) and on fits to data from research trawl surveys (CSIRO and Kapala). However, there are no data to estimate many of the key parameters of the operating model (e.g. those that define the relationship between fishing effort and fishing mortality) so the base-case choices for many parameters are guesstimates and sensitivity is examined to a range of plausible values for these parameters. The base-case values for such parameters (see Section 3 of Appendix E) are generally chosen so that the base-case trial does not violate the assumptions underlying the assessment methods to a great extent (e.g. fishing mortality is related linearly to fishing effort for the base-case trial). The base-case value for the depletion of each population at the start of 1999 is taken to be 0.5 in the absence of actual assessments for the four species. Sensitivity tests examine performance over a relatively wide range of alternatives (0.1 – 0.8).

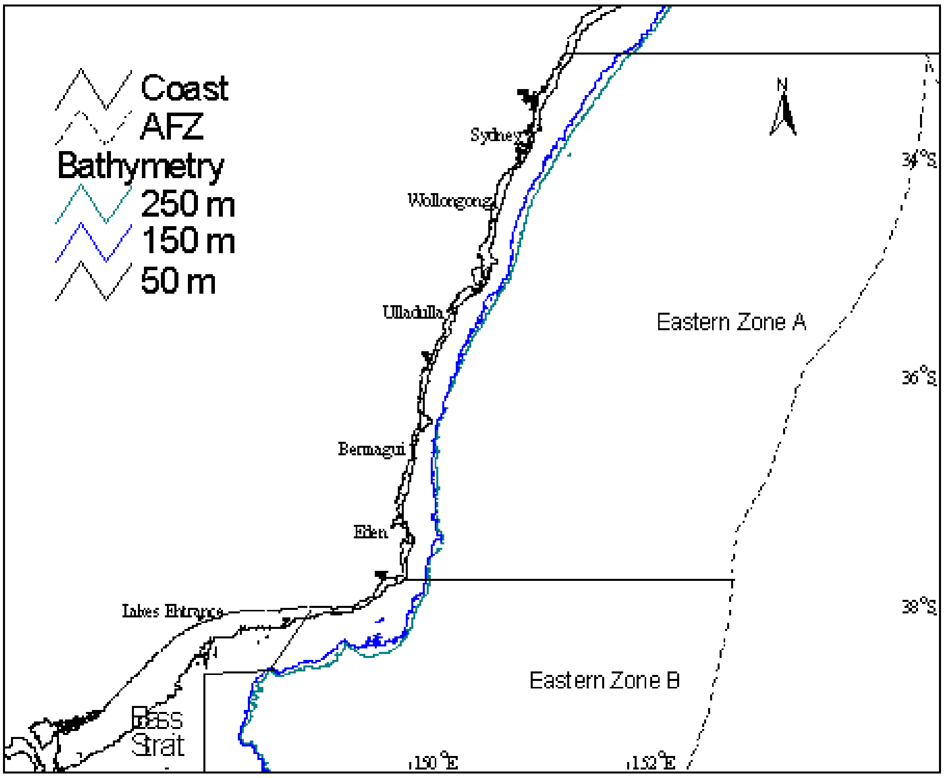

Figure 4 : Map of the region considered in the project showing the four depth zones.

[1] The assumptions about "market catches" in this study relate to the situation in 1998. Changes over time in market demands should be expected but cannot be predicted.

The operating model is used to generate the data available to the assessment methods. These data include catches, catch rates, discard rates, and the length and age-composition of the landed and discarded catches (see Section 2 of Appendix E). The operating model can generate estimates of absolute or relative abundance based on fishery-independent surveys. However, the data available for the base-case trial do not include the results of such surveys.

4.3 Stock assessment methods

Five alternative methods of stock assessment are considered in this report (Table 1; Appendix F). Except for production models, these methods have formed the basis for recent assessments of SEF species (Table 1). They differ in terms of their complexity (production models ignore the age-structure of the population; age-structured and production models assume deterministic dynamics) and the data that can be included in the assessment. All of the stock assessment methods considered in this report base their estimates of management-related quantities on the point estimates of the parameters, primarily due to the computational demands of bootstrap and Bayesian methods. The evaluations should be extended to consider these methods but only after the range of stock assessment methods and operating model scenarios have been narrowed to the point at which the calculations are computationally feasible.

4.4 Harvest strategies

There are many types of harvest strategies. These range from simple to complicated. The simplest type of harvest strategy pre-specifies the time-series of future *TAC*s while the most complicated adjust the level of target biomass to allow for uncertainty (e.g. de la Mare (1989a)). Appendix F and Table 2 outline the six types of harvest strategy considered in this report. One of these (the empirical type) is not based on a formal stock assessment method but instead determines the *TAC* based on the trend in a relative abundance index or in estimates of total mortality. The other five harvest strategies involve formal stock assessment and catch control law components. Variants of each harvest strategy can be constructed by changing the parameters of the catch control law. For the majority of the harvest strategies, these variants involve changing the target level of fishing mortality (Table 2). The target level of fishing mortality can be "tuned" to achieve different balances between risk and reward.

4.5 Evaluating assessment methods and performance indicators

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

$$E_y^{i,j} = 100\frac{\hat{Q}_y^{i,j} - Q_y^{i,j}}{Q_y^{i,j}} \tag{1}$$

where $E_y^{i,j}$ is the relative error for quantity i for simulation j based on an assessment conducted in 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 in 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 mean value (i.e. the bias), the square root of the mean of the squared relative errors (i.e. the RMSE), the median and 90% intervals of the relative errors, and the median of the absolute values for the relative errors (abbreviation MARE).

4.6 Evaluating harvest strategies

A harvest strategy is evaluated by how well it is able to satisfy AFMA's legislative objectives. Consideration of economic efficiency should ideally involve the development of a detailed model of the fishery (including how fishers make investment decisions). Unfortunately, this is beyond the scope of the current project so, instead, an approximate solution is adopted, namely to report trends in (discounted) catch and effort as well as the average level of catch and effort over the 25-year projection period. Similarly it is impossible to develop a model of management costs as these involve issues that are beyond the scope of the current project (such as how future governments might change the cost-recovery policy). Instead, a less ambitious approach is adopted, namely to attempt to quantify how much data is needed for assessments and hence the provision of management advice. Different harvest strategies can then be compared in terms of their monitoring costs.

Assessing performance relative to the objective of Ecologically Sustainable Development can also not be addressed fully within the scope of this project. This is because, for example, it is currently impossible to develop models of how catches impact the overall ecosystem. Therefore, in common with how this issue is dealt with internationally, attention will only be focussed on the target species[2]. The types of statistics used to measure the performance of a harvest strategy will therefore quantify how catches change over time and whether the resources are reduced to undesirably low levels. The risk to the ecosystem is captured to some extent by consideration of this latter issue because the impact of the fishery on the ecosystem is likely to be larger if the population is more depleted. There is, at present, no objective basis for identifying the "biomass that we must not drop below because something bad will happen" although it is very likely that there must be such a biomass.

The performance measures used to measure risk are based on those used during assessments of SEF species and internationally.

a) The median and 90% intervals for the lowest ratio of the spawner biomass (see Equation D.6) to its pre-exploitation equilibrium size over the projection period (1999-2023) (abbreviation "lowest depletion");
b) The median and 90% intervals for the ratio of the spawner biomass to its pre-exploitation equilibrium size at the end of the projection period (2023) (abbreviation "final depletion");
c) The probability of the available biomass (see Equation E.7) being larger than that at which (deterministic) *MSY* is achieved (abbreviation $P(AB > AB_{MSY})$);
d) The probability of the available biomass being larger than the lowest available biomass between 1986 and 1994 (abbreviation $P(AB > AB_{86-94})$);

[2] It is possible, in principle, to apply the MSE framework to contrast the implications of different management actions in terms of broader ecosystem objectives but this has occurred only rarely in practice (Sainsbury *et al.*, 2000)

e) The probability of the spawner biomass being larger than that at which recruitment is expected to be half of that at the pre-exploitation equilibrium level (abbreviation $P(SB > SB_{50})$);
f) The probability of the spawner biomass being larger than 20% of the pre-exploitation equilibrium spawner biomass (abbreviation $P(SB > 0.2 B_0)$); and
g) The probability of the spawner biomass being larger than 40% of the pre-exploitation equilibrium spawner biomass (abbreviation $P(SB > 0.4 B_0)$);

The third of the probability measures is considered because $B_{\rm MSY}$ is commonly used as a limit (United Nations, 1995) and a target (Annala, 1993) reference point, while 20% of the pre-exploitation equilibrium biomass has been taken to be "a level below one does not want to go" in several studies (e.g. Beddington and Cooke, 1983; Francis, 1992; Punt, 1995, 1997). 20% and 40% of B_0 have also been used as reference points in the assessments for blue warehou and blue grenadier (Smith, 1999a, 1999b). The probability of not dropping below B_{50} is increasingly being used as a limit reference point for U.S. fisheries (V.R. Restrepo, ICCAT, pers. commn). Finally, the measure $P(AB > AB_{86-94})$ is an operational reflection of the "management strategy" for many SEF species "to set a *TAC* for the Commonwealth-managed portion of the fishery that maintains the standardized catch per unit effort (CPUE) in the fishery above its lowest annual average from 1986 to 1994" (Tilzey, 1999). These probabilities can be defined for a specific year (e.g. the probability that the biomass in 2002 exceeds AB_{MSY}) or in terms of the probability that the condition is true over several years (e.g. the probability that the available biomass does not drop below AB_{MSY} between 1999 and 2002).

The performance measures used to assess the performance of a harvest strategy relative to the needs of industry are:

a) The median and 90% intervals for the total catch from 1999 to 2023, where catches are discounted by 0, 5 and 10%:

$$\sum_{y=1999}^{2023} C_y \, e^{-\delta(y-1999)} \tag{2}$$

where δ is the economic discount rate (0, 0.05 or 0.1), and
C_y is the landed catch (in mass) for year y.

b) The median and 90% intervals of the total effort from 1999 to 2023, where effort is discounted by 0, 5 or 10%:

$$\sum_{y=1999}^{2023} E_y \, e^{-\delta(y-1999)} \tag{3}$$

where E_y is the (actual) fishing effort during year y (see Equation D.15).

c) The median and 90% intervals for the average annual absolute change in catch (AAV):

$$\frac{100\sum_{y=1999}^{2023}\left|C_y - C_{y-1}\right|}{\sum_{y=1999}^{2023} C_y} \qquad (4)$$

d) The median and 90% intervals for the difference between the landed catch and the *TAC*:

$$\frac{100\sum_{y=1999}^{2023}\left(C_y - TAC_y\right)}{\sum_{y=1999}^{2023} TAC_y} \qquad (5)$$

The first three measures are commonly employed to assess the performance of harvest strategies (e.g. Punt and Butterworth, 1995; Punt and Smith, 1999). The fourth measure is included in this study because *TAC*s for SEF species are frequently substantially larger than the actual landed catches.

Previous evaluations of harvest strategies have not explicitly considered discarding. However, the extent of discarding can be substantial in some years and for some species and harvest strategies. The median and 90% intervals for the following quantity are therefore reported to quantify the extent of discarding over time:

$$\frac{100\sum_{y=1999}^{2023} D_y}{\sum_{y=1999}^{2023}\left(D_y + C_y\right)} \qquad (6)$$

where D_y is the discarded catch (in mass) for year y.

These performance measures could be considered to provide information relative to broader ecosystem issues.

4.7 Software design

The code used to implement the specifications in Appendices D, E and F was designed using object-oriented methods. This approach to software design should make it relatively straightforward for others to modify the software (e.g. add additional components to the operating model / expand the set of harvest strategies). Separate computer programs were developed to implement the operating model and to implement the harvest strategies, again to simplify the process of software modification. Appendix G provides more information about the software.

5. RESULTS / DISCUSSION

5.1 Evaluating assessment methods and performance indicators

Performance indicators are based on quantities estimated during assessments. Therefore, an evaluation of performance indicators essentially involves assessing how well different quantities can be estimated from the types of data available for assessment purposes. For the purposes of this study, twelve possible quantities upon which performance indicators could be based have been identified (the symbol y_{curr} is used to denote the last year for which assessment data are available – 1999 for the majority of the analyses):

a) The spawner biomass at the start of year y_{curr}.
b) The available biomass in the start of year y_{curr}.
c) The ratio of the spawner biomass at the start of year y_{curr} to the pre-exploitation equilibrium spawner biomass.
d) The ratio of the available biomass at the start of year y_{curr} to the pre-exploitation equilibrium available biomass.
e) The ratio of the spawner biomass at the start of year y_{curr} to that at the start of 1991.
f) The ratio of the available biomass at the start of year y_{curr} to that at the start of 1991.
g) Maximum Sustainable Yield, *MSY*.
h) The ratio of the available biomass at the start of year y_{curr} to the biomass at which *MSY* is achieved, B_{MSY} (abbreviation B_{1999}/B_{MSY})
i) The ratio of the spawner biomass at the start of year y_{curr} to the spawner biomass at which expected recruitment is half that at the pre-exploitation equilibrium level, B_{50} (abbreviation B_{1999}/B_{50})
j) The ratio of *MSY* to B_{MSY}.
k) The ratio of the catch when the spawner biomass is reduced to 40% of its pre-exploitation equilibrium level to the corresponding available biomass (abbreviation $C(F_{40\%})/B(F_{40\%})$).
l) The ratio of the catch when the spawner biomass is reduced to 30% of its pre-exploitation equilibrium level to the corresponding available biomass (abbreviation $C(F_{30\%})/B(F_{30\%})$).

Both spawner and available biomass are considered in quantities a) – f). This is because while spawner biomass is often included in the definitions for management objectives and performance indicators, the assessment data relate mainly to the biomass available to the fishery. The spawner biomass is included in the available biomass if the age-at-maturity is larger than the age-at-recruitment. However, if maturity occurs before recruitment to the fishery or if the behaviour of the animal is such that larger animals are less available to the gear (as appears to be the case for pink ling), the spawner biomass can be much larger than the available biomass.

Quantities e) and f) are included to assess how much better the methods of stock assessment perform at estimating the change in biomass over years for which data (length-frequency data and age-length keys in this case) are available. Quantities g), j), k), and l) all relate to assessing how productive the population is at some commonly used target (and limit) reference points. Quantity h) attempts to assess the status of the stock relative to B_{MSY}; dropping the resource below B_{MSY} is a traditional definition of biological overexploitation (Smith TD, 1994). Quantity i), on the other hand, assesses the status of the stock relative to what is now becoming an increasingly popular limit reference point (V.R. Restrepo, ICCAT, pers. commn).

5.1.1 Detailed results for one estimator and one trial

Figure 5 shows distributions of relative error for each of the four species for quantities a) – l) for assessments conducted at the start of the first year for which a *TAC* is set (1999). The data are generated by the base-case trial and the estimator applied is the base-case Integrated Analysis (see Section 4.4 of Appendix F for details). The analyses focus on this estimator because it is the most commonly applied approach to stock assessment in the SEF. Appendix H lists the medians and 90% intervals for the relative errors and the absolute values of the relative errors for this combination of trial and estimator.

The magnitudes of the relative errors in Figure 5 depend both on the management quantity and the species. However, several general conclusions can be drawn from Figure 5. The estimates for tiger flathead are generally the least biased and most precise while those for spotted warehou are very poorly defined. The results for pink ling and jackass morwong tend to be intermediate between those for tiger flathead and spotted warehou. The estimates of current spawner and available biomass (in absolute terms) for tiger flathead, jackass morwong and pink ling are negatively biased while those for spotted warehou exhibit severe positive bias (Figures 5a and 5b). The estimates of current available biomass for pink ling are markedly less biased than those of spawner biomass. This is because the assessment is unaware that the selectivity pattern for pink ling is dome-shaped and assumes instead that selectivity follows a logistic form (see Equation F.38). It may be initially surprising that the spawner rather than available biomass exhibits large bias when the incorrect assumption is made about selectivity, which defines the available biomass. The reason for this is that the assessment data relate primarily to available biomass, and so spawner biomass is largely just an output of the assessment model, based on a fit to data that relate to the available biomass.

As expected from previous studies (e.g. Punt, 1995, 1997), the estimates of biomass relative to the pre-exploitation equilibrium level (Figures 5c and 5d) and (particularly) those relative to the biomass in 1991 (Figures 5e and 5f) are much more accurate and precise than the estimates of absolute biomass. The estimates of the ratio of the current to the 1991 biomass are the most accurate and precise because length-frequency data and age-length keys are available for the years 1991 to y_{curr}. The estimates of biomass relative to the pre-exploitation equilibrium level involve essentially extrapolating backwards from the first year for which data are available to 1958 based solely on information on catches. This extrapolation can be highly uncertain if recruitment is very variable.

The inability to estimate absolute biomass impacts the ability to estimate quantities that involve absolute biomass, such as *MSY*. The estimates of *MSY* are negatively biased for jackass morwong, tiger flathead and pink ling but positively biased for spotted warehou (Figure 5g; Appendix H). These estimates are also imprecise for all four species. This is perhaps not surprising because a key parameter defining *MSY* is steepness and the data are insufficient to provide reliable estimates of steepness. This occurs because the data series is short and, for the base-case trial at least, the population has not been driven to levels at which there is likely to be much change in average recruitment compared with that at the pre-exploitation equilibrium level. Poor estimation of steepness is evident for spotted warehou; some estimates of *MSY* are much smaller than the true value while others are much greater. As expected from the biases identified for *MSY*, the ratio of current available biomass to B_{MSY}, B_{1999} / B_{MSY}, is positively biased for spotted warehou and negatively biased for jackass morwong and tiger flathead (Figure 5h).

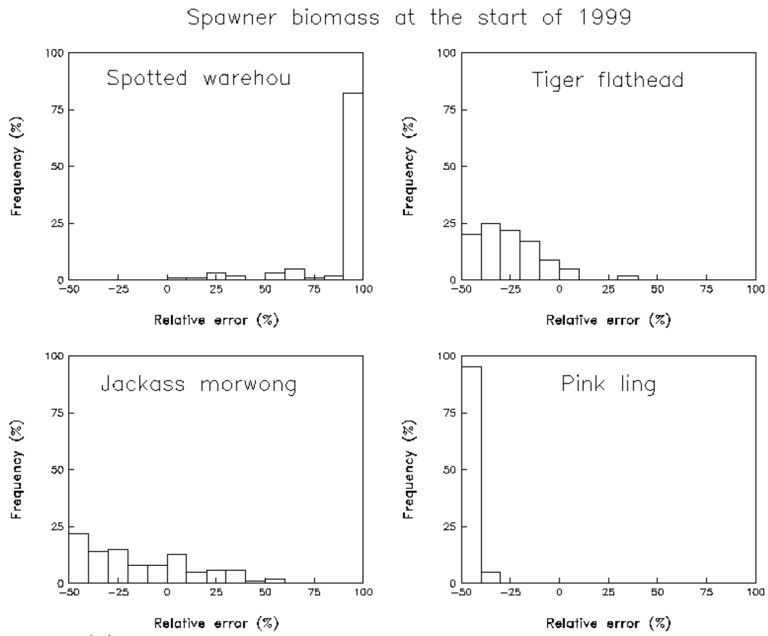

Figure 5(a)

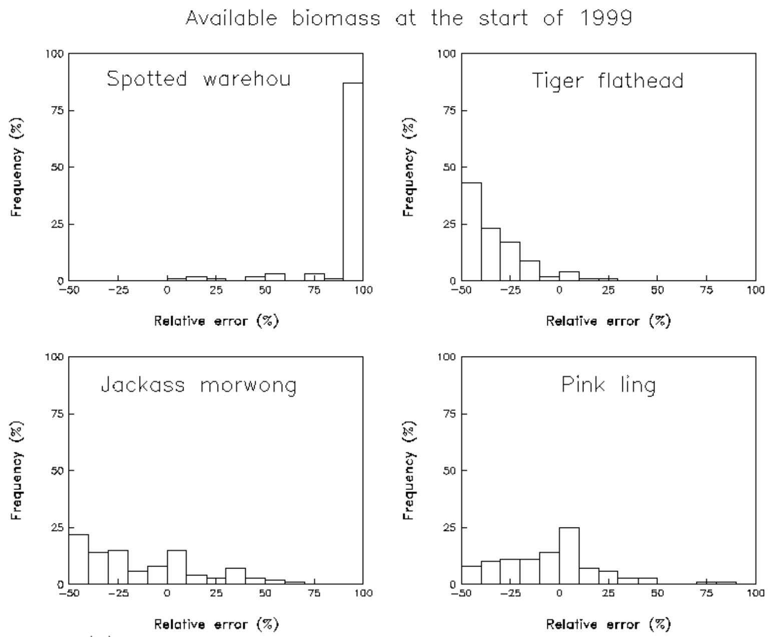

Figure 5(b)

Figure 5 : Histograms of relative error for the base-case Integrated Analysis estimator and the base-case trial for twelve quantities of interest to management. Results are shown for each of the four species. For ease of presentation, relative errors less than –50% are pooled at –50% and relative errors in excess of 100% are pooled at 100%.

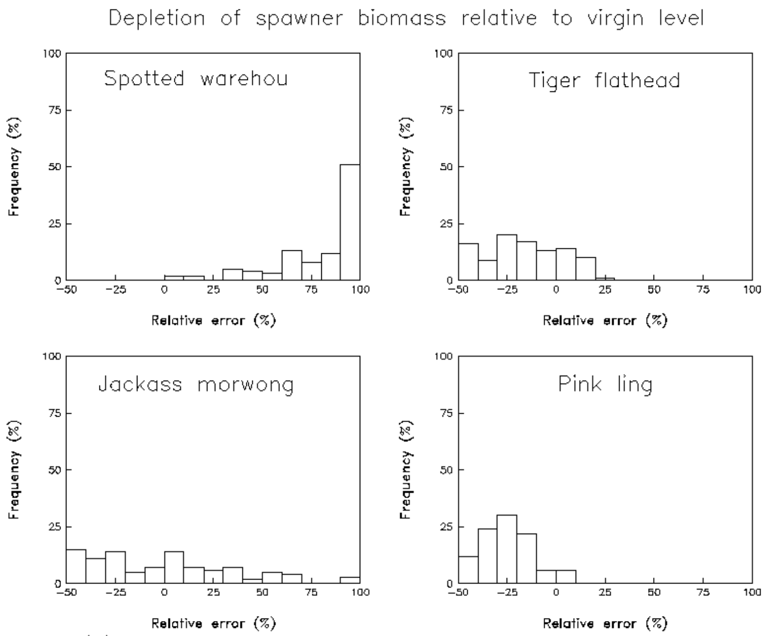

Figure 5(c)

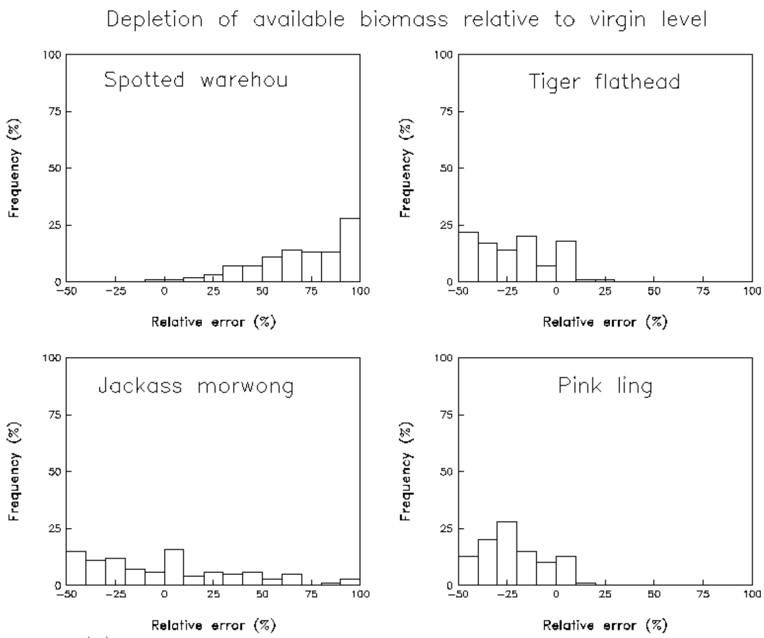

Figure 5(d)

Figure 5 : Histograms of relative error for the base-case Integrated Analysis estimator and the base-case trial for twelve quantities of interest to management. Results are shown for each of the four species. For ease of presentation, relative errors less than –50% are pooled at –50% and relative errors in excess of 100% are pooled at 100%.

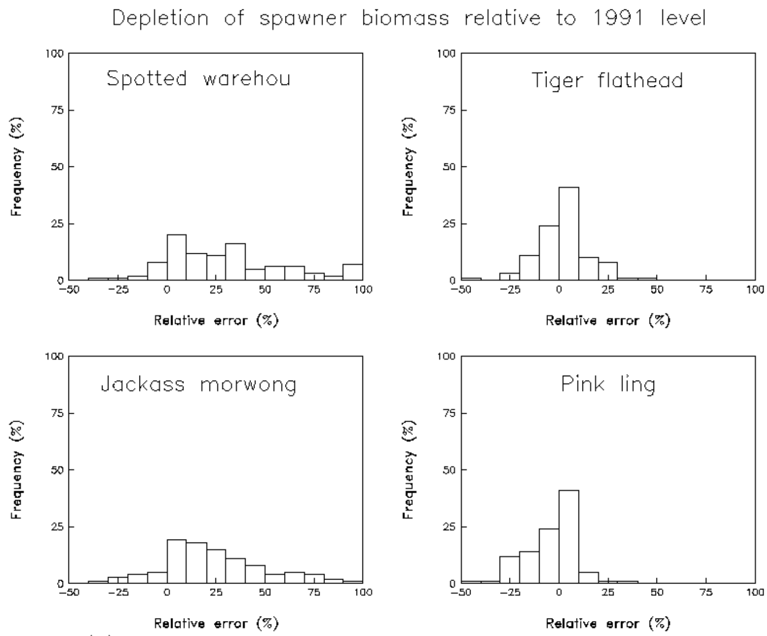

Figure 5(e)

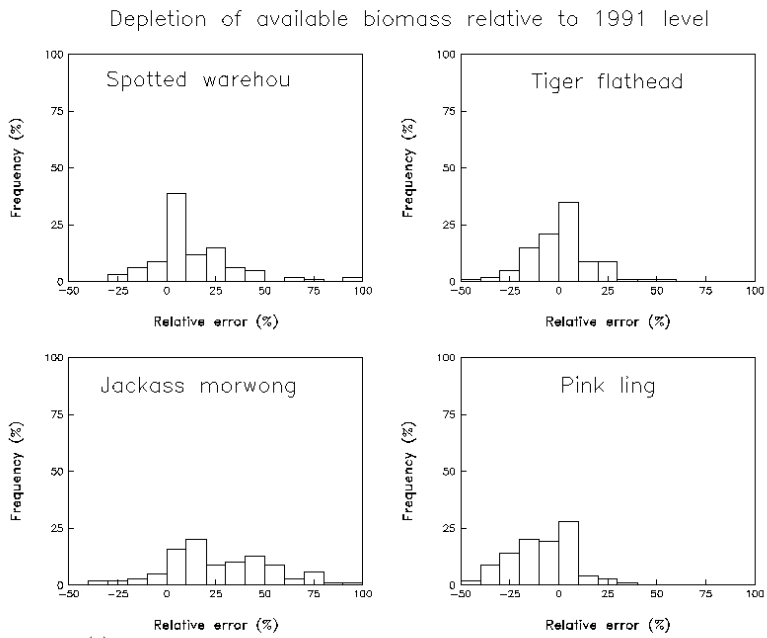

Figure 5(f)

Figure 5 : Histograms of relative error for the base-case Integrated Analysis estimator and the base-case trial for twelve quantities of interest to management. Results are shown for each of the four species. For ease of presentation, relative errors less than –50% are pooled at –50% and relative errors in excess of 100% are pooled at 100%.

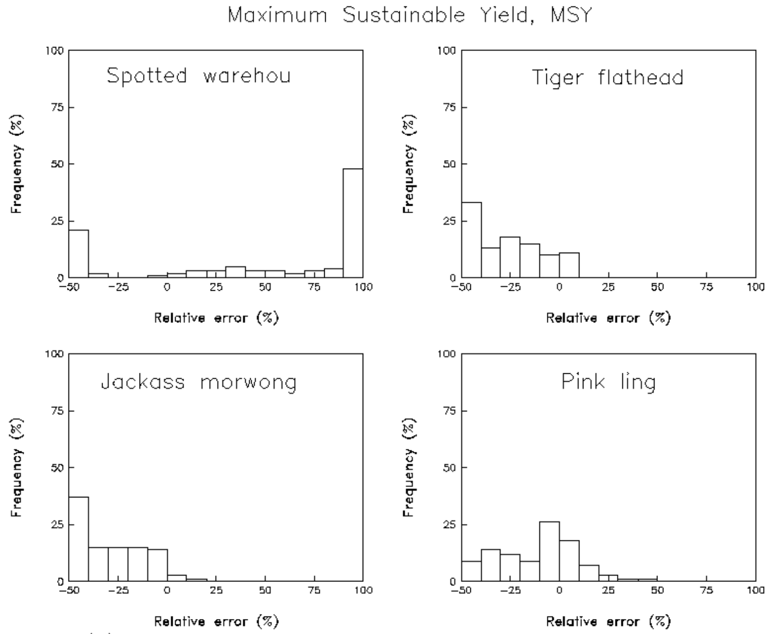

Figure 5(g)

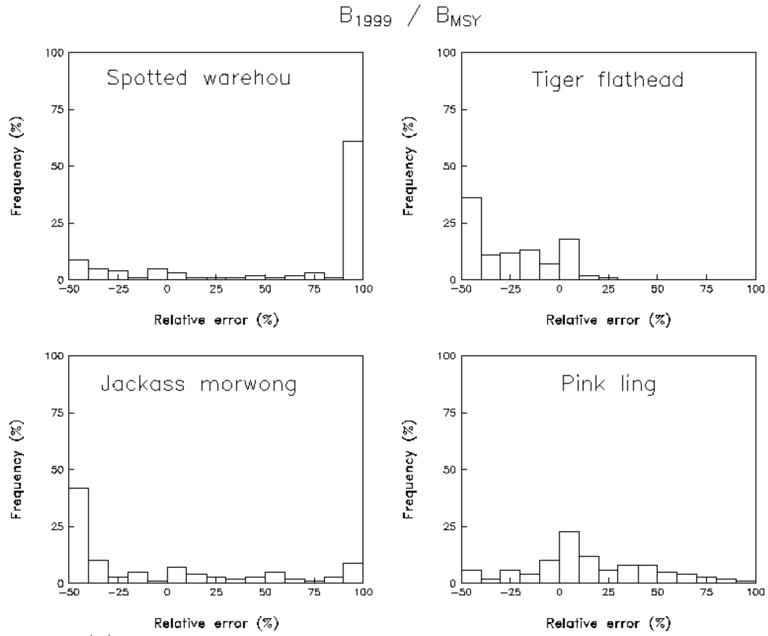

Figure 5(h)

Figure 5 : Histograms of relative error for the base-case Integrated Analysis estimator and the base-case trial for twelve quantities of interest to management. Results are shown for each of the four species. For ease of presentation, relative errors less than –50% are pooled at –50% and relative errors in excess of 100% are pooled at 100%.

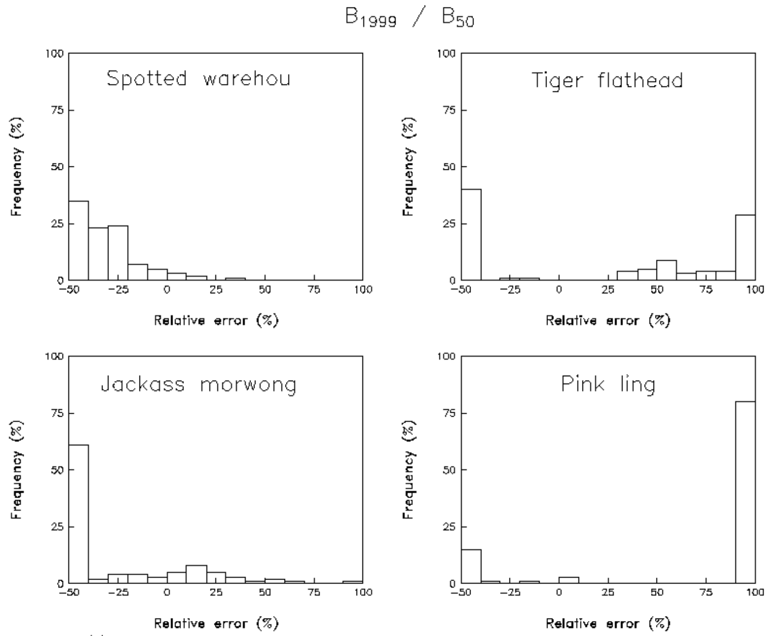

Figure 5(i)

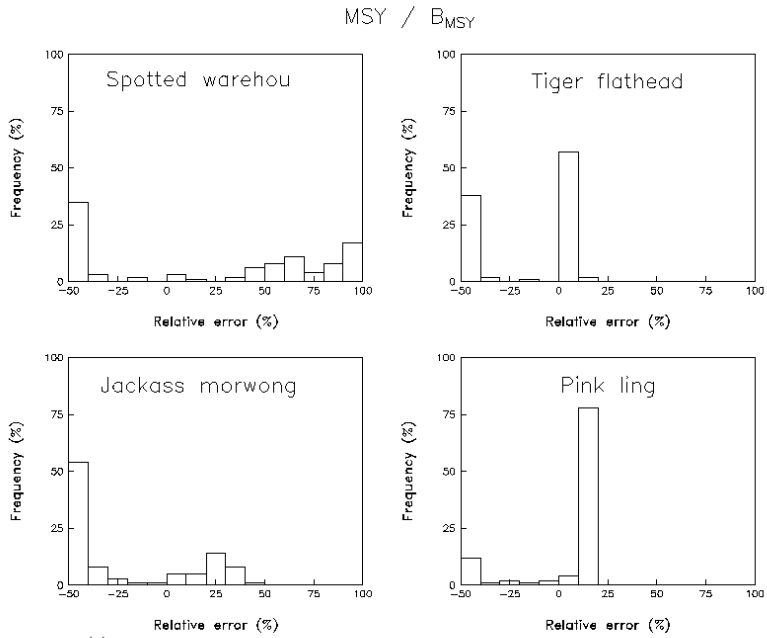

Figure 5(j)

Figure 5 : Histograms of relative error for the base-case Integrated Analysis estimator and the base-case trial for twelve quantities of interest to management. Results are shown for each of the four species. For ease of presentation, relative errors less than –50% are pooled at –50% and relative errors in excess of 100% are pooled at 100%.

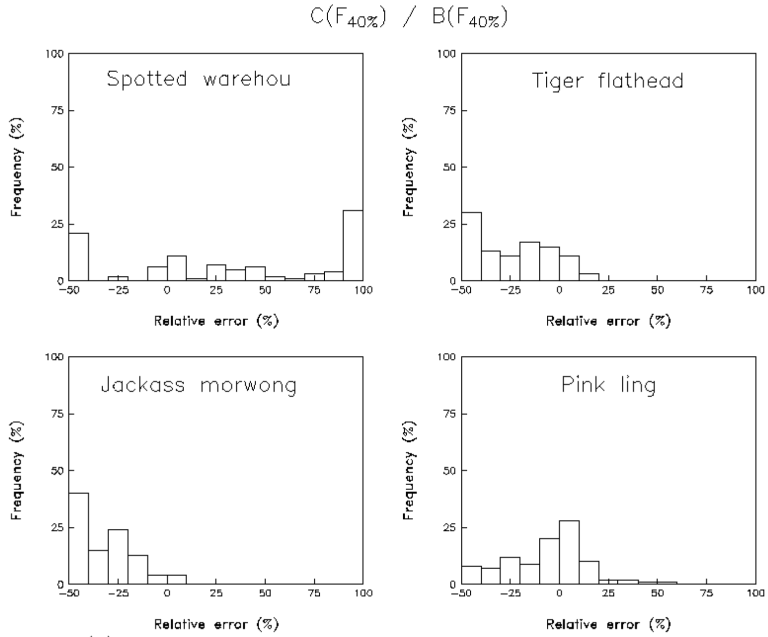

Figure 5(k)

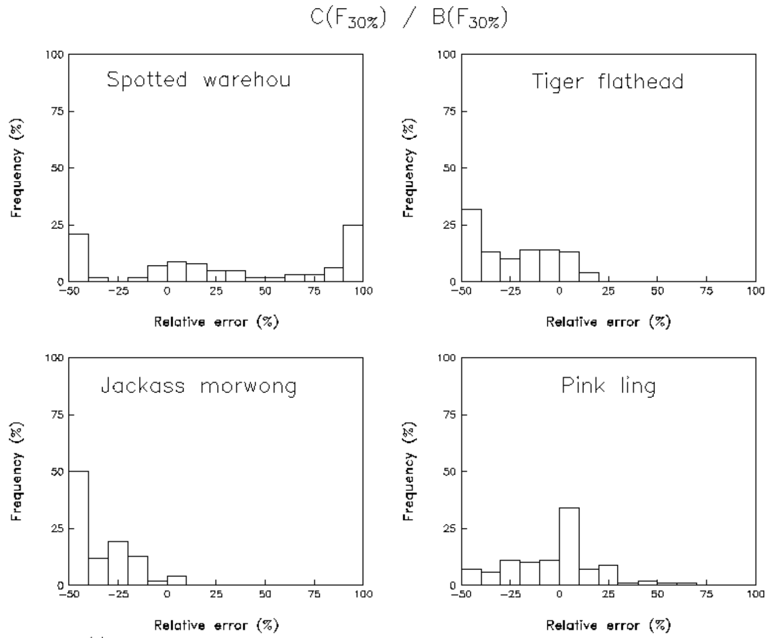

Figure 5(l)

Figure 5 : Histograms of relative error for the base-case Integrated Analysis estimator and the base-case trial for twelve quantities of interest to management. Results are shown for each of the four species. For ease of presentation, relative errors less than –50% are pooled at –50% and relative errors in excess of 100% are pooled at 100%.

The ratio of current spawner biomass to B_{50} is very poorly determined (Figure 5i). In particular, the estimates are very highly positively biased for pink ling and very highly negatively biased for jackass morwong. The estimates of the ratio of *MSY* to $B_{\rm MSY}$ (Figure 5j) are surprising. For tiger flathead and pink ling, the estimates are relatively similar to the true value for many of the simulations. However, this is not the case for spotted warehou and jackass morwong. The estimates for quantities k) and l) behave, as expected, in a qualitatively manner similar to those for *MSY* (Figures 5k and 5l).

5.1.2 Summarising the results further

Presenting the results of the evaluation of estimation performance in the form of histograms of errors (*sensu* Figure 5) leads to an enormous volume of results. Therefore the results have been condensed. This both simplifies the presentation and enables the results for different estimators / trials to be contrasted easily. Figure 6(a) provides an example of how the results for multiple estimators / trials are presented in the remainder of this report. The four large blocks contain results for each of the four species: (i) top left - spotted warehou, (ii) top-right – tiger flathead, (iii) bottom-left – jackass morwong, and (iv) bottom-right – pink ling. Three panels are provided within each block (i.e. for each species). The upper panel provides results (in the form of the medians and 90% intervals of the relative error distributions) for current spawner biomass, the middle panel for available biomass relative to the pre-exploitation equilibrium level, and the lower panel for *MSY*. These three quantities represent “orthogonal” estimation issues. The current spawner biomass provides an indication of the size of the resource, the ratio of the current available biomass to the pre-exploitation equilibrium level an indication of the status of the resource relative to target and limit references points, and *MSY* an indication of the likely long-term average productivity of the resource.

5.1.3 Understanding the behaviour of the Integrated Analysis estimator for the base-case trials

The results in Figure 5 suggest that the Integrated Analysis estimator is both inaccurate and imprecise. Some reasons for the biases evident from Figure 5 are readily apparent (e.g. the estimates of spawner biomass for pink ling are biased because the selectivity pattern is incorrectly assumed to be of the logistic form). However, the reasons for the very high positive bias associated with the estimates of spawner biomass for spotted warehou are not obvious from Figure 5. A number of additional trials have therefore been constructed to identify the reasons for this bias:

a) As for the base-case trial, except that the extent of variability in movement, natural mortality, and selectivity (see Equations D.3, D.4, and D.13) is set equal to zero (abbreviation “Less vars”).
b) As for the base-case trial, except that the spatial structure is ignored (abbreviation “One area”).
c) As for b) except that there is only one growth group so there is no variation in length-at-age (abbreviation “No growth”).
d) As for c) except that the extent of variability in natural mortality and selectivity is set equal to zero (abbreviation “Less vars 2”).
e) As for d) except that discarding is ignored (and the estimator is aware of this) (abbreviation “No discards”).

Base−case trial / Base−case Integrated Analysis

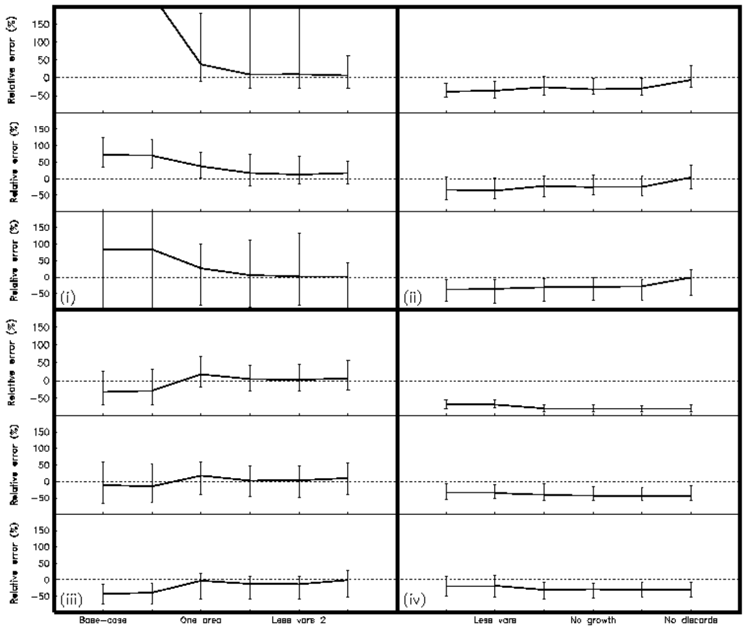

Figure 6(a)

Base−case trial / Base−case Integrated Analysis

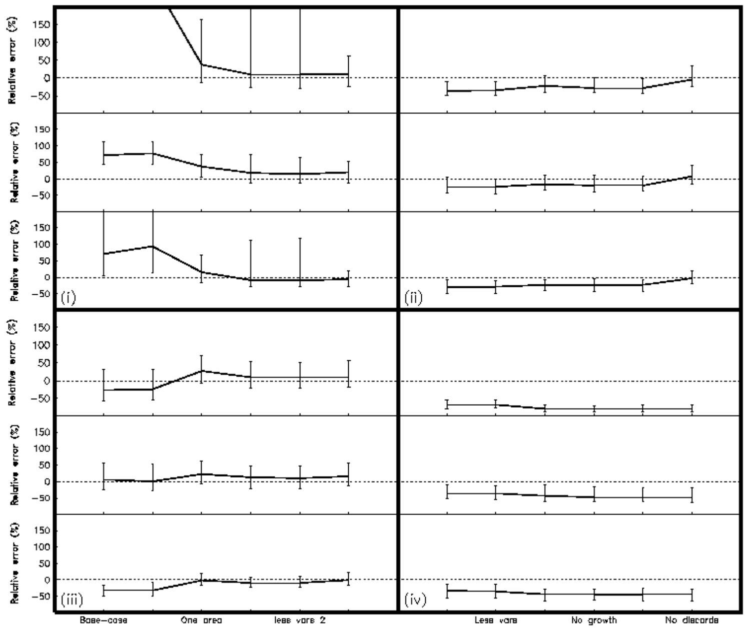

Figure 6(b)

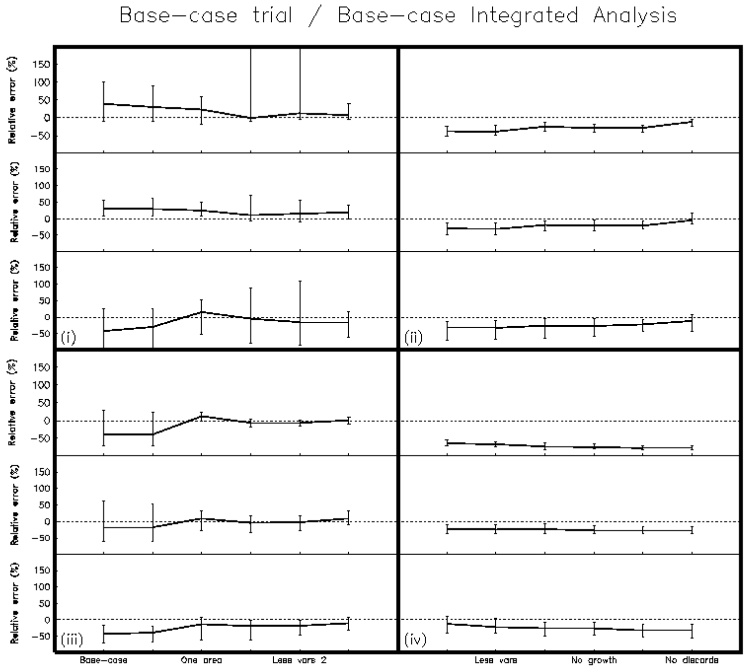

Figure 6(c)

Figure 6 : Relative error distributions (medians and 90% intervals) for the base-case trial and five variants thereof. Results are shown in (a) for the base-case Integrated Analysis estimator, in (b) for an estimator that is provided with the correct value for steepness, and in (c) for an estimator that is provided with data for which $\sigma_q = 0.001$. The results for each species are shown in the four bolded blocks: i) spotted warehou, ii) tiger flathead, iii) jackass morwong, and iv) pink ling. The panels for each species (top to bottom) show results for current spawner biomass, depletion of the available biomass, and *MSY*.

Figure 6(a) shows relative error distributions for the Integrated Analysis estimator for the base-case trial and the five variants of this trial listed above. Figures 6(b) and 6(c) show similar results to Figure 6(a), except that the value of steepness is assumed to be known for Figure 6(b), and for Figure 6(c) the value of σ_q is set equal to 0.001. Figures 6(b) and 6(c) therefore indicate respectively the value of having biological data on productivity and (substantially) improving the precision of the catch-rate index.

The impact of knowing the value of steepness is relatively small for the estimates of spawner biomass and current depletion for spotted warehou and pink ling although the MAREs for the current depletion for tiger flathead and jackass morwong decrease if steepness is known (Table 3; Figure 6). As expected, however, knowing steepness has a large impact on the ability to estimate *MSY*. Somewhat surprisingly, the bias and MARE of *MSY* for pink ling actually increase when steepness is known. This is, however, probably due to the assessment making an incorrect assumption concerning the selectivity pattern. Assuming that catch rate is almost exact has a marked impact on the sizes of the biases for spotted warehou (Table 3a) but much less of an impact on the biases for the other species. As expected, however, the distributions of relative error get tighter and the MAREs are consequently smaller given more precise data.

The impact of removing the variability in natural mortality, movement and selectivity ("less vars" in Table 3 and Figure 6) is minor (in some cases the MAREs actually increase when this type of variability is removed from the operating model). Except for pink ling, moving from a four region to a single region model leads to markedly less bias and greater precision. This result indicates the possible importance of spatial structure when conducting stock assessments. No attempt has been made to date to include spatial structure and fish movement in stock assessments for SEF species. However, the results in Figure 6 and Table 3 indicate that consideration of developments along these lines may be valuable. Ignoring variability in growth also improves the estimates (particularly for jackass morwong and spotted warehou). These last two results indicate the importance of considering model error. Moving from a four region to one region operating model and ignoring variability in growth makes the operating model more similar to the model underlying the Integrated Analysis.

As expected from the results for the "Less vars" case, ignoring noise in selectivity and natural mortality ("Less vars 2" in Table 3 and Figure 6) has little impact on performance when the operating model includes only one region and ignores variability in growth. Note that even when all these simplifications to the operating model are made, the operating model is still not exactly structurally the same as the model underlying the Integrated Analysis. For example, selectivity in the Integrated Analysis is a function of age whereas it is a function of length in the operating model.

Estimation performance for flathead improves markedly if discarding is ignored although similar improvements are not evident for the other species. This is perhaps not surprising as the discard fraction for flathead is assumed to be twice that for the other species (see Table E.3).

5.1.4 The performances of different stock assessment methods

Figure 7 shows the medians and 90% intervals for the relative error for current (spawner) biomass, the current depletion of the available biomass, and *MSY* for the base-case trial for six different stock assessment methods. Table 4 lists the biases and MAREs for these management-related quantities and stock assessment methods. The six methods are Integrated Analysis, Schaefer production model, Fox production model, Age-structured production model (ASPM), *ad hoc* tuned VPA, and ADAPT-VPA. The steepness of the (Beverton-Holt) stock-recruitment relationship for the last two of these assessment methods was set equal to 1 (i.e. recruitment is assumed to be independent of spawner biomass even if this is not the case in the operating model) as this leads to more stable estimation (and lower relative errors).

The methods that ignore the age-composition data (the two production models and ASPM) provide very wide distributions of relative error (particularly for current spawner biomass). The ADAPT-VPA estimates are highly positively biased for all four species, markedly more so than those for *ad hoc* tuned VPA. The reasons for the poor performance of ADAPT-VPA are unclear but may relate to the attempt to estimate all of the numbers-at-age for the most recent year. Some applications of ADAPT-VPA (e.g. Powers and Restrepo (1992)) estimate only a subset of these numbers-at-age and use an (assumed) selectivity pattern to estimate the remaining numbers-at-age for the most recent year. Future work could examine alternative ADAPT-VPA formulations.

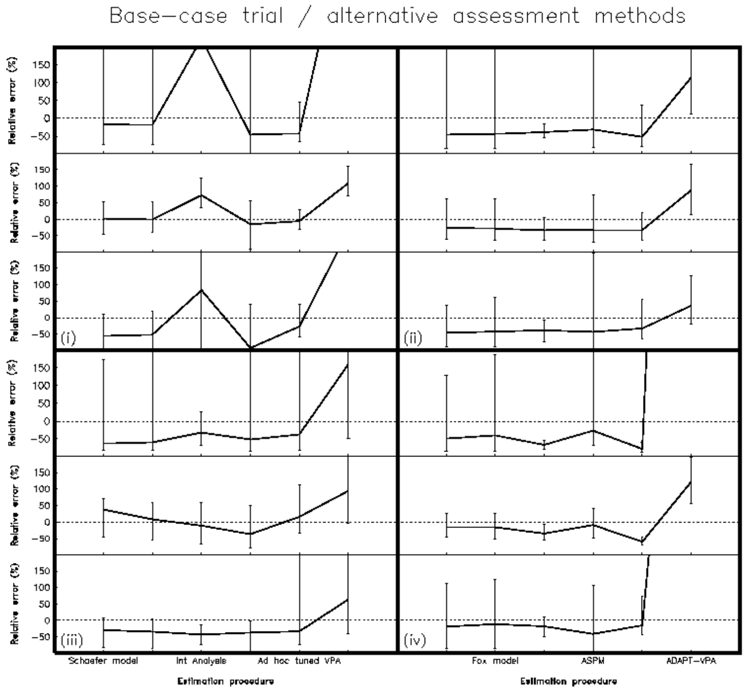

Figure 7 : Relative error distributions (medians and 90% intervals) for current spawner biomass, the depletion of the available biomass, and *MSY* for the base-case trial. Results are shown for six alternative stock assessment methods for the four species.

None of the methods perform particularly well for spotted warehou (Figure 7i). The *ad hoc* tuned VPA is notable for being the only approach that did not lead to very wide distributions of relative error for this species although its estimates are nevertheless notably biased. *Ad hoc* tuned VPA is the best of the estimation methods for spotted warehou in terms of median absolute relative errors (Table 4). Of the six stock assessment methods, Integrated Analysis clearly outperforms the other five methods for tiger flathead as its estimates are no more biased and markedly more precise than those for the other methods (Figure 7ii; Table 4).

There is little to choose among five of the six stock assessment methods in terms of their ability to estimate current depletion and (to a lesser extent) *MSY* for jackass morwong (Figure 7iii). However, Integrated Analysis clearly provides better (i.e. more precise) estimates of current biomass for this species and, overall, should therefore be considered as the best method for this species. The estimates of absolute abundance provided by the two production models and ASPM for pink ling are highly imprecise (Figure 7iv). Integrated Analysis is again the preferable method of stock assessment given its lower variance for spawner biomass and current depletion.

Clearly none of the assessment methods are particularly accurate or very precise. However, overall (and even taking consideration of its poor performance for spotted warehou), Integrated Analysis (which makes use of more data than the two production models and ASPM) appears to be the best performing assessment method (with *ad* *hoc* tuned VPA in second place). For ease of presentation, all of the results that follow are based on the Integrated Analysis method.

5.1.5 Sensitivity to current depletion

Figure 8 shows relative error distributions for the simulation trials in which the current year (y_{curr}=1999) depletion of the resource (in the operating model) is changed from $0.1B_0$ to $0.8B_0$. Ideally the estimates of spawner biomass, depletion and *MSY* should be unbiased and precise. Clearly, this is not the case for the base-case trial (Figure 5). Nevertheless, performance indicators based on the results of assessments can still be useful if the extent of bias does not depend on the actual depletion (i.e. the estimates of current depletion may be positively biased but, if the extent of bias is a constant, it should be possible to obtain reasonably useful estimates of trend from assessments).

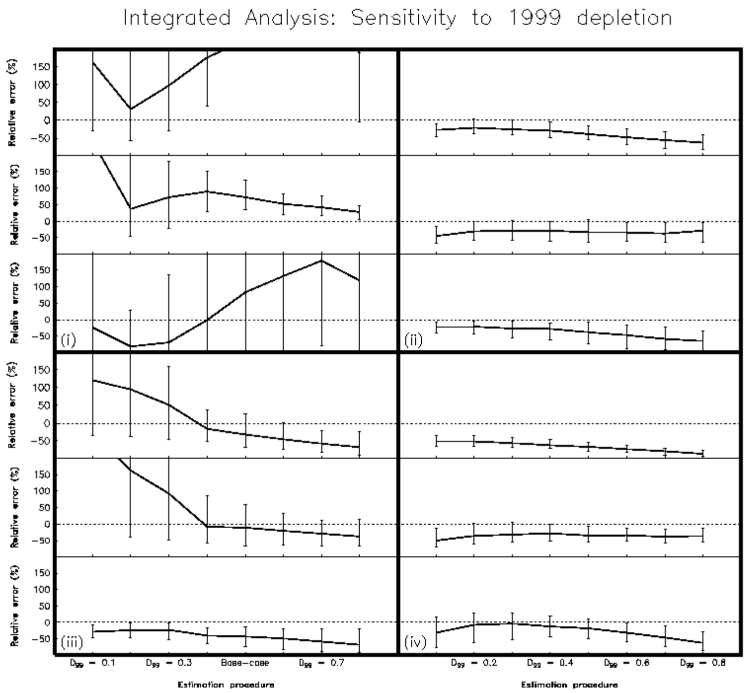

Figure 8 : Relative error distributions (medians and 90% intervals) for current spawner biomass, the depletion of the available biomass, and *MSY* for trials in which the depletion of the spawner biomass at the start of 1999 is varied from 0.1 to 0.8. Results are shown for the Integrated Analysis estimator for the four species.

Unfortunately, the extent of bias is very much a function of current depletion, at least for spotted warehou and jackass morwong (Figures 8i and 8iii). The estimates for spotted warehou are poor for all choices for the current depletion of the resource but particularly so for depletions less than $0.2B_0$ when even the estimates of current depletion are grossly positively biased (Figure 8i). The ability to estimate absolute or relative biomass is also very poor for jackass morwong (positive biases of 100% and larger) if the current depletion is $0.3B_0$ or lower (Figure 8iii). The results in Figures 8i and 8iii imply that estimates of current depletion for spotted warehou and jackass morwong are likely to be poor indicators of stock depletion if the stock is actually severely depleted. In contrast, the extent of bias for tiger flathead and pink ling

(Figures 8ii and 8iv) is largely insensitive to the assumed current depletion of the resource although this is not the case for the estimates of *MSY* which show increasing negative bias as the depletion of the resource is increased from $0.1B_0$ to $0.8B_0$.

5.1.6 Sensitivity to structural assumptions

The ability to estimate the three quantities of interest is largely insensitive to the true steepness of the stock-recruitment relationship and whether this relationship is depensatory (Figure 9). The only notable feature of Figure 9 is that the relative errors for *MSY* for spotted warehou and pink ling increase as the value for steepness is reduced. The lack of impact of depensation on estimation performance in this case is perhaps not surprising because, for the choice of an initial depletion of $0.5B_0$, the population is never driven to levels at which depensation has a notable impact. As expected, if catchability is density-dependent and fishing efficiency is increasing over time (effort options 1 and 2), the estimates are more likely to be positively biased (Figure 10). In contrast, if fishing efficiency is decreasing over time (perhaps because of the impact of changed fishing practices), the relative errors become more negative (effort option 3). Somewhat surprisingly, the results are not particularly sensitive to allowing catchability to be correlated among species (effort options 4 and 5). Results (not shown here) indicate that estimation performance is also not notably sensitive to allowing recruitment to be correlated temporally and among species, to density-dependence in growth, and to how historical discarding is modelled (see Table E.5 for the details of these scenarios).

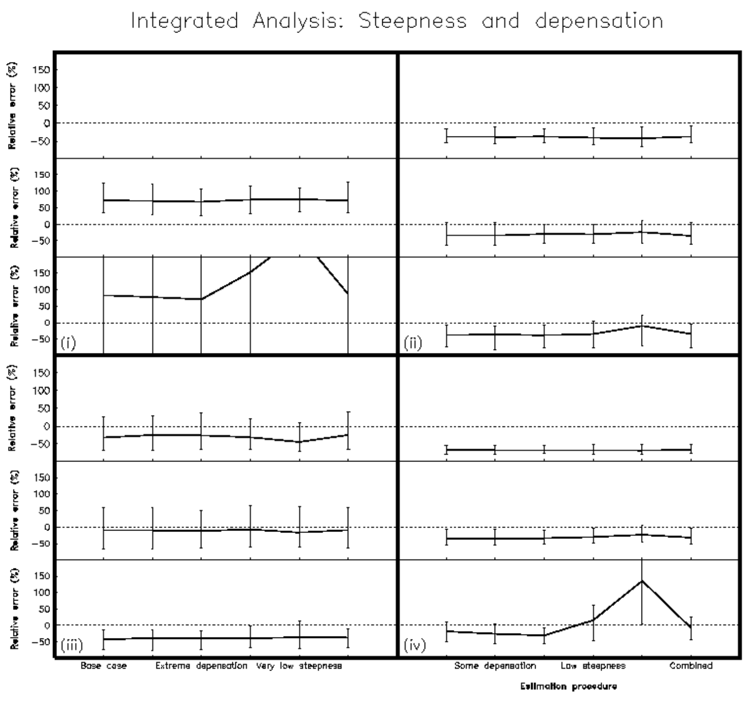

Figure 9 : Relative error distributions (medians and 90% intervals) for current spawner biomass, the depletion of the available biomass, and *MSY* for trials with depensation and different choices for steepness. Results are shown for the Integrated Analysis estimator for the four species.

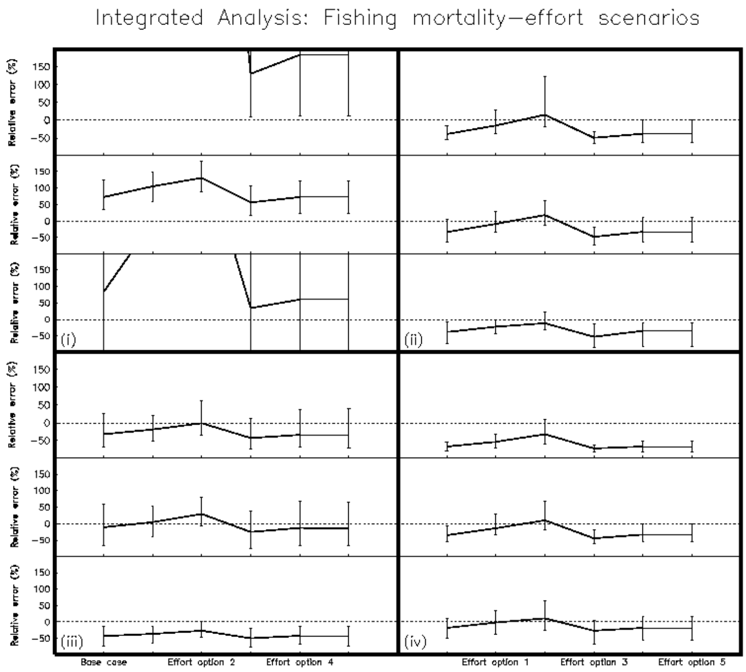

Figure 10 : Relative error distributions (medians and 90% intervals) for current spawner biomass, the depletion of the available biomass, and *MSY* for trials in which fishing efficiency is changing over time and catchability may be density-dependent. Results are shown for the Integrated Analysis estimator for the four species.

The impact of the value assumed for *M* when conducting assessments differing from the true value is examined in Figure 11. Basing assessments on a value for *M* that is less than the true value ("True M high" in Figure 11) leads to (additional) negative bias whereas basing assessments on a value for *M* that is greater than the true value ("True M low" in Figure 11) leads to additional positive bias. The impact of errors in the value assumed for *M* is, however, not symmetric, with the effects of assuming an over-estimate for *M* generally being greater than assuming an under-estimate for *M*.

The results are not noticeably sensitive to changes to the specifications related to the amount of variability in selectivity and movement (Figure 12). However, as expected, the precision of the estimates decreases if the extent of variation in births about the stock-recruitment relationship, σ_r, is 1 rather than its base-case value of 0.6. Precision also decreases if selectivity is more correlated among length-classes than is assumed in the base-case trial ($\tau_s = 0.9$ in Figure 12).

5.1.7 Sensitivity to data availability

Figure 13 examines the hypothetical impact of having an estimate of absolute abundance for 1998 ("survey in 1998" in Figure 13), and having estimates of absolute abundance since 1986. As expected, the ability to estimate spawner biomass (for spotted warehou, tiger flathead, and jackass morwong) improves substantially even if only one estimate of absolute abundance is available. Somewhat surprisingly, the ability to estimate *MSY* for spotted warehou is poorer when estimates of absolute abundance are available since 1986. Changing the sample sizes for length-frequencies and age-length keys does not have a notable impact on estimation ability (Figure 14).

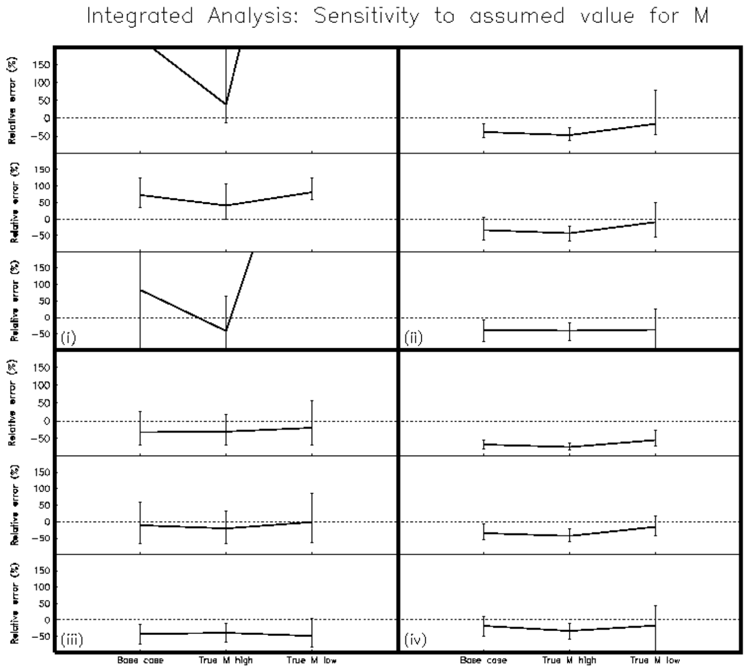

Figure 11 : Relative error distributions (medians and 90% intervals) for current spawner biomass, the depletion of the available biomass, and *MSY* for trials in which the value assumed for the rate of natural mortality, *M*, when conducting assessments differs from the true value. Results are shown for the Integrated Analysis estimator for the four species.

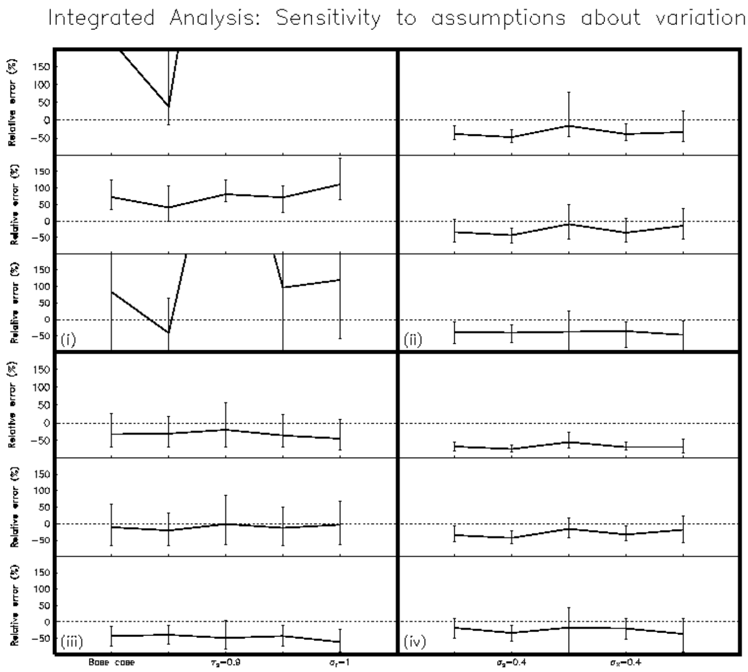

Figure 13 : Relative error distributions (medians and 90% intervals) for current spawner biomass, the depletion of the available biomass, and *MSY* for trials in which either an estimate of absolute abundance is available for 1998, or a time series of such estimates is available from 1986.

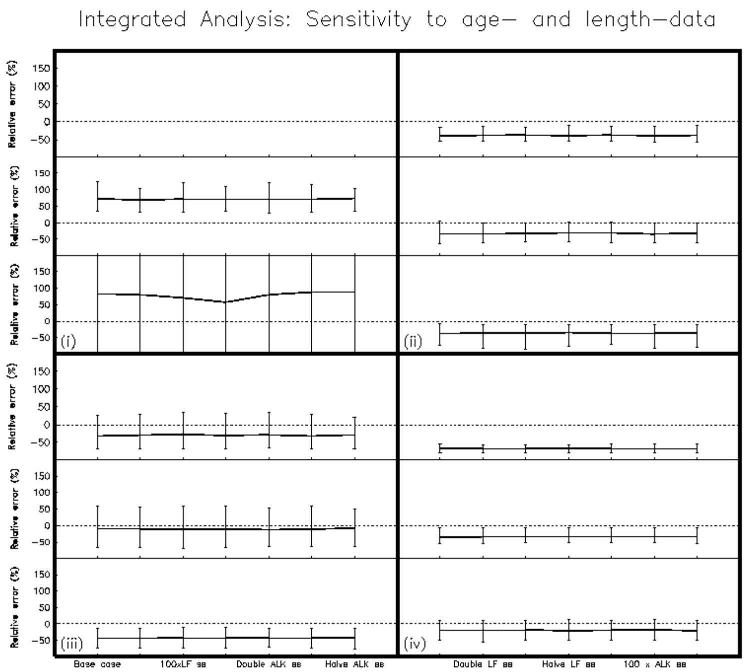

Figure 14 : Relative error distributions (medians and 90% intervals) for current spawner biomass, the depletion of the available biomass, and *MSY* for trials in which the sample sizes for the length-frequency data and the

age-length keys are changed. Results are shown for the Integrated Analysis estimator for the four species.

5.1.8 Improvements in estimation ability over time

One of the reasons for the poor performance of the stock assessment methods in Figures 5 – 14 is the relatively short time-series of data (8 years for length-frequencies and age-length keys and 13 years for catch rates). The question that this raises is whether it can be expected that estimation ability will improve in the future. This can be examined by projecting the system forwards for 25 years and assessing the relative error distributions every sixth year starting in 1999. Results are shown in Figure 15 for one of several sets of results. The results for the other analyses were qualitatively identical to those shown in Figure 15 and have been omitted to reduce the volume of results.

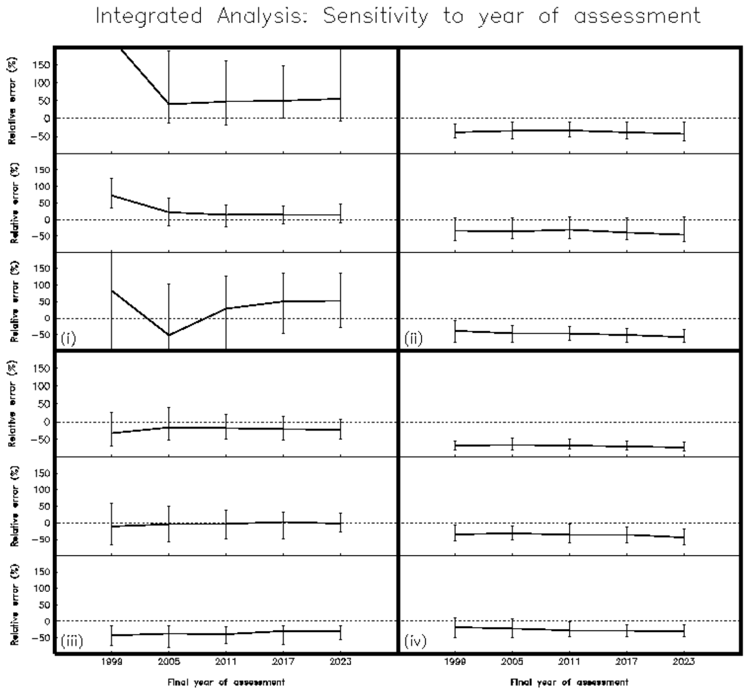

Figure 15 : Relative error distributions (medians and 90% intervals) for current spawner biomass, the depletion of the available biomass, and *MSY* at the start of various future years. Results are shown for the base-case trial and a harvest strategy based on an Integrated Analysis estimator and the F_{MSY} target level of fishing mortality.

As expected, the bias and the widths of the 90% intervals for spotted warehou drop markedly over time (Figure 15i). However, although the bias for current depletion is close to zero by 2023, this is not the case for absolute biomass and *MSY*. Furthermore, the 90% intervals are still very wide even if assessments are based on data up to 2023. Finally, there are no obvious signs of markedly improved estimation performance for the other three species. This result may initially appear surprising as it might have been expected that additional data should lead to the estimates converging to the true values. The reasons for this lack of improvement in estimation performance with time are not fully understood. However, model mis-specification, the fact that each additional year's data implies the estimation of an additional recruitment parameter when applying Integrated Analysis, the noise associated with the assessment data, and a lack of data contrast (Hilborn, 1979) are probably key factors.

5.1.9 General discussion

None of the methods of stock assessment considered in this report outperformed all of the others. However, some general conclusions can be reached:

a) Integrated Analysis seemed to be the most adequate of the methods overall. In particular, it tended to produce results that were more precise than those produced by the other methods. This may be because the model underlying the Integrated Analysis estimator is structurally more similar to the operating model (although by no means identical) and because it uses all of the information generated by the operating model. However, the substantial biases for spotted warehou serve as a warning that this method can produce very poor estimates if its assumptions are violated.
b) The ADAPT-VPA approach performed poorest of the six methods considered, although the reasons for this are not fully understood. Until this situation changes, the use of this method of stock assessment in the SEF should be discouraged.
c) The methods that ignore age-structure data tend to be much less precise than Integrated Analysis and *ad hoc* tuned VPA, highlighting the importance of collecting this information (but not perhaps too much of it – see Figure 14).

The results make clear that estimation ability differs (sometimes markedly) among quantities of interest to management. Table 5 compares the MAREs for the twelve statistics for the base-case trial and the Integrated Analysis estimator. To ease interpretation of the results, the statistics have been ranked according to the size of the MARE (1 for the lowest, 2 the next lowest, etc.) and the ranks summed across species.

Two of the management-related quantities (the ratio of the current spawner biomass to that in 1991 and the ratio of the current available biomass to that in 1991) are clearly estimated best. Five management-related quantities [c), d), j), k), and l)] are ranked next best followed by the remaining five quantities [a), b), g), h), and i)]. This suggests that if performance indicators are to be developed, the ratio of the current to some relatively recent population size is the most appropriate basis for such an indicator, certainly more so than the ratio of current abundance to the pre-exploitation equilibrium level. Of the productivity-related quantities, it is clear that quantities k) and l) outperform quantity h) (*MSY*). To date no SEF assessment has attempted to estimate quantities k) and l). Note that the above ranking is based solely on estimation performance. Consideration also needs to be given to whether the quantity relates to the management objectives for the fishery. For example, it is unclear whether the best estimated quantities are actually useful performance statistics (in the sense that they are measures of performance against common management objectives).

Previous studies have reached similar conclusions to those identified above. For example, Maunder and Starr (1995) found that estimation of the ratio of current biomass to B_{MSY} can be very poor while Punt (1989) found that depletion was better estimated than absolute abundance. However, Punt (1989) also found that it was possible to estimate *MSY* relatively precisely and accurately. The difference between that result and the results obtained here can be attributed to lack of contrast in the data for SEF species. In comparison to the SEF, the data set on which the analyses of Punt (1989) were based exhibited considerable contrast.

In contrast to the current study, Patterson and Kirkwood (1995) found that ADAPT-VPA provided more precise and less biased estimates than *ad hoc* tuned VPA. However, that study was based on the assumption that the catch-at-age matrix is known exactly. In one of the few evaluations of the performance of stock assessment methods based on Integrated Analysis, Bence *et al*. (1993) found that estimation performance was sensitive to the precision of the survey index and the selectivity pattern for the surveys. The biases in that study were lower than those in the current study possibly because, in that study, the operating model was identical to the estimator.

5.2 Evaluation of harvest strategies

It is not possible to consider all combinations of harvest strategy and operating model due to computational demands and constraints on presentation. Instead, the results for different harvest strategies are presented by first outlining (in detail) the results for a single harvest strategy for the base-case trial. The results for variants of this harvest strategy are then shown for a few key operating models. Finally, results for a broader range of harvest strategies (e.g. based on the different underlying stock assessment methods) are shown for a small subset of the operating models.

5.2.1 Results for a single harvest strategy

A harvest strategy based on Integrated Analysis with the *TAC* determined using a target fishing mortality ϕF_{MSY} (see 4.1.1 of Section F) was applied to the base-case trial (100 simulations, 25-year projection). The value for ϕ was (arbitrarily) set to 1 for illustrative purposes. Given perfect information about the system, this harvest strategy would (if there were no constraints on fishing effort and catch) move the resource towards B_{MSY} over time.

Figures 16(a) to 16(d) show the medians and 90% intervals for the time-trajectories for the following quantities for each of the four species [a) spotted warehou; b) tiger flathead; c) jackass morwong; d) pink ling] for this combination of harvest strategy and trial:

1) spawner biomass (expressed as a percentage of the pre-exploitation equilibrium level) (plot (i), upper left panel),
2) available biomass (expressed as a percentage of the pre-exploitation equilibrium level) (plot (i), upper right panel),
3) available biomass (expressed as a percentage of B_{MSY}) (plot (i), lower left panel),
4) landed catch (plot (ii), upper left panel),
5) effort (plot (ii), upper right panel),
6) Total Allowable Catch (plot (ii), centre left panel),
7) landed catch (expressed as a percentage of the *TAC*) (plot (ii), centre right panel),
8) total catch (landed and discard catch combined) (plot (ii), bottom left panel),
9) discarded catch (expressed as a percentage of the total catch) (plot (ii), bottom right panel),
10) the average landed catch from 1999 to the year indicated on the x-axis (plot (iii), upper left panel),
11) the average effort from 1999 to the year indicated on the x-axis (plot (iii), upper right panel),
12) the discounted average landed catch (discount rate = 10%) from 1999 to the year indicated on the x-axis (plot (iii) lower left panel), and
13) the discounted average effort (discount rate = 10%) from 1999 to the year indicated on the x-axis (plot (iii) lower right panel).

Figure 17 shows the probability of being above $0.2B_0$, $0.4B_0$, B_{MSY}, B_{50} and the lowest available biomass from 1986 to 1994 for each of the four species. Results are shown in Figure 17 for the annual probabilities (left panels) and for probabilities evaluated over the whole period from 1958 to the value on the x-axis (right panels).

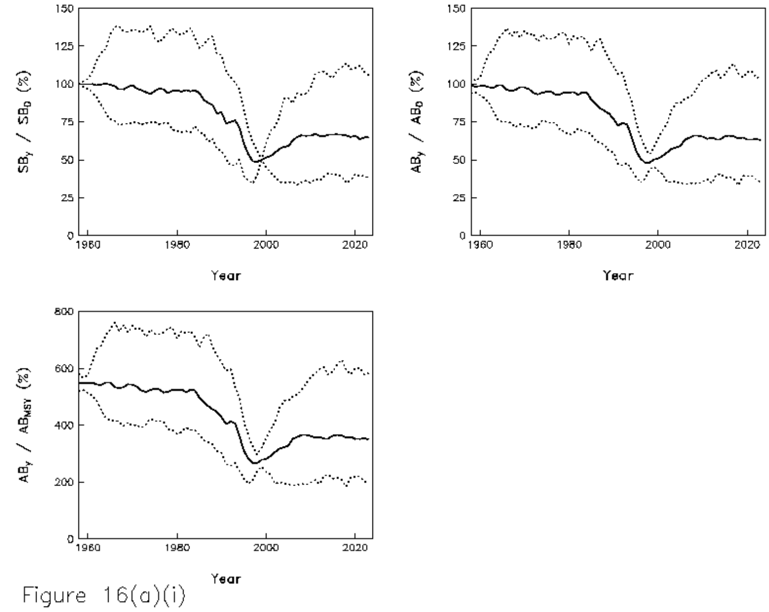

Figure 16(a)(i)

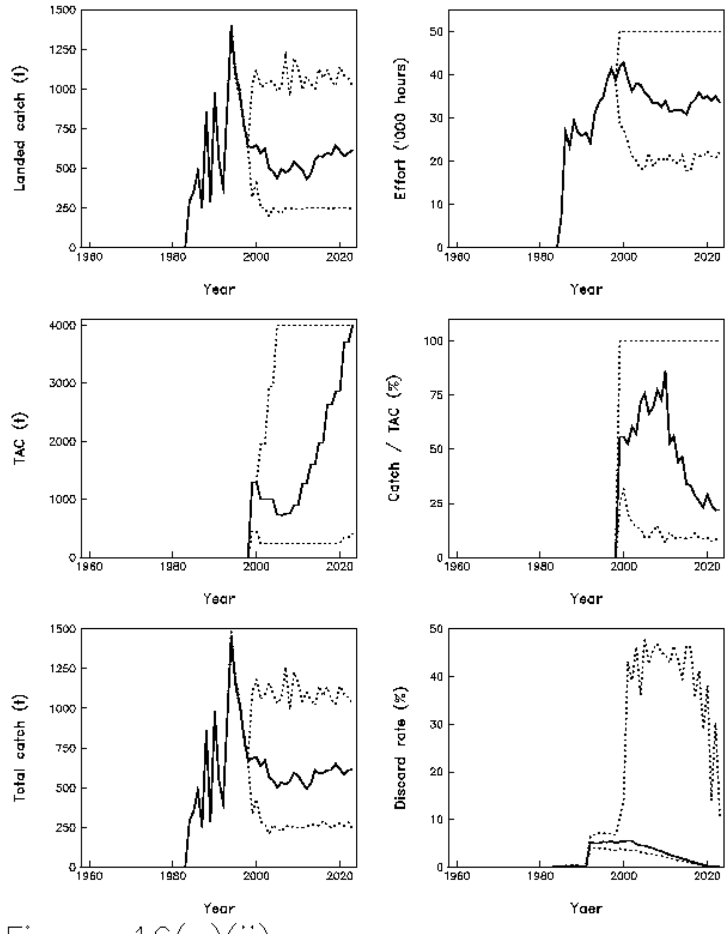

Figure 16(a)(ii)

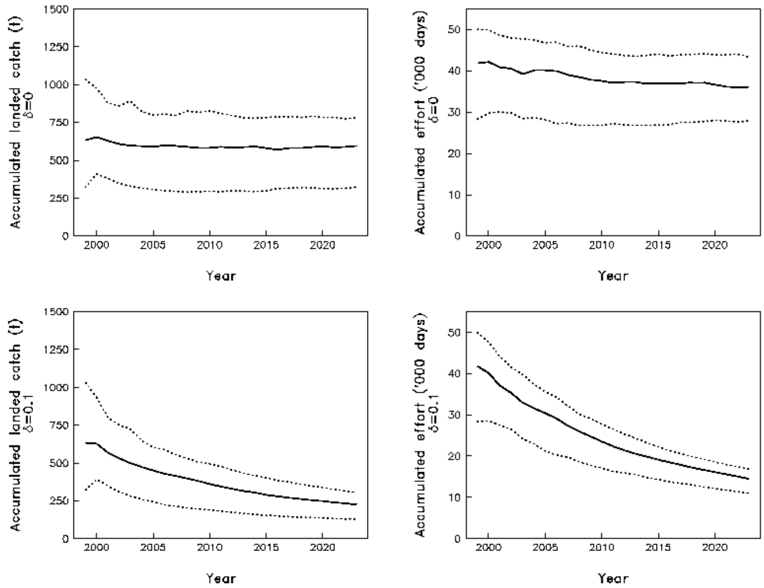

Figure 16(a)(iii)

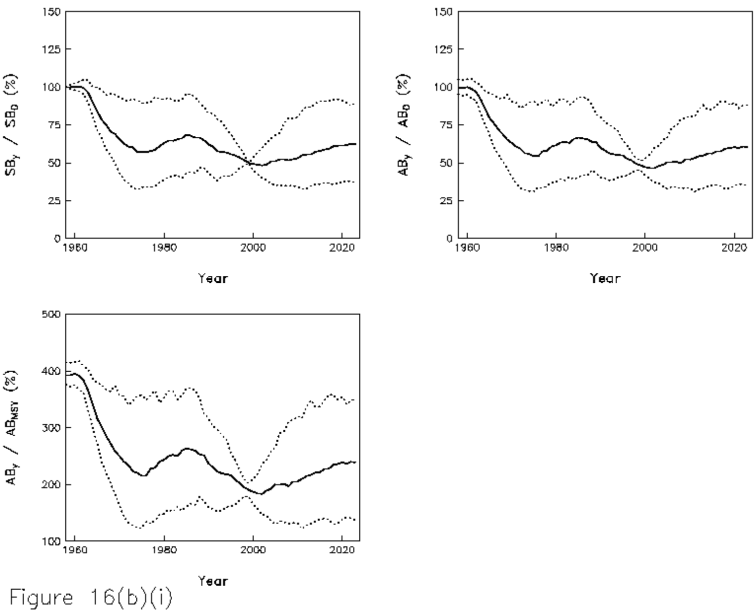

Figure 16(b)(i)

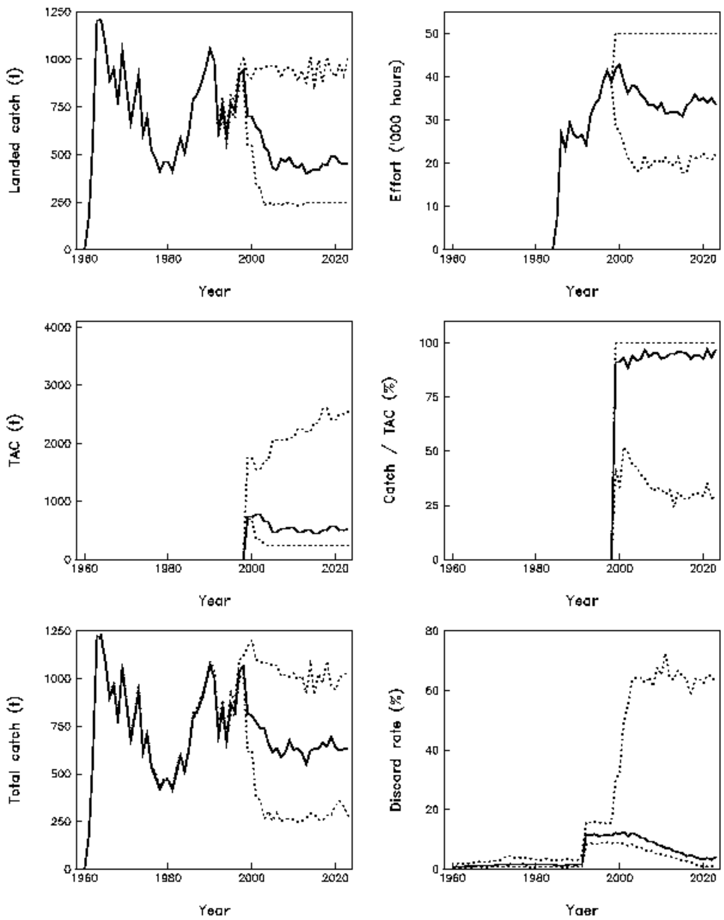

Figure 16(b)(ii)

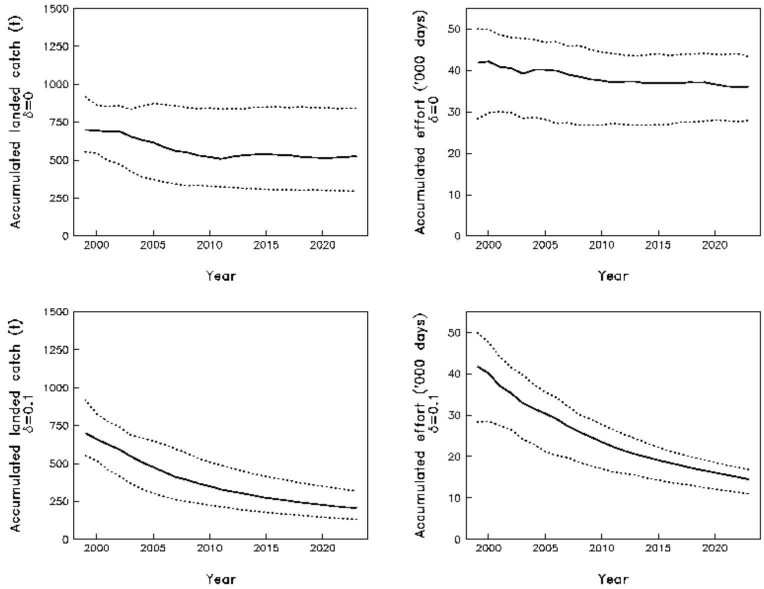

Figure 16(b)(iii)

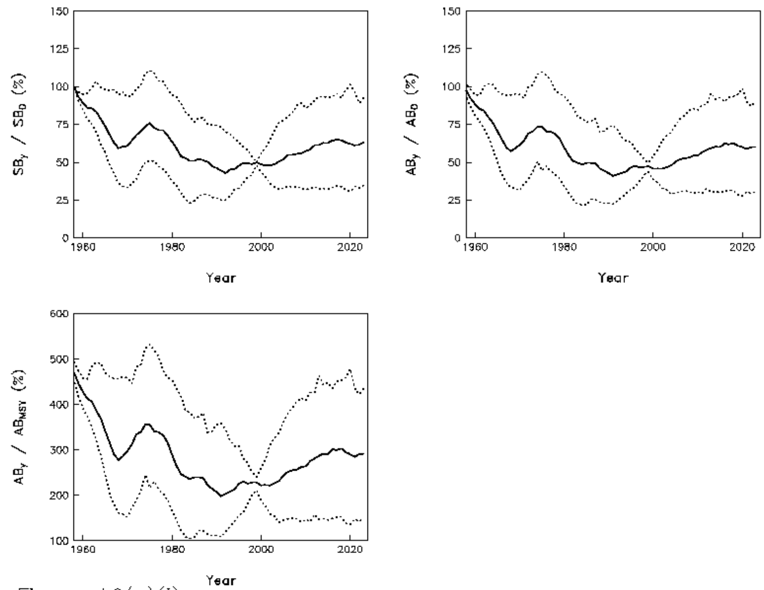

Figure 16(c)(i)

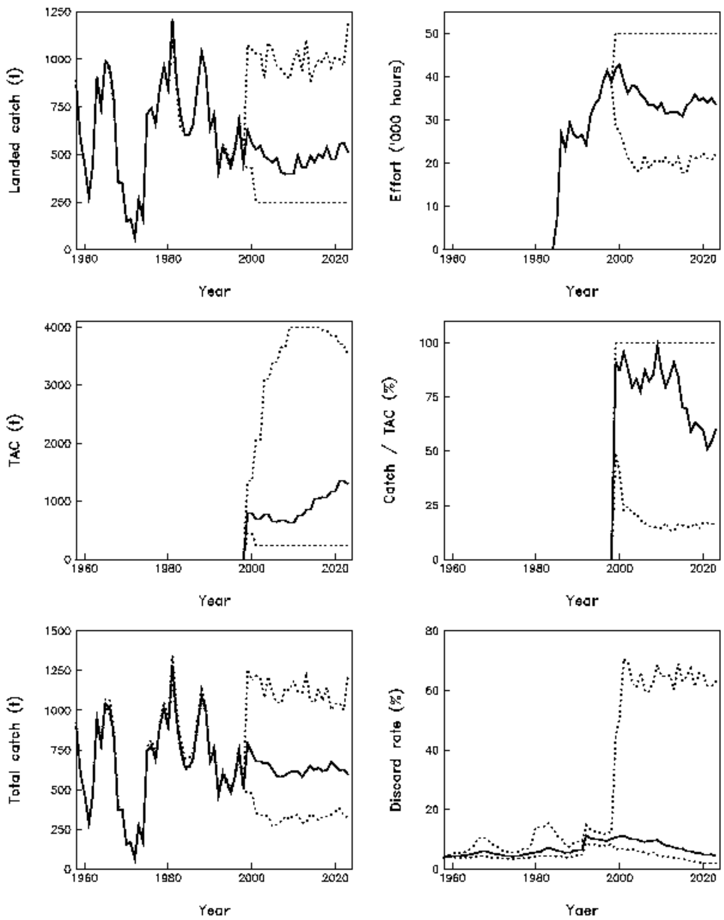

Figure 16(c)(ii)

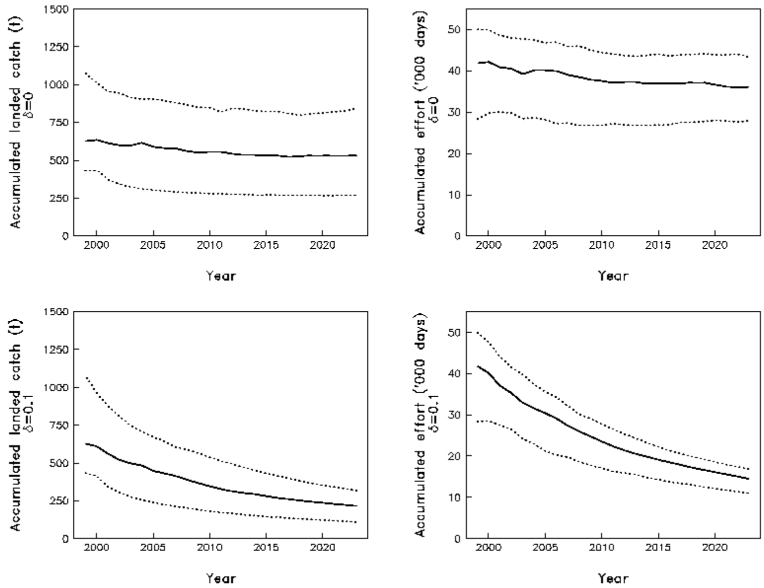

Figure 16(c)(iii)

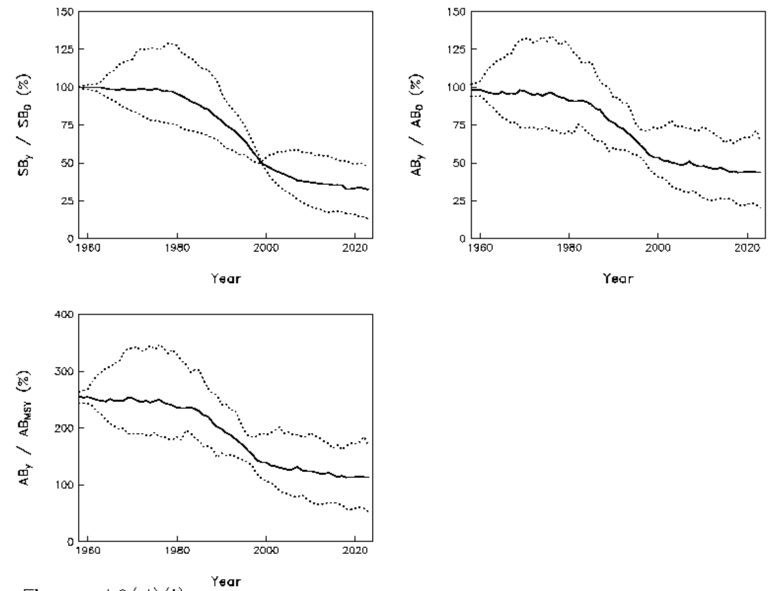

Figure 16(d)(i)

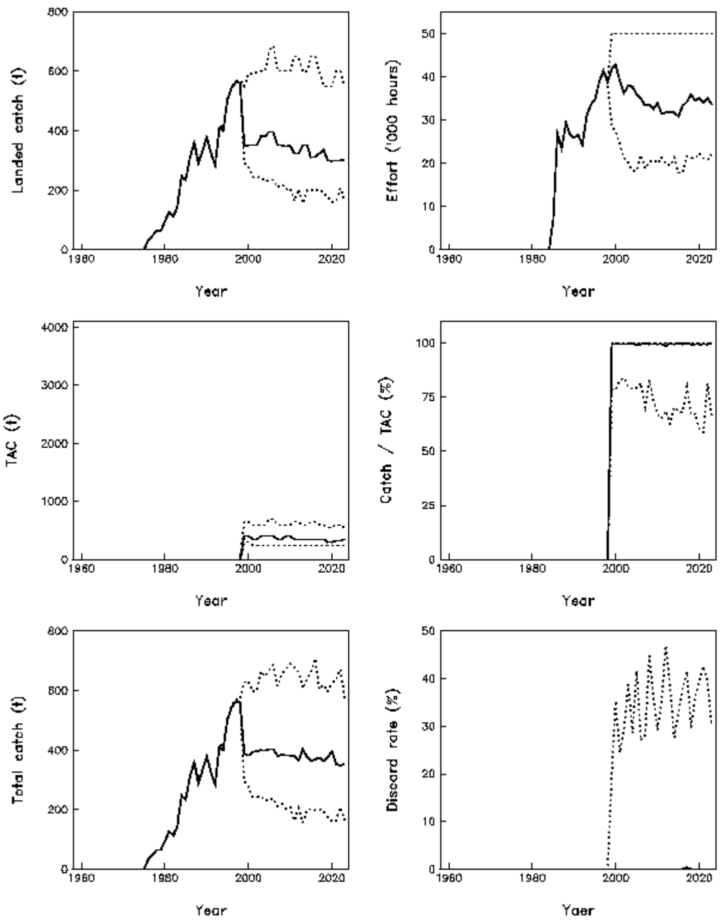

Figure 16(d)(ii)

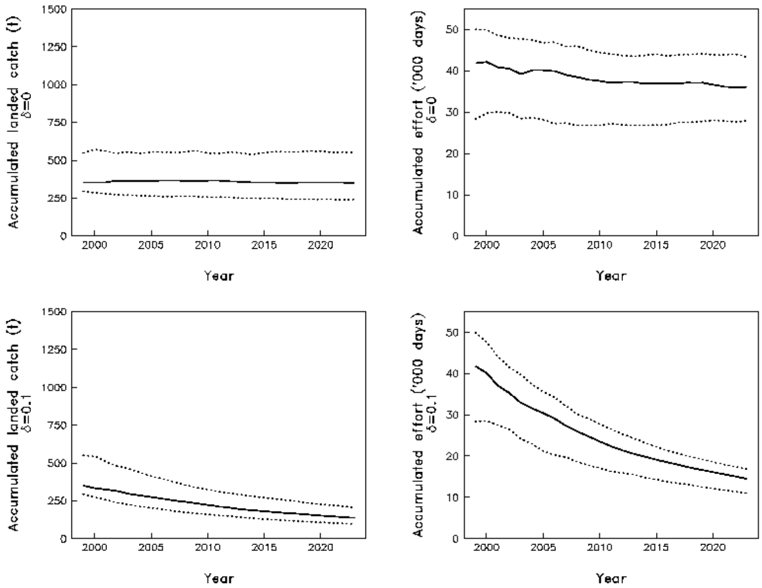

Figure 16(d)(iii)

Figure 16 : Medians and 90% intervals for the time-trajectories of various quantities of interest to management for the base-case trial for an illustrative harvest strategy. Results are shown in (a) for spotted warehou, in (b) for tiger flathead, in (c) for jackass morwong, and in (d) for pink ling.

The spawner biomass at the start of 1999 is always half of that in 1958 as this is one of the specifications of the base-case trial. The ratio of the available biomass in 1999 to that in 1958 differs from 50% (particularly for ling – Figure 16(d)(i)) because available biomass is not identical to spawner biomass. There is some "recovery" for spotted warehou, tiger flathead and jackass morwong after the application of the harvest strategy, while the biomass of ling continues to drop over time. It should be noted, however, that the biomass for the first three of these species is not below the level at which *MSY* is achieved, B_{MSY}, in 1999, i.e. this harvest strategy underutilises the resource. This result is perhaps surprising because, at least for spotted warehou, the results in Section 5.1 indicate that biomass and *MSY* are generally over-estimated for this species (see, for example, Figure 7). In contrast, the estimates of biomass and of *MSY* for the other three species tend to be negatively biased.

The wide 90% intervals of biomass prior to 1999 reflect the impact of random variation in recruitment. The change in the median biomass over time prior to 1999 reflects the impact of the historical catches. For spotted warehou and pink ling, species that were first targeted intensively only in the 1980s, the median biomass is relatively constant until the mid-1980s. In contrast, the median biomass trajectories for jackass morwong and tiger flathead are inversely correlated with the historical catches of these species. This feature of the results arises because there is no attempt to estimate historical recruitments for any of the species (due to lack of data). It may have been that the periods of high catches of tiger flathead and jackass morwong corresponded to periods of above average recruitment (rather than to say above average availability) but, in the absence of data on the age-composition of the historical catches, it is not possible to verify this.

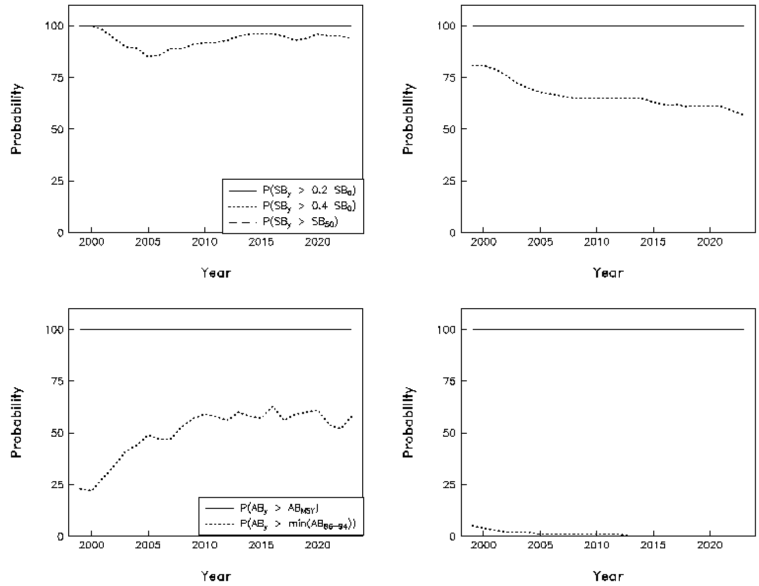

Figure 17(a)

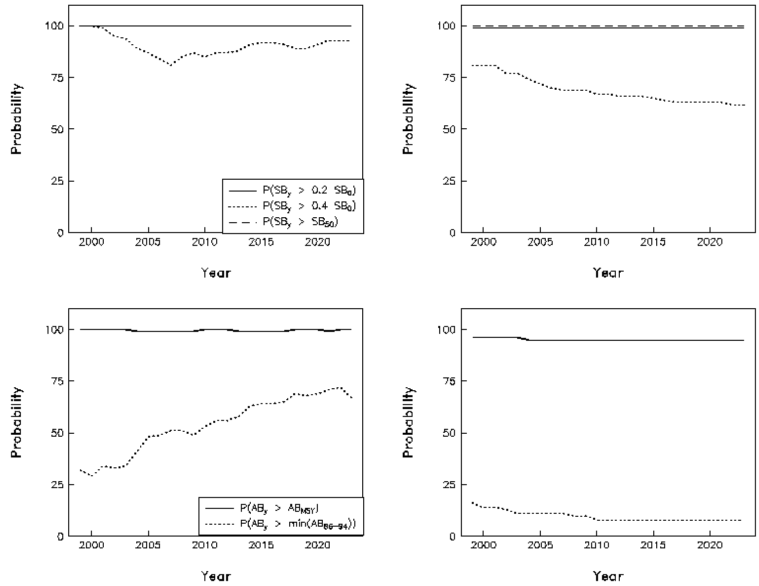

Figure 17(b)

Figure 17 : Time-trajectories of the probability of being above $0.2B_0$, $0.4B_0$, B_{MSY}, B_{50}, and the lowest available biomass between 1986 and 1994 for the base-case trial for an illustrative harvest strategy. Results are shown in (a) for spotted warehou, in (b) for tiger flathead, in (c) for jackass morwong, and in (d) for pink ling. The results in the leftmost panel are the annual values and those in the rightmost panel relate to the probability evaluated over the years from 1958 until the year indicated on the x-axis.

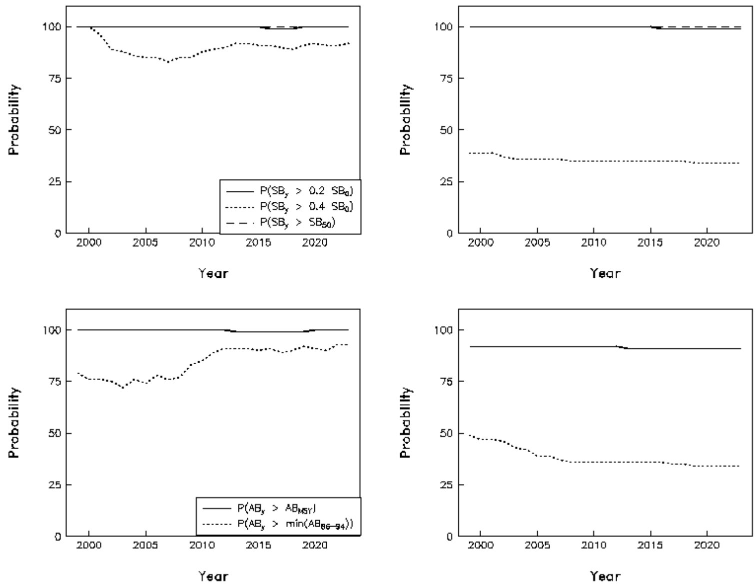

Figure 17(c)

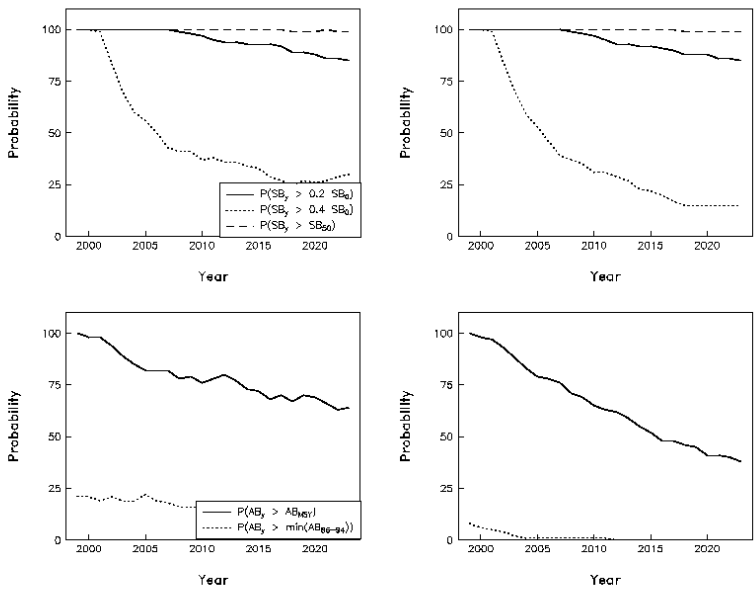

Figure 17(d)

Figure 17 : Time-trajectories of the probability of being above $0.2B_0$, $0.4B_0$, B_{MSY}, B_{50}, and the lowest available biomass between 1986 and 1994 for the base-case trial for an illustrative harvest strategy. Results are shown in (a) for spotted warehou, in (b) for tiger flathead, in (c) for jackass morwong, and in (d) for pink ling. The results in the leftmost panel are the annual values and those in the rightmost panel relate to the probability evaluated over the years from 1958 until the year indicated on the x-axis.

The distributions of future landed catch are very wide, although this is consistent with the time-sequence of historical catches for spotted warehou, tiger flathead and jackass morwong which also exhibit considerable variability over time. The median trajectories of catch (and effort) track downward over time and then stabilise. As a consequence, for example, the catches for pink link after 1999 are (in median terms) smaller than those from 1993 to 1998. The levels of effort required to take the future annual catches also vary considerably between simulations but, in median terms, remain above 1993 levels. A not inconsequential fraction of the distribution of the future annual effort equals the maximum limit set in the operating model of 50,000 hours. It should be recalled that the operating model relates only to a subset of the SEF (see Figure 2) and so the results in Figure 16 may differ quite substantially from application of the base-case harvest strategy to data for the entire SEF.

The *TAC*s for tiger flathead and pink ling remain relatively constant over time. In contrast, those for jackass morwong and (particularly) those for spotted warehou increase substantially over the 25-year projection period. As a consequence of this, the landed catches are similar to the *TAC*s for tiger flathead (Figure 16(b)(ii)) and pink ling (Figure 16(d)(ii)) whereas the ratio of the landed catch to the *TAC* declines markedly over time for the other two species. The inability of the landed catch to match the *TAC* for spotted warehou and jackass morwong is attributable to a variety of factors, e.g. limits on effort, but primarily because the annual catch is constrained by the "market catch" (see Sections 5 of Appendix D and Section 3 of Appendix E). The implications of these limits are explored further in the next section.

The most evident feature of the distribution for the discard rate is the very high 95%iles in the years after 1998. The bulk of the discard rate distributions are close to the (pre-specified) levels but occasional major differences between the *TAC* and the catch corresponding to the effort expended can lead to large-scale discarding. This is most evident for pink ling, the discard rate for which is virtually zero in over 50% of the simulations but exceeds 30% in some 5% of simulations. While this result is disturbing as it reflects both a loss in biomass and in catch, it is hardly unexpected given the attempt by the harvest strategy to reduce catches of pink ling when the *TAC*s for the other species caught primarily in the same depths (mainly spotted warehou) are increasing over time.

The results in Figure 17 are as expected given the results in Figure 16. There is only small probability of dropping below 40% of the pre-exploitation equilibrium biomass and a negligible probability of dropping below 20% of the pre-exploitation equilibrium biomass and B_{MSY}. The exception to this is pink ling (Figure 17d) for which the probability of being above 40% of the pre-exploitation equilibrium level drops to as low as 0.25 in 2018. There is an increasing trend over time in the probability of being above the lowest available biomass from 1986 to 1994 for all species except pink ling.

The results in Figure 16 confirm the importance of the interaction between effort (by depth zone) and the (landed) catches that the model attempts to match (the "target" catch, i.e. the minimum of the *TAC* and the "market" catch – see Section 5 of Appendix D). Figure 18 plots the relationship between the "target" catch and the landed catch corresponding to the levels of effort selected (the "fitted" catch – see Equation D.18a). Each point in Figure 18 is the result for a single trial. The results in Figure 18 pertain to the base-case trials and the year 1999. Plots for other years and trials exhibit similar patterns. Figure 19 examines the differences between the "target" and “fitted” catches further by plotting the inter-species cross-correlations among the residuals (“target” – “fitted”) based on the information in Figure 18.

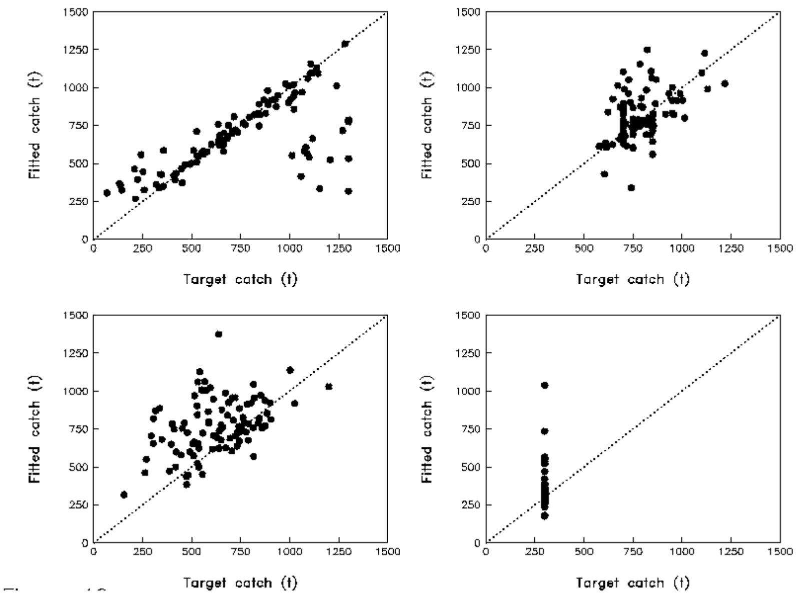

Figure 18 : Relationship between the “target catch” for a species for 1999 and the best fit values. The results in this figure relate to the base-case trials and an illustrative harvest strategy.

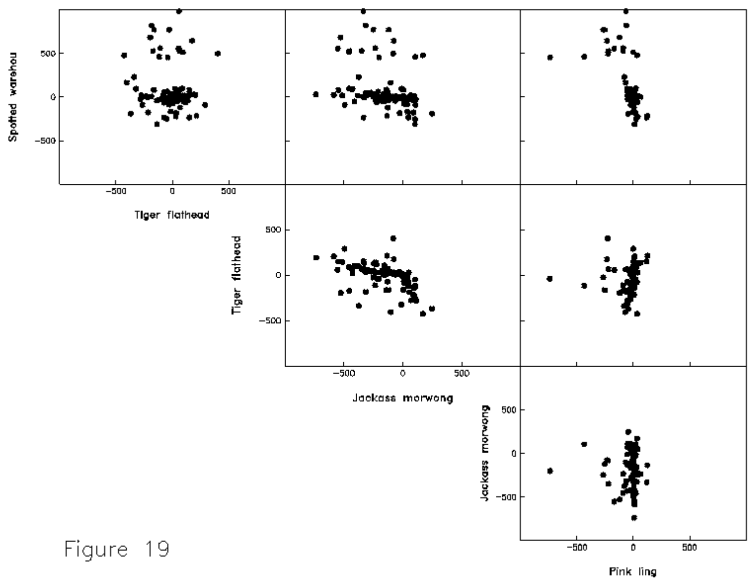

Figure 19 : Inter-species cross-correlations among the differences between the fitted and “target” catches for 1999. The results in this figure relate to the base-case trial and an illustrative harvest strategy.

The dots in Figure 18 would all fall along the diagonals if it was possible to select effort levels by depth zone to match the “target” catches exactly. However, this is not always possible. Most of “fitted” catches for spotted warehou are “similar” to the “target” catches although the “fitted” catches are generally higher than the “target” catches for low “target” catches and lower than the “target” catches for high “target” catches (upper left panel of Figure 18). In contrast, the “fitted” catches for tiger flathead are almost randomly distributed about the “target” values while those for jackass morwong tend to be larger than the “target” values. The results for pink link are uninformative as the *TAC* was 300*t* for all 100 simulations. However, the bulk of the “fitted” catches are close to 300*t* (Figure 19). Somewhat surprisingly, there is no clear evidence from Figure 19 that the “residuals” are negatively correlated among species.

5.2.2 Sensitivity to the target level of fishing mortality

Figure 20 shows the trade-off among five performance measures (the median average total catch, the median average landed catch, the median AAV (see Equation 4), the median discard rate, and the median of the ratio of the landed catch to the *TAC*) and the median final depletion of the spawner biomass. Results are shown in Figure 20 for a range of harvest strategies based on the Integrated Analysis estimator and a catch control law in which the target level of fishing mortality is set to ϕF_{MSY}. Values for ϕ from 0.1 to 2.9 in steps of 0.2 are considered to capture a range of harvest strategies from highly conservative to highly exploitative. Note that the *TAC*s are constrained to be in the range 250 – 4,000*t* and not to change by more than 50% from one year to the next.

Results are shown in Figure 20 for four trials: (a) the base-case trial, (b) a trial in which the maximum effort is increased from 50,000 hours to 100,000 hours (abbreviation “Maximum effort = 100,000”), (c) a trial in which the “market” catches are assumed to be infinite (abbreviation “Infinite “market” catches”), and (d) a trial in which the “market” catches are assumed to be infinite and in which the maximum effort is increased to 100,000 hours (abbreviation “No constraints”). These trials therefore examine the sensitivity of the results to the (assumed) maximum effort level and the assumptions regarding “market” catches.

There is a clear (and almost linear) trade-off between the size of the total removals (i.e. discards and landed catches combined) and the median final depletion (Figure 20a). Not surprisingly, the trade-offs achieved in the four trials are essentially identical. It is noteworthy, however, that the lowest median final depletion (that corresponding to setting *TAC*s using a “target” fishing mortality of $2.9F_{MSY}$) is sensitive to the specifications related to “market” catches and to the maximum effort level. In particular, the lowest depletions occur when the “market” catches are infinite and no limitations are placed on effort. The base-case constraints limit the lowest median final depletion to 59%, 52%, 52% and 21% for the four species respectively.

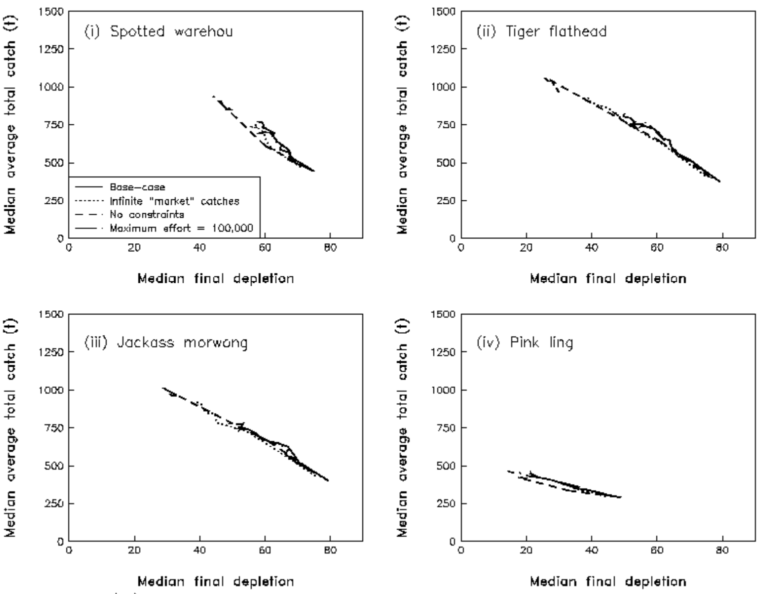

Figure 20(a)

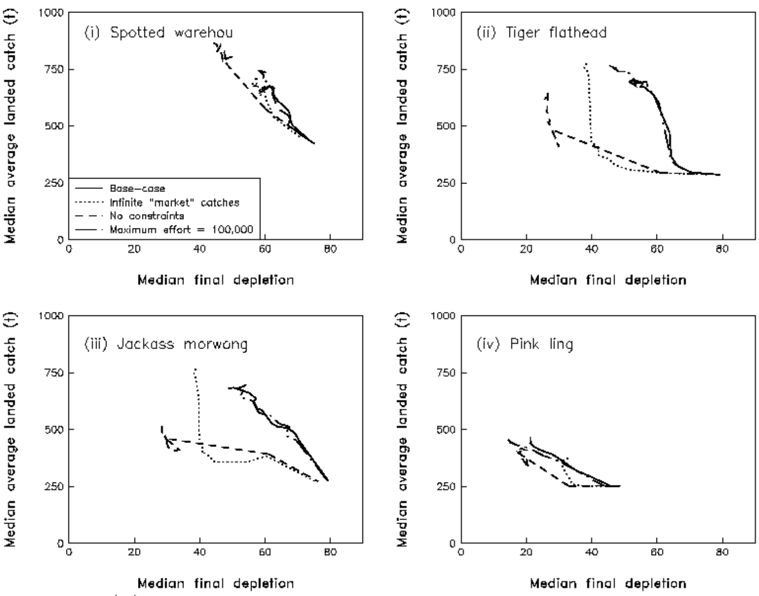

Figure 20(b)

Figure 20 : Trade-off between five performance measures (see text for details) and median final depletion. Results are shown in panels (i)-(iv) for the four species. This figure explores sensitivity to the target level of fishing mortality and the limitations placed by the maximum effort level and the magnitude of the "market" catches.

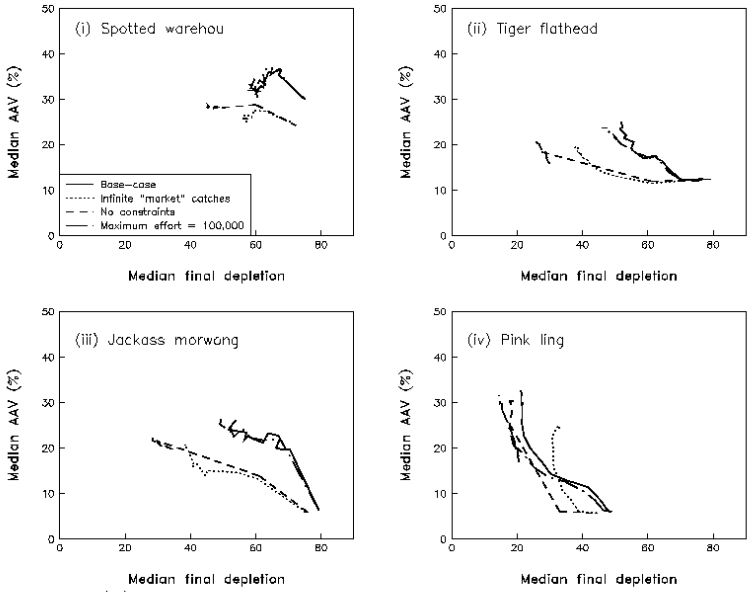

Figure 20(c)

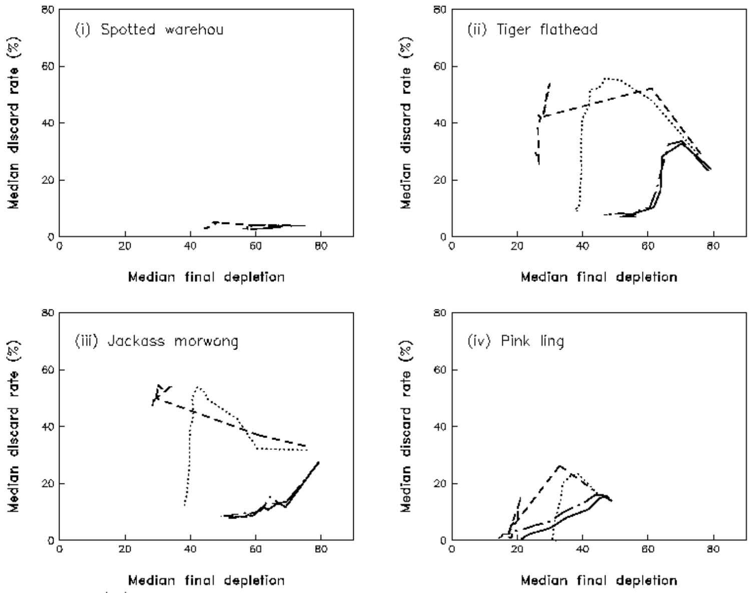

Figure 20(d)

Figure 20 : Trade-off between five performance measures (see text for details) and median final depletion. Results are shown in panels (i)-(iv) for the four species. This figure explores sensitivity to the target level of fishing mortality and the limitations placed by the maximum effort level and the magnitude of the “market” catches.

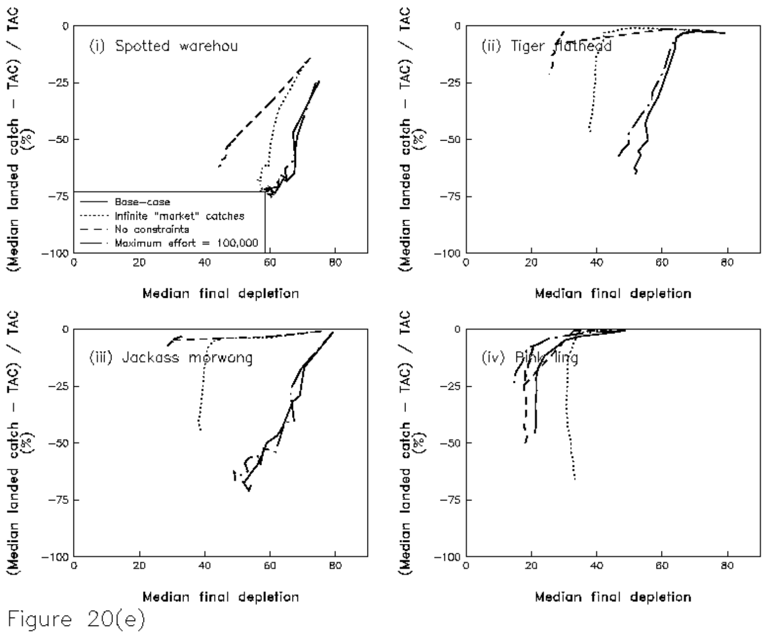

Figure 20 : Trade-off between five performance measures (see text for details) and median final depletion. Results are shown in panels (i)-(iv) for the four species. This figure explores sensitivity to the target level of fishing mortality and the limitations placed by the maximum effort level and the magnitude of the "market" catches.

The linear pattern and the clear trade-off between average catch and final depletion evident in Figure 20(a) is not evident in Figure 20(b), which plots the median average landed catch against the median final depletion. For example, for tiger flathead and jackass morwong, the average catch increases very sharply for depletions between 35 and 45% for the case in which the "market" catches are infinite (Figures 20b(ii) and 20b(iii)). Furthermore, in contrast to the situation in Figure 20(a), the average catch for a given median final depletion differs among the four trials. In general, the base-case and maximum effort = 100,000 hours trials achieve the highest landed catches while the "no constraints" trial achieves the lowest landed catches. The extent of inter-annual variability in catches is lowest for the trials in which the "market" catches are infinite. The AAV is also sensitive to the species (highest for spotted warehou and lowest for tiger flathead) and the level of final depletion (Figure 20c).

The reason for the differences among trials evident in Figure 20(b) is that discard rates differ among these trials (Figure 20d). The discard rates for the trials in which the "market" catches are infinite are far higher than those for the trials in which the "market" catches are based on the historical data. The higher discard rates for the trials in which the "market" catches are infinite occur because of increased mis-matches between the *TAC*s for the different species. Such mis-matches are a consequence of an imprecise estimator, which can result in *TAC*s that fluctuate markedly over time, combined with quite different levels of productivity among species. The discard rates drop with decreasing median final depletion and hence with increasing landed catches for the base-case and "Maximum effort = 100,000 hours" trials. The landed catches for these latter trials differ markedly from the *TAC*s (Figure

20e). This is not surprising because the landed catches are bound by the "market" catches for these trials.

The results in Figure 20 suggest that although in some trials the effort equals the maximum possible (see, for example, Figure 16), the approach used to model the "market" catches has a much larger impact on the overall results.

5.2.3 Summarising the results further

There is an enormous volume of results for each trial. In order to compare the results for different harvest strategies for a given trial or the results for one harvest strategy across several trials, it is necessary to summarise the results further. This has been achieved by means of a graphical summary (e.g. Figure 21). The graphical summary provides the medians and 90% intervals for the final depletion (spawner biomass), the lowest depletion (spawner biomass), the average landed catch over the years 1999 to 2023, the AAV (see Equation 4), the difference between the *TAC*s and the landed catches (see Equation 5), and the discard rate (see Equation 6) for each harvest strategy (or trial). The graphical summary also shows the probability of being above three key reference points at the end of the projection period: $0.2B_0$, B_{MSY}, and the lowest available biomass over the period 1986–94. Results are shown in panel (a) for spotted warehou, in panel (b) for tiger flathead, in panel (c) for jackass morwong, and in panel (d) for pink ling.

For the purposes of comparing among trials, it is necessary to select a "reference" harvest strategy. The harvest strategy chosen in this study to be a "reference" is based on the Integrated Analysis estimator and sets *TAC*s according to an ϕF_{MSY} rule. The value of ϕ is chosen separately for each species so that for spotted warehou, tiger flathead, and jackass morwong, the probability in 2023 of exceeding the lowest available biomass during 1986–94 is close to 0.5 for the base-case trial. For pink ling, this criterion leads to an unrealistically low value for ϕ, so the value for ϕ has been chosen so that the probability in 2023 of exceeding the lowest available biomass during 1986–94 is 0.3 for the base-case trial. This "reference" harvest strategy is therefore relatively consistent with the current "management strategy" for SEF species to keep the biomass above the lowest biomass during 1986–94.

5.2.4 Sensitivity to the initial depletion level

Figure 21 contrasts the performance of the "reference" harvest strategy for trials in which the initial (1999) depletion is varied from 0.1 to 0.8. Perhaps not unexpectedly, the final and lowest depletions and the average catch are correlated with the initial depletion. The relationship between the initial depletion and the average catch are not as clearcut as might have been expected. For example, the median average catch for spotted warehou increases from 393*t* for an initial depletion of 0.1 to 640*t* for an initial depletion of 0.5 but levels off for higher initial depletions (Figure 21a). This behaviour is a consequence of the impact of the "market" catches which limit the landings of spotted warehou, tiger flathead and jackass morwong. This is also evident from the distributions for the difference between the landed catch and the *TAC*, which become more negative as the initial depletion is increased. The discard rate tends to decrease as the initial depletion is increased.

Figure 21(a)

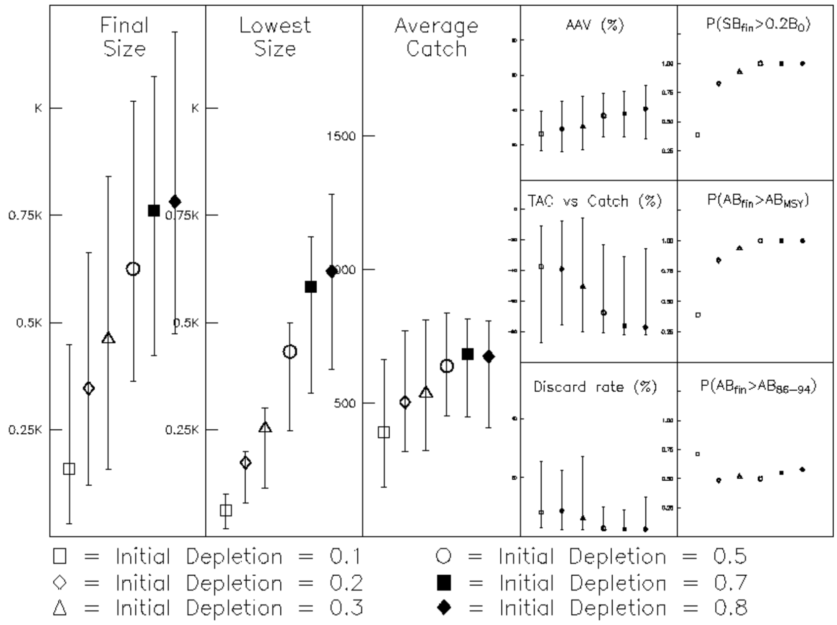

Figure 21(b)

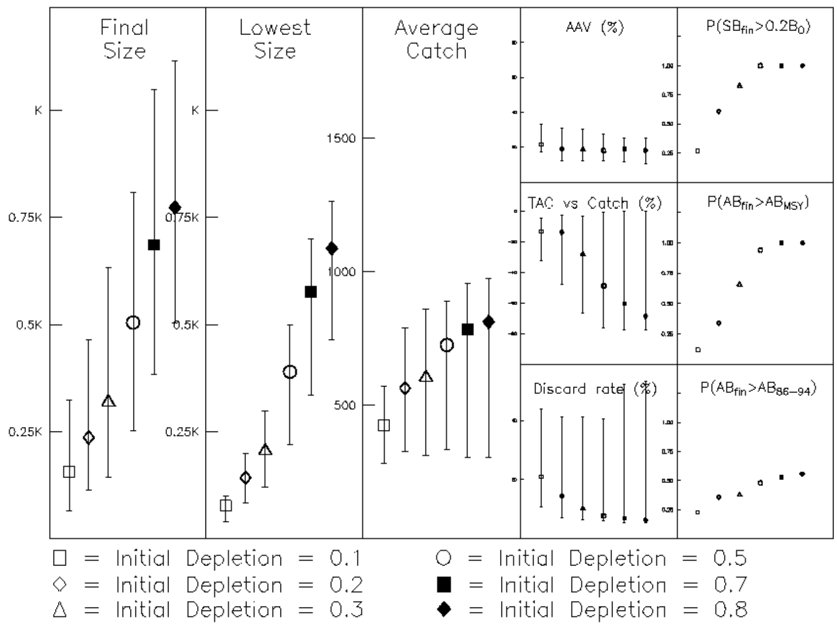

Figure 21 : Comparison plot to evaluate the implications of different initial depletions for the “reference” harvest strategy. Results are shown in (a) for spotted warehou, in (b) for tiger flathead, in (c) for jackass morwong, and in (d) for pink ling.

Figure 21(c)

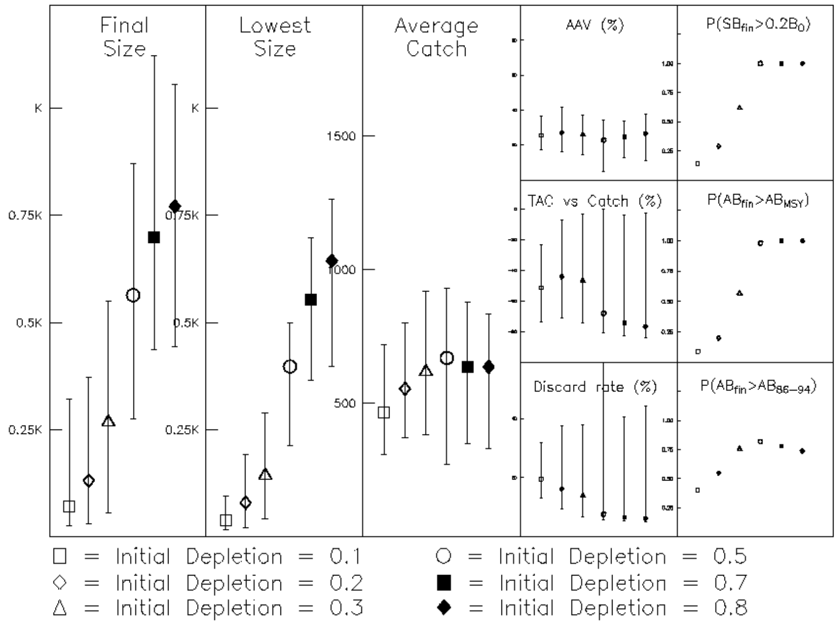

Figure 21(d)

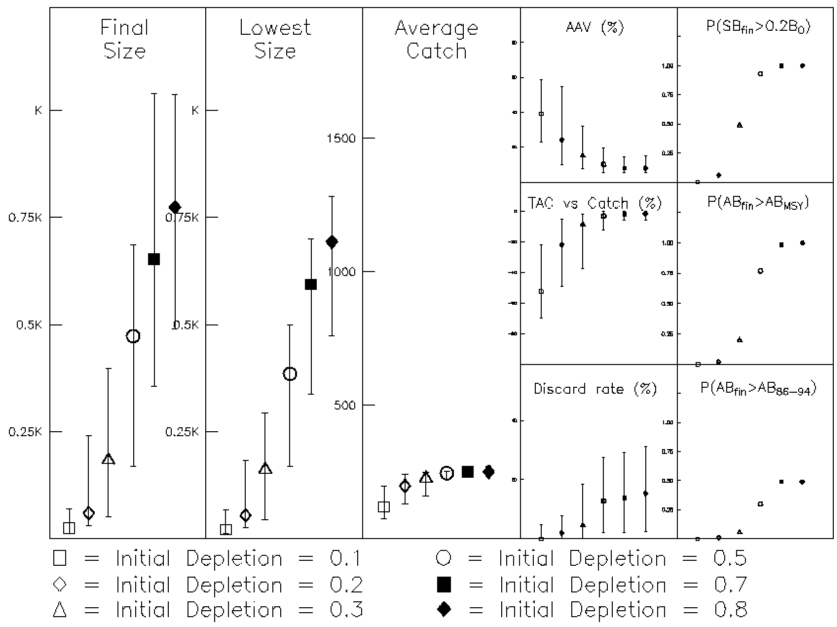

Figure 21 : Comparison plot to evaluate the implications of different initial depletions for the "reference" harvest strategy. Results are shown in (a) for spotted warehou, in (b) for tiger flathead, in (c) for jackass morwong, and in (d) for pink ling.

The values for the statistic $P(AB_{fin} > AB_{86-94})$ also indicate the behaviour of the harvest strategy. For the lowest initial depletions, the tendency is for the available biomass in 2023 not to be larger than the lowest available biomass during 1986–94.

This pattern is, however, not evident for spotted warehou (the value of the statistic is 0.75 for an initial depletion of 0.1 for spotted warehou) because there is substantial recovery from low initial depletions for spotted warehou.

The extent of recovery from a highly depleted state is relatively poor. For example, both jackass morwong and pink ling decline further if the harvest strategy is applied when the initial depletion is 0.1 or 0.2 (Figures 21c and 21d). Recovery from low levels does occur for tiger flathead and (particularly) for spotted warehou. The extent of recovery clearly depends on the values assumed for ϕ. Figure 22 therefore also shows results for the case ϕ=1. As expected, the extent of recovery from low population size is greater if the value assumed for ϕ is lower. For example, the median final depletion for tiger flathead increases from 16 to 32% for the trial in which the resource is initially at 10% of its pre-exploitation equilibrium level when ϕ is reduced from its "reference" value of 2.0 to 1.0 (Figure 21). The improvement in recovery potential when ϕ is set to 1 has, however, to be traded off against generally higher levels of discarding and lower landed catches (particularly for an initial depletion of 50%). The increased recovery rate evident for spotted warehou, tiger flathead and jackass morwong is not evident for pink ling because the reference value for ϕ is less than 1 for pink ling.

The results for pink ling in Figure 21 are perhaps particularly surprising; even when the stock is initially at 80% of its pre-exploitation equilibrium level, the estimator is unable to determine this and sets a low *TAC*. The harvest strategy is also completely unable to allow recovery from low initial depletions. The latter is perhaps not surprising because even if the *TAC* is set equal to the lowest possible (250*t*) continued decline will still occur for the lowest initial depletions. Another reason for the poor performance for pink ling is that for low initial depletions, the estimate of *MSY* is unbiased or slightly negatively biased whereas the estimate of *MSY* can be highly negatively biased for high initial depletions (Figure 8).

5.2.5. Sensitivity to structural assumptions

Figure 23 examines the performance of the "reference" harvest strategy for the case in which the parameters of the stock-recruitment relationship are modified to be more pessimistic than those for the base-case trial. For ease of presentation, only the more extreme of the scenarios regarding the extent of depensation and the value of steepness (See Table E.5) are included in Figure 23.

Allowing for depensation at low stock size does not impact the results negatively, except to a slight extent for spotted warehou. This is because, although the functional form chosen to model depensation (see Equation D.5) implies low recruitment at low spawner stock size, it also implies more resilience of recruitment to reductions in spawner stock size at high levels of spawner stock size. The harvest strategy does not drive the resource to low levels so it is the benefits of the functional form chosen come into play. The results for this trial would, of course, have been much more pessimistic had the trials been conducted starting at a lower initial depletion.

Figure 22(a)

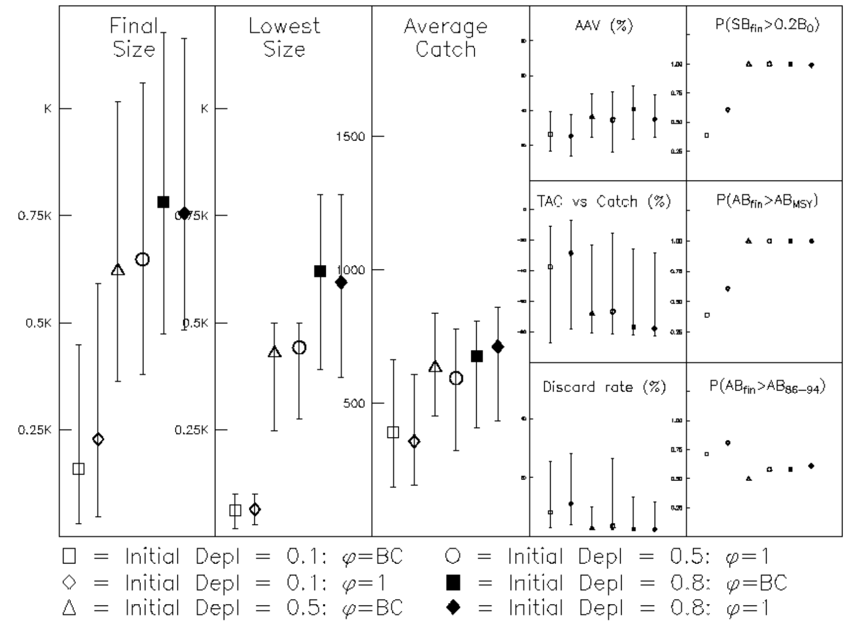

Figure 22(b)

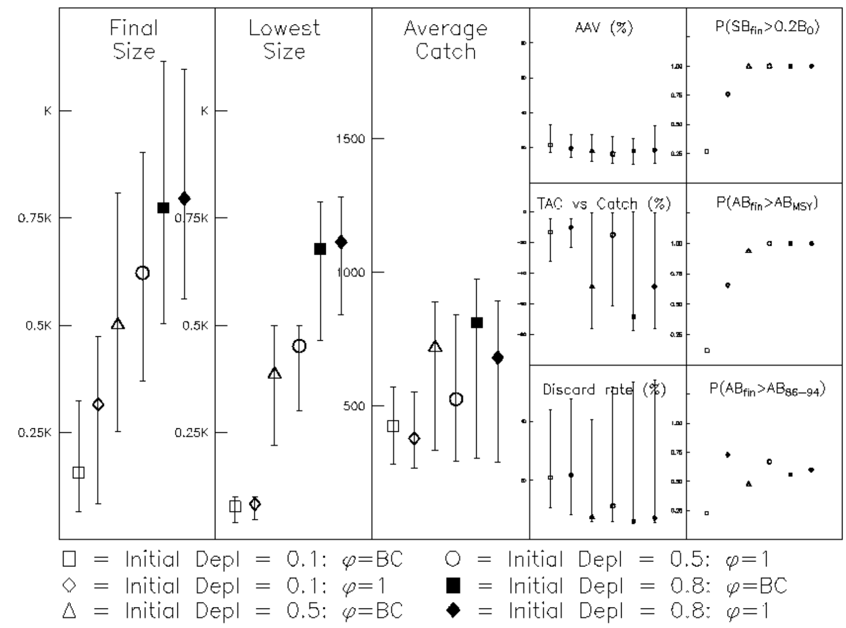

Figure 22 : Comparison plot to evaluate the implications of three different initial depletions for the "reference" harvest strategy (BC) and a variant thereof in which the value of ϕ used in the catch control law is set equal to 1 for all species (ϕ=1).

Figure 22(c)

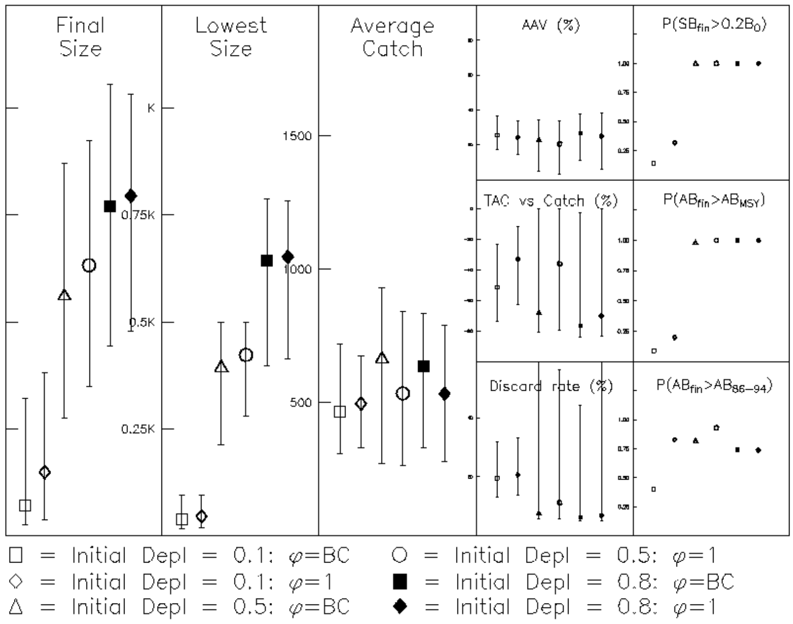

Figure 22(d)

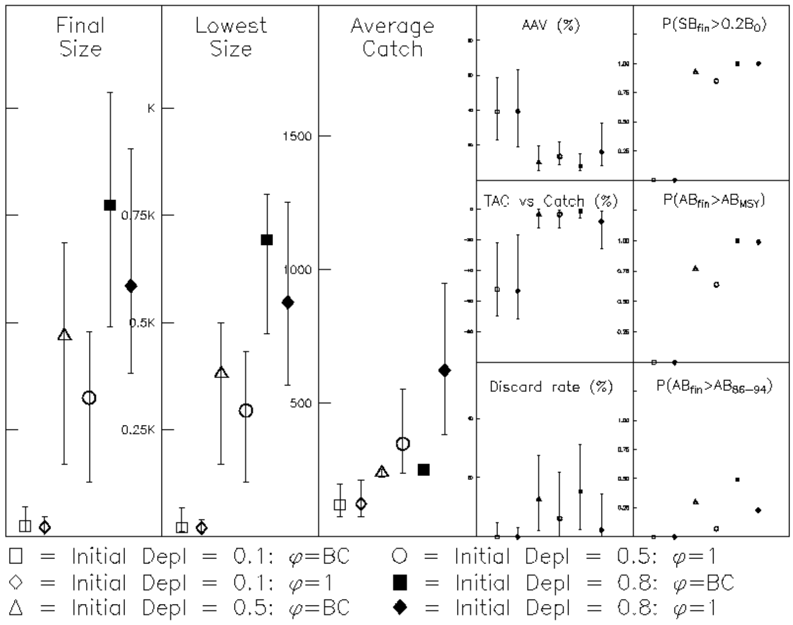

Figure 22 : Comparison plot to evaluate the implications of three different initial depletions for the "reference" harvest strategy (BC) and a variant thereof in which the value of ϕ used in the catch control law is set equal to 1 for all species (ϕ=1*)*.

Figure 23(a)

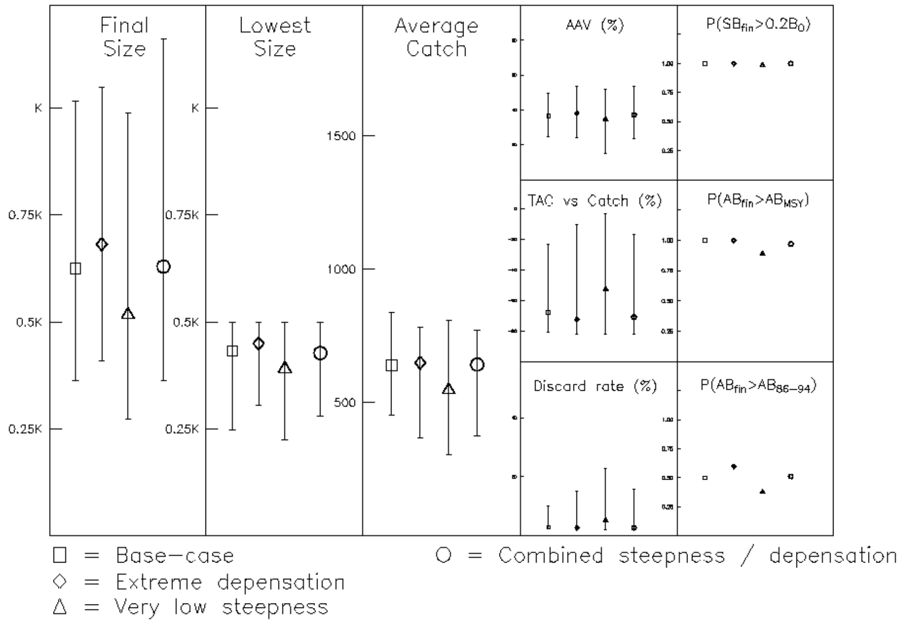

Figure 23(b)

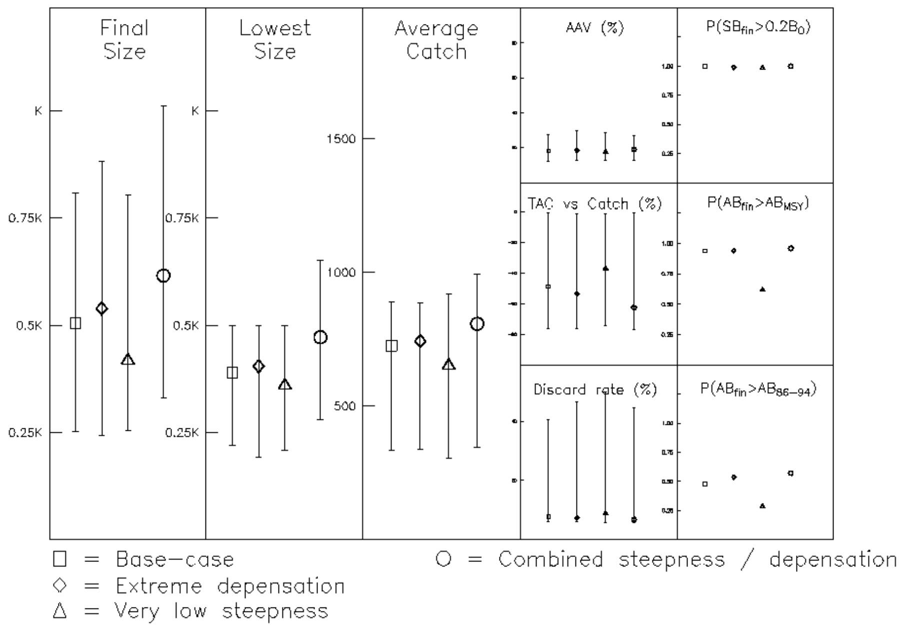

Figure 23 : Comparison plot to evaluate the implications for the "reference" harvest strategy of different specifications for the stock-recruitment relationship.

Figure 23(c)

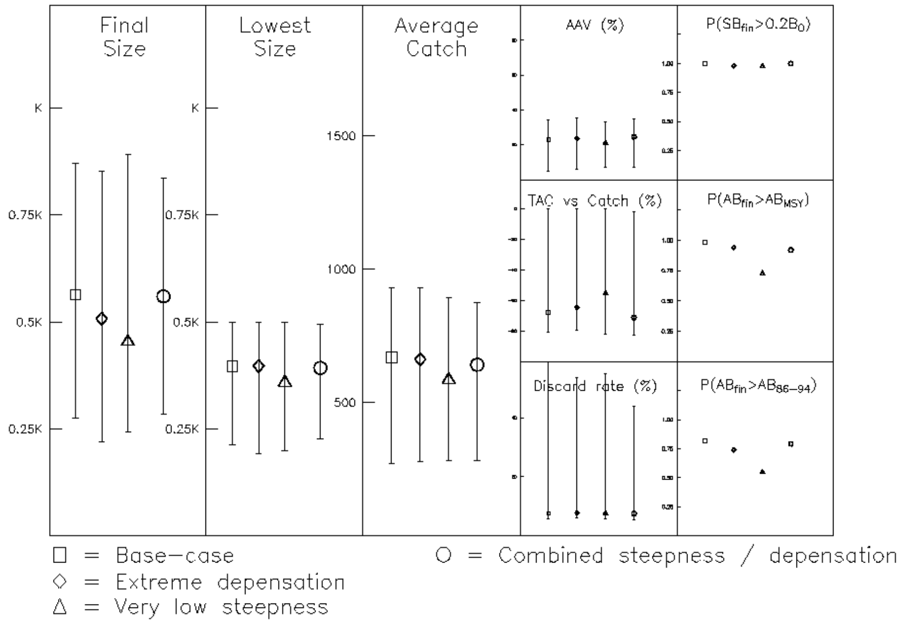

Figure 23(d)

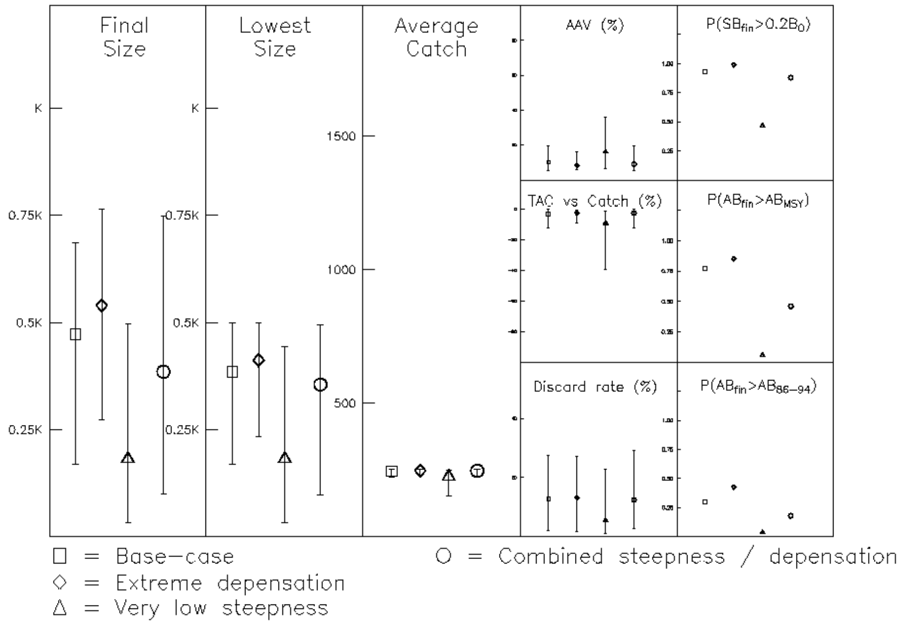

Figure 23 : Comparison plot to evaluate the implications for the "reference" harvest strategy of different specifications for the stock-recruitment relationship.

Figure 24(a)

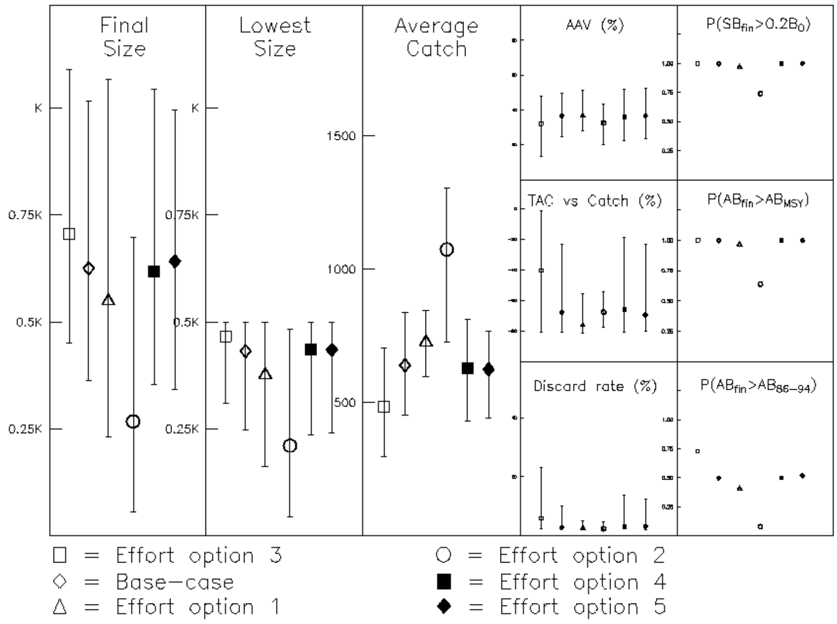

Figure 24(b)

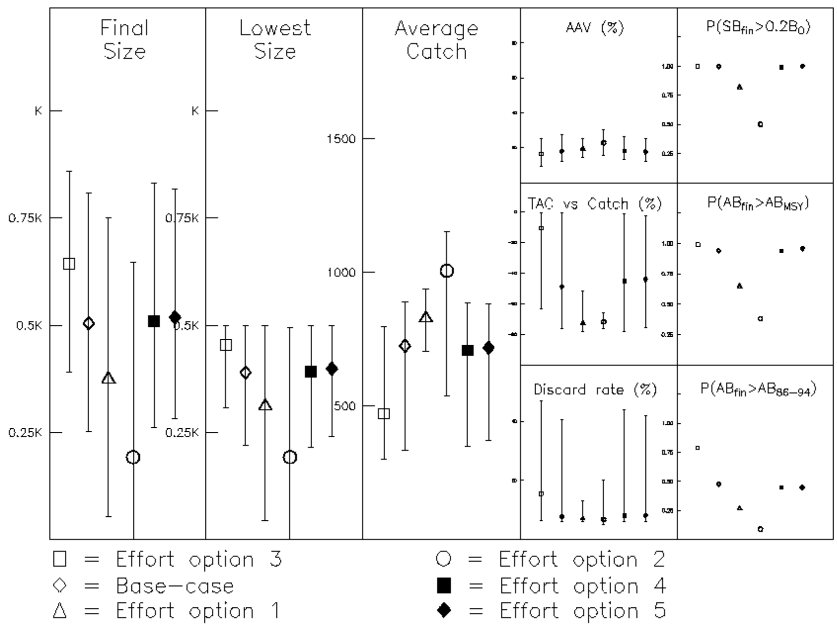

Figure 24 : Comparison plot to compare the implications for the "reference" harvest strategy of different specifications for the relationship between fishing effort and fishing mortality.

Figure 24(c)

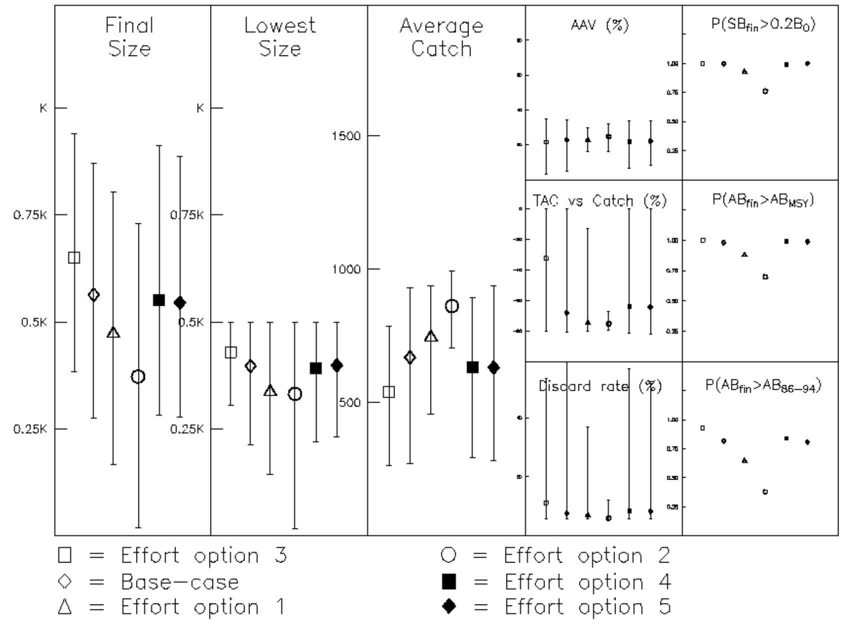

Figure 24(d)

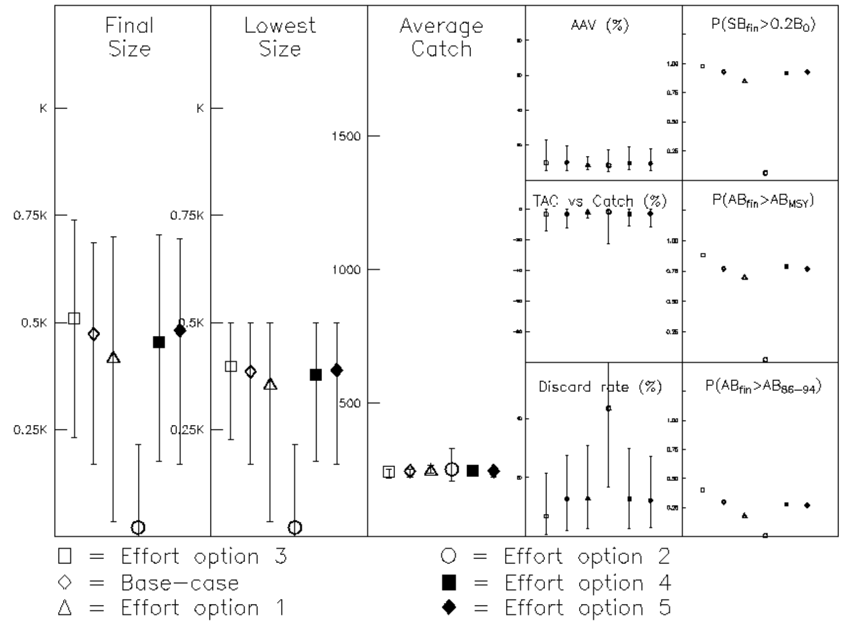

Figure 24 : Comparison plot to compare the implications for the “reference” harvest strategy of different specifications for the relationship between fishing effort and fishing mortality.

In contrast to the results for the “extreme depensation” trial, the results for the “very low steepness” trial are markedly more pessimistic than those for the base-case trial. Both the final depletions and the average catches are lower when steepness is less than the values assumed for the base-case trial. This is evident for all four species but particularly for pink ling for which the median final depletion is less than 40% of that for the base-case trial (Figure 23d). This effect is due, in part, to the constraint that *TAC*s cannot be set lower than 250*t* which restricts the extent to which the harvest strategy can react to a low steepness (if, indeed, it is able to detect that steepness is low). The results for the combined trial are intermediate between the trials that examine the implications of depensation and lower steepness.

Figure 24 examines the implications of changing the relationship between fishing effort and fishing mortality to include density-dependence in catchability and (undetected) time-trends in catchability (see Section 3 of Appendix D). As expected, final sizes are lower and catches higher when efficiency is increasing over time (effort options 1 and 2) while final sizes are higher and average catches lower when efficiency is decreasing over time (effort option 3). The impact of changing the rate of change in efficiency from –0.02 to 0, 0 to 0.02 and 0.02 to 0.05 is "linear" in its impact on the median final depletion for tiger flathead and jackass morwong (Figure 24(b) and 24(c)). However, for the other two species, the impact of a change in fishing efficiency from 0.02 to 0.05 is much greater than would be expected from the results for the other two change rates. The implications of a 5% per annum increase in efficiency for pink ling is particularly catastrophic. Somewhat surprisingly, allowing catchability to increase (or decrease) for a period of years and allowing catchability to be correlated over time and among species (effort options 4 and 5) has relatively little impact on the results (Figure 24).

The results in Figure 11 indicate that estimation ability depends substantially on the ability to estimate *M*. In contrast, the results in Figure 25 suggest that in a feedback-control context, the impact of assuming an incorrect value for *M* is not particularly substantial. As expected from Figure 11 the results for pink ling (Figure 25d) are more optimistic when *M* is under-estimated than that assumed by the "reference" harvest strategy and *vice versa*. In contrast, the final sizes are higher for tiger flathead and jackass morwong when *M* is over-estimated (Figures 25b and 25c) because the "reference" harvest strategy detects a high total mortality from the age-composition data and reduces the *TAC*s (particularly for tiger flathead).

Figure 26 contrasts the implications of changing the assumptions related to the generation of recruitment. As expected, the widths of the final and lowest depletion distributions are very sensitive to the assumed level of variability in recruitment. Higher levels of recruitment variability ($\sigma_r = 1$) lead to a slightly greater probability of dropping below B_{MSY} while the converse is true for lower levels of recruitment variability ($\sigma_r = 0.3$). The widths of the distributions of final and lowest depletion and average catch are greater when recruitment is positively correlated over time and between species ("Correlation option 1" – see Section 4 of Appendix E for the detailed specifications for this trial).

Results (not shown here) indicate that density-dependent growth, changing the parameters related to variability and temporal correlation in selectivity, and the parameter related to variability in movement have little impact on the results.

Figure 25(a)

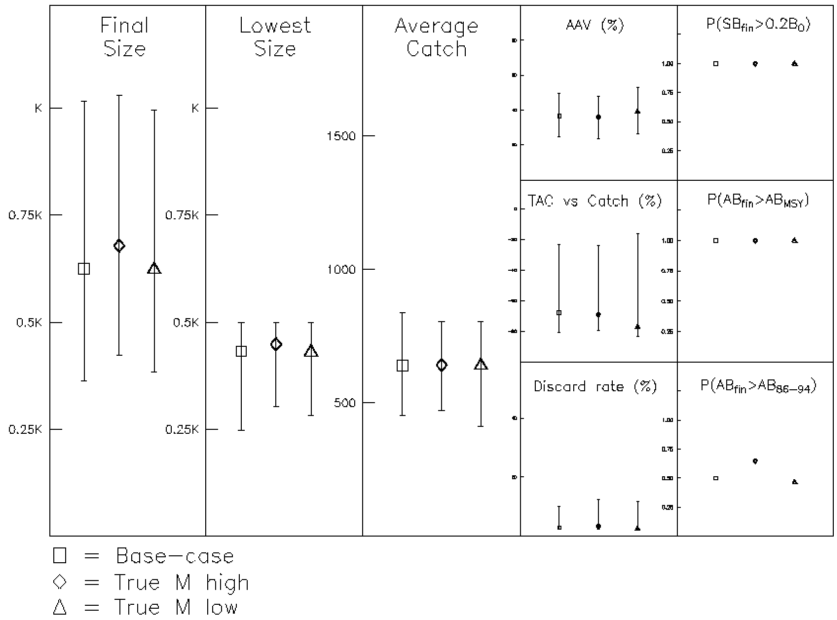

Figure 25(b)

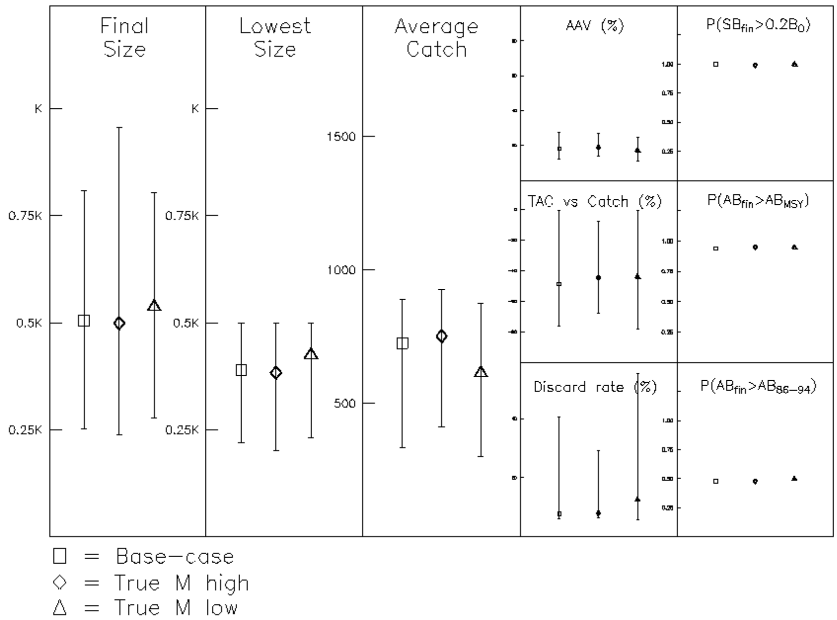

Figure 25 : Comparison plot to compare the implications for the "reference" harvest strategy of the value assumed for *M* differing from the true value.

Figure 25(c)

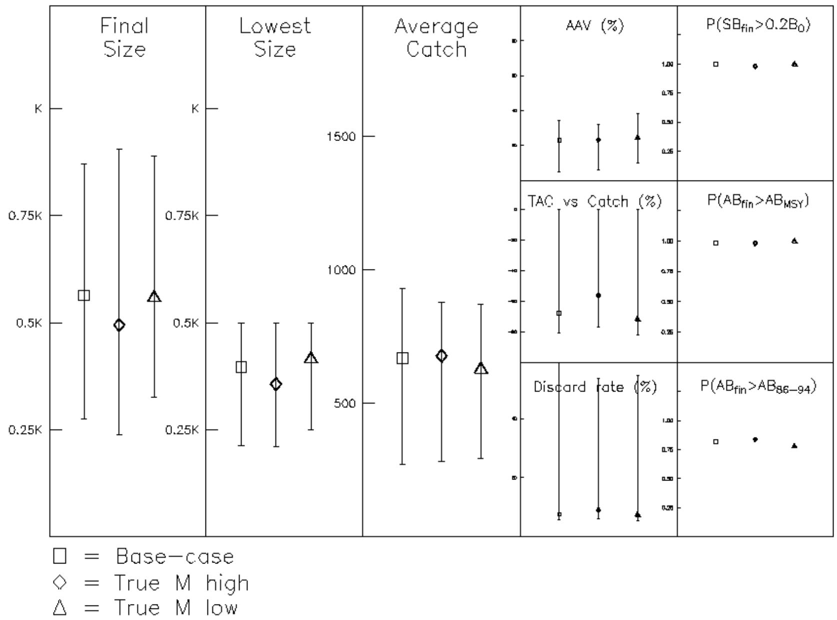

Figure 25(d)

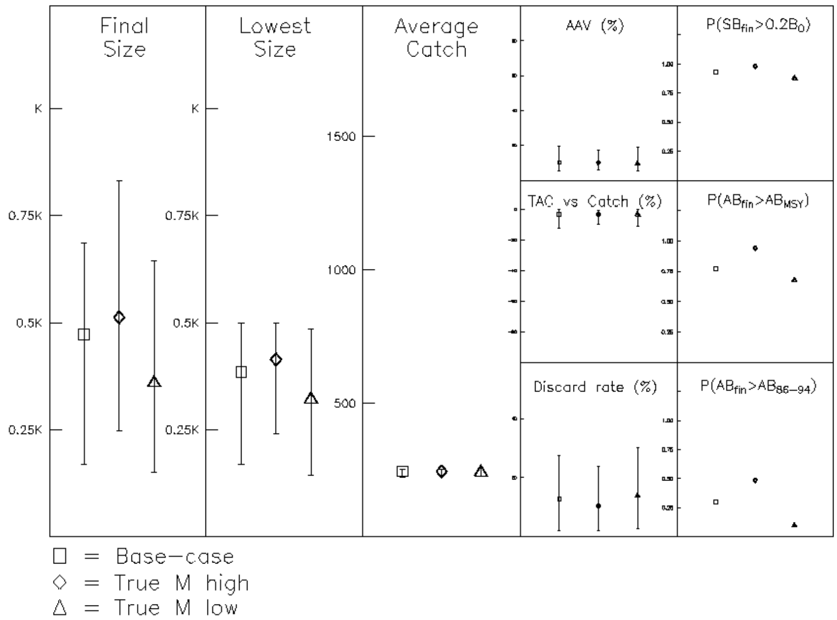

Figure 25 : Comparison plot to compare the implications for the "reference" harvest strategy of the value assumed for *M* differing from the true value.

Figure 26(a)

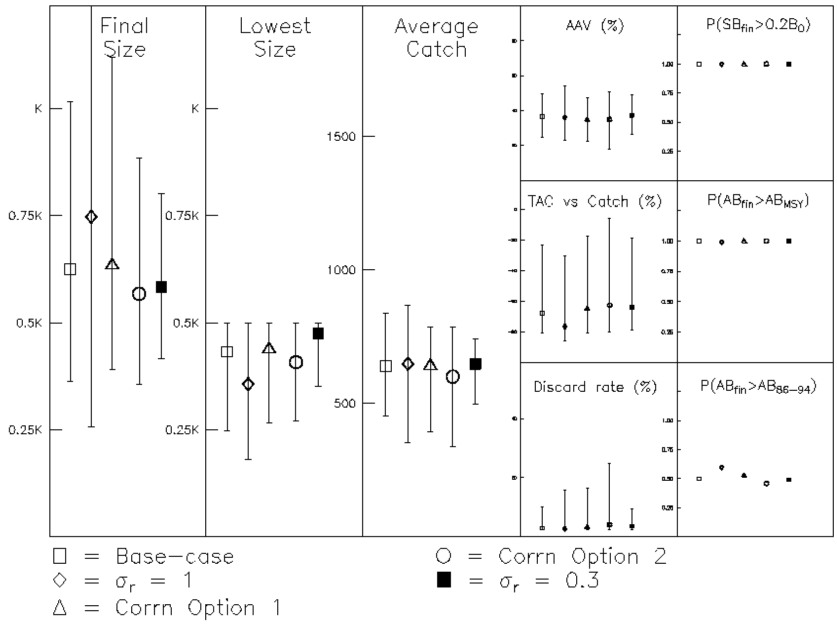

Figure 26(b)

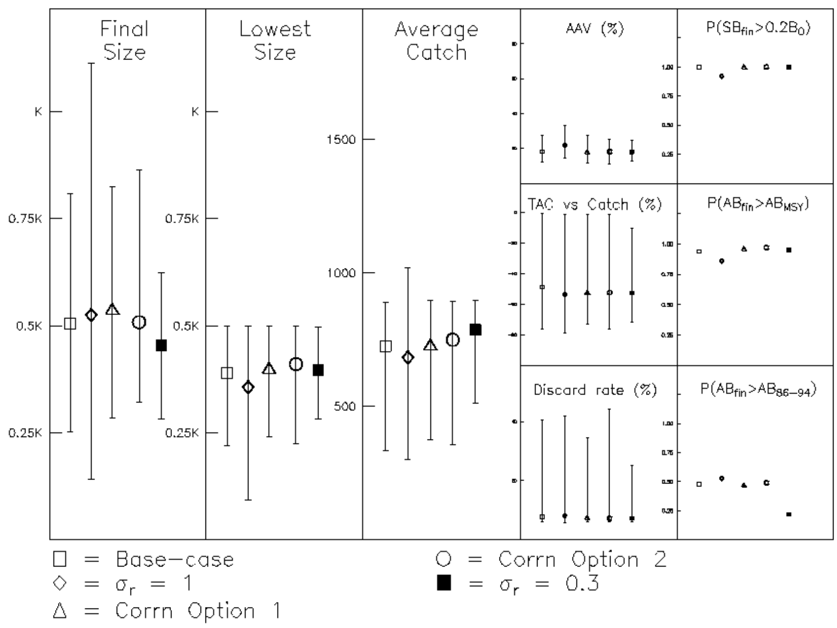

Figure 26 : Comparison plot to compare the implications for the "reference" harvest strategy of changing the specifications for how future recruitment is generated.

Figure 26(c)

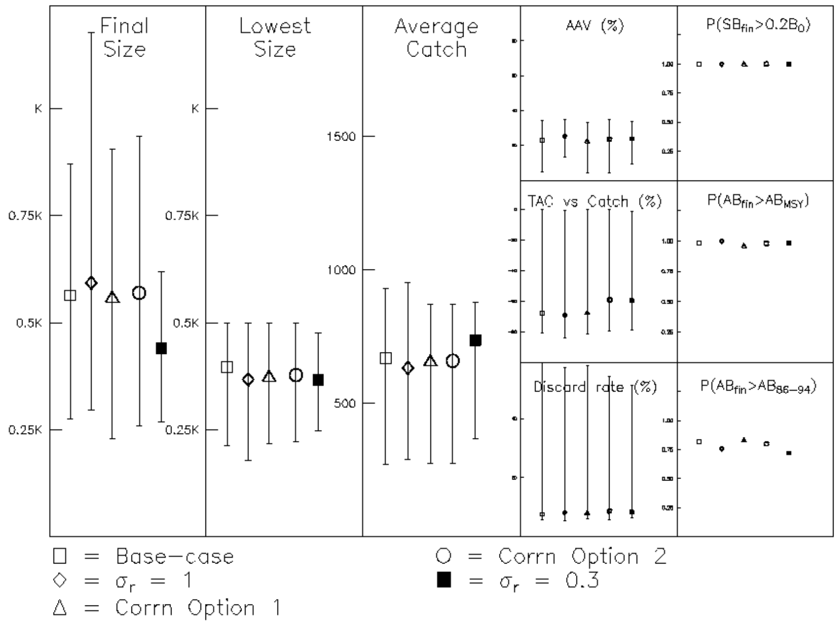

Figure 26(d)

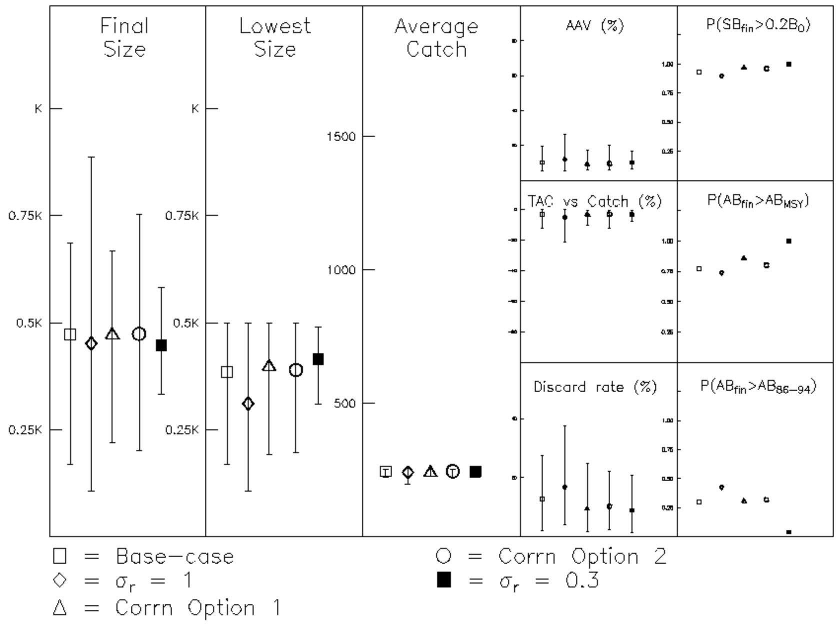

Figure 26 : Comparison plot to compare the implications for the "reference" harvest strategy of changing the specifications for how future recruitment is generated.

5.2.6 Sensitivity to the constraints on inter-annual variation in TACs

Section 6 of Appendix F lists the constraints imposed on inter-annual variability in *TAC*s. The variation in landings is, however, high (AAVs of 20-40%). In order to explore whether changing the constraint that *TAC*s are not allowed to change by more than 50% from one year to the next might impact (possibly reduce) this variation variants of the "reference" harvest strategy in which the constraint was set to 10%, 25%, 50% (base-case) and 100% were applied to the base-case trial. The results are reported in Figure 27.

Somewhat surprisingly, there is not a clear relationship between the size of the constraint and the extent of variation in landed catches. This is because for spotted warehou, tiger flathead and jackass morwong, the inter-annual variation in catches is due more to variation in the "market" catches than in the *TAC*s. There is a tendency for average catches to decrease and discarding to increase as the size of the constraint is increased from 10 to 100%. For spotted warehou and tiger flathead lower values for the constraint also imply a closer relationship between the landed catch and the *TAC*. In contrast, the value of the statistic $P(AB_{fin} > AB_{86-94})$ is higher if lesser constraints are placed on inter-annual variation in *TAC*s. It would seem appropriate therefore that any eventual harvest strategy should include quite tight limits on *TAC* variability. This is because: (a) from an industrial stability view point it is best to keep *TAC* variability low and (b) there appear to be no serious negative consequences in terms of resource conservation associated with tight limits on inter-annual *TAC* variability.

The *TAC*s for the "reference" harvest strategy are constrained to lie between 250 and 4000*t*. This is a very wide range so Figure 28 examines the implications of changing these restrictions. Reducing the maximum *TAC* from 4000 to 2000*t* ("Maximum TAC = 2000t" in Figure 28) has little impact on the results, although the differences between the landed catches and the *TAC*s are smaller for spotted warehou, tiger flathead and jackass morwong (Figure 28(a) – 28(c)). In contrast, imposing a minimum *TAC* of 100 rather than 250*t* has a much larger impact. In particular, the median and lower 5 percentile of the average catch distribution are lower and catch variability somewhat higher for spotted warehou, tiger flathead and jackass morwong. The impact of a low minimum *TAC* for pink ling is very substantial: the final and lowest depletions are much higher, average catches much lower (and more variable) and the discard rates are substantially higher (Figure 28d). The results in Figure 28 suggest that harvest strategies should certainly consider lower maximum and minimum *TAC*s than those imposed by the "reference" harvest strategy.

The "reference" harvest strategy involves conducting assessments (and hence changing the *TAC*) every second year. Figure 29 examines the impact on performance of conducting assessments annually, biennially (the "reference" assumption), every third year, and every fifth year. There is surprisingly little impact of increasing the inter-assessment period. There is a slight declining trend in the final and lowest sizes and in the AAV with increasing inter-assessment period. The upper 5th percentile of the discard rate distribution for tiger flathead (Figure 29(b)) drops substantially as the inter-assessment period is increased from one to five years. The match between the *TAC* and the landed catch also increases as the inter-assessment period is increased. The lack of sensitivity of the results to changing the inter-assessment period occurs for spotted warehou, tiger flathead, and jackass morwong because the catches are determined more by the "market" catches than by the *TAC*s. For pink ling, this occurs because the *TAC*s are always close to the minimum possible *TAC*.

Figure 27(a)

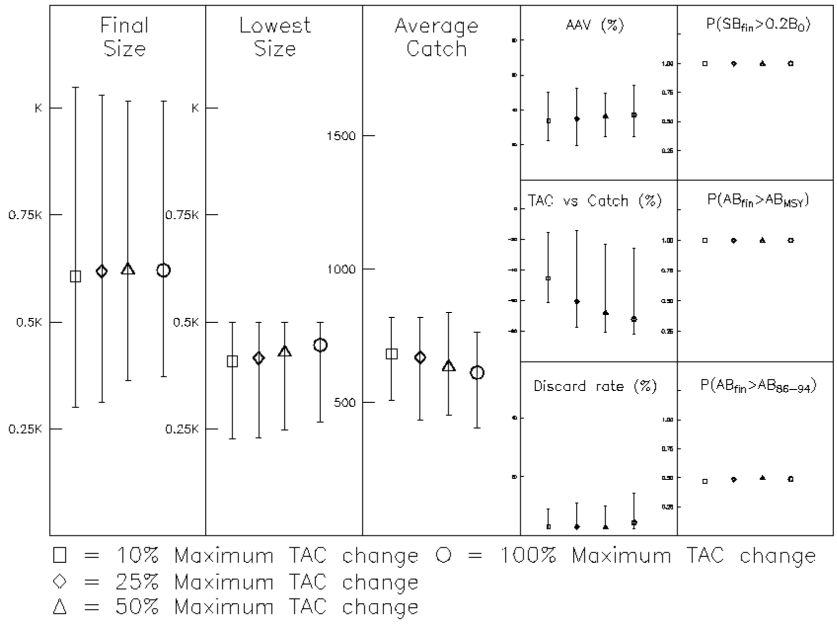

Figure 27(b)

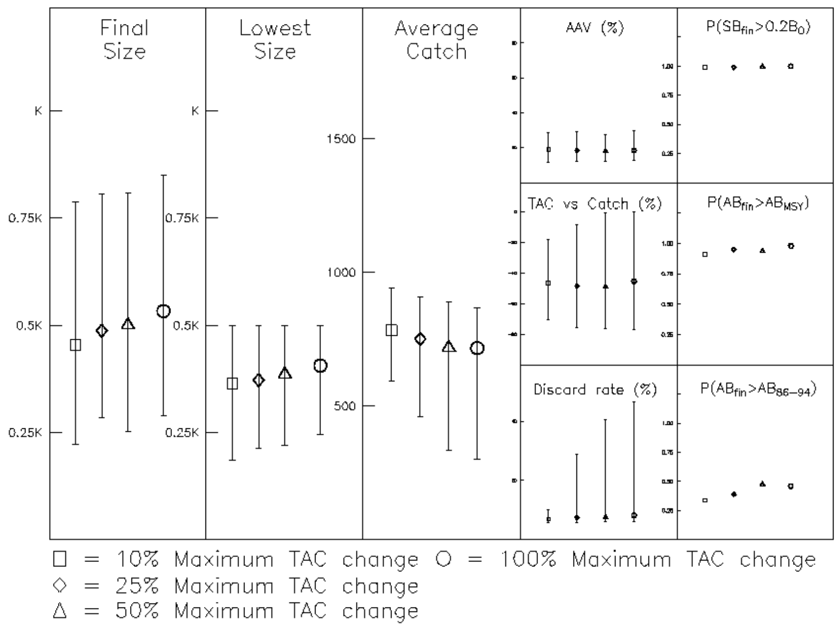

Figure 27 : Comparison plot to evaluate the implications of different constraints on inter-annual variation in *TAC*s.

Figure 27(c)

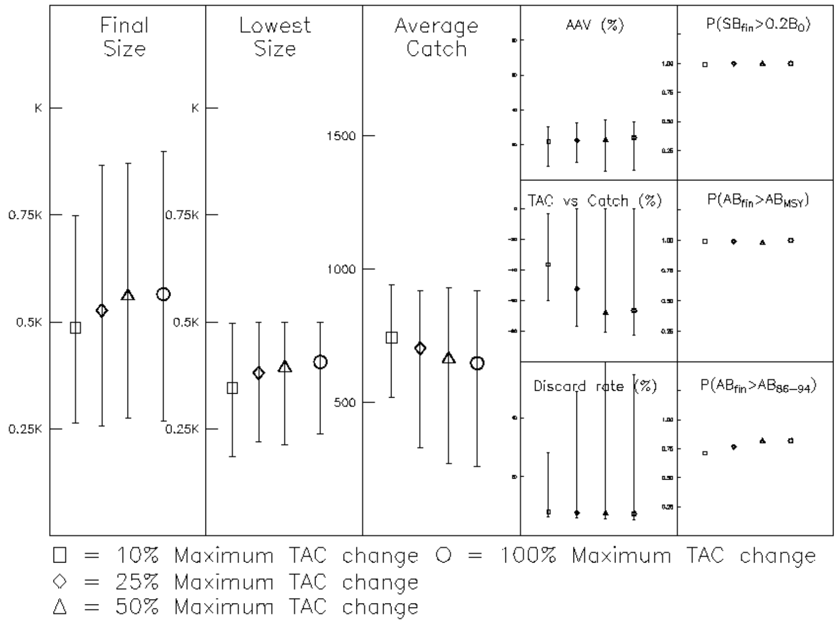

Figure 27(d)

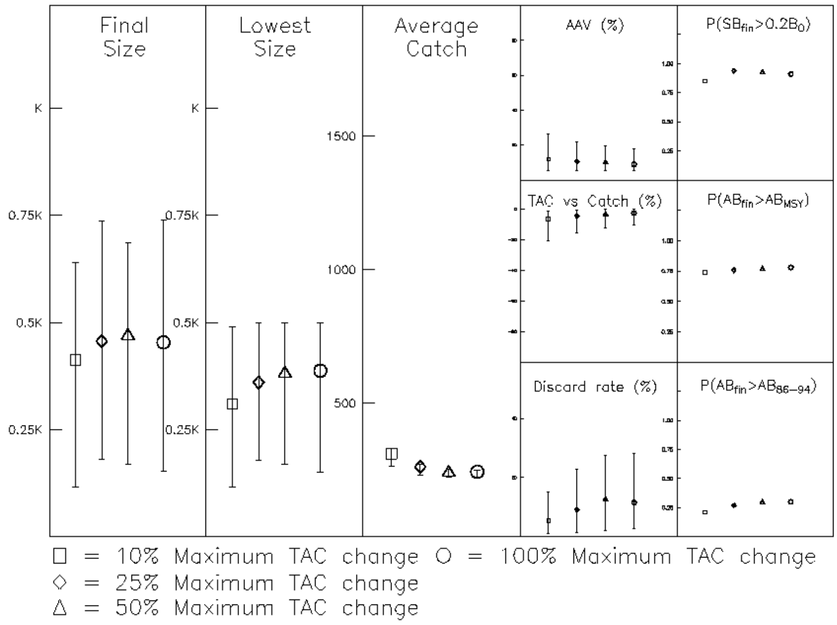

Figure 27 : Comparison plot to evaluate the implications of different constraints on inter-annual variation in *TAC*s.

Figure 28(a)

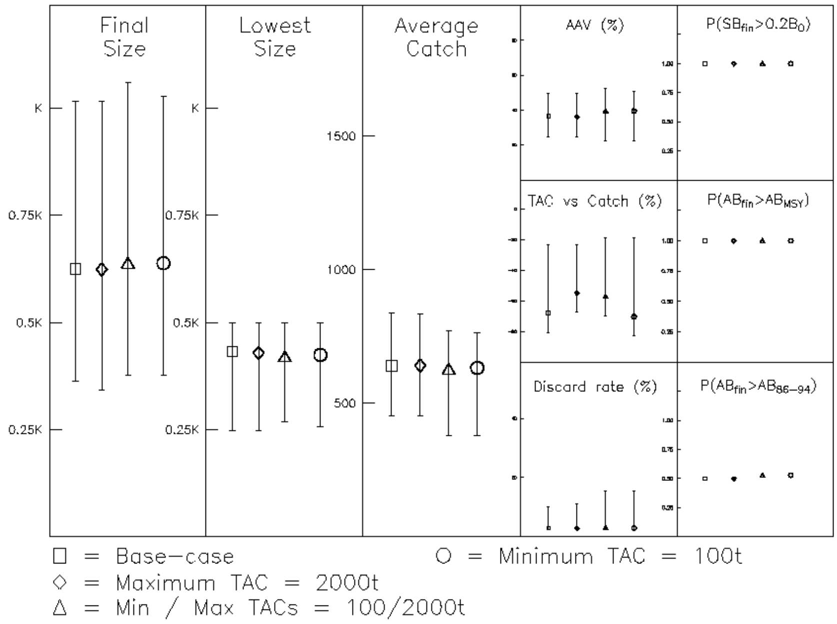

Figure 28(b)

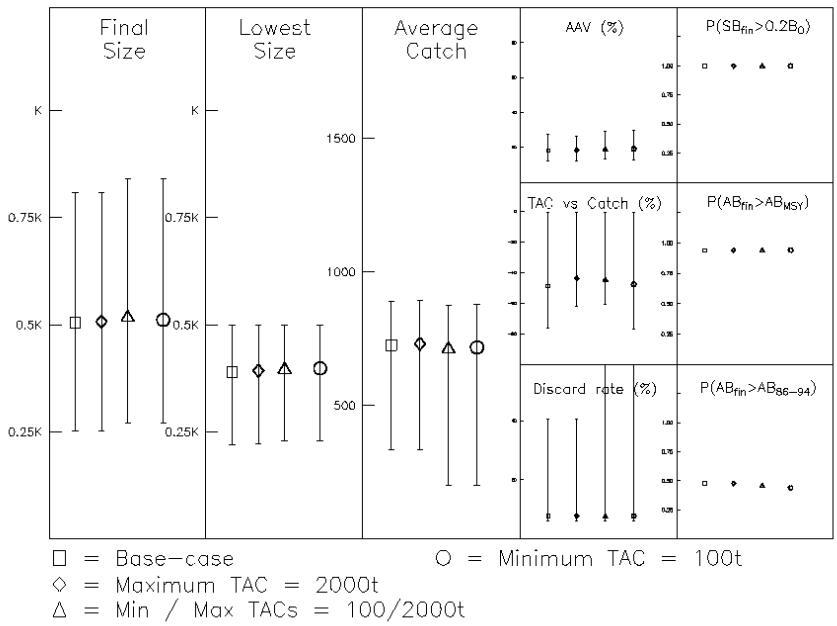

Figure 28 : Comparison plot to evaluate the implications of different maximum and minimum *TAC*s.

Figure 28(c)

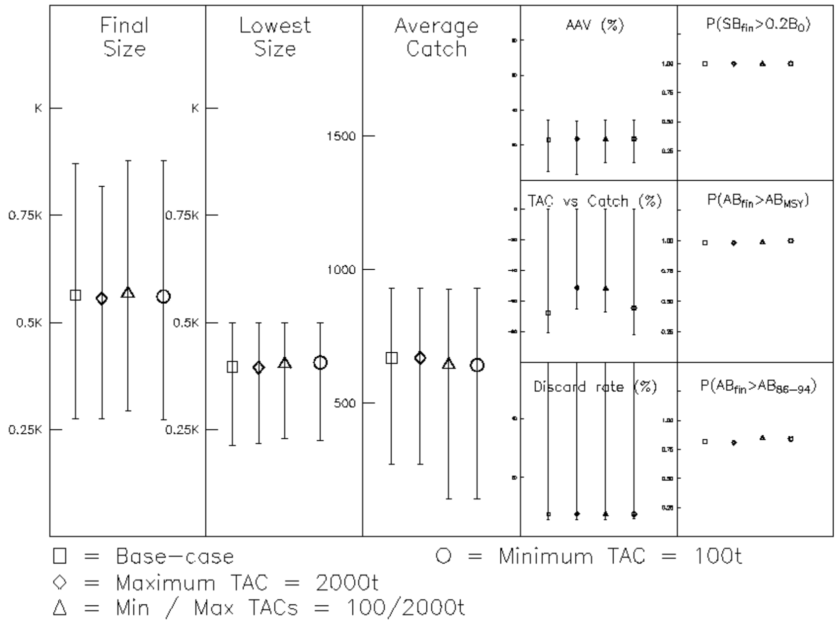

Figure 28(d)

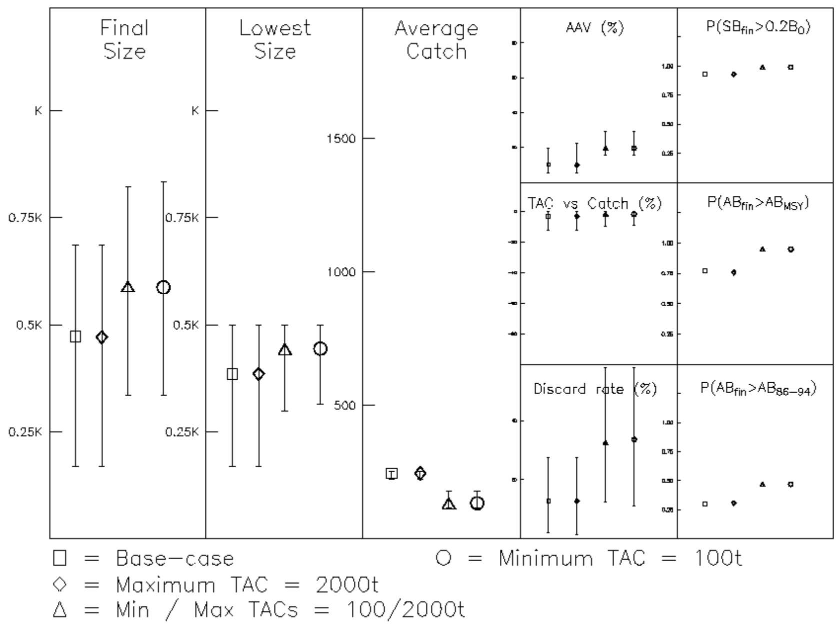

Figure 28 : Comparison plot to evaluate the implications of different maximum and minimum *TAC*s.

Figure 29(a)

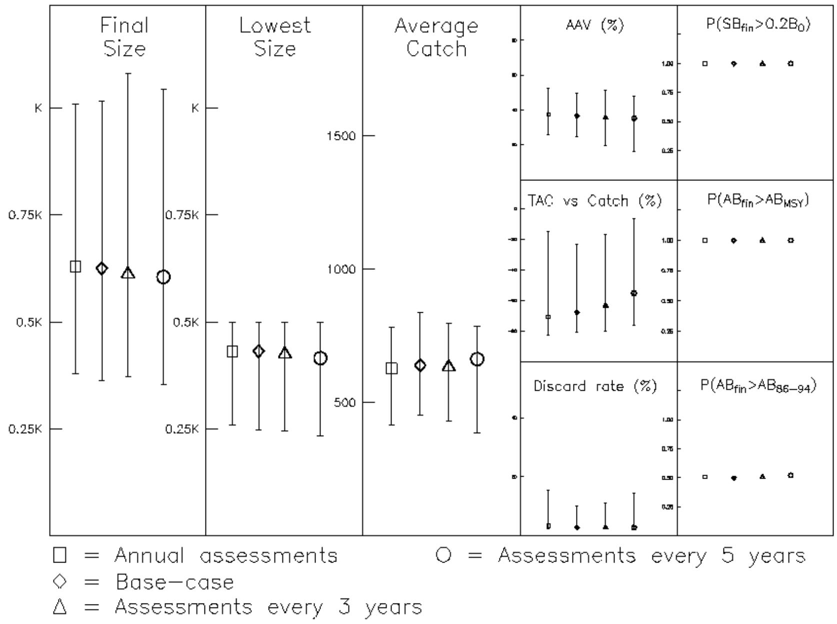

Figure 29(b)

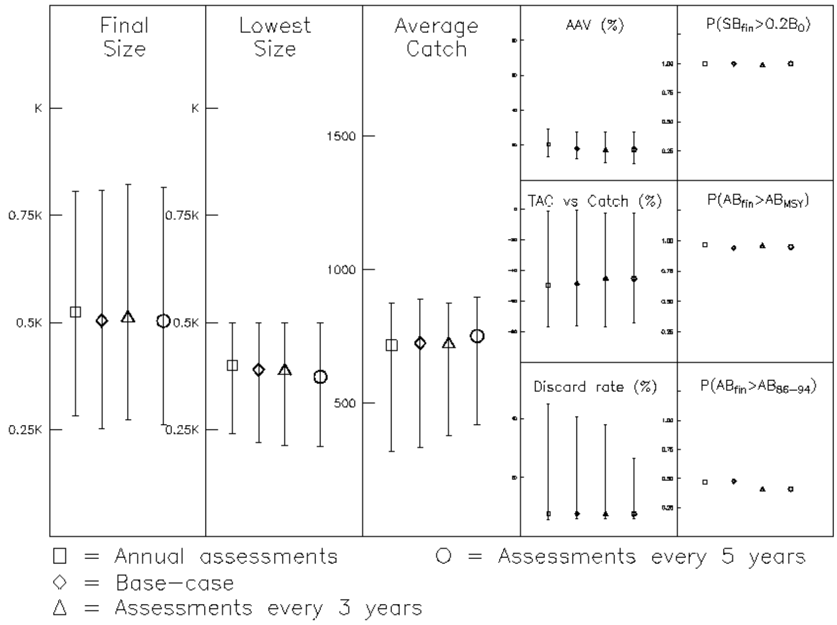

Figure 29 : Comparison plot to evaluate the implications of different inter-assessment periods.

Figure 29(c)

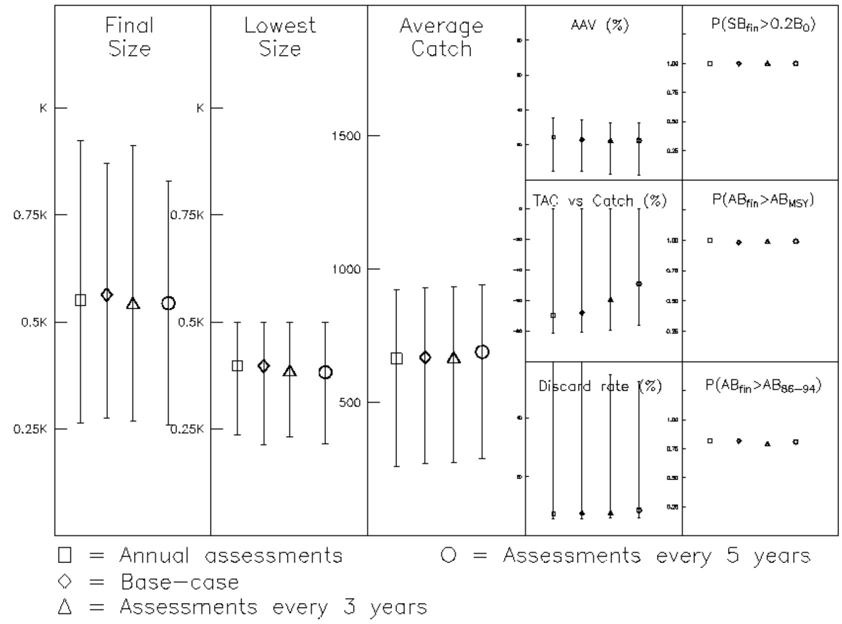

Figure 29(d)

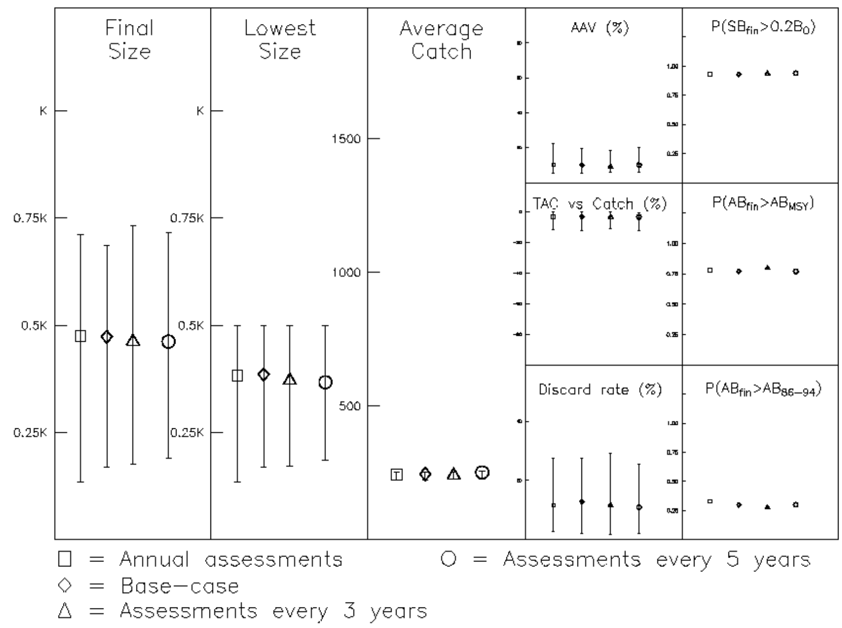

Figure 29 : Comparison plot to evaluate the implications of different inter-assessment periods.

Figures 30 and 31 show analogous results to Figure 29, except that the initial depletion is 0.1 B_0 (Figure 30) or 0.8 B_0 (Figure 31). The results for an initial depletion of 0.1 B_0 indicate little sensitivity to the inter-assessment period (Figure 30). However, there is a notable downward trend in AAV and an increasing trend in the probability of satisfying the biomass reference points with increasing inter-assessment period for spotted warehou, tiger flathead and jackass morwong. For jackass morwong, the extent of difference between the *TAC* and the landed catch decreases as the inter-assessment period is increased. There is virtually no difference among the results for different inter-assessment periods for an initial depletion of 0.8 B_0 (Figure 31).

Figure 30(a)

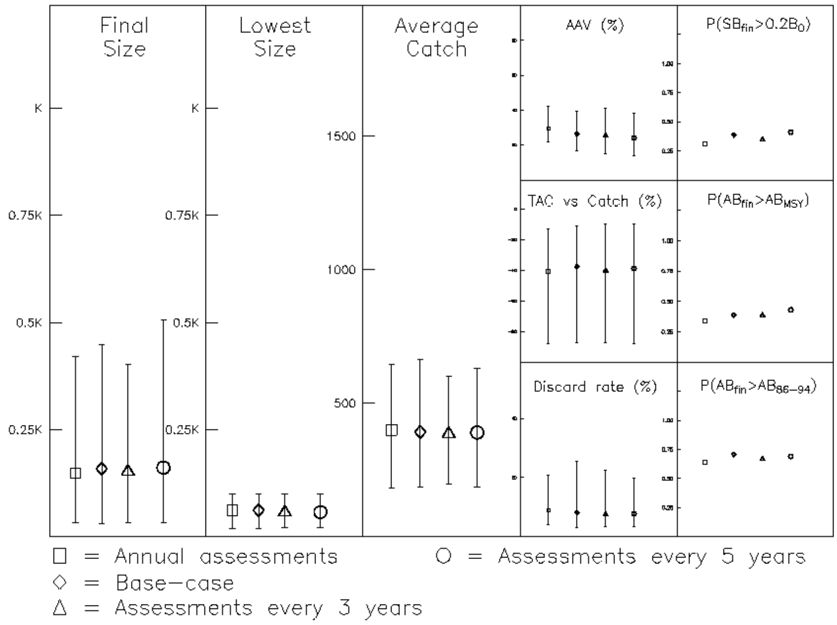

Figure 30(b)

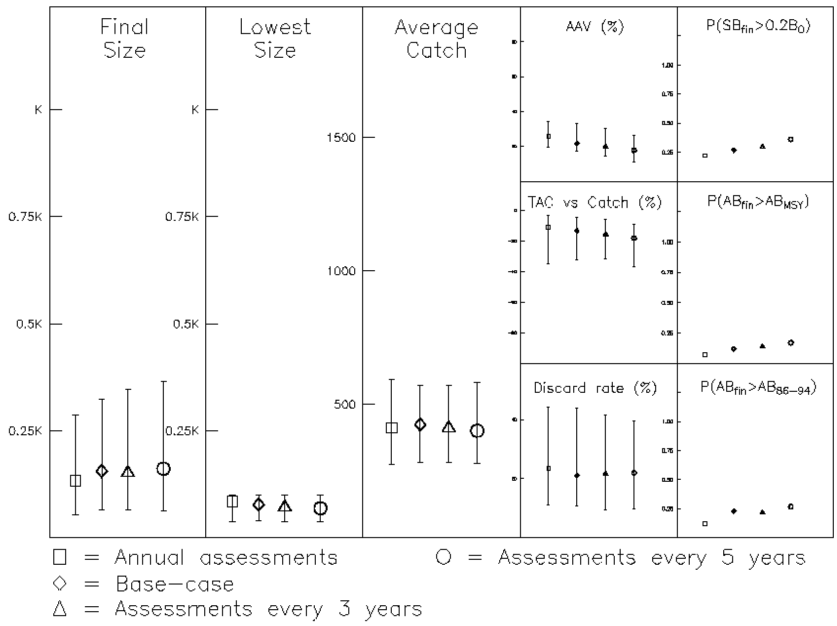

Figure 30 : As for Figure 29, except that the initial depletion is assumed to be 0.1 B_0 .

Figure 30(c)

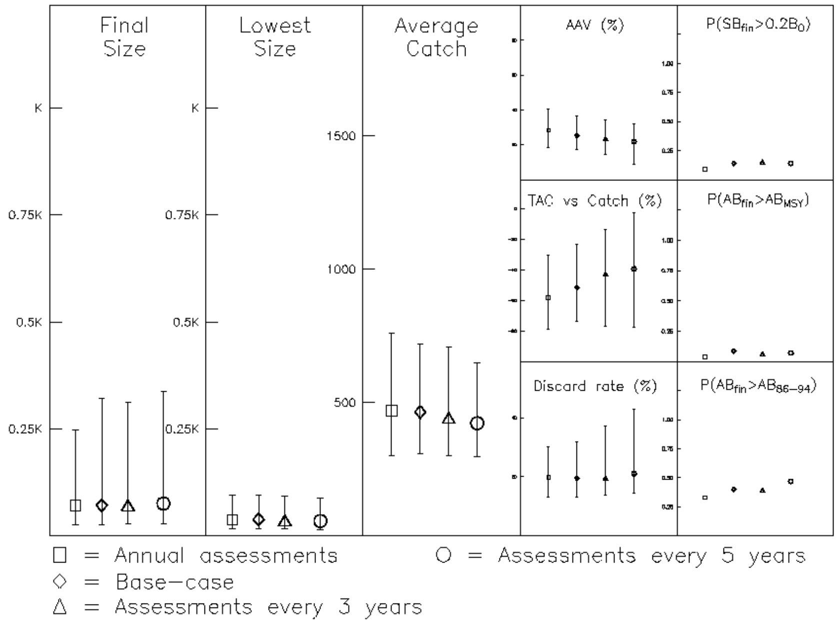

Figure 30(d)

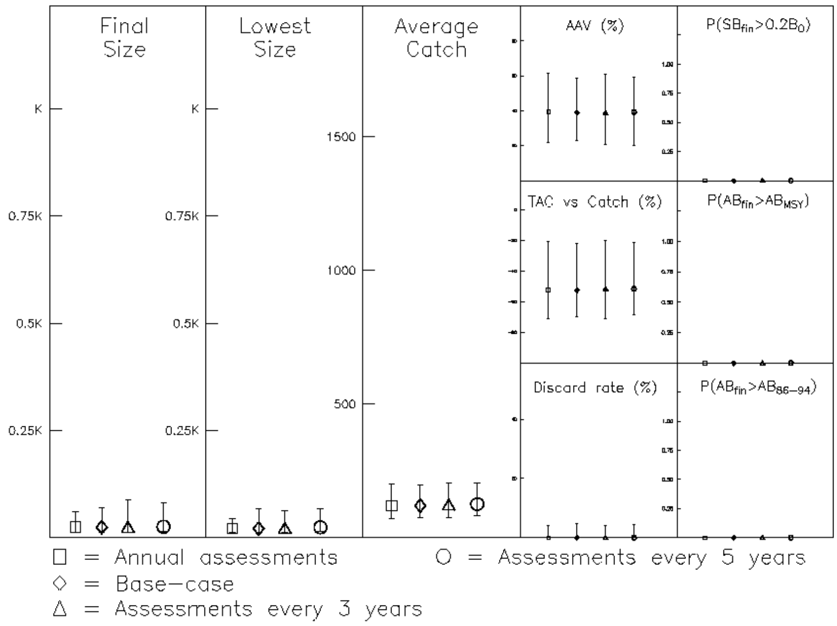

Figure 30 : As for Figure 29, except that the initial depletion is assumed to be 0.1 B_0.

Figure 31(a)

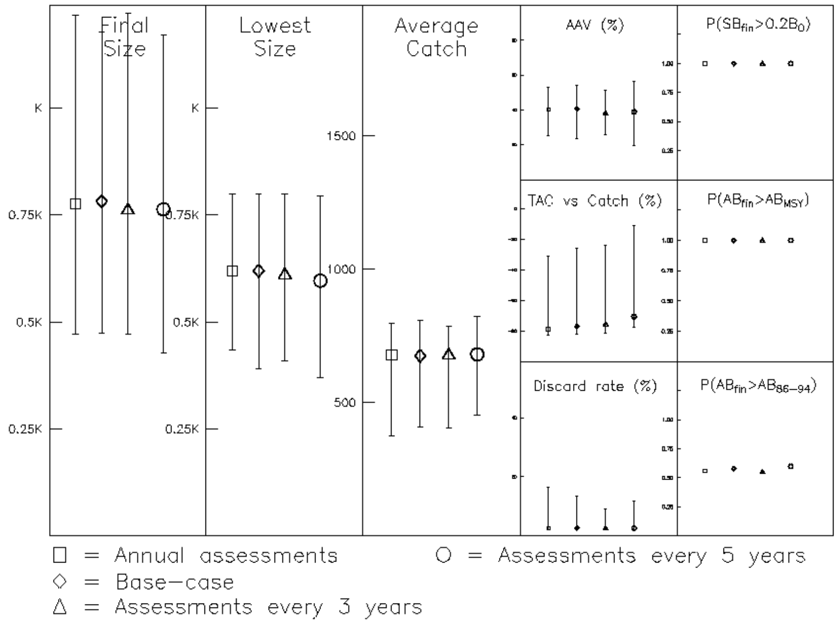

Figure 31(b)

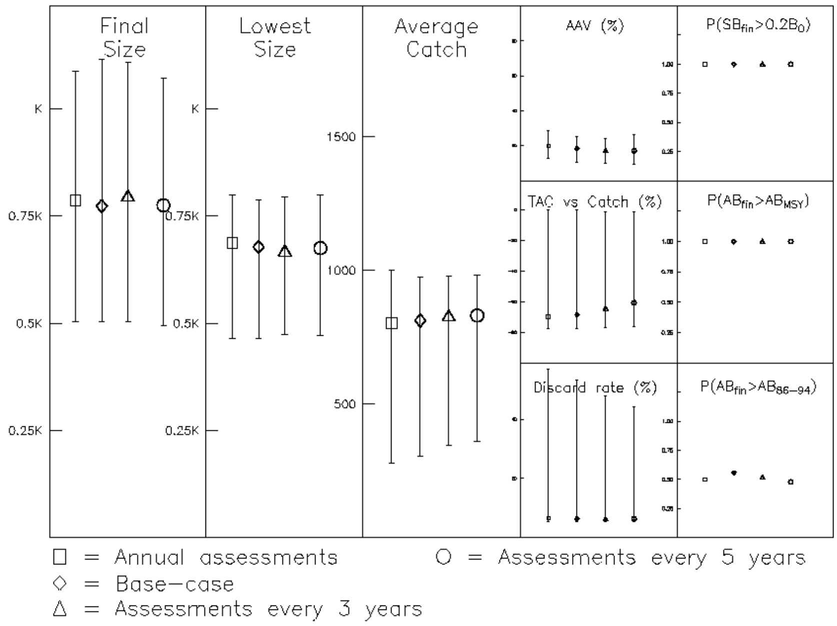

Figure 31 : As for Figure 29, except that the initial depletion is assumed to be 0.8 B_0 .

Figure 31(c)

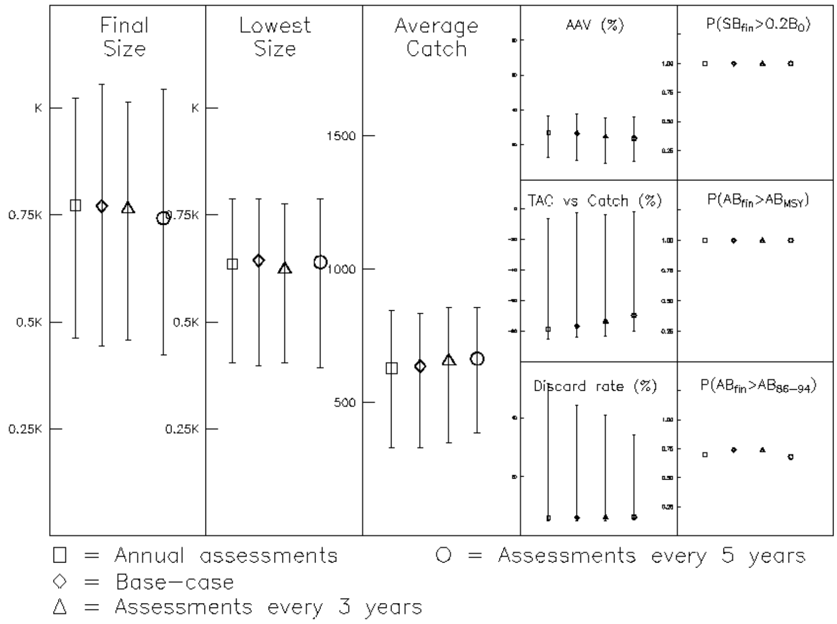

Figure 31(d)

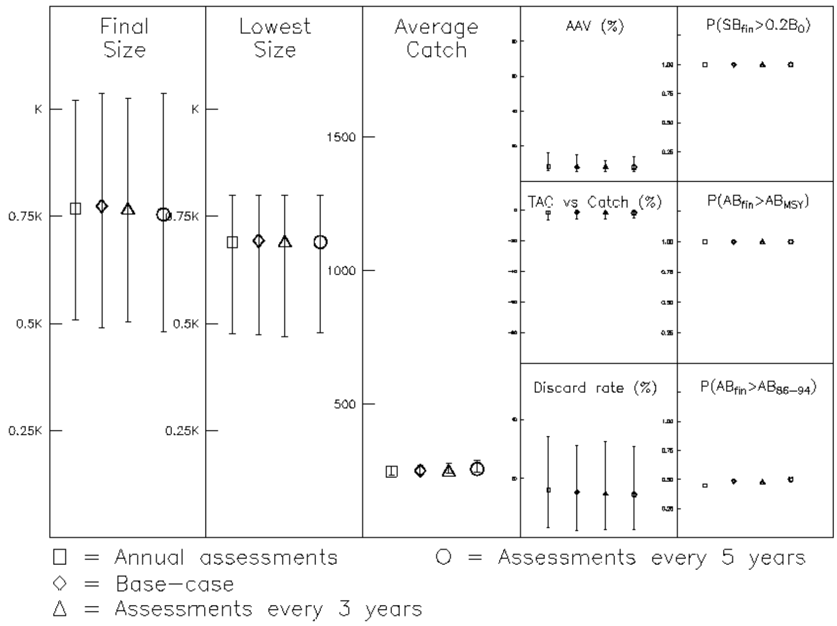

Figure 31 : As for Figure 29, except that the initial depletion is assumed to be 0.8 B_0 .

5.2.7 Results for alternative harvest strategies

The results in the previous sections are all based on an Integrated Analysis estimator and a target level of fishing mortality equal to some multiple of F_{MSY}. It is clear from the preceding sections that the constraints placed by limitations on effort and particularly the level of catch that the market can take, restrict the behaviour of harvest strategies noticeably. It is desirable to remove these constraints when comparing alternative harvest strategies so that the results reflect primarily the behaviour of the harvest strategies rather than the impact of the constraints on effort and catch. Four trials have been constructed that examine likely extreme scenarios for the four species:

a) The spawner biomass of each stock is 20% of its pre-exploitation equilibrium level at the start of 1999 and steepness is 0.5 (abbreviation: the reference trial).
b) The spawner biomass of each stock is 20% of its pre-exploitation equilibrium level at the start of 1999 and steepness is 0.75 (abbreviation: higher steepness).
c) The spawner biomass of each stock is 80% of its pre-exploitation equilibrium level at the start of 1999 and steepness is 0.5 (abbreviation: 80% depletion).
d) The spawner biomass of each stock is 80% of its pre-exploitation equilibrium level at the start of 1999 and steepness is 0.75 (abbreviation: 80% depletion; higher steepness).

The trials have been conducted with no constraints on landings and with a maximum effort level of 100,000 hours. In addition, the level of variability in recruitment, σ_r, has been set to 0.3. This level of recruitment variability is probably lower than that for most South East Fishery species but setting σ_r to a lower value than the 0.6 used earlier eases the process of comparing alternative harvest strategies because changes in biomass are less attributable to the impact of fluctuations in recruitment. Results are shown for only three of the four species (spotted warehou, tiger flathead, and jackass morwong) as the results for pink ling are not particularly informative given the minimum *TAC* of 250*t*.

5.2.7.1 Results for the reference trial

Table 6 lists the values for five performance measures for a variety of harvest strategies (see Table 2 for a list of the alternative harvest strategies considered in this project). The five performance measures are: the median final depletion, the median annual landed catch, the (median) average annual variation in landed catches, the probability that the available biomass is larger at the end of the projection period than B_{MSY}, and the probability that the available biomass is larger at the end of the projection period than the lowest available biomass during 1986–94.

Table 6(a) contrasts the performances of five harvest strategies based on Integrated Analysis and a harvest strategy based on the age-structured production model approach. All of these harvest strategies use catch, catch rate, length frequency and age-composition data. The Integrated Analysis-based harvest strategies differ in terms of the target rate of fishing mortality: (a) the “reference” values (“base-case”), (b) F_{MSY} (“ϕ=1”), (c) the fishing mortality at which the spawner biomass is estimated to equilibrate at 30% of its pre-exploitation equilibrium level (“$F_{\text{targ}} = F_{30\%}$”), (d) the fishing mortality at which the spawner biomass is estimated to equilibrate at 40% of its pre-exploitation equilibrium level ("$F_{\text{targ}} = F_{40\%}$"), and (e) the fishing mortality at which recruitment is estimated to be 50% of its average pre-exploitation level ("$F_{\text{targ}} = F_{50\%R}$"),

All six harvest strategies allow the biomass of spotted warehou to increase and all achieve a very high probability of the available biomass exceeding B_{MSY} at the end of the projection period for this species. In contrast, none of the harvest strategies achieve even a 50% probability that available biomass at the end of the projection period is larger than the lowest available biomass during 1986–94 for spotted warehou. Two of the harvest strategies (base-case and $F_{\text{targ}} = F_{50\%R}$) fail to achieve an appreciable recovery for tiger flathead. In contrast, the $F_{\text{targ}} = F_{40\%}$ harvest strategy allows substantial recovery for tiger flathead. A comparison of this harvest strategy with the ϕ=1 and ASPM strategies reveals that, not only does the $F_{\text{targ}} = F_{40\%}$ harvest strategy achieve higher values for quantities such as $P > B_{MSY}$, but that it also achieves greater average catches. This is a case when one harvest strategy "dominates" another harvest strategy. The performances of the six harvest strategies for jackass morwong are qualitatively the same as those for tiger flathead. For this species, the base-case and $F_{\text{targ}} = F_{50\%R}$ harvest strategies are dominated by the $F_{\text{targ}} = F_{30\%}$ harvest strategy. If a selection among the six harvest strategies in Table 6(a) was to be made purely on the results of the reference trial, the selected harvest strategy would be either $F_{\text{targ}} = F_{30\%}$ or $F_{\text{targ}} = F_{40\%}$.

Table 6(b) lists results for a range of other model-based harvest strategies. If achieving 50% or higher for the statistic $P > B_{MSY}$ is used as a benchmark for success, then the performance of the *ad hoc* tuned VPA- and ADAPT VPA-based harvest strategies and that of the combination of the Schaefer production model and the replacement yield approach to setting *TAC*s would be judged not to have performed successfully. There is a direct trade-off between the Fox and Schaefer model-based harvest strategies when *TAC*s are set based on f_{msy}; the Fox model-based harvest strategy achieves lower catches and higher final depletions while the Schaefer model-based harvest strategy achieves the opposite trade-offs.

Table 6(c) shows results for harvest strategies based on the Schaefer production model where *TAC*s are set using a target effort level of $\phi\, f_{\text{msy}}$ and the value of ϕ is varied from 0.25 to 2.5. As expected, the harvest strategies based on higher values for ϕ lead to higher average catches but lower final depletions. The variability in catches increases with increasing average catch. This effect is most marked for spotted warehou and jackass morwong.

Tables 6(d) – (h) provide results for the empirical approaches to setting *TAC*s (Table 2). Results are shown for the two types of approach (Equations F.7 and F.8) and for different values for the tuning parameters for the Equation F.7 approach. Unfortunately, none of the empirical approaches perform adequately in terms of allowing some recovery. This is most evident for tiger flathead and jackass morwong. The high inter-annual variability in catches associated with these approaches is also noteworthly.

5.2.7.2 Results for the full set of four trials

Table 7 lists the values for the five performance measures for three harvest strategies for the four trials. Results are shown for the base-case, for the "$F_{\text{targ}} = F_{30\%}$" and for the "Schaefer; f_{msy}" harvest strategies. The results for the base-case harvest strategy are shown for reference purposes while the $F_{\text{targ}} = F_{30\%}$ strategy is considered because it achieved the highest catches in Table 6(a) without performing poorly in terms of the probability of leaving the available biomass below B_{MSY} at the end of projection period (the lowest value for the statistic "$P > B_{MSY}$" for this harvest strategy in Table 6(a) is 49%). The "Schaefer; f_{msy}" strategy is included in Table 7 because its performance in Table 6 was adequate but it does not make use of age-composition data so would be a more cost-effective harvest strategy than the "$F_{\text{targ}} = F_{30\%}$" strategy as there would be less need for collection of length-frequency and ageing data.

As expected, the $F_{\text{targ}} = F_{30\%}$ strategy dominates the base-case strategy for several species / trials. However, the base-case harvest strategy achieves much greater catches for tiger flathead and jackass morwong for the trials in which the biomass is initially 80% of the pre-exploitation equilibrium level. The $F_{\text{targ}} = F_{30\%}$ strategy performs adequately in terms of resource conservation; in only one case (jackass morwong for the trial "Higher steepness") is $P > B_{MSY}$ noticeably less than 50%. However, in this case, the $F_{\text{targ}} = F_{30\%}$ strategy keeps the available biomass above the lowest level during 1986–94, so its performance for the $P > B_{MSY}$ statistic is perhaps not too serious a concern.

The Schaefer model-based harvest strategy outperforms the $F_{\text{targ}} = F_{30\%}$ strategy in terms of resource conservation for all trials and species. However, its performance, in terms of adequately utilizing the resource, for the trials in which the stocks are initially at 80% of their pre-exploitation equilibrium levels is poor. This result must be attributable to some extent to the fact that the Schaefer model-based strategy is inherently more conservative but also to the fact that the $F_{\text{targ}} = F_{30\%}$ strategy makes use of additional (age-composition) data.

5.2.7.3 Trials for the $F_{\text{targ}} = F_{30\%}$ harvest strategy

The results in Table 7 suggest that the $F_{\text{targ}} = F_{30\%}$ strategy performs reasonably adequately across a reasonably wide range of biological scenarios. Table 8 therefore lists the values for seven performance measures for this strategy for nine additional trials. These trials are among the most extreme of those considered in Sections 5.2.1 to 5.2.4. The performance measures are those considered in Tables 6 and 7 along with the lower 5th percentiles of the final depletion and average catch distributions. In contrast to Tables 6 and 7, results are shown for all four species in Table 8.

The performance for the trial in which the stocks are initially (1999) depleted to 10% and 20% of their pre-exploitation levels (rows "Initial depletion = 0.1" and "Initial depletion = 0.2" in Table 8) suggest that some recovery occurs in the bulk of cases for spotted warehou, tiger flathead and jackass morwong. The probability of being above B_{MSY} at the end of the projection period exceeds 50% for the first two of these species even when the spawner biomass is initially only 10% of its pre-exploitation level. The poor performance for pink ling is, as noted before, attributable more to the minimum *TAC* of 250*t* than to the performance of the harvest strategy. This is evident from the results for the trial in which the minimum *TAC* is reduced from 250*t* to 100t (row "*TAC* range=(100*t*, 1000*t*)" in Table 8). The harvest strategy does not reduce the spawner biomass much below its initial level when this biomass is initially 80% of the pre-exploitation equilibrium level. This suggests that the harvest strategy "learns" poorly but is also attributable (to some extent) to the limits placed on landed catches.

The trials "CV_q=0.1" and "With surveys" are variants of the base-case trial that examine the implications of having a more precise catch rate index and annual estimates of absolute abundance respectively. Except for one case (pink ling for trial "with surveys"), improving the index of abundance leads, as expected, to lower inter-annual variability in catches. Somewhat surprisingly, the lower 5th percentile of the average catch distribution increases in only two cases (tiger flathead and jackass morwong for trial "with surveys"). There are, however, no other clear patterns for these trials although there is a tendency for the lower 5th percentiles of the final depletion distribution to increase slightly.

The performance of the $F_{\text{targ}} = F_{30\%}$ strategy is very poor if efficiency is increasing rapidly over time (row "Efficiency increase = 0.05" in Table 8). For this case, average catches are higher but the spawner biomasses of tiger flathead and (particularly) pink ling are reduced to very low levels. The performance of this strategy in terms of resource conservation does not improve markedly even if annual estimates of absolute abundance are available (trials "Efficiency increase = 0.05; with surveys" in Table 8), although the size of the landed catches are generally lower. This is a consequence of increased discarding.

5.2.8 General discussion

The results for the evaluation of harvest strategies are highly sensitive to the assumptions about the impact of "market" catches and (to a lesser extent) the maximum level of fishing effort. Most previous studies of harvest strategies have imposed a maximum level of fishing effort (by imposing a maximum possible level of fishing mortality). However, no previous investigation into the performances of harvest strategies has addressed the impact of upper bounds on the likely level of landings of one species on the catches (and discards) of other species. This is probably because the previous studies have concentrated on single-species fisheries where the maximum possible catch only limits the catch of the species of interest. In contrast, in this study, limits on catches of some species lead to discarding of other species if the *TAC*s for all species not "in sync". This is probably a common occurrence for multi-species fisheries managed under output controls. The quantitative results regarding the impact of "market" catches are likely to depend on how fleet behaviour is modelled and only one model of fleet behaviour was considered (see Section 5 of Appendix D). Final conclusions regarding the quantitative impact of "market" catches should therefore be based on a broader range of "fleet dynamics" models, although the qualitative conclusions of this study are likely to hold.

The performances of the harvest strategies are robust to many of the factors considered in this study including: pulses in catchability, density-dependent growth, and the values for the parameters that determine the inter-annual variation in movement and selectivity. However, they are not particularly robust to factors such as the initial depletion of the resource, the level of productivity, increases over time in efficiency, and the level of variation in recruitment. These factors have been identified as being of importance in determining the performance of harvest strategies in several other studies (Butterworth and Punt, 1999). The performances of the harvest strategies were found to be somewhat sensitive to assumptions about correlations in recruitment temporally and among species, the rate of natural mortality, and how discarding is assumed to operate.

Harvest strategies can be selected to achieve a reasonable probability of allowing some recovery for depleted resources or allowing underutilized resources to be driven to more productive levels. However, none of the harvest strategies examined were able to detect the underlying productivity of the resource well (see Section 5.1) and hence perform well in both the depleted and underutilized scenarios. The inability to estimate the productivity of the population is not very surprising – for only one stock in Australia (eastern gemfish) are estimates of productivity available (see Smith and Punt (1998) for details). Eastern gemfish is a case in which there is a substantial amount of data and a large amount of contrast in biomass and catch.

The bulk of the harvest strategies considered were based on the constraints on inter-annual variation in *TAC*s listed in Section 6 of Appendix F. However, it is clear from Figures 27-31 that improved performance could be obtained by varying some of these constraints. In particular, tighter constraints on inter-annual variation in *TAC*s, and lower minimum *TAC*s (particularly for pink ling) should lead to improved performance.

The performances of the empirical approaches to *TAC* setting were very poor if the stocks were highly depleted. In contrast, the model-based approaches allowed some recovery in these cases. The result that model-based approaches outperform empirical approaches has been observed in several previous studies (Butterworth and Punt, 1999). This result indicates that there is value in collecting data (for example on growth, selectivity, etc.) that could be used for model fitting purposes and that future development of harvest strategies for SEF species should concentrate on model-based approaches. The harvest strategies based on the Schaefer production model were dominated by those based on Integrated Analysis for some of the trials. Whether this was due to the two types of harvest strategies being tuned to different risk-reward trade-offs or because of the use of additional data in the case of the Integrated Analysis-based harvest strategies remains, however, unclear.

The importance of having an index of abundance that is related linearly to abundance cannot be over-emphasized. The poorest performance occurred when there were changes over time in fishing efficiency. This problem can be removed by basing harvest strategies on survey estimates. However, Table 8 indicates that if survey data and catch data rate are included together in an assessment and efficiency is increasing over time (but this is not known), a substantial deterioration in performance is still likely.

6. BENEFITS

The benefits of this project will flow to the fishers in the trawl and non-trawl sectors of the South East Fishery, specifically those with quota of pink ling, tiger flathead, jackass morwong, and spotted warehou. The benefits will result if the performance indicators for these species are modified based on whether they can be estimated reliably, as detailed in Section 5.1. The benefits of this project will also flow to those fishers who fish for a range of SEF species because the analyses conducted in this report are based on a relatively generic operating model so the conclusions are likely to apply to wider range of species than simply the four that formed the focus for the study.

Additional benefits of the project flow to all of the fisheries managed by AFMA as many of the conclusions of this study regarding how performance indicators and harvest strategies are to be chosen are generic, given the nature of the operating model used for the analyses. It should be possible to tailor the framework developed as part of this project to other species / regions reasonably quickly.

7. FURTHER DEVELOPMENT

This study has highlighted several areas where uncertainty has a major impact on the performance of estimators and harvest strategies. These areas should be brought to the attention of the SEF Research Sub-Committee to ensure that they are designated as high priority research areas.

7.1 Operating-model related

The results of this study are necessarily generic and should therefore be considered to relate to the four example species in a rough way only. In order to select appropriate harvest strategies for these species, it will be necessary to select parameter values for the operating model based on full formal stock assessments for each species. Such assessments were beyond the scope of the current project although, as part of FRDC project 97/115, assessment data have been assembled, and preliminary assessments conducted for two of the species considered in this project (spotted warehou and pink ling). The results of the evaluation of the ability to estimate management-related quantities (Section 5.1) suggest, however, that care needs to be taken when parameterizing operating models for these species as none of the methods of stock assessment considered in this report are likely to provide particularly accurate or precise estimates.

The evaluations of this project have not considered the implications of uncertainty in stock structure, an acknowledged problem for all four species (Tilzey, 1999). It is well-known that uncertainty about stock structure can lead to an inability to achieve management objectives (Butterworth and Punt, 1999). Stock structure uncertainty was ignored primarily because the evaluations were restricted to a relatively small region of the South East Fishery. Stock structure uncertainty will have to be considered if future evaluations of this type are to be based more precisely on these four species and if such evaluations consider a wider geographic area.

Another key uncertainty remains how to model fleet dynamics. It is clear from, *inter alia* Figure 20, that the results are highly dependent on the treatment of fleet dynamics and the behaviour of fishers generally. Unfortunately, fleet dynamics are poorly understood for almost all of the world's fisheries and considerable additional work is needed in this area before substantially more realistic fleet dynamics models can be included in evaluations of harvest strategies. A related-issue is that the operating model considers only the trawl sector of the fishery. In reality some of the catch is taken using non-trawl methods. Including multiple "fleets" in the operating model will permit issues such as the impact of differences in minimum fish sizes on overall performance to be assessed.

Uncertainty about model structure is clearly a major source of error for estimates from stock assessments (e.g. Figure 6). For the cases considered here, ignoring spatial structure and variability in growth leads to notably biased results for spotted warehou. It should be noted, however, that the parameters chosen for movement and variability in growth are based on few data (see Section 1 of Appendix E) so may differ quite markedly from the "real world". However, this uncertainty simply emphasises the need to consider these factors in the future. The large biases for pink ling are due to incorrect assumptions regarding selectivity. Allowance is made in the operating model for declining selectivity with size based on a comparison of trawl- and longline-length frequencies. Unfortunately, there is little reason to believe that this possibility would have even been considered had the longline data not been available (although this effect was also detected by Punt and Japp (1994) and was perhaps not unexpected in this case). Clearly there are likely to be a number of other key incorrect assumptions that we are simply not aware of.

7.2. Estimator and harvest strategy-related

The harvest strategies considered in this study are necessarily only a small sub-set of the full spectrum. However, it would seem appropriate that future examinations attempt to develop harvest strategies based on spatially-explicit population dynamics models. Similarly, consideration should be given in the future to assessing harvest strategies that avoid setting *TAC*s for species caught together that are poorly "matched", as this may lead to increased discarding. Other areas to which future attention should be directed when developing harvest strategies include the use of Bayesian methods, harvest strategies that are explicitly precautionary (e.g. de la Mare, 1989a; IWC, 1994; McAllister and Kirkwood, 1998; Punt and Smith 1999), and harvest strategies that use only length-frequency data. It should be noted, however, that Bayesian methods and spatially-explicit stock assessments and are computationally very intensive and this may limit the ability to evaluate the performances of harvest strategies based on these approaches.

Other areas worth investigating when developing future harvest strategies are alternative formulations for the ADAPT-VPA approach (fixing rather than estimating some of the selectivities for the most-recent-year), different approaches to standardising the catch and effort data, and different approaches to constructing the catch-at-age matrices that are used by methods such as Integrated Analysis and ADAPT-VPA (e.g. Punt and Smith, In press). The estimation of steepness is poor for all of the methods of stock assessment so consideration should be given in future to harvest strategies that fix rather than estimate steepness.

The empirical harvest strategies performed poorly in the tests conducted. However, given the lack of data for many SEF species, attempts to develop empirical harvest strategies should nevertheless continue. Research should be directed towards identifying the types of factors that lead to poor performance for empirical harvest strategies and when these strategies are likely to perform adequately. Harvest strategies used in some parts of the world (e.g. Bergh and Butterworth, 1987; Butterworth *et al*., 1993) are empirically-based.

The harvest strategies considered in this study do not include provisions for “carryover” and “carryunder”. The SEF is a fishery in which *TAC*s are rarely fully caught and carryover / carryunder are therefore key components of the management system. It is possible to assess the implications of carryover and carryunder rules by simulation (e.g. IWC (2001)) and these rules should therefore be explicitly included in future harvest strategy evaluation exercises for the SEF.

Except for Section 5.1.3, this study has not attempted to examine the reasons for the behaviour of the estimators and harvest strategies in detail. Such an examination should be conducted once the number of operating models has been reduced and the operating models parameterised to the specifics of the species for which harvest strategies are required. Methods for conducting this examination range from exploring the fits to some of the simulated data sets in detail, and applying the estimator to a set of operating models that range from being identical to the model underlying the estimator to operating models as complex as is needed to represent the actual situation.

7.3. Data-related

Clearly, given the results in Figures 10 and 24, any efforts to assess the relationship between fishing effort and fishing mortality should be supported. The results in Figure 6 illustrate the benefits of using precise indices while those in Figures 10 and 24 provide examples of the detrimental impact of the index of abundance used for assessment purposes not being related linearly to abundance. The value of having occasional estimates of absolute abundance therefore cannot be over-emphasized as they “pin down” the population abundance far better than can relative abundance data (see, for example, Figure 13). NRC (1998) recommended that “at a minimum, at least one reliable abundance index should be available for each stock. Fishery-independent surveys offer the best choice for achieving a reliable index.”

Development of improved estimators should be possible if there is prior information about key biological parameters. It is clear, for example, that having good information on *M* and steepness are key to obtaining accurate and precise estimates of management-related quantities. Unfortunately, these are quantities that are usually very poorly defined from the data collected for assessment purposes. One potential research topic on which attention should therefore be focused is the use of data for better-studied species using the techniques of meta-analysis (e.g. Liermann and Hilborn, 1997; Myers *et al*., 1999). Initial work to use meta-analysis for SEF species has already commenced (Koopman *et al*., 2000).

8. CONCLUSIONS

Objective 1: To evaluate performance indicators in measuring performance against management objectives for the SEF

- The ratio of the current biomass (spawner and available) to that in 1991 is the best estimated management-related quantities considered.

- The absolute level of spawner (and available) biomass, *MSY*, the ratio of current available biomass to B_{MSY}, and the ratio of the current spawner biomass to the spawner biomass at which recruitment is 50% of that at the pre-exploitation level are very poorly determined.
- Of the productivity-related quantities, the exploitation rates corresponding to reductions in spawner biomass to pre-specified levels are estimated better than F_{MSY}.

Objective 2: To select robust assessment methods and harvest strategies for the SEF

- Integrated Analysis performed best overall of the six stock assessment methods considered. The *ad hoc* tuned VPA method of stock assessment performed second best of these six methods and ADAPT VPA poorest. Integrated Analysis is the approach that forms the basis at present for the assessments of orange roughy, blue grenadier, blue warehou, eastern gemfish and the preliminary assessments for redfish, spotted warehou and pink ling. The results of this project therefore support continued use of Integrated Analysis for these species.
- The performances of the model-based harvest strategies were clearly superior to those of the empirical harvest strategies (such as the "catch rate strategy" that is currently used as a basis for management advice for many SEF species). The empirical strategies were shown to lead to inadequate recovery for depleted populations.
- Harvest strategies where the target level of fishing mortality was based on aiming at stabilising the spawner biomass at some pre-specified fraction of its pre-exploitation level appeared to outperform those that set *TAC*s based on estimates of F_{MSY}.
- The harvest strategies considered were robust to many of the types of uncertainties considered. The factors that influenced performance to the greatest extent included the extent to which landed catches were limited by market demands, the depletion of the resource when the harvest strategy was first applied, the variation in recruitment, and productivity.
- Fairly tight limits can be placed on how much the *TAC* can be varied from one year to the next and any minimum *TAC* levels should be low. There appears to be little benefit to conducting assessments (and changing *TAC*s) frequently

Objective 3: To evaluate the costs and benefits associated with data acquisition strategies for the SEF with particular reference to different monitoring strategies (fishery-dependent and fishery-independent)

- Estimators that make use of information on the age-composition and length-structure of the catch outperform those that ignore this information.
- Applying stock assessment methods to catch-rate data when efficiency is changing over time leads to misleading estimates of management-related quantities and poor performance of harvest strategies. Use of information from fishery-independent surveys may be useful to overcome this problem.

Objective 4: To develop the modelling software in a manner which lends itself to tailoring (by CSIRO and other agencies) to suit other Commonwealth or State fisheries

The software was designed in C++ to be modular. The operating model and the harvest strategies are coded in separate computer programs and the latter can be run independently of the operating model program as a stock assessment tool. It is straightforward to include new harvest strategies and assessment methods, to change the information output by the assessment methods, and to change the specifications of the operating model. In particular, little modification to the software is needed to conduct harvest strategy evaluation calculations for single species situations or to increase the number of species from four.

9. ACKNOWLEDGEMENTS

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10. REFERENCES

Annala, J.H. 1993. Fishery assessment approaches in New Zealand's ITQ system. pp. 791-805. In: G. Kruse, D.M. Eggers, R.J. Marasco, C. Pautzke and T.J. Quinn II [Ed.] Proceedings of the International Symposium on Management Strategies for Exploited Fish Populations. Alaska Sea Grant College Program Report No. 93-02. University of Alaska Fairbanks.

Annala, J.H. (Comp.) 1994. Report from the Fishery Assessment Plenary, May 1994: stock assessments and yield estimates. 242 pp. (Unpublished report held in MAF Fisheries Greta Point library, Wellington).

Anon. 1998. AFMA Annual Report 1997-98. Australian Fisheries Management Authority, Canberra. vi + 206 pp.

Bax, N.J. and A. Williams. 2000. Habitat and fisheries production in the South East Fishery System. Report of FRDC 94/040. CSIRO Marine Research, Hobart. 425 pp.

Beddington, J.R. and J.G. Cooke. 1983. The potential yield of fish stocks. *FAO Fish. Tech. Pap.* 242: 1-47.

Bence, J.R., Gordoa, A. and J.E. Hightower. 1993. Influence of age-selective surveys on the reliability of stock synthesis assessments. *Can. J. Fish. Aquat. Sci.* 50: 827-840.

Bergh, M.O. and S.J. Johnson. 1992. A size-structured model for renewable resource management with application to resources of rock lobster in the South-east Atlantic. *S. Afr. J. Mar. Sci*. 12: 1005-1016.

Breiwick, J.M., Eberhardt, L.L. and H.W. Braham. 1984. Population dynamics of western Arctic bowhead whales (*Balaena mysticetus*). *Can. J. Fish. Aquat. Sci*. 41: 484-496.

Butterworth, D.S. and P.A. Andrew. 1984. Dynamic catch-effort models for the hake stocks in ICSEAF Divisions 1.3 to 2.2. *Colln scient. Pap. int. Commn SE. Atl. Fish.* 11(1): 29-58.

Butterworth, D.S. and A.E. Punt. 1999. Experiences in the evaluation and implementation of management procedures. *ICES J. Mar. Sci*. 56: 985-998.

Butterworth, D.S., Hughes, G.S. and F. Strumpfer. 1990. VPA with *ad hoc* tuning: implementation for disaggregated fleet data, variance estimation, and application to the horse mackerel stock in ICSEAF Divisions 1.3+1.4+1.5. *S. Afr. J. Mar. Sci.* 9: 327-357.

Butterworth, D.S., De Oliveria, J.A.A and K.L. Cochrane. 1993. Current initiatives in refining the management procedure for the South African anchovy resource. pp. 439-473. In: G. Kruse, D.M. Eggers, R.J. Marasco, C. Pautzke and T.J. Quinn II [Ed.] Proceedings of the International Symposium on Management Strategies for Exploited Fish Populations. Alaska Sea Grant College Program Report No. 93-02. University of Alaska Fairbanks.

Clark, W.G. 1991. Groundfish exploitation rates based on life history parameters. *Can. J. Fish. Aquat. Sci*. 48: 734-750.

Clark, W.G. 1993. The effects of recruitment variability on the choice of a target level of spawning biomass per recruitment. pp. 233-246. In: G. Kruse, D.M. Eggers, R.J. Marasco, C. Pautzke and T.J. Quinn II [Ed.] Proceedings of the International Symposium on Management Strategies for Exploited Fish Populations. Alaska Sea Grant College Program Report No. 93-02. University of Alaska Fairbanks.

Clay, D. 1991. Atlantic bluefin tuna (*Thunnus thynnus thynnus* (L.)): A review. pp. 89-179. In: R.B. Deriso and W.H. Bayliff [Ed.] World meeting on stock assessment of bluefin tunas: Strength and weaknesses. *IATTC Spec. Rep.* 7.

Collie, J.S. and M.P. Sissenwine. 1983. Estimating population size from relative abundance data measured with error. *Can. J. Fish. Aquat. Sci*. 40: 1871-1879.

de la Mare, W.K. 1986. Fitting population models to time series of abundance data. *Rep. int. Whal. Commn* 36: 399-418.

de la Mare, W.K. 1989a. Further simulation studies on management procedures. *Rep. int. Whal. Commn* (Special Issue 11). 157-169.

de La Mare, W.K. 1989b. The model used in the Hitter and Fitter program. *Rep. Int. Whal. Commn* 39: 150-151.

Deriso, R.B. 1980. Harvesting strategies and parameter estimation for an age-structured model. *Can. J. Fish. Aquat. Sci*. 43: 268-282.

Deriso, R.B. and A.M. Parma. 1988. Dynamics of age and size for a stochastic population model. *Can. J. Fish. Aquat. Sci*. 45: 1054-1068.

Deriso, R.B., Quinn, T.J. and P.R. Niel. 1985. Catch-age analysis with auxiliary information. *Can. J. Fish. Aquat. Sci*. 42: 815-824.

Donovan, G.P. 1989. The Comprehensive Assessment of Whale Stocks: The Early Years. *Rep. int. Whal. Commn* (Special Issue 11). 210 pp.

Doubleday, W.G. 1976. A least squares approach to analysing catch at age data. *Res. Bull. Int. Comm. Northw. Atl. Fish*. 12: 69-81.

FAO. 1995. Precautionary approach to fisheries. Part 1: Guidelines on the precautionary approach to capture fisheries and species introductions. *FAO Fish. Tech. Pap.* 350/1. 52 pp.

Fournier, D. and C.P. Archibald. 1982. A general theory for analyzing catch at age data. *Can. J. Fish. Aquat. Sci*. 39: 1195-1207.

Fournier, D.A. and I.J. Doonan. 1987. A length-based stock assessment method utilizing catch at age data. *Can. J. Fish. Aquat. Sci*. 44: 422-437.

Fournier, D.A., Sibert, J.R., Majkowski, J. and J. Hampton. 1990. MULTIFAN a likelihood-based method for estimating growth parameters and age composition from multiple length frequency data sets illustrated using data for southern bluefin tuna (*Thunnus maccoyii*). *Can. J. Fish. Aquat. Sci*. 47: 301-317.

Francis, R.I.C.C. 1992. Use of risk analysis to assess fishery management strategies: a case study using orange roughy (*Hoplostethus atlanticus*) on the Chatham Rise, New Zealand. *Can. J. Fish. Aquat. Sci.* 49: 922-930.

Gavaris, S. 1988. An adaptive framework for the estimation of population size. *Can. Atl. Fish. Sci. Adv. Com. (CAFSAC) Res. Doc*. 88/29. 12 pp.

Givens, G.H., Zeh, J.E. and A.E. Raftery. 1995. Assessment of the Bering-Chukchi-Beaufort Seas stock of bowhead whales using the Baleen II model in a Bayesian synthesis framework. *Rep. int. Whal. Commn* 45: 345-364.

Graham K.J., Wood B.R. and N.L. Andrew. 1997. The 1996-97 survey of upper slope trawling grounds between Sydney and Gabo Island (and comparisons with the 1976-77 survey). Kapala Cruise Report No. 117. NSW Fisheries, Cronulla. 96 pp.

Gulland, J.A. and L.K. Boerema. 1973. Scientific advice on catch levels. *Fish. Bull. US* 71: 325-335.

Hilborn, R. 1979. Comparison of fisheries control systems that utilize catch and effort data. *J. Fish. Res. Board Can.* 36: 1477-1489.

Hilborn, R. 1990. Estimating the parameters of full age-structured model from catch and abundance data. *Bull. Int. North Pac. Fish. Commn* 50: 207-213.

Hilborn, R., Pikitch, E.K. and M.K. McAllister. 1994. A Bayesian estimation and decision analysis for an age-structured model using biomass survey data. *Fish. Res*. 19: 17-30.

Hoenig, J.M. 1983. Empirical use of longevity data to estimate mortality rates. *Fish Bull*. 81: 898-903.

Horwood, J.W. 1994. Modelling of fisheries management strategies. Privately published. 85 pp.

International Whaling Commission. 1994. The Revised Management Procedure (RMP) for baleen whales. *Rep. int. Whal. Commn* 44: 142-152.

International Whaling Commission. 2001. Report of the Standing Working Group on the Development of an Aboriginal Subsistence Whaling Management Procedure. Annex E to the Report of the Scientific Committee. *J. Res. Cet. Manage*. 3(Suppl.) 00-00.

Jacobson, T. 1992. Biological reference points for North-east Arctic cod and haddock. *ICES J. Mar. Sci*. 49: 155-166.

Jacobson, T. 1993. The behaviour of F_{low}, F_{med} and F_{high} in response to variation in the parameters used in their estimation. pp. 119-125. In: S.J. Smith, J.J. Hunt and D. Rivard [Ed.] Risk evaluation and biological reference points for fisheries management. *Can. J. Fish. Aquat. Sci. Spec. Publ.* 120.

Kimura, D.K. 1989. Variability, tuning, and simulation for the Doubleday-Deriso catch-at-age model. *Can. J. Fish. Aquat. Sci*. 46: 941-949.

Kimura, D.K. 1990. Approaches to age-structured separable sequential population analysis. *Can. J. Fish. Aquat. Sci*. 47: 2364-2374.

Kirkwood, G.P. 1981. Estimation of stock size using relative abundance data – a simulation study. *Rep. int. Whal. Commn* 31: 729-735.

Knuckey, I.A., Grieve, C. and D.C. Smith. 1999. Evolution of the integrated scientific monitoring programme in Australia's South East Fishery. pp. 231-248. In: C.P. Nolan [ed.] Proceedings of the International Conference on Integrated Fisheries Monitoring, Sydney, Australia. 1-5 February 1999. FAO, Rome.

Knuckey, I.A. and M.I. Sporcic. 1998. South East Fishery Integrated Scientific Monitoring Program: July – October 1998. Progress Report to the Australian Fisheries Management Authority. Marine and Freshwater Research Institute, Queenscliff. 14 pp.

Koopman, M.T., Punt, A.E. and D.C. Smith. 2000. Production parameters from the fisheries literature for SEF-like species. Report of ARF project 99/0308. 66 pp.

Liermann, M. and R. Hilborn. 1997. Depensation in fish stocks: a hierarchic Bayesian meta-analysis. *Can. J. Fish. Aquat. Sci*. 54: 1976-1984.

Ludwig, D., Walters, C.J. and J. Cooke. 1988. Comparison of two models and two methods for catch and effort data. *Nat. Resour. Model*. 2: 457-498.

Mace, P.M. 1994. Relationships between common biological reference points used as thresholds and targets of fisheries management strategies. *Can. J. Fish. Aquat. Sci*. 51: 110-122.

Mace, P.M. and M.P. Sissenwine. 1993. How much spawning per recruit is enough? pp. 101-118. In: S.J. Smith, J.J. Hunt and D. Rivard [Ed.] Risk evaluation and biological reference points for fisheries management. *Can. J. Fish. Aquat. Sci. Spec. Publ.* 120.

Magnusson, K.G. 1992. A feedback and probing strategy to regulate harvesting from a renewable resource. *IMA J. Math. Appl. Med. Biol*. 9: 43-65.

Magnusson, K.G. and G. Stefansson. 1989. A feedback strategy to regulate catches from a whale stock. *Rep. Int. Whal. Commn* (Special Issue 11): 171-189.

Maunder, M.N. and P.J. Starr. 1995. Sensitivity of management reference points to the ratio of B_{msy}/B_0 determined by the Pella-Tomlinson shape parameter fitted to New Zealand rock lobster data. *N.Z. Fish. Ass. Res. Doc*. 95/10. 22 pp.

McAllister, M.K. and J.N. Ianelli. 1997. Bayesian stock assessment using catch-age data and the sampling – importance resampling algorithm. *Can. J. Fish. Aquat. Sci*. 54: 284-300.

McAllister, M.K. and G.P. Kirkwood. 1998. Using Bayesian decision analysis to help achieve a precautionary approach for managing developing fisheries. *Can. J. Fish. Aquat. Sci.* 55: 2642-2661.

McAllister, M.K., Pikitch, E.K., Punt, A.E. and R. Hilborn. 1994. A Bayesian approach to stock assessment and harvest strategy decisions using the sampling/importance resampling algorithm. *Can. J. Fish. Aquat. Sci*. 51: 2673-2687.

McDonald, A.D. and A.D.M. Smith 1997. A tutorial on evaluating expected returns from research for fishery management. *Nat. Resour. Model*. 10: 185-216.

McDonald, A.D., Smith, A.D.M., Punt, A.E., Tuck, G.N. and A.J. Davidson. 1997. Empirical evaluation of expected returns from research on stock structure for determination of total allowable catch. *Nat. Resour. Model*. 10: 3-29.

McDonald, A.D., Smith, A.D.M. and A.J. Davidson. 1998. Evaluating the costs and benefits of research on stock structure for management of the orange roughy fishery. Report of FRDC 96/109. CSIRO Marine Research, Hobart. 73 pp.

Megrey, B.A. 1989. Review and comparison of age-structured stock assessment models from theoretical and applied points of view. *Am. Fish. Soc. Symp*. 6: 8-48.

Methot, R.D. 1989. Synthetic estimates of historical abundance and mortality for northern anchovy. *Am. Fish. Soc. Symp.* 6: 66-82.

Methot, R.D. 1990. Synthesis model: an adaptable framework for analysis of diverse stock assessment data. *Int. North Pac. Fish. Comm. Bull*. 50: 259-277.

Mohn, R. 1991. Length-based virtual population analysis: A review and swordfish example. ICCAT Document SCRS/91/36. 20 pp.

Montgomery, S.S. 1985. Aspects of biology of the tiger flathead *platycephalus richardsoni* and the associated fishery. M.Sc. Thesis, University of NSW, Sydney. 181 pp.

Myers, R.A., Bowen, K.G. and N.J. Barrowman. 1999. Maximum reproductive rate of fish at low population sizes. *Can. J. Fish. Aquat. Sci*. 56: 2404-2419.

National Research Council (NRC). 1998. Improving Fish Stock Assessments. National Academy Press, Washington, D.C. 177 pp.

Pascual, M.A. and O.O. Iribarne. 1993. How good are empirical predictions of natural mortality? *Fish. Res.* 16: 17-24.

Patterson, K.R. and G.P. Kirkwood 1995. Comparative performance of ADAPT and Laurec-Shepherd methods for estimating fish population parameters and in stock management. *ICES J. Mar. Sci.* 52: 183-196.

Pauly, D., Moreau, J. and N. Abad. 1995. Comparison of age-structured and length-converted catch curves of brown trout *Salmo trutta* in two French rivers. *Fish. Res*. 22: 197-204.

Polacheck, T., Hilborn, R. and A.E. Punt. 1993. Fitting surplus production models: comparing methods and measuring uncertainty. *Can. J. Fish. Aquat. Sci*. 50: 2597-2607.

Pope, J.G. 1983. Analogies to the status-quo TACs: their nature and variance. pp. 99-113. In: W.G. Doubleday and D. Rivard [Ed.] Sampling commercial catches of marine fish and invertebrates. *Can. Spec. Publ. Fish. Aquat. Sci*. 66.

Pope, J.G. and D. Gray. 1983. An investigation of the relationship between the precision of assessment data and the precision of total allowable catches. pp. 151-157. In: W.G. Doubleday and D. Rivard [Ed.] Sampling commercial catches of marine fish and invertebrates. *Can. Spec. Publ. Fish. Aquat. Sci*. 66.

Pope, J.G. and J.G. Shepherd. 1982. A simple method for the consistent interpretation of catch-at-age data. *J. Cons. Int. Explor. Mer*. 40: 176-184.

Pope, J.G. and J.G. Shepherd. 1985. A comparison of the performance of various methods for tuning VPAs using effort data. *J. Cons. Int. Expl. Mer*. 42: 129-151.

Powers, J.E. and V.R, Restrepo. 1992. Additional options for age-sequenced analysis. *ICCAT Col. Vol. Sci. Pap.* 39(2): 540-553.

Prager, M.H. 1994. A suite of extensions to a nonequilibrium surplus-production model. *Fish. Bull., US* 92: 374-389.

Punt, A.E. 1988. Model Selection for the dynamics of Southern African Hake resources. *BEP Report No. 15*. 402 pp.

Punt, A.E. 1989. Bias and variance of catch-effort based model estimation procedures used in the management of the ICSEAF hake stocks - a preliminary comparative investigation. *Sel. Pap. Int. Commn SE. Atl. Fish*. 1: 39-54.

Punt, A.E. 1993. The comparative performance of production-model and *ad hoc* tuned VPA based feedback-control management procedures for the stock of Cape hake off west coast of South Africa. pp. 283-299. In: S.J. Smith, J.J. Hunt and D. Rivard [Ed.] Risk evaluation and biological reference points for fisheries management. *Can. J. Fish. Aquat. Sci. Spec. Publ.* 120.

Punt, A.E. 1994. Assessments of the stocks of Cape hake *Merluccius* spp. off South Africa. *S. Afr J. Mar. Sci.* 14: 159-186.

Punt, A.E. 1995. The performance of a production-model management procedure. *Fish. Res.* 21: 349-374.

Punt, A.E. 1997. The performance of VPA-based management. *Fish. Res*. 29: 217-243.

Punt, A.E. 1998. Specifications related to the key uncertainties that need to be considered in the 1998 assessment of the eastern stock of gemfish. Document submitted to the 18 - 19 August 1998 meeting of EGAG. Australian Fisheries Management Authority, Canberra. 11 pp.

Punt, A. E. 1999a. An assessment of blue warehou for 1999 based on integrated analysis. Document submitted to the 7-8 June 1999 meeting of BWAG. Australian Fisheries Management Authority, Canberra. 37 pp.

Punt, A. E. 1999b. ADAPT and integrated analysis assessments of school whiting. Document submitted to the 17-18 June 1999 school whiting workshop. Australian Fisheries Management Authority, Canberra. 18 pp.

Punt, A.E. and D.S. Butterworth. 1995. The effects of future consumption by the Cape fur seal on catches and catch rates of the Cape hakes. 4. Modelling the biological interaction between Cape fur seals *Arctocephalus pusillus pusillus* and Cape hakes *Merluccius capensis* and *M. paradoxus*. *S. Afr. J. Mar. Sci.* 16: 255-285.

Punt, A.E. and D.S. Butterworth. In press. An examination of certain of the assumptions made in the Bayesian approach used to assess the eastern Pacific stock of gray whales (*Eschrichtius robustus). Rep. int. Whal. Commn (Special Issue)*.

Punt, A.E. and D.W. Japp. 1994. Stock assessment of the kingklip *Genypterus capensis* off South Africa. *S. Afr. J. Mar. Sci*. 14: 133-149.

Punt, A.E. and R. Hilborn. 1996. Biomass dynamic models. User's manual. *FAO Computerized Information Series (Fisheries).* No. 10. Rome, FAO. 62 pp.

Punt, A.E. and R.B. Kennedy. 1997. Population modelling of Tasmanian rock lobster, *Jasus edwardsii*, resources. *Mar. Freshw. Res.* 48: 967-980.

Punt, A.E. and A.D.M. Smith. 1999. Harvest strategy evaluation for the eastern stock of gemfish (*Rexea solandri*). *ICES J. Mar. Sci.* 56: 860-875.

Punt, A.E. and D.C. Smith. In press. Assessments of South East Fishery species can be sensitive to the method used to convert from size to age composition data. *Mar. Freshw. Res* 00: 00-00.

Punt, A.E., Campbell, R. and A.D.M. Smith. In press-a. Evaluating empirical indicators and reference points for fisheries management: Application to the broadbill swordfish fishery off Eastern Australia. *Mar. Freshw. Res.* 00: 00-00.

Punt, A.E., Cooke, J.G., Borchers, D.L. and S. Strindberg. 1997a. Estimating the extent of additional variance for Southern Hemisphere minke whales from the results of the IWC/IDCR cruises. *Rep. int. Whal. Commn* 47: 431-434.

Punt, A.E., Kennedy, R.B. and S. Frusher. 1997b. Estimating the size-transition matrix for Tasmanian rock lobster, *Jasus edwardsii*. *Mar. Freshw. Res*. 48: 981-992.

Punt, A.E., McAllister, M.K., Pikitch, E.K. and R. Hilborn. 1994. Stock assessment and decision analysis for hoki (*Macruronus novaezelandiae*) for 1994. *N.Z. Fish. Ass. Res. Doc*. 94/13. 47 pp.

Punt, A.E., Smith, A.D.M. and G. Cui. In press-b. Review of progress in the introduction of Management Strategy Evaluation (MSE) approaches in Australia's South East Fishery. *Mar. Freshw. Res.* 00: 00-00.

Punt, A.E., Smith D.C., Thomson, R.B., Haddon, M., He, X. and J. Lyle. In press-c. A model-based examination of trends in the abundance of blue grenadier, *Macruronus novaezelandiae* in south eastern Australia. *Mar. Freshw. Res.* 51: 00-00.

Rosenberg, A.A. and S. Brault. 1993. Choosing a management strategy for stock rebuilding when control is uncertain. pp. 243-249. In: S.J. Smith, J.J. Hunt and D.

Rivard [Ed.] Risk evaluation and biological reference points for fisheries management. *Can. J. Fish. Aquat. Sci. Spec. Publ.* 120.

Sainsbury, K.J., Punt, A.E. and A.D.M. Smith. 2000. Design of operational management strategies for achieving fishery ecosystem objectives. *ICES. J. Mar. Sci.* 57: 731-741.

Schnute, J. 1985. A general theory for the analysis of catch and effort data. *Can. J. Fish. Aquat. Sci.* 42: 414-429.

Schnute, J. 1987. A general fishery model for a size-structured fish population. *Can. J. Fish. Aquat. Sci.* 44: 924-940.

Schnute, J. and D. Fournier. 1980. A new approach to length-frequency analysis: growth structure. *Can. J. Fish. Aquat. Sci*. 37: 1337-1351.

Sissenwine, M.P. and J.G. Shepherd. 1987. An alternative perspective on recruitment overfishing and biological reference points. *Can. J. Fish. Aquat. Sci*. 44: 913-918.

Smith, A.D.M. 1994. Management Strategy Evaluation – The Light on the Hill. pp. 249-253. In: D.A. Hancock [Ed.] Population dynamics for fisheries management. Australian Society for Fish Biology Workshop Proceedings, Perth 24-25 August 1993, Australian Society for Fish Biology, Perth.

Smith D.C. (Ed) 1999a. Blue grenadier 1998. Stock Assessment Report, South East Fishery Assessment Group. Australian Fisheries Management Authority, Canberra.

Smith D.C. (Ed) 1999b. Blue warehou 1998. Stock Assessment Report, South East Fishery Assessment Group. Australian Fisheries Management Authority, Canberra.

Smith, T.D. 1994. *Scaling fisheries: The science of measuring the effects of fishing*. University of Cambridge Press, Cambridge. x + 392 pp.

Smith, A.D.M., and A.E. Punt. 1998. Stock assessment of gemfish (*Rexea solandri*) in eastern Australia using maximum likelihood and Bayesian methods. pp. 245-286. In: T.J. Quinn II, F. Funk, J. Heifetz, J.N. Ianelli, J.E. Powers, J.F. Schweigert, P. J. Sullivan and C-I Zhang [Ed.] Fisheries Stock Assessment Models. Alaska Sea Grant College Program, AK-SG-98-01. University of Alaska Fairbanks.

Smith, D.C. and D.A. Robertson. 1995. Jackass Morwong, Stock Assessment Report, South East Fishery Assessment Group. Australian Fisheries Management Authority, Canberra. 40 pp.

Southward, G.M. 1968. A simulation of management strategies in the Pacific Halibut fishery. *Int. Pac. Halibut Comm Sci. Rept.* 47: 1-70.

Sullivan, K., Smith, D.C. and A. Gason. 1994. Getting the right information for age-structured models. pp. 91-98. In: D.A. Hancock [Ed.] Population dynamics for fisheries management. Australian Society for Fish Biology Workshop Proceedings, Perth 24-25 August 1993, Australian Society for Fish Biology, Perth.

Sullivan, P.J., Lai, H.L. and V.F. Gallucci. 1990. A catch-at-length analysis that incorporates a stochastic model of growth. *Can. J. Fish. Aquat. Sci*. 47: 184-198.

Tilzey, R.D.J. (Ed) 1999. The South East Fishery 1998, Fishery Assessment Report compiled by the South East Fishery Assessment Group. Australian Fisheries Management Authority: Canberra. xv + 199 pp.

United Nations. 1995. Structure and Process of the 1993-1995 United Nations Conference on Straddling Fish Stocks and Highly Migratory Fish Stocks. *FAO Tech. Circ.* 898.

Vetter, E.F. 1988. Estimation of natural mortality in fish stocks: a review. *Fish. Bull.* 86: 25-43.

Wade, P.R. 1996. Gray whale stock assessment. Paper SC/48/AS8 presented to the IWC Scientific Committee, June 1996. International Whaling Commission, Cambridge. 17 pp.

Zheng, J., Murphy, M.C. and G.H. Kruse. 1995. A length-based population model and stock-recruitment relationships for red king crab, *Paralithodes camtschaticus*, in Bristol Bay, Alaska. *Can. J. Fish. Aquat. Sci*. 52: 1229-1246.

Zheng, J., Murphy, M.C. and G.H. Kruse. 1996. A catch-length analysis for crab populations. *Fish. Bull. US* 94: 576-588.

Table 1 : Details of the five stock assessment methods.

Details	Production model	*Ad hoc* tuned VPA	ADAPT-VPA	Age-structured production model	Integrated Analysis
Data used					
Relative abundance data	Yes	Yes	Yes	Yes	Yes
Absolute abundance data	Yes	No	Yes	Yes	Yes
Age-composition data	No	Yes	Yes	No	Yes
Size-composition data	No	No	No	No	Yes
Examples in the SEF	N/A	Blue warehou; Eastern gemfish; Redfish	School whiting	Orange roughy	School whiting; Blue warehou; Eastern gemfish; Blue grenadier; Orange roughy; Ling*; Spotted warehou*. Redfish*

* Under development

Table 2 : Details of the harvest strategies.

Stock assessment method	Catch control law	Variants
Empirical		
1. Trends in catch rate, fishing mortality, mean length of the catch, ratio of the catch to the *TAC*	Equation F.7	Gain = ϕ
2. Catch versus *TAC*	Equation F.8	α, β_1, β_2
Production model	f_{MSY} strategy	Effort = ϕf_{MSY}
	Replacement yield, *RY*	Quota = *RY*
Ad hoc tuned VPA	Equation F.20	$F_{targ} = \phi f_{MSY}$
ADAPT-VPA	Equation F.20	$F_{targ} = \phi f_{MSY}$
Age-structured production model	Equation F.21	$F_{targ} = \phi f_{MSY}$
Integrated Analysis	Equation F.21	$F_{targ} = \phi f_{MSY}$
		$F_{targ} = \phi f_{0.n}$
		$F_{targ} = F_{40\%}$
		$F_{targ} = F_{30\%}$

Table 3 : Performance measures for the estimates of (i) current spawner biomass, (ii) depletion of the available biomass, and (iii) *MSY*. Results are shown for eighteen scenarios based on the base-case trial and the base-case Integrated Analysis estimator. Results are shown in (a) for mean relative errors and in (b) for median relative errors.

(a) Mean relative errors (bias)

Scenario	Species / Management quantity											
	Spotted warehou			Tiger flathead			Jackass morwong			Pink ling		
	(i)	(ii)	(iii)	(i)	(ii)	(iii)	(i)	(ii)	(iii)	(i)	(ii)	(iii)
Base-case												
Base-case	224.1	72.2	83.4	-39.0	-33.2	-37.9	-31.8	-10.7	-42.4	-67.1	-34.8	-17.9
Less vars	234.5	70.2	84.3	-36.2	-36.1	-35.9	-28.9	-14.4	-39.1	-67.5	-34.5	-18.1
One area	37.1	37.6	26.4	-26.6	-21.8	-30.4	17.2	17.9	-2.7	-78.6	-40.9	-30.2
No growth	8.9	17.4	5.4	-32.5	-25.7	-29.7	4.2	2.2	-12.4	-78.6	-43.3	-28.3
Less vars 2	9.6	12.2	3.0	-29.9	-24.5	-27.5	2.5	3.3	-12.6	-79.6	-44.0	-30.1
No discards	6.7	17.5	3.2	-5.9	4.0	-0.7	6.1	10.2	-0.3	-79.3	-43.6	-29.2
Known steepness												
Base-case	224.0	71.8	70.2	-36.0	-24.3	-30.2	-26.4	6.3	-31.4	-67.7	-36.9	-33.2
Less vars	275.8	77.0	93.3	-34.8	-23.8	-28.9	-24.5	0.3	-31.8	-67.7	-36.2	-35.1
One area	37.8	37.6	15.5	-21.7	-16.4	-23.3	27.6	22.2	-1.6	-78.9	-43.7	-43.3
No growth	9.7	18.0	-9.2	-28.6	-19.6	-24.9	9.2	12.8	-8.7	-79.0	-47.0	-43.3
Less vars 2	9.9	14.2	-9.4	-28.1	-19.7	-23.4	10.9	10.6	-9.1	-79.9	-47.2	-44.3
No discards	10.5	19.9	-5.6	-4.7	7.3	-2.8	10.1	16.0	-0.5	-80.4	-47.4	-44.2
$\sigma_q = 0.001$												
Base-case	39.1	31.5	-42.0	-38.2	-30.0	-32.9	-38.1	-18.0	-42.8	-63.9	-22.1	-12.4
Less vars	30.0	29.8	-30.1	-38.8	-31.2	-32.3	-39.5	-17.4	-38.8	-66.8	-24.2	-21.8
One area	23.6	24.6	15.0	-25.0	-19.3	-25.6	12.0	9.1	-12.6	-73.2	-23.5	-25.7
No growth	-0.8	11.0	-5.2	-29.0	-20.2	-27.2	-6.6	-4.1	-18.9	-74.6	-27.4	-24.9
Less vars 2	12.6	15.6	-15.2	-28.6	-21.1	-22.5	-6.7	-2.2	-17.4	-77.0	-28.4	-32.4
No discards	7.0	18.7	-17.7	-11.7	-5.1	-11.7	0.4	8.8	-10.2	-76.9	-28.5	-31.6

(Table 3 Continued)

(b) Median absolute relative errors (MAREs)

Scenario	Species / Management quantity											
	Spotted warehou			Tiger flathead			Jackass morwong			Pink ling		
	(i)	(ii)	(iii)	(i)	(ii)	(iii)	(i)	(ii)	(iii)	(i)	(ii)	(iii)
Base-case												
Base-case	224.1	72.2	97.3	39.0	33.2	37.9	35.3	35.8	42.4	67.1	34.8	19.6
Less vars	234.5	70.2	97.7	37.0	36.1	35.9	34.0	33.8	39.1	67.5	34.5	20.6
One area	39.2	37.6	50.7	28.4	25.1	30.4	21.7	27.3	16.9	78.6	43.3	30.2
No growth	22.0	21.7	24.6	32.6	26.1	29.7	18.3	22.1	16.4	78.6	43.3	28.3
Less vars 2	21.2	18.6	25.5	30.7	24.7	27.5	17.6	23.1	16.6	79.6	44.0	30.1
No discards	22.8	20.3	30.6	16.2	15.8	15.4	17.4	22.0	19.3	79.3	43.6	29.3
Known steepness												
Base-case	224.0	71.8	70.2	36.6	24.8	30.2	30.9	19.6	31.4	67.7	36.9	33.2
Less vars	275.8	77.0	93.3	35.0	24.4	28.9	28.1	18.0	31.8	67.7	36.2	35.1
One area	38.8	37.6	19.9	22.2	18.4	23.3	28.9	22.2	9.0	79.0	46.1	43.8
No growth	20.8	20.8	15.5	29.7	20.7	24.9	17.8	17.9	11.0	79.0	47.0	43.3
Less vars 2	21.4	18.5	15.2	29.4	20.2	23.4	17.1	16.1	10.9	79.9	47.2	44.3
No discards	23.1	21.1	12.4	13.0	12.5	9.5	17.5	17.8	10.0	80.4	47.4	44.2
$\sigma_q = 0.001$												
Base-case	39.1	31.5	48.6	38.2	30.0	32.9	39.9	35.9	42.8	63.9	22.1	15.7
Less vars	30.0	29.8	40.6	38.8	31.2	32.3	41.2	33.9	38.8	66.8	24.2	22.6
One area	25.8	24.6	32.1	25.0	19.3	25.6	12.2	16.9	15.4	73.2	24.5	26.1
No growth	7.8	12.9	23.6	29.0	20.3	27.2	6.9	12.4	19.1	74.6	27.5	25.6
Less vars 2	12.8	15.7	34.2	28.6	21.1	22.5	7.7	10.5	17.4	77.0	28.6	32.6
No discards	8.0	19.1	22.5	12.0	10.9	14.4	4.6	11.2	11.1	76.9	28.5	31.6

Table 4 : Bias and median relative errors for the estimates of (i) current spawner biomass, (ii) depletion of the available biomass, and (iii) *MSY*. Results are shown for six stock assessment methods for the base-case trial.

Scenario	Species / Management quantity											
	Spotted warehou			Tiger flathead			Jackass morwong			Pink ling		
	(i)	(ii)	(iii)	(i)	(ii)	(iii)	(i)	(ii)	(iii)	(i)	(ii)	(iii)
Bias												
Schaefer model	-16.7	1.8	-55.2	-45.7	-26.1	-46.0	-63.6	38.0	-29.1	-49.0	-14.7	-18.9
Fox model	-19.2	-1.2	-51.6	-43.8	-28.9	-42.6	-59.9	7.8	-33.8	-40.4	-15.6	-11.1
Integrated Analysis	224.1	72.2	83.4	-39.0	-33.2	-37.9	-31.8	-10.7	-42.4	-67.1	-34.8	-17.9
ASPM	-45.6	-15.2	-91.4	-32.0	-32.6	-43.5	-51.8	-36.4	-36.7	-26.8	-9.4	-40.3
Ad hoc tuned VPA	-42.3	-5.5	-27.3	-52.1	-32.9	-32.3	-37.2	15.4	-33.2	-78.0	-59.5	-14.4
ADAPT-VPA	572.7	108.8	262.7	114.4	87.9	36.0	159.4	94.4	63.1	2883.9	121.9	1506.4
MARE												
Schaefer model	56.7	21.9	60.2	70.6	38.9	70.7	69.3	49.5	33.9	63.8	24.8	67.6
Fox model	53.5	21.0	54.5	73.8	41.5	63.9	67.1	37.3	35.0	64.6	26.3	71.2
Integrated Analysis	224.1	72.2	97.3	39.0	33.2	37.9	35.3	35.8	42.4	67.1	34.8	19.6
ASPM	90.6	39.2	93.6	62.4	47.4	61.6	66.5	45.9	42.0	53.0	24.7	78.9
Ad hoc tuned VPA	48.5	15.8	38.8	57.5	37.0	42.2	72.6	32.5	51.8	78.4	60.1	31.1
ADAPT-VPA	572.7	108.8	262.7	114.4	87.9	36.6	159.4	94.4	64.8	2883.9	121.9	1506.4

Table 5 : MAREs for each of the 12 management-related quantities for the base-case trial and the Integrated Analysis estimator, the ranks (by species) for each management-related quantity, and the summed (over the four species) ranks.

Species	Management-related quantity (see Section 5.1 for details)											
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)
MARE												
Spotted warehou	224.1	254.9	90.7	72.2	27.6	14.4	97.3	142.5	43.9	77.8	76.3	73.0
Tiger flathead	39.0	47.6	26.5	33.2	12.8	14.2	37.9	37.0	93.2	6.7	33.0	33.4
Jackass morwong	35.3	34.5	35.1	35.8	24.5	28.0	42.4	60.0	79.3	55.5	44.7	50.0
Pink ling	67.1	21.2	35.0	34.8	13.3	19.4	19.6	26.3	393.0	15.3	18.2	18.2
Ranks												
Spotted warehou	11	12	9	4	2	1	8	10	3	7	6	5
Tiger flathead	10	11	4	6	2	3	9	8	12	1	5	7
Jackass morwong	5	3	4	6	1	2	7	11	12	10	8	9
Pink ling	11	7	10	9	1	5	6	8	12	2	3.5	3.5
Overall rank	37	33	27	25	6	11	30	37	39	20	22.5	24.5

Table 6 : Performance measures for three of the four species for a trial (the reference trial) in which steepness is low and the current spawner biomass is 20% of the pre-exploitation equilibrium level. Results are shown for a range of harvest strategies. "Median B_{final}" is the median of the distribution of the ratio of the spawner biomass at the end of the projection period (2023) to the corresponding pre-exploitation equilibrium level, "Median catch" is the median of average annual catch distribution, "Median AAV" is the median of the distribution of the AAV statistic (Equation 4). The two values for γ_{emp} for the empirical harvest strategies relate to the values to use when the index of abundance is increasing / decreasing respectively.

(a) Integrated Analysis-based harvest strategies

Harvest strategy option	Spotted warehou					Tiger flathead					Jackass morwong				
	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>$B_{86\text{-}94}$ (%)	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>$B_{86\text{-}94}$ (%)	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>$B_{86\text{-}94}$ (%)
Base-case	28.9	395	18.8	91	4	12.6	365	16.8	1	0	11.6	322	13.0	3	4
ϕ=1	43.6	335	16.6	99	36	31.3	310	15.0	79	56	29.7	311	7.8	77	77
$F_{\text{targ}} = F_{30\%}$	38.2	359	16.4	100	18	26.3	332	15.4	49	22	25.1	326	9.2	63	58
$F_{\text{targ}} = F_{40\%}$	45.8	348	17.2	100	35	33.1	314	15.5	92	67	31.6	310	7.7	84	87
$F_{\text{targ}} = F_{50\%\text{R}}$	33.1	354	17.1	88	11	16.3	345	17.1	11	0	15.3	283	10.2	13	14
ASPM; ϕ=1	44.7	310	14.8	98	40	28.1	312	15.3	63	29	26.3	325	8.8	62	62

(b) Other model-based harvest strategies

Harvest strategy option	Spotted warehou					Tiger flathead					Jackass morwong				
	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>$B_{86\text{-}94}$ (%)	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>$B_{86\text{-}94}$ (%)	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>$B_{86\text{-}94}$ (%)
Integrated Analysis	28.9	395	18.8	91	4	12.6	365	16.8	1	0	11.6	322	13.0	3	4
ϕ=1	43.6	335	16.6	99	36	31.3	310	15.0	79	56	29.7	311	7.8	77	77
Schaefer model; f_{msy}	48.0	317	10.0	99	50	35.6	290	15.5	83	73	31.2	333	9.3	81	79
Ad hoc VPA	17.0	356	22.7	35	0	1.8	287	19.2	0	0	2.5	299	22.3	0	0
Fox model; f_{msy}	58.6	263	7.8	100	83	42.4	270	15.7	98	94	40.2	266	3.5	99	96
ADAPT VPA	17.2	360	23.4	46	0	1.4	300	24.5	0	0	2.3	283	22.5	0	0
Sch model; RY	18.5	458	17.9	54	0	10.9	335	16.0	0	0	8.2	380	14.8	3	2

(Table 6 Continued)

(c) Schaefer model-based harvest strategies

Harvest strategy option	Spotted warehou					Tiger flathead					Jackass morwong				
	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>$B_{86\text{-}94}$ (%)	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>$B_{86\text{-}94}$ (%)	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>$B_{86\text{-}94}$ (%)
ϕ=0.25	56.1	263	7.6	99	80	41.8	270	15.9	93	90	40.1	266	3.9	94	92
ϕ=0.5	55.8	263	7.6	98	73	41.8	271	15.5	86	83	38.8	266	4.5	87	84
ϕ=1	48.0	317	10.0	99	50	35.6	290	15.5	83	73	31.2	333	9.3	81	79
ϕ=1.5	35.8	406	12.2	97	22	26.3	305	14.4	55	29	21.5	381	11.6	45	36
ϕ=2	26.1	423	15.3	85	5	18.2	314	15.8	8	3	14.2	382	15.0	12	7
ϕ=2.5	19.1	423	18.2	60	0	9.7	319	16.7	2	0	6.3	388	18.2	1	0

(d) Trends in catch rates

Harvest strategy Option	Spotted warehou					Tiger flathead					Jackass morwong				
	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>$B_{86\text{-}94}$ (%)	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>$B_{86\text{-}94}$ (%)	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>$B_{86\text{-}94}$ (%)
γ_{emp} = (1, 1)	8.5	411	24.0	9	0	0.6	293	32.0	0	0	0.8	271	25.9	0	0
γ_{emp} = (.5, .5)	17.8	440	27.3	49	0	1.9	318	25.1	0	0	2.9	317	25.9	0	0
γ_{emp} = (.25, .25)	18.3	442	27.1	61	0	1.9	317	26.2	0	0	3.0	313	24.6	0	0
γ_{emp} = (2, 2)	14.8	372	13.3	41	1	1.2	323	20.0	0	0	1.7	284	23.5	0	0
γ_{emp} = (4, 4)	17.0	379	18.4	42	2	1.7	330	20.1	0	0	2.4	311	22.8	0	0
γ_{emp} = (.5, 1)	9.4	394	21.1	10	0	0.6	291	31.9	0	0	0.8	266	25.4	0	0

(Table 6 Continued)

(e) Trends in the fishing mortality from age-based catch curves

Harvest strategy option	Spotted warehou					Tiger flathead					Jackass morwong				
	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>B_{86-94} (%)	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>B_{86-94} (%)	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>B_{86-94} (%)
γ_{emp} = (1, 1)	19.6	438	26.0	67	0	1.9	322	26.4	0	0	3.0	310	25.0	0	0
γ_{emp} = (.5, .5)	19.0	438	26.0	69	0	2.0	319	26.0	0	0	3.1	310	24.8	0	0
γ_{emp} = (.25, .25)	19.4	438	26.0	67	0	1.9	322	25.9	0	0	3.0	310	24.9	0	0
γ_{emp} = (2, 2)	19.8	439	26.1	66	0	1.9	324	25.9	0	0	2.8	310	24.8	0	0
γ_{emp} = (4, 4)	18.8	423	23.7	58	0	1.8	324	24.9	0	0	2.7	305	24.7	0	0
γ_{emp} = (.5, 1)	19.5	438	26.0	68	0	1.9	322	26.6	0	0	3.0	310	24.9	0	0

(f) Trends in the fishing mortality from length-based catch curves

Harvest strategy option	Spotted warehou					Tiger flathead					Jackass morwong				
	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>B_{86-94} (%)	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>B_{86-94} (%)	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>B_{86-94} (%)
γ_{emp} = (1, 1)	19.1	441	27.2	65	0	2.0	325	26.4	0	0	3.1	310	25.1	0	0
γ_{emp} = (.5, .5)	19.2	439	26.1	69	0	1.9	321	25.8	0	0	3.1	311	24.9	0	0
γ_{emp} = (.25, .25)	19.4	438	26.1	67	0	1.9	322	25.9	0	0	3.0	310	24.9	0	0
γ_{emp} = (2, 2)	18.8	440	27.5	57	0	1.9	323	25.4	0	0	2.9	311	24.8	0	0
γ_{emp} = (4, 4)	18.9	437	26.3	53	0	1.9	323	25.7	0	0	2.9	316	24.6	0	0
γ_{emp} = (.5, 1)	19.1	438	26.6	62	0	1.9	325	25.9	0	0	3.1	310	25.3	0	0

(Table 6 Continued)

(g) Trends in the mean length of the catch

Harvest strategy option	Spotted warehou					Tiger flathead					Jackass morwong				
	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>$B_{86\text{-}94}$ (%)	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>$B_{86\text{-}94}$ (%)	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>$B_{86\text{-}94}$ (%)
γ_{emp} = (1, 1)	15.4	342	14.6	40	2	1.1	300	21.5	0	0	1.6	288	23.5	0	0
γ_{emp} = (.5, .5)	16.1	410	26.9	32	0	1.5	304	26.5	0	0	2.0	297	28.9	0	0
γ_{emp} = (.25, .25)	18.7	439	26.2	64	0	1.8	321	25.7	0	0	2.8	311	24.9	0	0
γ_{emp} = (2, 2)	21.6	342	18.9	61	2	1.8	321	22.2	0	0	2.8	297	25.4	0	0
γ_{emp} = (4, 4)	19.1	343	20.6	53	2	1.8	317	24.1	0	0	2.6	296	25.4	0	0
γ_{emp} = (.5, 1)	22.5	315	11.2	64	11	1.1	301	18.7	0	0	2.6	291	22.0	3	1

(Table 6 Continued)

(g) Trends in the ratio of the catch to the *TAC*

Harvest strategy option	Spotted warehou					Tiger flathead					Jackass morwong				
	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>B_{86-94} (%)	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>B_{86-94} (%)	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>B_{86-94} (%)
γ_{emp} = (1, 1)	17.8	441	25.9	55	0	1.8	312	25.9	0	0	2.6	303	25.0	0	0
γ_{emp} = (.5, .5)	18.2	435	27.1	65	0	1.8	313	26.2	0	0	3.0	309	25.4	0	0
γ_{emp} = (.25, .25)	19.1	438	26.0	63	0	1.9	317	26.9	0	0	3.0	309	24.8	0	0
γ_{emp} = (2, 2)	16.8	421	23.7	34	0	1.6	311	25.9	0	0	2.5	303	26.7	0	0
γ_{emp} = (4, 4)	13.5	392	21.5	26	0	1.0	300	29.8	0	0	1.7	294	28.3	0	0
γ_{emp} = (.5, 1)	18.0	425	24.7	51	0	1.7	310	26.4	0	0	2.7	304	25.2	0	0

(h) Difference between the catch and the *TAC*

Harvest strategy option	Spotted warehou					Tiger flathead					Jackass morwong				
	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>B_{86-94} (%)	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>B_{86-94} (%)	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>B_{86-94} (%)
γ_{emp} = (1, 1)	16.4	447	27.9	29	0	1.7	326	25.4	0	0	2.6	317	23.7	0	0

Table 7 : Performance measures (see Table 6 for details) for five "key" simulation trials for a subset of the harvest strategies.

(a) Base-case Integrated Analysis

Scenario	Spotted warehou					Tiger flathead					Jackass morwong				
	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>B_{86-94} (%)	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>B_{86-94} (%)	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>B_{86-94} (%)
Reference	28.9	395	18.8	91	4	12.6	365	16.8	1	0	11.6	322	13.0	3	4
Higher steepness	19.1	454	21.0	53	1	9.2	378	17.8	0	0	6.7	491	26.2	1	1
80% depletion	69.6	950	30.5	100	17	56.7	1368	21.9	100	6	59.8	507	19.8	100	18
80% depletion, higher steepness	73.9	974	29.8	100	30	56.5	1429	22.1	100	6	58.9	502	20.0	100	13

(b) Base-case Integrated analysis with F=F_{30}%

Scenario	Spotted warehou					Tiger flathead					Jackass morwong				
	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>B_{86-94} (%)	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>B_{86-94} (%)	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>B_{86-94} (%)
Reference	38.2	359	16.4	100	18	26.3	332	15.4	49	22	25.1	326	9.2	63	58
Higher steepness	29.1	440	17.0	91	21	26.8	380	15.2	49	30	18.0	564	20.0	24	54
80% depletion	68.9	981	30.9	100	16	61.2	567	15.9	100	14	63.2	378	16.8	100	23
80% depletion, higher steepness	74.8	1025	31.6	100	26	61.8	583	17.8	100	11	61.5	394	17.5	100	25

(c) Schaefer model; ϕ=1

Scenario	Spotted warehou					Tiger flathead					Jackass morwong				
	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>B_{86-94} (%)	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>B_{86-94} (%)	Median B_{final} (%)	Median catch	Median AAV	P>B_{MSY} (%)	P>B_{86-94} (%)
Reference	48.0	317	10.0	99	50	35.6	290	15.5	83	73	31.2	333	9.3	81	79
Higher steepness	46.2	437	8.2	100	84	49.9	359	13.5	100	99	38.6	515	7.6	88	99
80% depletion	82.0	438	14.6	100	45	81.3	307	11.6	100	57	83.4	413	13.1	100	71
80% depletion, higher steepness	87.2	439	17.0	100	61	82.7	316	12.5	100	61	82.8	399	13.0	100	80

Table 8 : Performance measures (see text and Table 6 for details) for the $F_{targ} = F_{30\%}$ harvest strategy for nine trials.

Trial Scenario	Spotted warehou							Tiger flathead						
	Low 5th B_{final} (%)	Median B_{final} (%)	Low 5th catch	Median catch	Median AAV	P>B_{MSY} (%)	P>B_{86-94} (%)	Low 5th B_{final} (%)	Median B_{final} (%)	Low 5th catch	Median catch	Median AAV	P>B_{MSY} (%)	P>B_{86-94} (%)
Base-case	39.7	65.3	387	558	36.9	100	59	38.2	64.6	296	411	15.7	100	73
Initial depletion = 0.1	5.5	28.7	201	330	18.7	70	88	14.8	39.0	262	360	18.9	83	87
Initial depletion = 0.2	21.0	42.7	276	439	22.1	97	72	26.8	45.1	279	436	17.0	96	90
Initial depletion = 0.8	49.2	77.6	356	658	39.2	100	60	55.1	78.8	293	686	17.5	100	56
Efficiency increase = 0.05	8.1	29.1	722	1033	32.7	69	8	0.0	22.4	564	984	21.2	36	6
$CV_q = 0.1$	37.7	65.9	362	588	36.1	100	57	41.3	62.5	294	530	14.4	100	81
With surveys	42.4	65.8	304	506	28.6	100	61	37.7	57.1	393	660	15.7	100	57
Efficiency increase = 0.05; with surveys	10.78	26.7	278	441	21.9	73	7	0.1	19.9	407	769	13.8	38	7
TAC range=(100*t*,2000*t*)	42.9	69.8	240	558	37.8	100	68	41.2	64.3	180	443	18.9	100	77

Trial Scenario	Jackass morwong							Pink ling						
	Low 5th B_{final} (%)	Median B_{final} (%)	Low 5th catch	Median catch	Median AAV	P>B_{MSY} (%)	P>B_{86-94} (%)	Low 5th B_{final} (%)	Median B_{final} (%)	Low 5th catch	Median catch	Median AAV	P>B_{MSY} (%)	P>B_{86-94} (%)
Base-case	38.7	63.1	266	548	22.6	100	94	13.3	44.8	236	253	8.3	76	23
Initial depletion = 0.1	5.9	18.3	339	485	20.5	30	93	1.2	2.4	78	124	38.4	0	0
Initial depletion = 0.2	7.8	25.7	383	535	20.9	56	95	2.7	5.4	131	206	21.9	4	2
Initial depletion = 0.8	51.4	78.6	273	569	24.8	100	74	47.6	73.9	248	295	10.2	100	41
Efficiency increase = 0.05	7.4	38.7	498	839	23.2	79	39	0.0	1.7	232	331	11.2	1	0
$CV_q = 0.1$	39.0	65.5	266	505	18.4	100	94	14.6	46.8	236	257	8.1	78	28
With surveys	32.7	57.4	310	609	19.7	100	87	21.4	43.6	231	300	12.2	81	21
Efficiency increase = 0.05; with surveys	10.7	39.0	340	701	17.1	74	40	0.0	1.8	191	275	11.1	0	0
TAC range=(100*t*,2000*t*)	43.5	66.7	144	516	22.9	100	94	30.8	52.0	123	190	16.8	97	37

Appendix A : Intellectual Property

No intellectual property has arisen from the project that is likely to lead to significant commercial benefits, patents or licences. Any intellectual property associated with this project will be shared 80.99 : 19.01 between the Fisheries Research and Development Corporation and CSIRO Marine Research.

Appendix B : Staff

André E. Punt	Senior Research Scientist, CMR	20%
Anthony D.M. Smith	Project Leader, CMR	10%
Nicholas J. Bax	Senior Research Scientist, CMR	5%
Peter Cui	Modeller, CMR	100%

Appendix C : Glossary

Terms in italics are defined in the glossary.

Assessment method: Method of analysing the data collected from a fishery to estimate quantities of interest to management such as *current biomass*, *Maximum Sustainable Yield*.

Biomass: The mass of fish of a pre-specified type (e.g. spawner biomass, recruited biomass).

Catch control law: A function that relates the outputs of a stock assessment model to the *TAC*. The output from the catch control law may be modified to avoid unduly large fluctuations in *TAC*s.

Harvest strategy: A harvest strategy is a set of rules that specify the data to be collected for management purposes and how those data are to be used to determine management actions.

Limit reference point: A *limit reference point* is used to indicate "the state of a fishery and / or a resource that is not considered desirable".

Management objectives: Statements that define the goals of the fishery management system. In actual analyses these are quantified by means of *performance measures*.

Management strategy: See *harvest strategy*.

Maximum Sustainable Yield: *MSY* is the largest (average) catch that can be taken indefinitely from a resource. It depends on the biology of the species, its pre-exploitation equilibrium size and the mix of gear types used in the fishery.

Operating model: A model the represents the "true" situation in the fishery. A number of alternative *operating models* are considered because there is always uncertainty.

Performance indicator: A quantity that indicates the status of a fishery. *Performance indicators* are often used as *target* or *limit reference points*.

Performance measure: Statistics used to quantify the performance of a *harvest strategy* relative to a set of *management objectives*.

Target reference point: A *target reference point* is used to indicate "the state of a fishery and / or a resource that is considered desirable".

Total Allowable Catch (*TAC*): A catch limit set as an output control on fishing.

Appendix D: The population and fleet dynamics model component of the operating model

D.1 Basic population dynamics

The dynamics of each of the species are represented using age- and size-structured models. The area over which fishing takes place is divided into discrete regions to allow for spatial structure (in fishing mortality and population structure). Each age-class is divided into several "growth-groups" and it is assumed all animals in a growth-group have the same growth rate. This permits individual variation in growth to be modelled in a relatively parsimonious manner.

The age- and size-specific dynamics of species i are governed by the equation:

$$N^{i,l,A}_{y+1,a} = \begin{cases} N^{i,l,A}_{y+1,0} & \text{if } a = 0 \\ \sum_{A'} X^{i,A',A,\tilde{L}^{i,l}_{y,a}}_{y} \, N^{i,l,A'}_{y,a-1} \, e^{-Z^{i,l,A'}_{y,a-1}} & \text{if } 1 \le a \le x-1 \\ \sum_{A'} X^{i,A',A,\tilde{L}^{i,l}_{y,x}}_{y} \, (\tilde{N}^{i,l,A'}_{y,x-1} e^{-Z^{i,l,A'}_{y,x-1}} + \tilde{N}^{i,l,A'}_{y,x} e^{-Z^{i,l,A'}_{y,x}}) & \text{if } a = x \end{cases} \quad \text{(D.1)}$$

where $N^{i,l,A}_{y,a}$ is the number of fish of species i and age a in growth-group l and region A at the start of year y,

$Z^{i,l,A}_{y,a}$ is the total mortality on fish of species i and age a in growth-group l in region A during year y:

$$Z^{i,l,A}_{y,a} = M^{i}_{y,a} + F^{i,l,A}_{y,a} \quad \text{(D.2)}$$

$M^{i}_{y,a}$ is the instantaneous rate of natural mortality on fish of species i and age a during year y:

$$M^{i}_{y,a} = \begin{cases} M^{i}_{a} & \text{if } y = y_{init} \\ \chi M^{i}_{y-1,a} + (1-\chi) M^{i}_{a} (1 + \varepsilon^{i}_{1,y} + \varepsilon^{i}_{1,y,a}) & \text{otherwise} \end{cases} \quad \text{(D.3)}$$

$\tilde{L}^{i,l}_{y,a}$ is, for a fish of species i, the length-class corresponding to age a and growth-group l at the start of year y,

$X^{i,A',A,\tilde{L}}_{y}$ is the probability that an animal of species i in length-class $\tilde{L}$ in region A' at the end of year y moves to region A:

$$X^{i,A',A,\tilde{L}}_{y} = X^{i,A',A,\tilde{L}} e^{\varepsilon^{i,A',A,\tilde{L}}_{X,y}} / \sum_{A''} X^{i,A',A'',\tilde{L}} e^{\varepsilon^{i,A',A'',\tilde{L}}_{X,y}} \qquad \varepsilon^{i,A',A,\tilde{L}}_{X,y} \sim N(0;\sigma^2_X) \quad \text{(D.4)}$$

$F^{i,l,A}_{y,a}$ is the instantaneous rate of fishing mortality on fish of species i and age a in growth-group l and region A during year y,

χ is the parameter that determines the extent of temporal correlation in natural mortality,

σ_X is the parameter that determines the extent of inter-annual variation in movement between depth zones,

y_{init} is the first year considered in the model, and

x is the maximum (lumped) age-class.

The error structure assumed for natural mortality takes (very) approximate account of multi-species biological interactions (Horwood, 1994).

The number of 0-year-olds added to the population each year (i.e. the number of births) is given by:

$$N_{y,0}^{i,l,A} = \pi^{i,l,A} \frac{(\tilde{B}_y^i / \tilde{B}_0^i)^{\gamma^i}}{\alpha^i + \beta^i (\tilde{B}_y^i / \tilde{B}_0^i)^{\gamma^i}} e^{\varepsilon_{r,y}^i - (\sigma_r^i)^2/2} \tag{D.5}$$

where $\tilde{B}_y^i$ is the spawner biomass for species i at the start of year y:

$$\tilde{B}_y^i = \sum_A \sum_{a=1}^{x} \sum_l m_{\tilde{L}_{y,a}^{i,l}}^i \, w_{\tilde{L}_{y,a}^{i,l}}^i \, N_{y,a}^{i,l,A} \tag{D.6}$$

$m_{\tilde{L}}^i$ is the proportion of fish of species i in length-class $\tilde{L}$ that are mature,

$w_{\tilde{L}}^i$ is the average mass of a fish of species i in length-class $\tilde{L}$,

$\alpha^i, \beta^i, \gamma^i$ are the parameters of the relationship between spawner biomass and year-class strength for species i,

$\varepsilon_{r,y}^i$ is the recruitment residual for year y and species i:

$$\varepsilon_{r,y}^i = \tau_r^i \, \varepsilon_{r,y-1}^i + \sqrt{1-(\tau_r^i)^2}\, \varepsilon_{r,y}^{i'} \tag{D.7}$$

$\pi^{i,l,A}$ is the fraction of births to species i that are found in growth-group l and region A,

$\varepsilon_{r,y}^{i'}$ is the i'th element of a vector generated from a multivariate normal distribution, $N(\underline{0}, \mathbf{W}_r)$, where $\mathbf{W}_r$ is a variance-covariance matrix with diagonal elements $(\sigma_r^i)^2$ and off-diagonal elements $\tau_r^{i,j}\, \sigma_r^i\, \sigma_r^j$,

σ_r^i is the standard deviation of the logarithm of the multiplicative fluctuations in year-class strength for species i,

$\tau_r^{i,j}$ is the extent of correlation between the recruitment residuals for species i and j (correlation among the recruitment residuals might be anticipated because of the impact of common environmental variables on recruitment success), and

τ_r^i is the magnitude of inter-annual correlation in the recruitment residuals for species i.

The form of the stock-recruitment relationship (Equation D.5) allows for depensatory processes. The values for the parameters of this relationship are derived from specifications for the pre-exploitation equilibrium spawner biomass, $\tilde{B}_0^i$, the steepness of the stock-recruitment relationship, h^i (Francis, 1992), and $\tilde{q}^i$, the ratio of the number of births expected at $0.1\tilde{B}_0^i$ for the depensatory stock-recruitment relationship to that expected at this biomass for a Beverton-Holt stock-recruitment relationship when both relationships are assumed to produce the same number of births at $0.2\tilde{B}_0^i$ (Liermann and Hilborn, 1997; Punt, 1998). Adjunct D.1 describes how the values for α, β and γ are calculated from those for $\tilde{B}_0$, h, and $\tilde{q}$.

D.2 Growth

The average mass and length of a fish of species *i* and age *a* in growth-group *l* at the start of year *y* are given by the equations:

$$w^i_{\tilde{L}} = e^i_1(\bar{L}_{\tilde{L}})^{e^i_2} \tag{D.8a}$$

$$L^{i,l}_{y,a} = L^{i,l}_\infty(1 - e^{-\kappa^{i,l}_{y,a}(a - t^i_0)}) \tag{D.8b}$$

where $L^{i,l}_\infty$ is the asymptotic length for a fish of species *i* in growth-group *l*,

e^i_1, e^i_2 are the parameters of the relationship between length and mass for species *i*,

$\kappa^{i,l}_{y,a}$ is the growth rate for a fish of species *i* and age *a* in growth-group *l* during year *y* (Figure D.1):

$$\kappa^{i,l}_{y,a} = \kappa^{i,l}(\tilde{R}^i_{y-a})^{\delta^i} \tag{D.9}$$

$\kappa^{i,l}$ is the growth rate for a fish of species *i* in growth-group *l* at (deterministic) pre-exploitation equilibrium,

$\bar{L}_{\tilde{L}}$ is the average of the upper and lower bounds for length-class $\tilde{L}$.

$\tilde{R}^i_y$ is the number of births to species *i* during year *y* as a fraction of the average number of births at unexploited equilibrium:

$$\tilde{R}^i_y = \begin{cases} 1 & \text{if } y \le y_{init} \\ \frac{1}{R^i_0}\sum_l \sum_A N^{i,l,A}_{y,0} & \text{otherwise} \end{cases} \tag{D.10}$$

R^i_0 is the expected number of births when the population is at its unexploited equilibrium size,

$$R^i_0 = \tilde{B}^i_0 / \sum_A \sum_{a=1}^{x} \sum_l m^i_{\tilde{L}^{i,l}_{y_{init},a}} w^i_{\tilde{L}^{i,l}_{y_{init},a}} N^{i,l,A}_{y_{init},a} \tag{D.11}$$

$N^{i,l,A}_{y_{init},a}$ is the number of animals of species *i* and age *a* in growth-group *l* and region *A* at (deterministic) pre-exploitation equilibrium,

δ^i is the parameter that determines the extent of density-dependence in the growth rate for species *i*, and

t^i_0 is the "age" at which a fish of species *i* has zero length.

This formalism ignores the possibility that mass-at-age varies inter-annually for environmental reasons although it does allow mass-at-age to change as a function of density because the growth rate is a function of density (see Equation D.9).

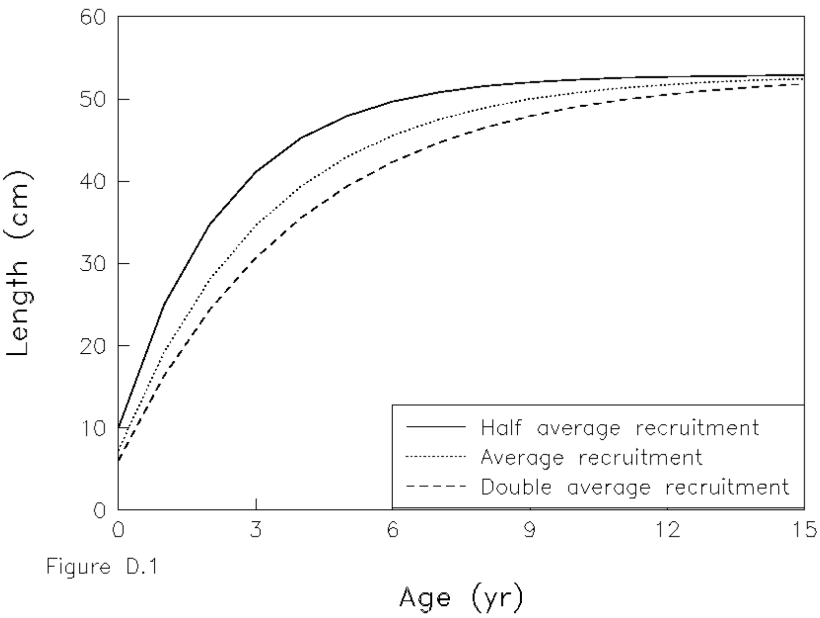


Figure D.1 : Growth curves for spotted warehou. Results are shown for the choice $\delta = -0.5$ and for cohorts that are half, double, and equal to the expected pre-exploitation recruitment.

D.3 Fishing mortality and fleet dynamics

The mortality due to fishing is determined using the equation:

$$F_{y,a}^{i,l,A} = S^{i}_{y,\tilde{L}^{i,l}_{y,a+1/2}} \, F_{y}^{i,A} \tag{D.12}$$

where $S^{i}_{y,\tilde{L}}$ is the relative selectivity on fish of species i in length-class $\tilde{L}$ during year y:

$$S^{i}_{y,\tilde{L}} = S^{i}_{\tilde{L}} \, e^{\varepsilon^{i}_{s,\tilde{L}} - \sigma_s^2/2} \tag{D.13}$$

$F_{y}^{i,A}$ is the "fully-selected" fishing mortality on fish of species i in region A during year y,

$$F_{y}^{i,A} = \sum_{s} q^{i,s,A} \, \tilde{E}_{y}^{s,A} \tag{D.14}$$

$\varepsilon^{i}_{s,\tilde{L}}$ is the selectivity residual, generated from the multivariate normal distribution, $N(\underline{0}, \mathbf{W}_s)$ where $\mathbf{W}_s$ is a variance-covariance matrix with diagonal elements $(\sigma^{i}_{s})^2$; the off-diagonal elements of the variance-covariance matrix are calculated from the assumption that the correlation between the selectivity residuals for adjacent length-classes is τ_s^i,

σ_s^i is the parameter that determines the magnitude of the fluctuations in selectivity about its expected value,

$\tilde{E}_y^{s,A}$ is the effective fishing effort in region A during season s (winter / summer) of year y, and

$q^{i,s,A}$ is the relative probability of catching a fully-selected animal of species i in region A during season s (the catchability of species i in region A during season s).

The effective fishing effort in region A during season s of year y is related to the actual fishing effort (hours fished) in region A during season s of year y, $E_y^{s,A}$, after accounting for changes over time in fishing efficiency and random variation in catchability:

$$\tilde{E}_y^{s,A} = (B_y^{i,A} / B_0^{i,A})^{\theta} \, E_y^{s,A} \, e^{\lambda y} \, e^{\varepsilon_{q,y}^{i,s,A} - (\sigma_q)^2/2 + \eta_{q,y}^i} \qquad \text{(D.15)}$$

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

$B_y^{i,A}$ is the available biomass for species i in region A at the start of year y:

$$B_y^{i,A} = \sum_a \sum_l w_{\tilde{L}_{y,a}^{i,l}}^i \, S_{y,\tilde{L}_{y,a}^{i,l}}^i \, N_{y,a}^{i,l,A} \qquad \text{(D.16)}$$

λ is the parameter that determines changes over time in efficiency,

$\varepsilon_{q,y}^{i,s,A}$ is the catchability residual for species i, year y, season s and region A:

$$\varepsilon_{q,y}^{i,s,A} = \tau_q^i \, \varepsilon_{q,y-1}^{i,s,A} + \sqrt{1-(\tau_q^i)^2} \, \varepsilon_{q,y}^{i',s,A} \qquad \text{(D.17)}$$

$\varepsilon_{r,y}^{i',s,A}$ is the i'th element of a vector generated from a multivariate normal distribution, $N(\underline{0}, \mathbf{W}_q)$, where $\mathbf{W}_q$ is a variance-covariance matrix with diagonal elements $(\sigma_q^i)^2$ and off-diagonal elements $\tau_q^{i,j} \, \sigma_q^i \, \sigma_q^j$,

σ_q is the standard deviation of the logarithms of the random fluctuations in catchability,

$\tau_q^{i,j}$ is the extent of correlation between the catchability residuals for species i and j,

τ_q^i is the magnitude of the inter-annual correlation in the catchability residuals for species i, and

$\eta_{q,y}^i$ is a factor to model marked changes in availability among years.

Equation (D.15) models the impact of density-dependence in catchability through the term $(B_y^{i,A} / B_0^{i,A})^{\theta}$. If $\theta < 0$, reduced abundance leads to greater catchability. This mimics the impact of fish continuing to aggregate (predicably) as biomass decreases.

The term $e^{\lambda y}$ implies (for $\lambda > 0$) an exponential increase in catchability over time. This mimics the possible impact of improved technology and skill in the fishery. The catchability model (Equation D.17) allows catchability to change smoothly over time and to be correlated among species.

D.4 Catch (landings and discards)

The landed / discarded catches (by mass) of species *i* during year *y*, $C_y^{L,i}$ / $C_y^{D,i}$, are calculated using the equations:

$$C_y^{L,i} = (1 - D_y^i) \sum_A \sum_{a=0}^{x} \sum_l w^i_{\tilde{L}^{i,l}_{y,a+1/2}} \tilde{S}^{L,i}_{y,\tilde{L}^{i,l}_{y,a+1/2}} F_y^{i,A} N_{y,a}^{i,l,A} \frac{1-\exp(-Z_{y,a}^{i,l,A})}{Z_{y,a}^{i,l,A}} \qquad \text{(D.18a)}$$

$$C_y^{D,i} = \sum_A \sum_{a=0}^{x} \sum_l w^i_{\tilde{L}^{i,l}_{y,a+1/2}} F_y^{i,A} (\tilde{S}^{D,i}_{y,\tilde{L}^{i,l}_{y,a+1/2}} + D_y^i \tilde{S}^{L,i}_{y,\tilde{L}^{i,l}_{y,a+1/2}}) N_{y,a}^{i,l,A} \frac{1-\exp(-Z_{y,a}^{i,l,A})}{Z_{y,a}^{i,l,A}} \qquad \text{(D.18b)}$$

where D_y^i is the fraction of the catch of species *i* that could potentially be landed during year *y* that is discarded because operators lack sufficient quota:

$$D_y^i = \bar{D}_y^i e^{\varepsilon_{D,y} - \sigma_D^2/2} \qquad \varepsilon_{D,y} \sim N(0;\sigma_D^2) \qquad \text{(D.19)}$$

$\bar{D}_y^i$ is the expected amount of quota-related discarding for species *i* during year *y*:

$$\bar{D}_y^i = \begin{cases} 0 & \text{if } y < 1992 \\ \bar{D}^i & \text{if } 1993 \le y \le 2000 \\ \max(\bar{D}^i \frac{(2020-y)}{20}, 0) & \text{if } y > 2000 \end{cases} \qquad \text{(D.20)}$$

$\bar{D}^i$ is the expected amount of quota-related discarding for species *i* over the years 1993 to 2000, and

σ_D is the parameter that determines the extent of inter-annual variation in quota-related discarding.

Equation (D.18a) is the standard catch equation based on the selectivity pattern for the landed catch, modified to exclude the fraction of the catch that is discarded due to lack of quota. Equation (D.18b) is the combination of the catch of small fish (based on the “discard” selectivity pattern) and the catch that could be landed but is discarded due to lack of quota. The sum $C_y^{L,i} + C_y^{D,i}$ is the total catch according to the overall selectivity pattern. Equation (D.20) reflects the fact that no quota-based discarding occurred before the quota system was implemented in 1992 and also the increasing trend for operators to better “manage” their quota holdings to avoid quota-based discarding. The assumption that there will be no quota-based discarding in 2020 is optimistic but should be adequate for the purposes of this study.

The selectivity pattern for the discarded catch depends on the relative abundance of a length-class in the population:

$$\tilde{S}^{D,i}_{y,\tilde{L}} = \gamma^{D,i} \max\left(1, \frac{S^{i}_{y,\tilde{L}}\,(Q^{i}_{y,\tilde{L}})^{\phi^{D,i}}}{1+e^{-(\tilde{L}_{\tilde{L}}-L^{D,i}_{50})/\delta^{D,i}}}\right) \tag{D.21}$$

where $L^{D,i}_{50}$ is the length at which discarding for species i is half the maximum possible rate,

$Q^{i}_{y,\tilde{L}}$ is the abundance of animals of species i in length-class $\tilde{L}$ during year y relative to that in the pre-exploitation equilibrium state:

$$Q^{i}_{y,\tilde{L}} = \sum_{a}\sum_{l}\sum_{A} N^{i,l,A}_{y,a} / \sum_{a'}\sum_{l'}\sum_{A'} N^{i,l',A'}_{y_{init},a'} \tag{D.22}$$

where the summations over age and length-group are restricted so that $\tilde{L}^{i,l}_{y,a+1/2} = \tilde{L}$.

$\delta^{D,i}$ is the parameter that determines the width of the ogive defining discarding for species i,

$\gamma^{D,i}$ is the parameter that defines the maximum fraction of a catch of any length-class of species i that can be discarded, and

$\phi^{D,i}$ is the parameter that determines the extent of density-dependence in discarding for species i.

This approach to discarding is based on two sources for discarding: discarding because of lack of quota and discarding of small (and hence difficult to market) animals. The latter is based on the assumptions that discarding is a decreasing function of size and that discarding for a given length-class is likely to be greater when the abundance of that length-class is greater.

The selectivity function for the landed catch is given by:

$$S^{L,i}_{y,\tilde{L}} = S^{i}_{y,\tilde{L}} - S^{D,i}_{y,\tilde{L}} \tag{D.23}$$

The changes over time in the spatial distribution of effort leads to the overall (i.e. aggregated over the whole fleet) selectivity pattern changing over time.

D.5 Effort distribution

The sizes of the annual landed catches by species are driven by the constraints imposed by the *TAC* and by the ability to market catches. Each species is assumed to have a threshold catch level, $\tilde{C}^{L,i}_{y}$. For species that are easy to market such as pink ling, the threshold is the *TAC* (i.e. $\tilde{C}^{L,i}_{y} = TAC^{i}_{y}$) while for species that can be difficult to market, $\tilde{C}^{L,i}_{y}$ is the minimum of the *TAC* and a value generated from the historical catch data (to reflect the "market demand"). The actual effort in region A during season s of year y, $E^{s,A}_{y}$, is calculated as $E^{A}_{y}\,\omega^{s,A}_{y}$ where E^{A}_{y} is the total effort in region A during year y, and $\omega^{s,A}_{y}$ is the split of the effort in region A during year y between seasons. The value for $\omega^{s,A}_{y}$ is selected at random from the actual values for $\omega^{s,A}_{y}$ for the years 1986–98. The values for the E_y^A are selected to minimise the penalty function $P = P_1 + P_2$, where:

$$P_1 = 100(E_y^A / \sum_{A'} E_y^{A'} - \bar{E}^A / \sum_{A''} \bar{E}^{A''})^4 \tag{D.24a}$$

$$P_2 = \begin{cases} 4(C_y^{L,i} - \tilde{C}_y^{L,i})^2 & \text{if } C_y^{L,i} < \tilde{C}_y^{L,i} \\ (C_y^{L,i} - \tilde{C}_y^{L,i})^2 & \text{otherwise} \end{cases} \tag{D.24b}$$

where $\bar{E}^A$ is the average effort in region A over the years 1994–98.

The term P_1 places a penalty on changes in the spatial distribution of effort (severely penalising large departures from the average spatial effort distribution) by raising the difference between the spatial effort distribution for year y and the average spatial effort distribution to the power 4. The term P_2 places a penalty on not matching the threshold catch levels exactly. The values chosen for the E_y^A are subject to an additional constraint, namely that the total fishing effort does not exceed 50,000 days (20% above the largest effort ever recorded). The values for the control parameters in Equation D.24 are chosen so that the actual landed catches match the threshold catch levels relatively closely but without a huge change in the spatial distribution of fishing effort. Undercatching the threshold catch levels is penalised to a greater extent that overcatching it. If $C_y^{L,i}$ exceeds TAC_y^i, the difference between TAC_y^i and $C_y^{L,i}$ is assumed to be discarded.

D.6 Pre-exploitation equilibrium

The number of animals by age, growth-group, and region at pre-exploitation equilibrium, $N_{y_{init},a}^{i,l,A}$, is a function of age-specific natural mortality and the movement matrix, **X**. For ages 0 to x-1, $N_{y_{init},a}^{i,l,A}$ is given by the equation:

$$N_{y_{init},a}^{i,l,A} = \begin{cases} \pi^{i,l,A} R_0^i & \text{if } a = 0 \\ \sum_{A'} X^{i,A',A,\tilde{L}_{y_{init},a}^{i,l}} N_{y_{init},a-1}^{i,l,A'} e^{-M_{a-1}^i} & \text{if } 1 \le a \le x-1 \end{cases} \tag{D.25}$$

The number of animals of age x at pre-exploitation equilibrium by growth-group and region, $N_{t_{init},x}^{i,l,A}$, is calculated by solving the balance equation:

$$N_{y_{init},x}^{i,l,A} = \sum_{A'} X^{i,A',A,\tilde{L}_{y_{init},x}^{i,l}} (N_{y_{init},x}^{i,l,A'} e^{-M_x^i} + N_{y_{init},x-1}^{i,l,A'} e^{-M_{x-1}^i}) \tag{D.26}$$

Adjunct D.1 : The parameterisation of the stock-recruitment relationship

The parameters of the stock-recruitment relationship are α, β and γ (Equation D.5). The values for these parameters are determined from $\widetilde{B}_0$ (the pre-exploitation equilibrium spawner biomass), the steepness of the stock-recruitment relationship, *h*, and the ratio of the 0-year-class strength at 10% of the pre-exploitation equilibrium biomass to that expected had the stock-recruitment relationship been of the Beverton-Holt form with the same steepness and pre-exploitation equilibrium biomass, $\tilde{q}$, i.e.:

$$R_0 = \frac{1}{\alpha+\beta}; \quad h\,R_0 = \frac{0.2^\gamma}{\alpha+\beta\,0.2^\gamma}; \quad \frac{0.1^\gamma}{\alpha+\beta\,0.1^\gamma} = \tilde{q}\,\frac{0.1}{\alpha^{'}+\beta^{'}\,0.1} \tag{D.A.1}$$

where R_0 is the expected 0-year-class strength at $\widetilde{B}_0$, and

$\alpha^{'}, \beta^{'}$ are the parameters of the Beverton-Holt stock-recruitment relationship when steepness equals *h* and exploitation equilibrium biomass equals $\widetilde{B}_0$.

Now, the first two equations can be solved for α and β:

$$\alpha = \frac{0.2^\gamma(1-h)}{h\,R_0\,(1-0.2^\gamma)} \qquad \beta = \frac{h-0.2^\gamma}{h\,R_0\,(1-0.2^\gamma)} \tag{D.A.2}$$

The values for $\alpha^{'}$ and $\beta^{'}$ are found by setting γ=1 in Equation (D.A.2).

Now, the third part of equation (D.A.1) can be rewritten as:

$$\tilde{q} = \frac{0.1^\gamma\,(\alpha^{'}+\beta^{'}\,0.1)}{0.1(\alpha+\beta\,0.1^\gamma)} \tag{D.A.3}$$

which simplifies to:

$$\tilde{q} = \frac{(1.8-h)(1-0.2^\gamma)}{0.8(2^\gamma(1-h)+h-0.2^\gamma)} \tag{D.A.4}$$

Equation (D.A.4) is independent of R_0 and $\widetilde{B}_0$, and can be solved for γ given values for *h* and $\tilde{q}$.

Appendix E : Specification of simulation trials

Each species is divided into 16 growth-groups and the model incorporates n_L=75 length-classes per species (where each length-class is of size $\bar{L}_\infty / 50$). The model has four regions. These are defined by depth (25-50m, 50-150m, 150-250m, and 250m+). This choice for regions is based primarily on data availability for the estimation of movement between depth zones. Winter is defined as May – September and Summer as October – April. The values for the parameters related to the fishery are based on those for the otter trawl fleet off southern NSW (defined as Area 20 of the SEF combined with that part of Area 10 south of Bermagui – Figure 2).

E.1 Initial conditions

The state of the resource at the start of the first year that the harvest strategies are applied (1999) is defined by the ratio of the spawner biomass at the start of 1999 to that at the start of year y_{init} (1958). This ratio is assumed to be the same for each of the 100 simulations that constitute a simulation trial. This allows the impact of changes in biomass due to the application of the harvest strategy to be distinguished from those due to the depletion of the biomass at the start of the simulation. The pre-exploitation equilibrium biomass and the values for the catchability coefficients are chosen using the following algorithm.

a) Initial guesses are chosen for each of the $\tilde{B}_0$ s.

b) The model is projected from year y_{init} (1958) until 1999. In making this projection, the effort dynamics model (see Section 5 of Appendix D) is ignored and instead the fully-selected fishing mortality for species *i*, region *A*, and year *y* is chosen to satisfy the equation:

$$\sum_s C_y^{L,i,s,A,obs} = (1-D_y^i)\sum_{a=0}^{x}\sum_l w^i_{\tilde{L}^{i,l}_{y,a+1/2}} \tilde{S}^{L,i}_{y,\tilde{L}^{i,l}_{y,a+1/2}} F_y^{i,A} N_{y,a}^{i,l,A} \frac{1-\exp(-Z_{y,a}^{i,l,A})}{Z_{y,a}^{i,l,A}} \qquad \text{(E.1)}$$

where $C_y^{L,i,s,A,obs}$ is the recorded landed catch of species *i* in region *A* during season *s* of year *y*.

c) The values for the $\tilde{B}_0$ are modified until the specifications related to the state of the system at the start of 1999 are satisfied. This involves applying step b) several times with different choices for the $\tilde{B}_0$ s.

d) The values for the catchability coefficients by species and region are obtained using the equation (see Equations D.14 and D.15):

$$\ell n\, q^{i,A} = \tfrac{1}{n_F} \sum_{y>1986} \ell n\left(F_y^{i,A} /((B_y^{i,A} / B_0^{i,A})^{\theta}\, e^{\lambda y} \sum_s E_y^{s,A,obs})\right) \qquad \text{(E.2)}$$

where $E_y^{s,A,obs}$ is the recorded fishing effort (hours) in region *A* during season *s* of year *y*, and

n_F is the number of terms included in the summation in Equation (E.2).

e) The catchability coefficients by species, season and region are then computed using the equation:

$$\ell n q^{i,s,A} = \frac{1}{n_F} \sum_{y>1986} \left(\ell n[C_y^{L,i,s,A,obs} F_y^{i,A}] - \ell n[E_y^{s,A,obs} e^{\lambda y} (B_y^{i,A} / B_0^{i,A})^{\theta} \sum_{s'} C_y^{L,i,s',A,obs}] \right) \quad \text{(E.3)}$$

E.2 Data generation

The information generated by the operating model for each species includes catch-by-mass (landed and discarded by region), effort (by region), age-length keys, length-frequencies (landed and discarded by region) and survey estimates of relative and absolute abundance. This information is generated in a manner to replicate, as closely as is possible, the process by which these data are currently collected from the fishery (or, in the case of surveys, may be collected). The process of converting this information into the input for the harvest strategies (i.e. computation of the catch-at-age matrices, standardization of the catch and effort data) is part of each harvest strategy and is therefore described in Appendix F.

E.2.1 Catch and effort data

The landed catches-by-mass (Equation D.18a) are assumed to be measured without error. This is not an unreasonable assumption for the last 10 or so years given that there is a catch monitoring scheme currently in place for the fishery. The distribution of catches among regions prior to 1985 is not known, so the split of catches among regions for the years 1958–84 has been assumed to be the average of those for the years thereafter. The splits of the catches by region for the years 1993 and 1994 have been replaced by the average split. This is because the positions of catches during these years were systematically mis-reported to make use of a regulatory loophole (Tilzey, 1999).

In contrast to the situation for the estimates of landed catch, the estimates of the mass of fish discarded are not measured directly but are calculated from data collected by onboard observers (Knuckey *et al.*, 1999). These estimates are therefore subject to quite considerable uncertainty. For the purposes of this study, it is assumed that the estimates of discarded catch are unbiased but log-normally distributed. The coefficients of variation used for the base-case analyses are listed in Table E.1. The data are generated for the years for which actual data are available. This means, for example, that no data other than catches are available for the years prior to 1986. The information on (actual) fishing effort is also assumed to be measured without error. However, actual fishing effort differs from effective fishing effort because of the impact of changes over time in efficiency, density-dependence in catchability, and random variation in catchability (Equation D.15).

E.2.2 Length-frequency data

The catch / discard length-frequency data for a given region are generated by sampling multinomially from the actual catches-in-length for that region. The actual landed / discarded catch (in numbers) of species *i* in length-class $\tilde{L}$ during year *y* in region *A* is proportional to:

$$\sum_l \sum_a \tilde{S}^{L,i}_{\tilde{L}^{i,l}_{y,a+1/2}} N^{i,l,A}_{y,a} \frac{1-\exp(-Z^{i,l,A}_{y,a})}{Z^{i,l,A}_{y,a}} \quad \text{(E.4a)}$$

$$\sum_{l}\sum_{a}(\tilde{S}^{D,i}_{y,\tilde{L}^{i,l}_{y,a+1/2}}+D^{i}_{y}\,\tilde{S}^{L,i}_{y,\tilde{L}^{i,l}_{y,a+1/2}})\,N^{i,l,A}_{y,a}\,\frac{1-\exp(-Z^{i,l,A}_{y,a})}{Z^{i,l,A}_{y,a}} \qquad \text{(E.4b)}$$

where the summations over a and l are constrained so that $L^{i,l}_{y,a+1/2}$ lies in length-class $\tilde{L}$.

The distribution of the total sample size across regions is proportional to the catch (in mass) by region. Table E.1 lists the base-case choices for the annual number of fish sampled for length frequency. These choices are based on achieving a mean weighted coefficient of variation (MWCV) of 10%. The sampling for the ISMP is designed to achieve this level of MWCV. The MWCV is defined by the equation:

$$MWCV=\sum_{\tilde{L}}p_{\tilde{L}}\,CV_{\tilde{L}} \qquad \text{(E.5)}$$

where $p_{\tilde{L}}$ is the proportion of the catch in length-class $\tilde{L}$, and
$CV_{\tilde{L}}$ is the coefficient of variation of $p_{\tilde{L}}$.

Sullivan *et al.* (1994) describe the simulation approach used to estimate $CV_{\tilde{L}}$ for the SEF and hence determine the sample sizes for the ISMP. Given the approach used to generate the length-frequency data in this study, $CV_{\tilde{L}}$ is well approximated by $\sqrt{(1-p_{\tilde{L}})}/\sqrt{N\,p_{\tilde{L}}}$ where N is the sample size. The choices in Table E.1 are based on solving this equation for N when the values for the $p_{\tilde{L}}$ are based on sampling from a population at its unexploited equilibrium level.

E.2.3 Age-length keys

The age-length keys are generated by selecting animals at random from the landed / discard catch-at-age by length. The catch (in numbers) of species i of age a in length-class $\tilde{L}$ during year y is proportional to:

$$\sum_{l}\sum_{A}N^{i,l,A}_{y,a}\,\frac{1-\exp(-Z^{i,l,A}_{y,a})}{Z^{i,l,A}_{y,a}} \qquad \text{(E.6)}$$

where $L^{i,l}_{y,a+1/2}$ lies in length-class $\tilde{L}$.

Table E.1 lists the base-case choices for the annual number of fish sampled for age-length keys. These choices are based on the targets set by AFMA (Table 11 of Knuckey and Sporcic (1998)) where, for spotted warehou, jackass morwong, and tiger flathead, 80% of the samples are taken from the landed catch and 20% from the discarded catch. The estimate of the age of a fish is assumed to be unbiased but subject to age-reading error with a pre-specified coefficient of variation.

E.2.4 Survey biomass data

Fishery-independent data can be obtained using trawl surveys, acoustic surveys or the egg production method. The survey results for trawl (or acoustic) surveys are assumed to be lognormally distributed relative indices of exploitable biomass while the egg production method is assumed to provide lognormally distributed but unbiased estimates of spawner biomass (see Equation D.6). The exploitable biomass is defined as the available biomass in the middle of the year:

$$B_y^{i,s} = \sum_A \sum_a \sum_l w^i_{\tilde{L}^{i,l}_{y,a}} \, S^i_{\tilde{L}^{i,l}_{y,a}} \, N^{i,l,A}_{y,a} \, e^{-Z^{i,l,A}_{y,a}/2} \tag{E.7}$$

The base-case trials do not provide the harvest strategies with survey estimates of abundance because such surveys do not currently exist for the four species. The coefficient of variance provided to the harvest strategy is assumed to reflect sampling variability only. This coefficient of variation is therefore lower than the actual level of lognormal variation to account for additional variance (σ_A; Butterworth *et al.*, 1993; Punt *et al.*, 1997a).

E.3 The base-case trials

The base-case trials are based on a relatively ideal set of assumptions / parameters. For these trials therefore, the complications of depensation, density-dependent growth and discarding, quota-based discarding, pulse changes in catchability, and temporal and among-species correlations in the recruitment and selectivity residuals are all ignored. All four of the species are assumed to be depleted to half of their pre-exploitation biomass at the start of 1999. Sensitivity tests (see Section E.4) are conducted to assess the impact of violations of the specifications of the base-case trials.

Maturity is assumed to be a knife-edged function of length. Table E.2 lists the plus-group age, and the base-case values for the parameters related to growth (see Equations D.8 and D.9), maturity, and natural mortality (see Equation D.3). The sixteen growth-groups are based on the assumption that L_∞ and κ are lognormally distributed. Adjunct E.1 documents the procedure used to estimate the growth parameters.

Table E.2 also lists the base-case values for the parameters related to the generation of future 0-year-class strength. The resilience of the population is determined by the size of the steepness parameter, *h*. The base-case value for this parameter for spotted warehou, tiger flathead, and jackass morwong is chosen to be close to the mode of an empirical distribution for this quantity derived by Punt *et al*. (1994) from data for various haddock, whiting and hake species. The base-case choice for steepness for ling is set equal to 0.75 because the only quantitative assessment of a species of the same genus as ling that attempted to estimate steepness (Punt and Japp, 1994) suggests that this species may have relatively low resilience. The value assumed for the extent of variation in recruitment, σ_r, is largely an educated guess based on the results of Beddington and Cooke (1983).

The 0-year-olds are assumed to be found only in the shallowest region and distributed equally across growth-groups. The movement matrix *X* is parameterised using twenty parameters (four for each of the five areas):

$$X^{i,A,A',L} = \begin{cases} P_{bak}^{i,A',1} + (P_{bak}^{i,A',2} - P_{bak}^{i,A',1}) \frac{\bar{L}_L}{\bar{L}_\infty^i} & \text{if } A = A'+1 \\ P_{for}^{i,A',1} + (P_{for}^{i,A',2} - P_{for}^{i,A',1}) \frac{\bar{L}_L}{\bar{L}_\infty^i} & \text{if } A = A'-1 \\ 1 - \{P_{bak}^{i,A'} + P_{for}^{i,A',1} + (P_{bak}^{i,A',2} - P_{bak}^{i,A',1} + P_{for}^{i,A',2} - P_{for}^{i,A',1}) \frac{\bar{L}_L}{\bar{L}_\infty^i}\} & \text{if } A = A' \\ 0 & \text{otherwise} \end{cases} \quad \text{(E.8)}$$

where $P_{bak}^{i,A,1}$ and $P_{bak}^{i,A,2}$ determine the fraction of animals in a region that move to shallower waters at the end of the year and $P_{for}^{i,A,1}$ and $P_{for}^{i,A,2}$ determine the fraction of animals in a region that move to deeper waters at the end of the year. Equation (E.8) is modified appropriately for regions for which regions $A'+1$ or $A'-1$ do not exist. Adjunct E.1 documents the procedure used to estimate the values for the parameters that determine the movement matrix. The value assumed for σ_X, 0.2, is an educated guess.

Table E.3 lists the base-case values for the parameters related to selectivity and fishing mortality. Selectivity as a function of length is assumed to be governed by a double-logistic curve (in order to capture the possibility of either asymptotic or domed-shaped selectivity patterns):

$$S_L^i \propto \left(1 + e^{-\ell n 19 \frac{(L - L_{50}^{i,1})}{(L_{95}^{i,1} - L_{50}^{i,1})}}\right)^{-1} \left(1 + e^{-\ell n 19 \frac{(L - L_{50}^{i,2})}{(L_{95}^{i,2} - L_{50}^{i,2})}}\right)^{-1} \quad \text{(E.9)}$$

where $L_{95}^{i,1}$ is the length-at-50%-selectivity for fish of species *i*,

$L_{95}^{i,1}$ is the length-at-95%-selectivity for fish of species *i*,

$L_{50}^{i,2}$ is the length-at-50%-selectivity for fish of species *i* (used to model a dome-shaped (double-logistic) selectivity ogive), and

$L_{95}^{i,2}$ is the length-at-50%-selectivity for fish of species *i* (used to model a dome-shaped (double-logistic) selectivity ogive).

The values for σ_s and τ_s are largely educated guesses although the base-case value for σ_s, 0.2, has been used in previous studies (Punt, 1993, 1995, 1997). The parameters related to discarding of small fish are based on fits to discarded and retained length-frequencies (Adjunct E.2). Discarding of small ling is sufficiently rare that it is ignored for the purposes of this study. Catchability is assumed to be independent between years and among species and not to be subject to "pulses" in catchability.

The threshold catch level for ling is assumed to be equal to the *TAC* while the threshold catch levels for spotted warehou, tiger flathead and jackass morwong are generated from normal distributions based on the actual catches from 1986–98 (Table E.4).

E.4 Sensitivity tests

Table E.5 lists the sensitivity tests implemented in the software (detailed results are, however, not presented for all of the sensitivity tests). The sensitivity tests generally involve changing only a single aspect of the operating model. This is because of computational limitations (a full factorial design would be computationally prohibitive, especially if the factors considered are crossed with options for each harvest strategy). The values for the parameters for the sensitivity tests are primarily educated guesses aimed at determining whether the factor being examined has a noticeable impact on performance.

The "Correlated recruitment option 2" sensitivity test involves setting the correlation between recruitment for spotted warehou and ling to 0.5 and between jackass morwong and flathead to 0.5, and setting this correlation to –0.5 between spotted warehou and jackass morwong, and ling and flathead.

The pulse change in availability (sensitivity tests "Effort-related options 4 and 5") is modelled by applying the following algorithm (see Equation D.15):

a) If $\eta^i_{q,y-1} \neq \eta^i_{q,y-2}$ then $\eta^i_{q,y} = \eta^i_{q,y-1}$, end.

b) If $\eta^i_{a,y-1} = 0$, then $\eta^i_{a,y} = \bar{\eta}^i$ with probability 1/8 and $\eta^i_{q,y} = -\bar{\eta}$ with probability 1/8 otherwise $\eta^i_{a,y} = 0$, end.

c) If $\eta^i_{q,y-1} = \bar{\eta}$, then $\eta^i_{a,y} = 0$ with probability 1/8 otherwise $\eta^i_{a,y} = \bar{\eta}$, end

d) If $\eta^i_{q,y-1} = -\bar{\eta}$, then $\eta^i_{a,y} = 0$ with probability 1/8 otherwise $\eta^i_{a,y} = -\bar{\eta}$, end

This algorithm implies that $\eta^i_{a,y}$ can take one of three states ($-\bar{\eta}$, 0, $\bar{\eta}$), that pulse changes in availability last at least two years, and that probability of moving between states is 0.125.

The availability for jackass morwong and tiger flathead are negatively corrected for the "Effort-related option 5" sensitivity test so if one of these species experiences a pulse increase in availability the other experiences a pulse decrease in availability.

It has been argued by some in industry that wholesale reductions in *TAC* would not result in reduced catches. In contrast, they would result in increased discarding. The base-case model incorporates this to some extent (see Section 4 of Appendix D). However, it has also been said that even if all *TAC*s were reduced, this would not even reduce fishing effort (rather large-scale high-grading would occur). Rather than attempting to model this explicitly, one of the sensitivity tests involves placing a lower bound on the total annual effort of 35,000 hours.

The estimate of the index of average percent error (IAPE) for most SEF species is about 4-5% (I. Knuckey, MAFRI, pers. commn). The sensitivity test that examines the impact of ageing error assumes that age estimates are in error by 10%. This is because the IAPE only measure between-reader errors.

Table E.1 : Base-case specifications for data generation. The coefficients of variation for the estimates of the discards, the number of fish measured to determine the length-frequency of the catch, and the number of animals aged to determine age-length keys are given for each species. The year in parenthesis represents the first year for which the type of data concerned is generated.

Data source	Spotted warehou	Tiger flathead	Jackass morwong	Pink ling
CV of discard estimates	0.30 (1995)	0.30 (1995)	0.30 (1995)	-
CV of catchability	0.30 (1986)	0.30 (1986)	0.30 (1986)	0.30 (1986)
Length-frequency sample sizes				
Landed	1000 (1991)	1000 (1991)	1000 (1991)	1000 (1991)
Discarded	200 (1995)	200 (1995)	200 (1995)	-
Age-length keys				
Landed	600 (1991)	750 (1991)	400 (1991)	1000 (1991)
Discarded	150 (1995)	150 (1995)	100 (1995)	-
Age-reading error	0	0	0	0

Table E.2 : Base-case values for the growth-, natural mortality-, and recruitment-related parameters.

Parameter	Spotted warehou	Tiger flathead	Jackass morwong	Pink ling
Plus-group age – x (yr)	15[&]	20[&]	40[*]	25
Growth-related				
Mean asymptotic length - L_∞ (cm)	52.93[++]	88.23[++]	37.48[++]	122.27[++]
Mean asymptotic weight - W_∞ (kg)	2.51[++]	3.92[++]	0.94[++]	13.31[++]
Length-mass parameter - e_2	3.00[+]	3.31[+]	3.00[+]	3.14[&]
Mean growth rate - κ	0.304[++]	0.081[++]	0.305[++]	0.137[++]
"Age-at-zero length" - t_0	-0.488[++]	-1.346[++]	-0.409[++]	-0.965[++]
Density-dependence in growth rate - δ	0	0	0	0
Natural mortality				
Natural mortality-at-age - M (yr^{-1})	0.3	0.2	0.2[&]	0.15
Natural mortality residuals - $\varepsilon_{1,y}$, $\varepsilon_{1,y,a}$	U[-0.1, 0.1]	U[-0.1, 0.1]	U[-0.1, 0.1]	U[-0.1, 0.1]
Correlation in natural mortality - χ	0.3	0.3	0.3	0.3
Length at maturity (cm)	40[&]	30[&]	22[&]	72[&]
Recruitment				
Variation in 0-year-class strength - σ_r	0.6	0.6	0.6	0.6
Steepness – h	0.9	0.9	0.9	0.75
Extent of depensation – $\tilde{q}$	1	1	1	1

+ - I. Knuckey (MAFRI, pers. commn)
* - Central Ageing Fishery reported to Tilzey (1999).
& - Tilzey (1999)
++ – estimated from the approach in Adjust E.1.

Table E.3 : Base-case values for the parameters related to selectivity and fishing mortality.

Parameter	Spotted	Tiger flathead	Jackass	Pink ling
Selectivity				
L^1_{50}(cm)	40+	33&	25*	50+
L^1_{95}(cm)	45+	40+	30+	60+
L^2_{50}(cm)	-	-	-	52.84++
L^2_{95}(cm)	-	-	-	-21.10++
Variation in selectivity - σ_s	0.2	0.2	0.2	0.2
Correlation in selectivity - τ_s	0.3	0.3	0.3	0.3
Discard-related				
Maximum rate of discarding - γ^D	0.99**	0.99**	0.99**	0
Length-at-50%-discarduing - L^D_{50}	33.54**	31.86**	19.75**	N/A
Wide of discarding ogive - δ^D	-0.908**	-0.585**	-3.07**	N/A
Density-dependence in discarding - ϕ^D	0	0	0	N/A
Quota-related discarding - $\overline{D}$	0.05	0.1	0.05	0
Variation in quota-related discarding - σ_D	0.2	0.2	0.2	0
Effort – fishing mortality relationship				
Density-dependence in catchability - θ	0	0	0	0
Rate of change in efficiency - λ	0	0	0	0
Pulse change in catchability, $\eta_{q,y}$	0	0	0	0

* - Smith and Robertson (1995)
& - Montgomery (1985)
\+ - By inspection
++ - Estimated – see Adjunct E.1
** - Estimated – see Adjunct E.2

Table E.4 : Catches (1986–98) by the otter trawl fleet off southern NSW. Units are tonnes.

Year	Spotted Warehou	Tiger flathead	Jackass morwong	Pink ling
1986	482.0	788.8	656.5	309.1
1987	251.3	819.1	852.9	359.0
1988	855.3	879.7	1037.6	288.4
1989	286.0	954.6	937.5	332.2
1990	978.0	1054.5	633.6	379.2
1991	546.9	992.4	713.3	325.7
1992	404.9	690.8	431.3	284.6
1993	896.3	750.2	538.8	409.7
1994	1382.4	593.1	501.3	400.2
1995	1095.4	767.4	435.7	502.6
1996	978.5	730.4	526.8	543.4
1997	782.4	915.9	677.2	564.2
1998	637.6	940.9	453.6	560.1
Mean	736.7	836.8	645.8	404.5
Standard Deviation	337.1	132.7	196.0	104.0

Table E.5 : The sensitivity tests.

Abbreviation	Specifications			
	Spotted Warehou	Tiger flathead	Jackass morwong	Ling
Productivity-related				
Low steepness	h = 0.75	h = 0.75	h = 0.75	h = 0.5
Very low steepness	h = 0.5	h = 0.5	h = 0.5	h = 0.3
Some depensation	$\tilde{q}$ = 0.5			
Extreme depensation	$\tilde{q}$ = 0.25			
Combined	h=0.75; $\tilde{q}$ =0.5	h=0.75; $\tilde{q}$ =0.5	h=0.75; $\tilde{q}$ =0.5	h=0.5; $\tilde{q}$ =0.5
Density-dependent growth	δ = -0.5			
Effort-related				
Option 1	λ = 0.02; θ=-0.5			
Option 2	λ = 0.05; θ=-1			
Option 3	λ = -0.02; θ=0			
Option 4	$\tau_q = 0.7$; $\bar{\eta} = 1$			
Option 5	$\tau_q = 0.7$; $\tau_q^{i,j} = -0.5/0.5$; $\bar{\eta} = 1$			
Minimum effort	Minimum effort = 35,000 hours			
Discard-related				
Option 1	$\bar{D}$ = 0.1; $\sigma_D = 0.2$; ϕ^D = 0.5			
Option 2	$\bar{D}$ = 0.1; $\sigma_D = 0.2$; ϕ^D = 1			
Selectivity-related				
Selectivity variability	$\sigma_s = 0.4$			
Correlation in recruitment	$\tau_s = 0.9$			
Variance-related				
Movement-related	$\sigma_X = 0.4$			
Low recruitment variation	$\sigma_r = 0.3$			
High recruitment variation	$\sigma_r = 1$			
Correlated recruitment				
Option 1	τ^i = 0.5; $\tau_r^{i,j}$ = 0.5			
Option 2	τ^i = 0.5; $\tau_r^{i,j}$ = -0.5 / 0.5			
Natural mortality				
True M high	M=0.36yr^{-1}	M=0.24yr^{-1}	M=0.24yr^{-1}	M=0.18yr^{-1}
True M low	M=0.24yr^{-1}	M=0.16yr^{-1}	M=0.16yr^{-1}	M=0.12yr^{-1}

Annex E.1 : Estimation of the movement and growth parameters.

Information on length-frequency disaggregated by depth has been collected during surveys by New South Wales Fisheries (the Kapala surveys) (Graham *et al.*, 1997) and CSIRO Marine Research (Bax and Williams, 2000). These data can be used to estimate the growth parameters and the parameters that determine the movement matrix. This involves fitting a model that predicts the survey catch rate by depth and the length-frequency of the catch, by minimising the following objective function:

$$\begin{aligned} SS &= \lambda SS_1 + SS_2 + SS_3 \\ SS_1 &= \sum_f \sum_g \sum_A \frac{1}{2(\sigma^I_{f,g,A})^2}(I_{f,g,A} - \hat{I}_{f,g,A})^2 \\ SS_2 &= \sum_f \sum_g \sum_A \sum_{\tilde{L}} \frac{1}{2(\sigma^p_{f,g,A,\tilde{L}})^2}(p_{f,g,A,\tilde{L}} - \hat{p}_{g,A,\tilde{L}})^2 \\ SS_3 &= \sum_a \frac{1}{2(\sigma^L_a)^2}(L_a - \hat{L}_a)^2 \end{aligned} \quad \text{(E.1.1)}$$

where $I_{f,g,A}$ is the catch-rate index for region A based on survey-type f (CSIRO or Kapala) fishing with gear-type g,

$\hat{I}_{f,g,A}$ is the model-estimate of the catch-rate index for region A based on survey-type f fishing with gear-type g:

$$\hat{I}_{f,g,A} = q_f \sum_l \sum_a S^g_{\tilde{L}^l_{a+1/2}} N^{l,A}_a e^{-Z^{l,A}_a/2} \quad \text{(E.1.2)}$$

$\sigma^I_{f,g,A}$ is the (observed) standard deviation of $I_{f,g,A}$,

λ is the pre-specified weight assigned to the catch-rate data,

$p_{f,g,A,\tilde{L}}$ is the proportion of the catch in region A from fishing by survey-type f using gear-type g that is in length-class $\tilde{L}$,

$\hat{p}_{g,A,\tilde{L}}$ is the model-estimate of the proportion of the catch in region A from fishing using gear-type g that is in length-class $\tilde{L}$:

$$\hat{p}_{g,A,\tilde{L}} = \tilde{S}^g_{\tilde{L}} \tilde{N}^A_{\tilde{L}} / \sum_{\tilde{L}'} \tilde{S}^g_{\tilde{L}'} \tilde{N}^A_{\tilde{L}'} \quad \text{(E.1.3)}$$

$\sigma^p_{f,g,A,\tilde{L}}$ is the (observed) standard deviation of $p_{f,g,A,\tilde{L}}$,

$\hat{L}_a$ is the model-estimate of the mean length of a fish of age a:

$$\hat{L}_a = \sum_A \sum_l L^l_{a+0.5} S_{\tilde{L}^l_{a+1/2}} N^{l,A}_a e^{-Z^{l,A}_a/2} / \sum_{A'} \sum_{l'} S_{\tilde{L}^{l'}_{a+1/2}} N^{l',A'}_a e^{-Z^{l',A'}_a/2} \quad \text{(E.1.4)}$$

L_a is (observed) mean length of a fish of age a,

σ^L_a is the (observed) standard deviation of L_a,

$N_a^{l,A}$ is the number of animals of age a in growth-group l that are in region A,

$\tilde{N}_{\tilde{L}}^A$ is the number of animals in length-class $\tilde{L}$ that are in region A in the middle of the year:

$$\tilde{N}_{\tilde{L}}^A = \sum_a \sum_l N_a^{l,A} \, e^{-Z_a^{l,A}/2} \tag{E.1.5}$$

where the summations over age and growth-group are restricted so that $L_{a+1/2}^l$ lies in length-class $\tilde{L}$,

q_f is the catchability coefficient for survey-type f (assumed to be independent of gear-type),

S_L is (commercial) selectivity as a function of length, and

$\tilde{S}_{\tilde{L}}^g$ is the selectivity on fish in length-class $\tilde{L}$ by gear-type g.

The number of animals of age a in growth-group l and region A, $N_a^{l,A}$ is computed using an equilibrium version of the operating model in which fishing mortality is the same across areas, and selectivity is given by the parameters in Table E.3. The research surveys used a variety of mesh sizes. It was assumed here that the selectivity pattern for 90 mm mesh is the same as that for the commercial fishery while the selectivity pattern for 40 mm mesh (assumed to be the same as that for 44 mm mesh – a mesh size used during the Kapala surveys) is estimated. The other parameters of the model are those that determine the movement matrix, length as a function of age (see Table E.2), and fully-selected fishing mortality.

The model is able to capture the general pattern of the length-frequency data by depth (Figure E.1.1). However, the fits are far from perfect. This is usually because the data are inconsistent. For example, length-frequencies are available for jackass morwong for CSIRO and Kapala using approximately the same mesh size for depth-zone 2 (50-150m). However, the CSIRO length-frequency distribution is peaked between 100 and 200 mm while the Kapala length-frequency is peaked between 300 and 400 mm (Figures E.1.1e and f). Similar, but not as marked differences between the results based on the different survey types are evident for flathead (Figures E.1.1c and E.1.1d). Nevertheless, the model is able to fit the length-frequency data for flathead quite successfully. The fit to the data for spotted warehou is less affected by inconsistencies in data, but the model nevertheless appears to overestimate the abundance of larger (>600 mm) animals in depth-zone 4 (250-600m). The fits to the length-at-age data for all species appear relatively adequate (Figure E.1.2).

Figures E.1.3 and E.1.4 show the relative abundance and length-frequency by depth zone for each species. These figures provide results that conform to the prior expectations that flathead and to a lesser extent morwong are restricted to the inshore areas while ling and (particularly) spotted warehou are found in deeper water. Only ling is estimated to be found in waters deeper than 600m.

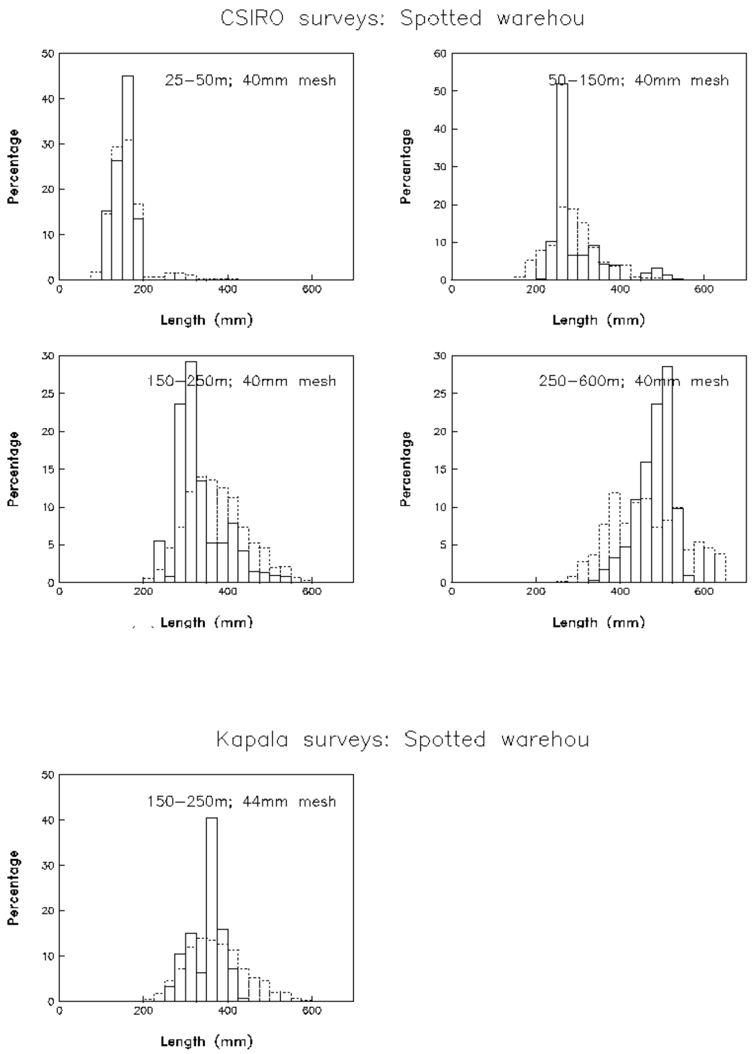


Figure E.1.1 : Observed (solid bars) and model-predicted (dotted bars) length-frequencies by survey type (CSIRO / Kapala), depth zone, and mesh size. Results are shown for each of the four species. For ease of presentation, the length-frequencies have all been scaled to 100.

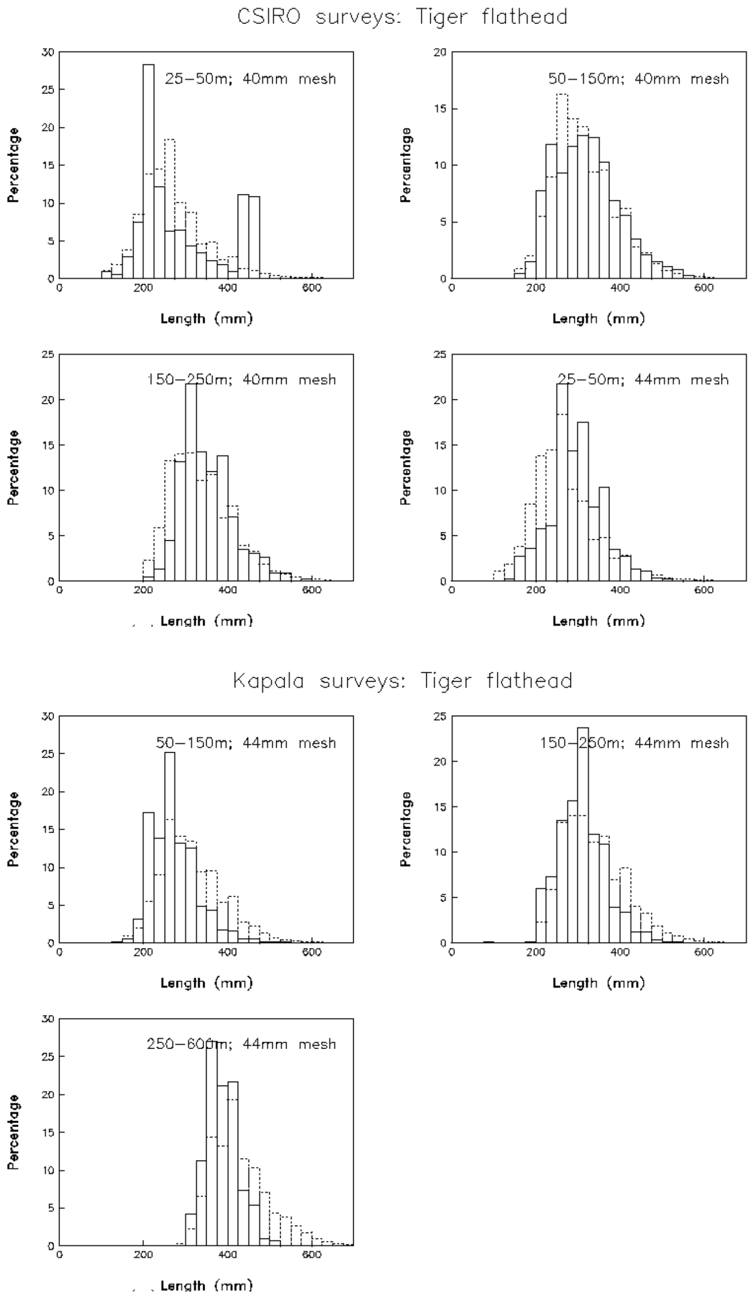


Figure E.1.1 : Observed (solid bars) and model-predicted (dotted bars) length-frequencies by survey type (CSIRO / Kapala), depth zone, and mesh size. Results are shown for each of the four species. For ease of presentation, the length-frequencies have all been scaled to 100.

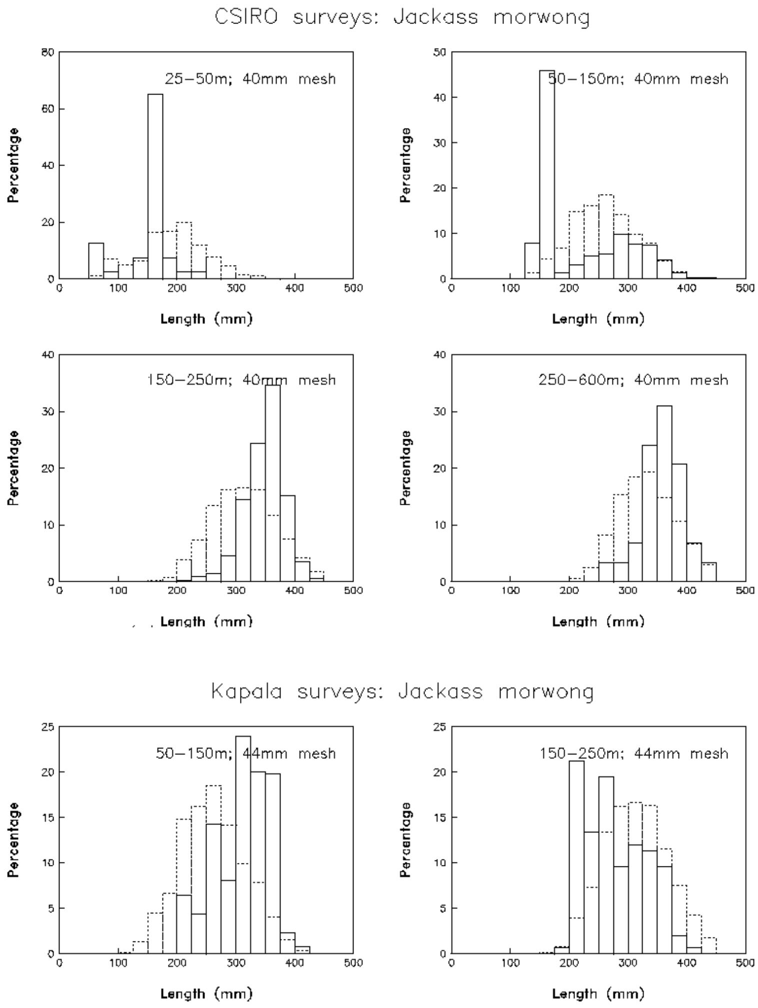


Figure E.1.1 : Observed (solid bars) and model-predicted (dotted bars) length-frequencies by survey type (CSIRO / Kapala), depth zone, and mesh size. Results are shown for each of the four species. For ease of presentation, the length-frequencies have all been scaled to 100.

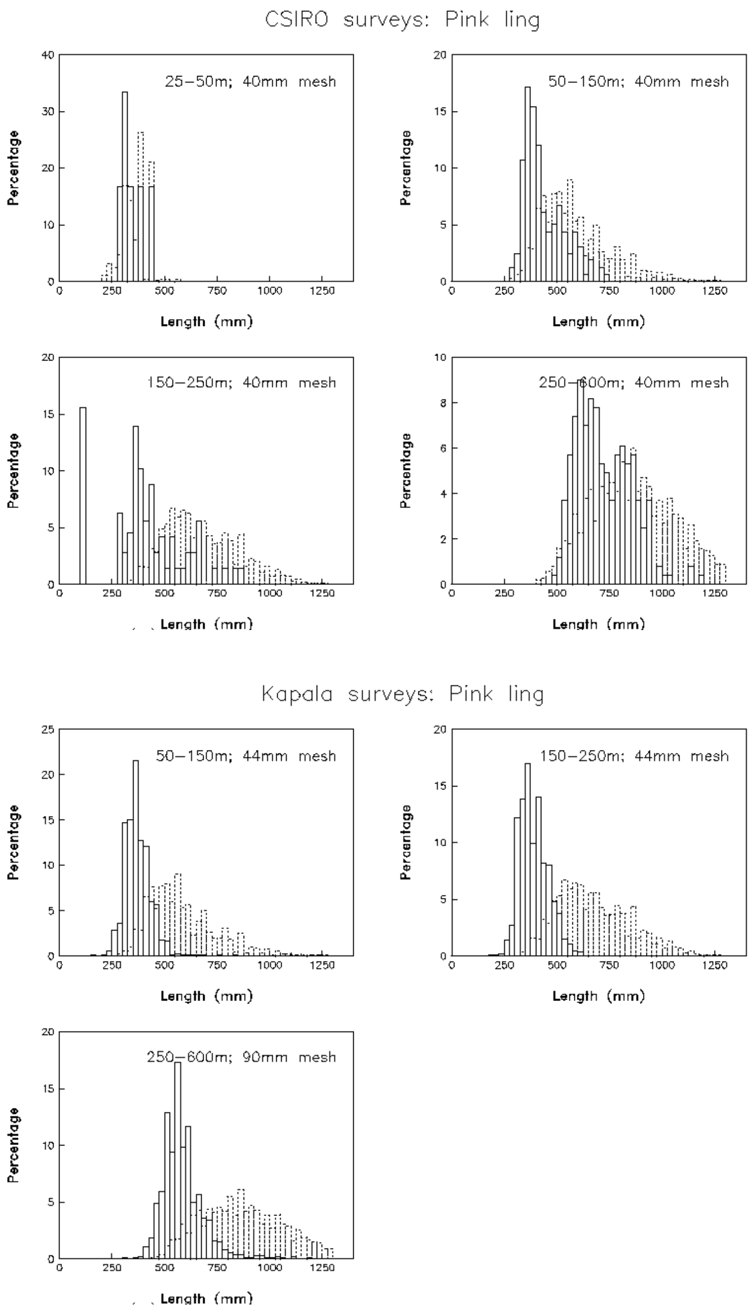


Figure E.1.1 : Observed (solid bars) and model-predicted (dotted bars) length-frequencies by survey type (CSIRO / Kapala), depth zone, and mesh size. Results are shown for each of the four species. For ease of presentation, the length-frequencies have all been scaled to 100.

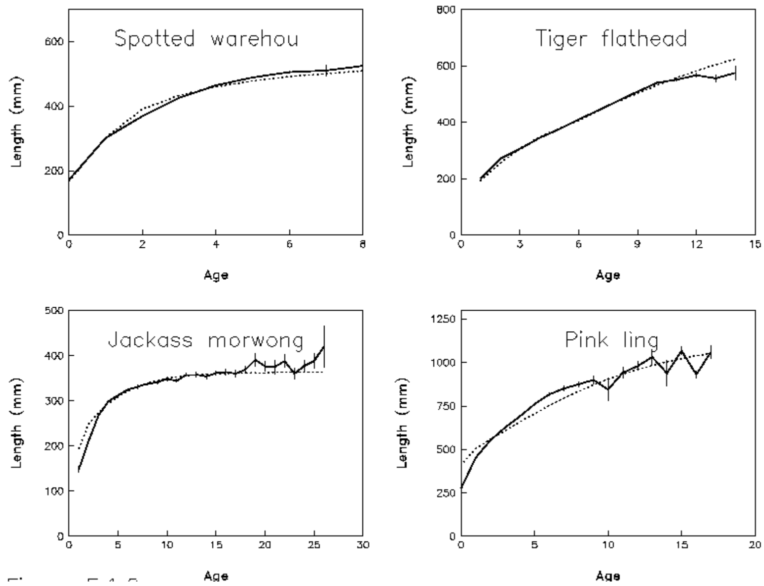


Figure E.1.2 : Observed (solid lines) and model-predicted (dotted lines) mean lengths at age for each of the four species. The vertical lines denote one standard error.

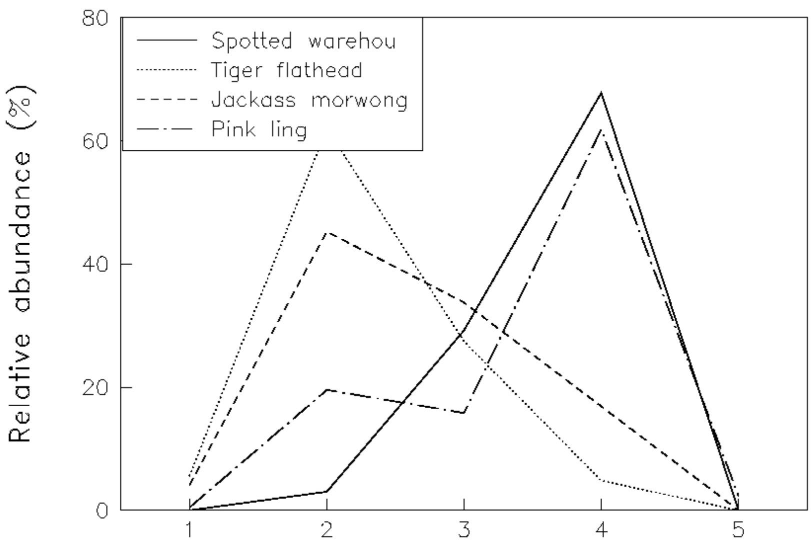


Figure E.1.3 : Model-predicted relative abundance by depth zone and species.

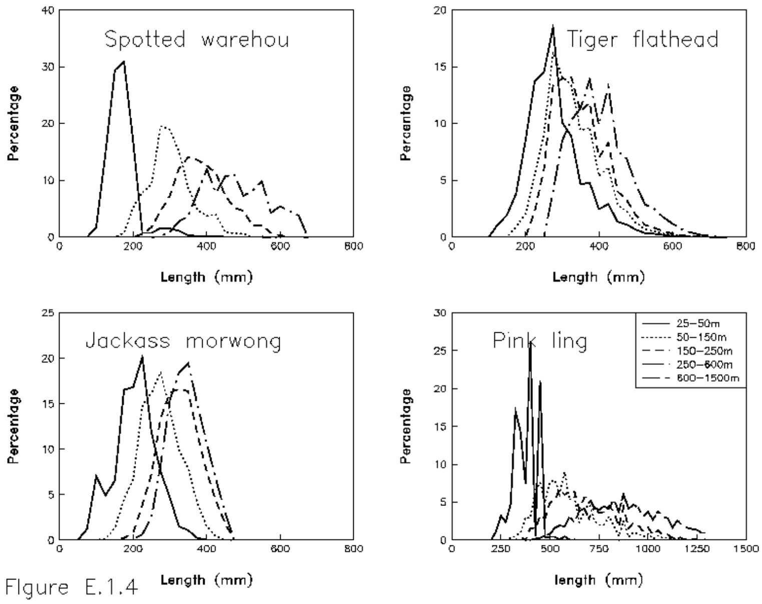


Figure E.1.4 : Model-predicted length-frequency distributions by depth zone (scaled to 100) for each of the four species.

Adjunct E.2 : Estimation of the parameters related to discarding

Information is available from the Integrated Scientific Monitoring Programme on discarded and retained catches off New South Wales (SEF areas A and B). From Equation (D.21), if density-dependent discarding is ignored, the ratio of the number of discarded to retained animals for animals of length L, DR_L, is given by:

$$DR_L = \frac{\gamma^D}{1+e^{-(L-L_{50}^D)/\delta^D}} \tag{E.2.1}$$

The values for the parameters γ^D, L_{50}^D, and δ^D can be determined by minimising the function:

$$SS = \sum_{\tilde{L}} (N_{\tilde{L}}^R + N_{\tilde{L}}^D) \left[\frac{N_{\tilde{L}}^D}{N_{\tilde{L}}^D + N_{\tilde{L}}^R} - DR_{\bar{L}_{\tilde{L}}} \right]^2 \tag{E.2.2}$$

where $N_{\tilde{L}}^R$ is the number of animals in length-class $\tilde{L}$ that were retained,
$N_{\tilde{L}}^D$ is the number of animals in length-class $\tilde{L}$ that were discarded, and
$\bar{L}_{\tilde{L}}$ is the average of the bounds for length-class $\tilde{L}$.

Equation (E.2.2) gives greater weight to length-classes for which sample size is larger. It is therefore approximately equivalent to the likelihood function that would arise if it was assumed that the discard rate was normally distributed. Figure E.2.1 shows the fit of model E.2.1 to the discard rate information. The fits for tiger flathead and spotted warehou are very good. In contrast, the data for jackass morwong do not define the discard function particularly well.

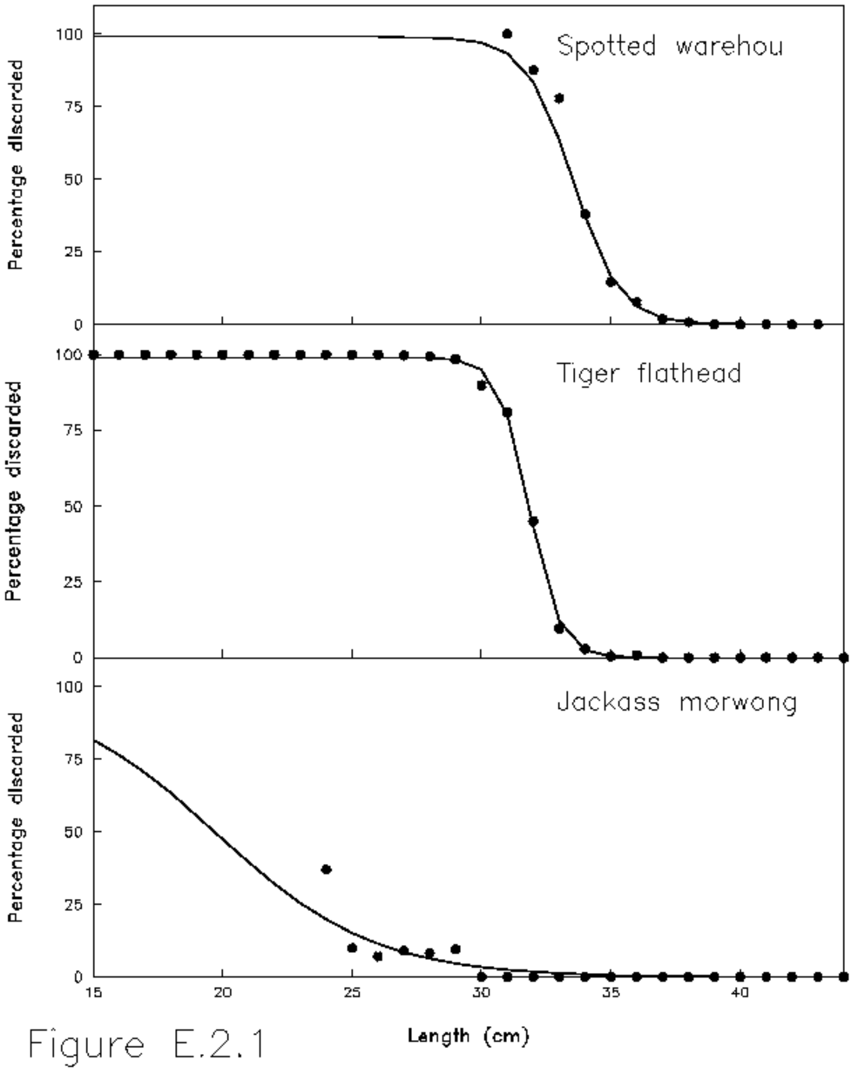


Figure E.2.1 : Observed and model-predicted discard ratios.

APPENDIX F : THE ALTERNATIVE HARVEST STRATEGIES

F.1 The data used for assessment purposes

F.1.1 Notation

The following symbols are used for the model observations throughout this Appendix. The dependence of all of the quantities on species has been omitted for ease of presentation

B_y^S	is the survey estimate of biomass (relative or absolute) during year *y*.
C_y	is the (landed) catch during year *y*: $$C_y = \sum_A C_y^{L,A}$$
$C_y^{L,A}$	is the landed catch from region *A* during year *y*.
$(C/E)_y$	is the observed catch rate during year *y*.
E_y	is the fishing effort during year *y* $(= C_y/(C/E)_y)$.
I_y	is the index of abundance (either catch rate or survey estimate) for year *y*.
L_a	is the length of an animal of age *a* according to the von Bertalanffy growth equation.
t+1	is the year for which a *TAC* is required.
w_a	is the mass of a fish of age *a* (assumed to be independent of time and based on a von Bertalanffy growth equation).
$A_{y,L,a}$	is the proportion, during year *y*, of animals in length-class *L* that are of age *a*.
$p_{y,L}^{land,obs}$	is the observed proportion of the landed catch during year *y* that lies in length-class *L*.
$p_{y,L}^{disc,obs}$	is the observed proportion of the discarded catch during year *y* that lies in length-class *L*.
$p_{y,a}^{land,obs}$	is the observed proportion of the landed catch during year *y* that is of age *a*.
$p_{y,a}^{disc,obs}$	is the observed proportion of the discarded catch during year *y* that is of age *a*.
$C_{y,a}^{land,obs}$	is the observed number of fish of age *a* landed during year *y*.
$C_{y,a}^{disc,obs}$	is the observed number of fish of age *a* discarded during year *y*.

F.1.2 Developing the input data

F.1.2.1 Catch rate data

The observed catch rate data are determined using one of two methods:

a) The "raw" catch rate (defined as the total catch divided by the total effort):

$$(C/E)_y = C_y / \sum_A E_y^A \tag{F.1}$$

where E_y^A is the fishing effort in region *A* during year *y*.

b) The catch rate for the depth zone in which the bulk of the catch has been taken:

$$(C/E)_y = C_y^{L,A} / E_y^A \tag{F.2}$$

where A is the region from which the bulk of the historical (post 1958) landed catch has been taken.

Results are only presented in this report for option b) as performance for option a) was very poor.

The effort in region A during year y, E_y^A, is generated by the operating model using the equation:

$$E_y^A = F_y^{i,A} / (q^{i,A} (B_y^A / B_0^A)^\theta e^{\lambda y} e^{\varepsilon_{q,y}^{A,s,A} - (\sigma_q)^2/2 + \eta_{q,y}^i}) \tag{F.3}$$

F.1.2.2 The age-composition data

The age-composition of the landed catch for year y is determined by applying the equation:

$$p_{y,a}^{land,obs} = \sum_L A_{y,L,a} \, p_{y,L}^{land,obs} \tag{F.4}$$

and the observed catch-at-age data for year y using the equation:

$$C_{y,a}^{land,obs} = p_{y,a}^{land,obs} \frac{C_y}{\sum_{a'} p_{y,a'}^{land,obs} \, w_{a'+1/2}} \tag{F.5}$$

The age-composition of the discarded catch is determined using variants of Equations (F.4) and (F.5) in which, for example, $p_{y,L}^{land,obs}$ is replaced by $p_{y,L}^{disc,obs}$.

F.1.2.3 Natural mortality

The age-independent rate of natural mortality is often estimated using the formula of Hoenig (1983):

$$M = -\frac{\ell n(p)}{a} \tag{F.6}$$

where p is the proportion of the population that reaches age a (or older) in an unexploited state. p is usually set equal to 0.01 when a is the "maximum age" observed (Annala, 1994).

However, as is the case for all empirical methods for estimating M, this method is subject to considerable uncertainty (Vetter, 1988; Pascual and Iribarne, 1993). The operating model incorporates a plus-group so Equation (F.4) cannot be used within the simulation framework. Instead, the extreme options assuming that M is known without error (base-case assumption) and that it is in error by 20% are examined (see Table E.5).

F.2 Empirical approaches for setting *TAC*s

The general principle underlying the empirical (i.e. non-model based) approaches to *TAC* setting is to identify some measurable statistic and then to change the *TAC* in response to changes in that statistic. In principle, the statistic should be a measure of (exploitable) biomass or of fishing mortality. The different levels of complexity of the statistics reflects (to some extent) the cost associated with data collection. The statistics considered in this study are:

a) Catch rate.
b) Estimates of total mortality from age-based catch curves.
c) Estimates of total mortality from size-based catch curves.
d) The mean size of the catch.
e) The ratio of the catch to the *TAC*.

Two types of empirical approach are considered. The first approach (Magnusson and Stefansson, 1989; Magnusson, 1992) involves changing the *TAC* using the formula:

$$TAC_{t+1} = TAC_t\,(1+\gamma_{emp}\,S_{emp,t}) \tag{F.7}$$

where γ_{emp} is a control parameter referred to as the feedback gain factor, and

$S_{emp,t}$ is the slope of a linear regression of some statistic (see above) over the years $t-y_{emp}+1$ to *t*, where, for this study, $y_{emp}=5$.

If set too high, the level of feedback gain can lead to instability in catch limits (Magnusson, 1992). Empirical approaches based on Equation (F.7) can incorporate a probing component (Magnusson, 1992). Such a component would be designed to assess whether it is possible to move the resource towards more productive levels if it is overexploited or close to the pre-exploitation level. However, a probing component is not considered in this study because it would result in occasional large changes in *TAC*, which would be undesirable from the view of industrial stability. In the context of a multi-species fishery, such a component would also probably encourage discarding of species that are "probed" downward and species not "probed" when the *TAC* for another species is "probed" upward. The feedback gain factor can differ depending on whether the population is estimated to be increasing or decreasing.

The second approach involves changing the *TAC* depending on how similar the catch for year *t* is to the *TAC* for that year:

$$TAC_{t+1} = \begin{cases} (1-\alpha)TAC_t & \text{if } C_t < \beta_1\,TAC_t \\ TAC_t & \text{if } \beta_1\,TAC_t \le C_t \le \beta_2\,TAC_t \\ (1+\alpha)TAC_t & \text{otherwise} \end{cases} \tag{F.8}$$

where α is the control parameter that determines by how much the *TAC* is to be changed (if it is to be changed at all), and

β_1, β_2 are thresholds that determine whether the *TAC* should be changed.

F.2.1 Empirical estimation of total mortality

An estimate of the total mortality during year *y*, Z_y, can be obtained from the age-structure of the landed catch for year *y* based on the assumptions that selectivity (and hence mortality) is independent of age above some age $a_{\rm rec}$, and that recruitment is constant (or has varied with little or no trend), using the regression:

$$\ell n(p_{y,a}^{land,obs}) = \alpha - Z_y\, a \qquad \text{(F.9)}$$

The regression includes all ages greater than $a_{\rm rec}$, the age at full recruitment, and less than a maximum age $a_{\max}$.

An estimate of the total mortality during year *y*, Z_y, can also be obtained using the size-composition of the landed catch for year *y*. The calculation (Pauly *et al.*, 1995) involves converting the size-composition data into age-composition data by assuming that growth follows a von Bertalanffy growth equation and then using regression Equation F.9 to calculate Z_y. For the purposes of this study, the catch of animals in length-class $\tilde{L}$ are assigned to the nearest age-class to the real age determined from the formula:

$$t_0 - \tfrac{1}{\kappa}\ell\text{n}(1 - \bar{L}_{\tilde{L}} / \ell_\infty) \qquad \text{(F.10)}$$

where κ, ℓ_∞ and t_0 are the von Bertalanffy growth parameters, and

$\bar{L}_{\tilde{L}}$ is the mid-point of length-class $\tilde{L}$.

This approach to constructing age-composition data from size-composition data is used extensively for species for which ageing is difficult (or impossible). For example, assessments of the bluefin tuna populations in the Atlantic are based on an approach that is similar to that described above (Clay, 1991). In principle, Equation (F.10) could be replaced by something more sophisticated (e.g. Schnute and Fournier (1980); Fournier *et al*. (1990)).

F.3 Production-model based approaches

Production (or biomass dynamics) models describe changes in biomass (due to the impact of mortality, growth, and recruitment) in terms of changes in biomass alone (Punt and Hilborn, 1996). Production models can be applied in situations in which age- / size-composition data are not available. However, this approach can be criticised for lack of biological realism. Production models can either be based on discrete (e.g. Butterworth and Andrew, 1984) or continuous (Prager, 1994) models. However, for relatively long-lived species such as those considered in this study, there is little difference between these two types of production model. In this study, consideration is only given to discrete models. This choice has been made primarily because discrete production models are less computationally intensive than the continuous production models. The general form of discrete production model can be written as:

$$B_{y+1} = (B_y + \tfrac{r}{p} B_y (1 - B_y / B_0)^p) e^{\varepsilon_y} - C_y \qquad \varepsilon_y \sim N(0;\sigma_r^2) \qquad \text{(F.11)}$$

where r is the intrinsic growth rate parameter,

B_0	is the pre-exploitation biomass (carrying capacity),
B_y	is the biomass at the start of year *y* ($B_{1958}=B_0$),
σ_r	is the extent of random variation in biomass, and
p	is the Pella-Tomlinson shape parameter.

F.3.1 The likelihood function

The contribution of the relative abundance data (commercial catch rates or survey estimates of relative abundance) to the negative of the logarithm of the likelihood function is based on the assumption that fluctuations in (survey or commercial) catchability are log-normally distributed with a CV of $\sigma^i_{y,q}$:

$$-\ell nL=\sum_i\sum_y\left(\ell n(\sigma^i_{y,q})+\frac{1}{2(\sigma^i_{y,q})^2}(\ell nI^i_y-\ell n(q^i\,B^i_y))^2\right) \tag{F.12}$$

where q^i is the catchability coefficient / survey bias for index-type *i*,

B^i_y is the biomass corresponding to index-type *i* for year *y*, either:

$$B^i_y=(B_y+B_{y+1})/2 \tag{F.13}$$

for the catch-rate indices or surveys during the middle of the year, or

$$B^i_y=B_y \tag{F.14}$$

for surveys at the start of the year,

I^i_y is the abundance index for year *y* and index-type *i*, and

$\sigma^i_{y,q}$ is the residual standard deviation for year *y* and index-type *i*.

The survey bias is set equal to 1 when a survey is assumed to provide indices of absolute abundance (e.g. estimates of abundance from egg production surveys). $\sigma^i_{y,q}$ is either estimated (for catch rate data) or assumed known (for survey estimates of abundance). The estimates of $\sigma_{y,q}$ for surveys usually relate only to sampling error and may therefore underestimate the actual uncertainty of a survey estimate as an index of biomass (e.g. Wade, 1996; Butterworth *et al*., 1993; Punt and Butterworth, in press; Punt *et al*., 1997a). Reasons for the "additional variance" of surveys include large scale catchability fluctuations and variation among years in the fraction of the population in the survey area. In principle, "additional variance" can be included in an assessment by estimating its value from the data (i.e. the value of $(\sigma^i_{y,q})^2$ in Equation (F.12) consists of the "known" sampling variance and a component that reflects "additional variance", Butterworth *et al*. (1993)).

F.3.2 Production model variants

Two important special cases of Equation (F.11) arise for *p*=2 and the limit $p\to 0$. The former is the Schaefer production model and the latter the Fox production model. The conventional form of this estimator involves ignoring process error (i.e. $\sigma^2_r=0$) and assuming that all of the error is in the relationship between the biomass time-series and the observed data (Polacheck *et al*., 1993). An alternative estimator ("total least squares" – Collie and Sissenwine (1983), Ludwig *et al*. (1988)) involves allowing for both observation and process error. This estimator is constructed by making an assumption about the ratio of the observation and process error variances (although the results are usually insensitive to a relatively wide range of choices) and then adding the following penalty function to the negative of the logarithm of the likelihood function:

$$\frac{1}{2\sigma_r^2}\sum_y \varepsilon_y^2 \tag{F.15}$$

"Total least squares" estimators are not considered in this study as they perform well only if there is substantial contrast in the data (A.E. Punt, unpublished data). For the same reason, the production model variants considered in this study are restricted to fixing, rather than estimating, p.

A variety of methods exist for setting *TAC*s using the results of a production model. These include a strategy of setting the *TAC* equal to (some multiple of) the current replacement yield ($=\frac{r}{p}B_{t+1}(1-B_{t+1}/B_0)^p$) and using the $f_{0.n}$ strategy. The $f_{0.n}$ harvesting strategy (f_{MSY} harvesting strategy for n=0) involves fixing future fishing effort at the level at which the slope of the equilibrium catch *versus* effort curve is one-tenth of that at the origin ($E_{0.n}$). The formula applied to obtain *TAC*s corresponding to the $f_{0.n}$ harvesting strategy for the year t+1, is:

$$TAC_{0.n}(t+1) = (\hat{C/E})_{t+1}\, E_{0.n} \tag{F.16}$$

An estimate of $(C/E)_{t+1}$ can be obtained under the assumption that the *TAC* estimated for year t+1 based on the $f_{0.n}$ strategy will in fact be taken (Punt, 1988):

$$(\hat{C/E})_{t+1} = \frac{2B_{t+1} + \frac{r}{p}B_{t+1}(1-B_{t+1}/B_0)^p}{2/q + E_{0.n}} \tag{F.17}$$

Results are only presented in this report for the choice n=0 although the software implements the general case $n > 0$.

F.4 Age-based methods

The most commonly used methods of fisheries stock assessment are based on age-composition data (Megrey, 1989). All such methods include specifications for the following:

a) The rate of natural mortality, M.
b) How the observed abundance indices are related to the quantities included in the model.
c) The relationship between the observed and model-predicted catches-at-age.
d) The relationship between spawner biomass and future recruitment.

The following symbols are common to the descriptions of all of the age-based methods:

$a_{\min}$	the lowest age considered in the analysis.
$a_{\max}$	the oldest age considered in the analysis (usually assumed to be a plus-group).
f_a	the proportion of animals of age *a* that are mature.
w_a	the mass of a fish of age *a* at the start of the year.
$y_{\min}$	the first year considered in the analysis.
$\tilde{B}_y$	the spawner biomass at the start of year *y*.
L_a	the mean length of a fish of age *a* (given by a von Bertalanffy growth equation).
L_{mat}	the length-at-maturity.
M	the (age-independent) rate of natural mortality.
$N_{y,a}$	the number of fish of age *a* at the start of year *y*.
S_a	the selectivity on fish of age *a*.

The following two relationships are common to all age-based methods.

Maturity is assumed to be a knife-edged function of length:

$$f_a = \begin{cases} 0 & \text{if } L_a < L_{mat} \\ 1 & \text{otherwise} \end{cases} \tag{F.18}$$

The spawner biomass is defined using the equation:

$$\tilde{B}_y = \sum_{a=1}^{x} f_a \, w_a \, N_{y,a} \tag{F.19}$$

F.4.1 Setting *TAC*s using the results of age-structured assessments

The general equation used to set the *TAC* for year *t*+1 is:

$$TAC_{t+1} = \sum_{a=a_{\min}}^{a_{\max}} w_{a+1/2} \frac{S_a F_{\text{targ}}}{M + S_a F_{\text{targ}}} N_{t+1,a} (1 - e^{-M - S_a F_{\text{targ}}}) \tag{F.20}$$

for models based on continuous fishing mortality and

$$TAC_{t+1} = \sum_{a=a_{\min}}^{a_{\max}} w_{a+1/2} \, S_a \, F_{\text{targ}} \, N_{t+1,a} \, e^{-M/2} \tag{F.21}$$

for models based on the assumption that fishing occurs instantaneously in the middle of the year.

F_{targ} is the target fishing mortality (Equation F.20) or the target exploitation rate (Equation F.21). Different harvest strategies correspond to different ways of specifying F_{targ}.

F.4.1.1 Yield-related fishing mortalities

For models based on continuous fishing mortality, the relationship between equilibrium yield, $C(F)$, and fully-selected fishing mortality, *F*, is given by:

$$C(F) = R(F) \sum_{a=a_{\min}}^{a_{\max}} w_{a+1/2} \frac{S_a F}{M + S_a F} N_a(F)(1 - e^{-M - S_a F}) \qquad \text{(F.22)}$$

where $N_a(F)$ is the number of animals of age *a* relative to the number of animals of age $a_{\min}$ when the fully-selected fishing mortality is *F*:

$$N_a(F) = \begin{cases} 1 & \text{if } a = a_{\min} \\ N_{a-1}(F)\, e^{-M - S_{a-1} F} & \text{if } a_{\min} < a < a_{\max} \\ \dfrac{N_{a_{\max}-1}\, e^{-M - S_{a_{\max}-1} F}}{1 - e^{-M - S_{a_{\max}} F}} & \text{if } a = a_{\max} \end{cases} \qquad \text{(F.23)}$$

$R(F)$ is the number of animals of age $a_{\min}$ as a function of *F*:

$$R(F) = (\alpha\, SB(F) - \beta) / SB(F) \qquad \text{(F.24a)}$$

for a Beverton-Holt stock-recruitment relationship or

$$R(F) = \frac{1}{\beta\, SB(F)} \ell\text{n}(\alpha\, SB(F)) \qquad \text{(F.24b)}$$

for a Ricker stock-recruitment relationship, and

$SB(F)$ is spawner-biomass-per-recruit as function of *F*:

$$SB(F) = \sum_{a=a_{\min}}^{a_{\max}} f_a\, w_a\, N_a(F) \qquad \text{(F.25)}$$

Equations (F.22) and (F.23) are modified appropriately if fishing mortality is assumed to occur instantaneously in the middle of the year.

Two target fishing mortalities based on the relationship between equilibrium yield and fishing mortality are F_{MSY}, the fishing mortality at which $C(F)$ is maximised, and $F_{0.1}$, the fishing mortality at which $\frac{d\,C(F)}{dF} = 0.1 \left. \frac{d\,C(F)}{dF} \right|_{F=0}$ (Gulland and Boerema, 1973). $F_{0.1}$ is considered by some (Mace, 1994; Mace and Sissenwine, 1993) to be a "conservative or cautious" proxy for F_{MSY}.

F.4.1.2 Spawner-biomass-per-recruit based fishing mortalities

A variety of authors have developed target fishing mortalities based on the relative spawner-biomass-per-recruit (i.e. $SB(F)/SB(0)$). Mace and Sissenwine (1993) advocate $SB(F)/SB(0)$=0.2 for stocks with "average resilience" and

$SB(F)/SB(0)$=0.35 for "little known" stocks while Clark (1991, 1993) advocates $SB(F)/SB(0)$=0.35 as a robust estimator of $F_{\rm MSY}$ and $SB(F)/SB(0)$=0.4 if there is evidence for strong serial correlation or considerable variability in recruitment. The harvest strategies considered in this report are based on the selections $SB(F)/SB(0)$=0.3 and $SB(F)/SB(0)$=0.4, except that the stock-recruitment relationship is taken account when computing $SB(F)/SB(0)$ rather than it being ignored.

F.4.1.3 Other target fishing mortalities

Pope (1983) and Pope and Gray (1983) describe the $F_{\rm status\text{-}quo}$ strategy. This strategy involves basing the *TAC* for year *t*+1 on the estimated fishing mortality for year *t*. It results in fairly precise *TAC*s (and hence little inter-annual variation in *TAC*s). However, it makes no attempt to recover overexploited resources nor to increase fishing mortality on underutilized resources. Sissenwine and Shepherd (1987) define three reference levels of fishing mortality based on the estimates of spawner biomass and recruitment. In a stock-recruitment plot straight lines that leave 90%, 50% and 10% of the points above a line drawn through the origin can be converted to fishing mortalities (referred to as $F_{\rm low}$, $F_{\rm med}$, and $F_{\rm high}$) using the relationship between spawner-biomass-per-recruit and fishing mortality. Jacokson (1992, 1993) shows that the estimates of $F_{\rm low}$, $F_{\rm med}$, and $F_{\rm high}$ are not particularly sensitive to uncertainty about *M*. However, the value of $F_{\rm med}$ depends on the past history of exploitation. This means *inter alia* that if $F_{\rm med}$ is based on a period in which the stock was overexploited, use of this reference point will keep the population in an overexploited state (Clark, 1991).

An additional level of stock protection can be applied by making the fishing mortality a function of the biomass. For example, a modified version of the $F_{\rm MSY}$ strategy would be:

$$F_{\rm targ} = F_{MSY}\, B_t / B_{\rm MSY} \qquad \text{(F.26)}$$

F.4.2 Virtual Population Analysis

The standard VPA back-calculations for each cohort, together with the selected tuning algorithms, are applied until convergence takes place to obtain the estimates of the fishing mortality (**F**) and numbers-at-age (**N**) matrices. The estimate of the N-matrix is then used to calculate the time-series of spawner biomass (Equation F.19) and hence estimate the relationship between spawner biomass and recruitment.

F.4.2.1 The VPA back-calculations

The VPA back-calculation process is used to calculate the entire numbers-at-age matrix from the numbers-at-age for the oldest age (taken to be a plus-group) and the most-recent year. For ages $a < a_{\rm max} - 1$, the equation used to calculate $N_{y,a}$ from $N_{y+1,a+1}$ is:

$$N_{y,a} = N_{y+1,a+1}\, e^{M+F_{y,a}} \qquad \text{(F.27)}$$

where $F_{y,a}$ is the instantaneous rate of fishing mortality on fish of age *a* during year *y*, calculated by solving the catch equation:

$$C_{y,a} = \frac{F_{y,a}}{M + F_{y,a}} N_{y+1,a+1} (e^{M+F_{y,a}} - 1) \tag{F.28}$$

The number of animals in the plus-group is computed by solving the equation:

$$N_{y+1,a_{\max}} = N_{y,a_{\max}} \, e^{-(M+F_{y,a_{\max}})} + N_{y,a_{\max}-1} \, e^{-(M+F_{y,a_{\max}-1})} \tag{F.29}$$

The algorithm used to solve Equation (F.29) is as follows:

a) Guess $F_{y,a_{\max}-1}$ and calculate $N_{y,a_{\max}-1}$ from Equation (F.28).
b) Apply the tuning algorithm for the oldest age (see Equation F.30) to determine $F_{y,a_{\max}}$.
c) Calculate $N_{y,a_{\max}}$ from Equation (F.28).
d) Substitute $F_{y,a_{\max}}$, $F_{y,a_{\max}-1}$, $N_{y,a_{\max}}$ and $N_{y,a_{\max}-1}$ into Equation (F.29) and compare the result with $N_{y+1,a_{\max}}$ which is known. If the difference is large, steps a) – d) are repeated.

F.4.2.2 Tuning procedure

The algorithm used to tune the oldest-age terminal fishing mortalities is based on the assumption that the age-specific selectivity function is flat over the oldest *r*+1 ages (where *r* is taken to be 2 in this study). The equation specifying the fishing mortality on the plus-group as a function of those on the *r* younger ages is:

$$\hat{F}_{y,a_{\max}} = \left[\prod_{a=a_{\max}-r}^{a_{\max}-1} F_{y,a} \right]^{1/r} \qquad y = 1,2,...,t \tag{F.30}$$

The method applied to tune the most-recent-year terminal fishing mortality rates is the Laurec-Shepherd tuning algorithm (Pope and Shepherd, 1985):

$$\hat{F}_{t,a} = \overline{q_a} \, E_t \qquad a = a_{\min}, ..., a_{\max} - 1 \tag{F.31}$$

where $\overline{q_a}$ is the catchability coefficient for age *a*:

$$\overline{q_a} = \left[\prod_{y} (F_{y,a} / E_y) \right]^{1/(n_y - 1)} \tag{F.32}$$

n_y is the number of years for which fishing effort data are available.

The product in Equation (F.32) is taken over all years for which effort data are available (except the year *t*).

F.4.2.3 Estimating the parameters of the stock-recruitment relationship

The number of animals of age $a_{\min}$ at the start of year *y* is assumed to be related to the spawner biomass at the start of year $y - a_{\min}$ according to either a Beverton-Holt or a Ricker stock-recruitment relationship. The estimates of the parameters of the stock-recruitment relationship are obtained by fitting to the estimates of $a_{\min}$-class strength produced by the VPA. This involves minimising the function:

$$SS = \sum_{y=y_{\min}+a_{\min}}^{t-y_{ig}} \left(\ell n N_{y,a_{\min}} - \ell n \hat{N}_{y,a_{\min}}\right)^2 \tag{F.33}$$

where y_{ig} is the number of years ignored when estimating the parameters of the stock-recruitment relationship, and

$\hat{N}_{y,a_{\min}}$ is the estimate of the $a_{\min}$-class strength for year y from the stock-recruitment relationship.

The estimates of $a_{\min}$-class strength for the years $t - y_{ig} + 1, \ldots t$ are omitted from this regression because their variances are usually very large (see, for example, Butterworth *et al.*, 1990).

F.4.3 ADAPT-VPA

The ADAPT-VPA approach (Gavaris, 1988) is similar to *ad hoc* tuned VPA in that the catch-at-age matrix is assumed to be known exactly so Equations F.27, F.28, and F.29 can be used to compute the numbers-at-age matrix given values for the numbers-at-age at the start of year $t+1$. Rather than estimate the terminal numbers-at-age by applying Equation F.31, these parameters are instead estimated by minimising the following objective function:

$$SS = \sum_{y} \sum_{a=a_{\min}}^{a_{\max}-1} \left(\ell n F_{y,a} - \ell n(\bar{q}_a\, E_y)\right)^2 \tag{F.34}$$

In principle, ADAPT-VPA can also incorporate survey estimates of biomass (e.g. Punt (1994)). However, this complication has been ignored here so that the results of the ADAPT-VPA are directly comparable with those for the *ad hoc* tuned VPA.

The estimates for the parameters of the stock-recruitment relationship are found using the same approach as for the *ad hoc* tuned VPA (Section F.4.2.3).

F.4.4 Integrated Analysis

The Integrated Analysis approach is based on separating the development of the population dynamics model from that of the likelihood function. The original development of this approach can be traced to Doubleday (1976). Various other authors (e.g. Fournier and Archibald, 1982; Pope and Shepherd, 1982; Collie and Sissenwine, 1983; Deriso *et al.*, 1985; Kimura, 1989, 1990; Methot, 1989, 1990; McAllister *et al.*, 1994; McAllister and Ianelli, 1997) continued the development of the general approach by modifying the structure of the population dynamics model, modifying the form of the likelihood function, and using a Bayesian rather than a maximum likelihood or a least squares estimation framework. Integrated Analysis forms the basis for several of the formal assessments of SEF species (e.g. Smith and Punt, 1998; Punt, 1999a, b; Punt *et al.*, In press-c). This is because Integrated Analysis can handle cases in which some data (e.g. age-composition information) is unavailable for some years and because it provides a clear basis for conducting forward projections under different future levels of catch.

The variant of Integrated Analysis considered in this study is based on an age-structured population dynamics model that explicitly considers discarding. Six sources of information are taken into account in the assessment (Section F.4.4.4). Five of these (catch in mass, catch age- / size-composition data, relative abundance indices, information on discards, and estimates of absolute abundance) are measurements of quantities contained in the model while the sixth represents *a priori* information about the extent of variation in recruitment.

F.4.4.1 Basic dynamics

The dynamics of animals aged 0 and above are governed by the equation:

$$N_{y+1,a} = \begin{cases} N_{y+1,0} & \text{if } \; a = 0 \\ N_{y,a-1}\, e^{-M}\,(1 - S_{a-1}\, F_y) & \text{if } \; 1 \le a < a_{\max} \\ (N_{y,x} + N_{y,x-1})\, e^{-M}\,(1 - S_x\, F_y) & \text{if } \; a = a_{\max} \end{cases} \tag{F.35}$$

where F_y is the fully-selected fishing mortality during year *y*.

The number of 0-year-olds at the start of year *y* is related to the spawner biomass at the start of year *y* according to the equation:

$$N_{y,0} = \tilde{B}_y / (\alpha + \beta\, \tilde{B}_y) e^{\varepsilon_y} \tag{F.36}$$

where α, β are the parameters of the stock-recruitment relationship, and
ε_y is the recruitment residual for year *y* (assumed to be temporally uncorrelated).

The values for α and β are determined from the steepness of the stock-recruitment relationship (*h*) and the pre-exploitation equilibrium biomass (B_0) using the equations of Francis (1992).

The specifications for the numbers-at-age at the start of year 1 (1958) are given by:

$$N_{1,a} = \begin{cases} R_0\, e^{-aM} & \text{if } a < x \\ R_0\, e^{-xM} / (1 - e^{-M}) & \text{if } a = x \end{cases} \tag{F.37}$$

where R_0 is the expected number of 0-year-olds at unexploited equilibrium.

F.4.4.2 Selectivity

The selectivity of the gear is governed by a logistic curve:

$$S_a = (1 + e^{-\ell n 19 (L_a - L_{50})/(L_{95} - L_{50})})^{-1} \tag{F.38}$$

where L_{50} is the length-at-50%-selectivity, and
L_{95} is the length-at-95%-selectivity.

F.4.4.3 Catches

The number of fish of age *a* landed during year *y*, $\hat{C}_{y,a}$, and the number of fish of age *a* discarded during year *y*, $\hat{D}_{y,a}$, are given by the equations:

$$\hat{C}_{y,a} = (1-P_a)\, S_a\, F_y\, N_{y,a}\, e^{-M/2} \tag{F.39a}$$

$$\hat{D}_{y,a} = P_a\, S_a\, F_y\, N_{y,a}\, e^{-M/2} \tag{F.39b}$$

where P_a is the probability of discarding a fish of age *a*:

$$P_a = \frac{\Omega}{1+e^{-(L_a - L_{50}^D)/\delta}} \tag{F.40}$$

Ω is the maximum possible discard rate,

L_{50}^D is the length at which discarding is half the maximum possible rate, and

δ is the parameter that determines the width of the relationship between length and the discard probability.

The model estimates of the catch (in mass) landed during year *y*, $\hat{C}_y$, and of the mass of fish discarded during year *y*, $\hat{D}_y$, are given by the equations:

$$\hat{C}_y = \sum_{a=0}^{x} w_{a+0.5}\, \hat{C}_{y,a} \qquad \hat{D}_y = \sum_{a=0}^{x} w_{a+0.5}\, \hat{D}_{y,a} \tag{F.41}$$

The value for F_y is selected by solving the equation $C_y = \hat{C}_y = \sum_{a=0}^{x} w_{a+0.5}\, \hat{C}_{y,a}$.

F.4.4.4 The likelihood function

The negative of the logarithm of the likelihood function includes five contributions. These relate to minimising the sizes of the recruitment residuals and fitting the observed discard rates, the observed catch / discard age-/size-compositions, the relative abundance data, and the estimates of absolute abundance.

$$L = \sum_{i=1}^{5} L_i \tag{F.42}$$

The contribution of the recruitment residuals to the negative of the logarithm of the likelihood function is based on the assumption that the inter-annual fluctuations in recruitment about the deterministic stock-recruitment relationship are independent and log-normally distributed with a CV of σ_r:

$$L_1 = \sum_y \tfrac{1}{2\sigma_r^2}\, \varepsilon_y^2 \tag{F.43}$$

where the summation over year runs to year t from the lesser of 1958 and the first year for which age- or size-composition data are available less the number of age-classes considered in the model.

The contribution of the observed mass of discards to the negative of the logarithm of the likelihood function is based on the assumption that the errors in measuring the fraction of the total catch that is discarded are log-normally distributed with a CV of σ_d:

$$L_2 = \sum_{y=1}^{t}\left(\ell n\sigma_d + \tfrac{1}{2\,\sigma_d^2}(\ell n p_y^{\mathrm{obs}} - \ell n\hat{p}_y)^2\right) \qquad \text{(F.44)}$$

where p_y^{obs} is the observed fraction of the catch in mass during year y that was discarded,

$\hat{p}_y$ is the model-predicted fraction of the catch in mass during year y that was discarded:

$$\hat{p}_y = \hat{D}_y / (\hat{C}_y + \hat{D}_y) \qquad \text{(F.45)}$$

σ_d is the residual standard deviation for the p_y^{obs}.

The contribution of the age-composition of the landed catch to the negative of the logarithm of the likelihood function is based either on the assumption that these data are determined from a random sample of $N_y^{\mathrm{age,land}}$ animals from the catch or that they are a realisation from a (multivariate) log-normal distribution:

$$L_3 = -\sum_y N_y^{\mathrm{age,land}} \sum_a \rho_{y,a}^{\mathrm{obs}}\, \ell n(\hat{\rho}_{y,a} / \rho_{y,a}^{\mathrm{obs}}) \qquad \text{(F.46a)}$$

or

$$L_3 = \sum_y \sum_a \left(\ell n(\sigma_w) - \gamma\,\ell n(\sqrt{\hat{\rho}_{y,a}}) + \tfrac{(\hat{\rho}_{y,a})^{\gamma}}{2\,(\sigma_w)^2}\left[\ell n \rho_{y,a}^{obs} - \ell n\hat{\rho}_{y,a}\right]^2\right) \qquad \text{(F.46b)}$$

where $\rho_{y,a}^{\mathrm{obs}}$ is the observed proportion which fish of age a made up of the landed catch during year y,

$\hat{\rho}_{y,a}$ is the model-estimate of the proportion which fish of age a made up of the landed catch during year y:

$$\hat{\rho}_{y,a} = \hat{C}_{y,a} / \sum_{a'=0}^{x} \hat{C}_{y,a'} \qquad \text{(F.47)}$$

γ is the parameter that determines the sensitivity of the variance of $\hat{\rho}_{y,a}$ to the value of $\hat{\rho}_{y,a}$, and

σ_w is a parameter that determines the weight assigned to fitting the age-composition data.

The summations over year include only those years for which age-composition data are available. The proportions for the oldest ages are pooled and treated as a single "age-class" when fitting to the catch proportion-at-age information. This is a standard technique when fitting models to age-composition data (e.g Smith and Punt, 1998) and prevents the data for old fish having an excessive influence on the results. Similarly, the proportions for the youngest ages are pooled and treated as a single "age-class" in the fitting procedure. Equation (F.47) is based on the assumption that ageing is exact. It is possible to make allowance for age-reading error when computing the model estimates of the proportion of the catch in each age-class (e.g. Punt *et al.*, In press-c). However, for simplicity, this complication has been ignored here.

The contribution of the age-composition of the discards to the negative of the logarithm of the likelihood function follows Equations (F.46) and (F.47), except that $\hat{\rho}_{y,a}$ is replaced by the model-estimate of the proportion which fish of age *a* made up of the discards during year *y*, $\rho^{obs}_{y,a}$ is replaced by the observed proportion which fish of age *a* made up of the discards during year *y*, and $N_y^{\text{age,land}}$ is replaced by $N_y^{\text{age,disc}}$. The residual standard deviation for the age-composition data for the discards is denoted σ_v.

The approach for including the size-composition data in the likelihood function follows Equation (F.46). The residual standard deviation for the size-composition data is denoted σ_z. The observed proportions represent the observed fraction of the catch by length-class. The model-estimated proportions are given by:

$$\hat{C}_{y,L} = \sum_a \hat{C}_{y,a}\, \Phi(a,L) \qquad \text{(F.48)}$$

where $\Phi(a,L)$ is the probability that a fish of age *a* lies in length-class *L*:

$$\Phi(a,L) = \int_{\ell n(L^-)}^{\ell n(L^+)} \frac{1}{\sqrt{2\pi}\phi_a} e^{-\frac{(\ell n\tilde{L} - \ell n L_{a+1/2})^2}{2(\phi_a)^2}}\, d\ell n\tilde{L} \qquad \text{(F.49)}$$

L^+, L^- are the limits of length-class *L*,

ϕ_a is the standard deviation of the logarithm of the length of a fish of age *a* (approximated here by the *CV* of $L_{a+1/2}$).

The contribution of the relative abundance data (commercial catch rates or survey estimates of relative abundance) to the negative of the logarithm of the likelihood function is based on the assumption that fluctuations in (survey or commercial) catchability are log-normally distributed with a CV of $\sigma^i_{y,q}$:

$$L_4 = \sum_i \sum_y \left(\ell\text{n}(\sigma^i_{y,q}) + \tfrac{1}{2(\sigma^i_{y,q})^2} (\ell\text{n} I^i_y - \ell\text{n}(q^i\, B^i_y))^2 \right) \qquad \text{(F.50)}$$

where q^i is the catchability coefficient for index-type *i*,

B_y^i is the biomass corresponding to index-type i and year y either:

$$B_y^i = (1 - F_y / 2)\sum_a w_{a+1/2}\,(1 - P_a)\, S_a\, N_{y,a}\, e^{-M/2} \qquad \text{(F.51a)}$$

for the catch-rate indices or surveys during the middle of the year, or

$$B_y^i = \tilde{B}_y \qquad \text{(F.51b)}$$

for surveys at the start of the year,

I_y^i is the abundance index for year y and index-type i, and

$\sigma_{y,q}^i$ is the residual standard deviation for year y and index-type i.

F.4.4.5 Variants of the estimator

Several variants of the estimator are considered. The most general variant involves assuming that the age- / size-composition data are multinomially rather than log-normally distributed and using age-composition data for those years for which it is available and size-composition data for any years for which size-composition data are available but age-composition data are not. The stock-recruitment relationship is assumed to be of the Beverton-Holt form, as is conventional when conducting assessments of SEF species. Table F.1 lists the parameters of this variant of the model, and how the value for each parameter is determined.

The following variants of the general model reflect methods of stock assessment based on Integrated Analysis that have been used in past assessments of marine fish species and can be shown to be special cases of the general model:

a) No age-composition, size-composition or discard data are included in the analysis, selectivity is pre-specified rather than being estimated, and variation in recruitment about the value expected from the stock-recruitment relationship is ignored (i.e. $\varepsilon_y = 0$). This variant is commonly referred to as "deterministic stock reduction analysis" or "age-structured production model" (e.g. Breiwick *et al.*, 1984; de la Mare, 1989b; Hilborn, 1990; Francis, 1992; Hilborn *et al.*, 1994; Punt, 1994; Punt and Japp, 1994; Givens *et al.*, 1995). The selectivity pattern for this variant is taken to be the true (operating model) selectivity pattern.
b) The age- / size-composition data are assumed to be log-normally distributed with γ=1; the residual standard deviations are all pre-specified.
c) Only the size-composition data are used for assessment purposes and any age-composition data are ignored. This variant could be used to examine the benefits of collecting age-length keys.
d) The information on discards is ignored.

F.5 Other approaches

F.5.1 Delay difference models

Delay difference models (e.g. Deriso, 1980; Schnute, 1985, 1987; Fournier and Doonan, 1987) represent age-structured processes (growth, natural mortality, etc.) using a delay-difference equation. However, it is necessary to make some simplifying assumptions (e.g. a particular growth curve / selectivity pattern) to use such models. Unfortunately, these simplifications can be unrealistic and it is now common to use fully age-structured models that permit arbitrary specification of such processes rather than using the restrictive delay-difference models (Hilborn, 1990).

F.5.2 Size-structured models

Methods that utilise size-structure data include those that consider the dynamics of both age- and size-structure (e.g. Deriso and Parma, 1988), and those that consider the dynamics of size-structure only (e.g. Bergh and Johnson, 1992; Sullivan *et al*., 1990; Zheng *et al*., 1995, 1996; Punt and Kennedy, 1997). However, evaluation of the methods for estimating the size-transition matrices needed to apply these methods of stock assessment (e.g. Punt *et al*., 1997b) is beyond the scope of the current study. The Integrated Analysis model (Section F.4.4) makes use of size-structure data by assuming that the distribution of length-at-age is invariant over time.

It is possible to apply age-based stock assessment methods to catch-at-age data determined by applying “age-slicing” (Equation F.10) (e.g. Mohn, 1991). The method proposed by Mohn (1991) involves specifying an “initial” catch-at-age matrix using the slicing method, applying a VPA-type approach, using the results of the VPA to calculate an age-length key for each year for which data are available, and using these age-length keys to update the catch-at-age matrix. While this approach shows some promise, we prefer to “integrate” age-composition and length-composition data through an Integrated Analysis approach (see Section F.4.4).

F.6 Inter-annual variability in quotas

The *TAC* from the harvest strategy is subject to additional constraints. First, it is not permitted to be larger than 4000*t* or less than 250*t*. Furthermore, the *TAC* for year t+1 is not permitted to differ from that for year t by more than a pre-specified percentage. For the base-case analyses, this percentage is 50.

F.7 Parameterisation

Table F.2 lists the values for the base-case parameters of the harvest strategies. Table F.2(a) lists the values of the parameters that are common across all of the age-based harvest strategies while Table F.2(b) lists the values for the parameters that are specific to particular harvest strategies.

Table F.1 : The parameters of the Integrated Analysis model. The symbol n_I denotes the number of indices of relative abundance. d_1 is the first year for which age- / size-composition data are available.

Parameter name / symbol	Number of parameters	Treatment
Maximum age (x)	1	Pre-specified
Natural mortality (M)	1	Pre-specified
Length-at-age (L_a^s, ϕ_a^s)	2 (x+1)	Pre-specified
Weight-at-age (w_a)	x+1	Pre-specified
Stock-recruitment parameters (α, β)	2	Estimated from B_0 and steepness (h)
Recruitment residuals (ε_y)	max(t, $t + x - d_1$)	Estimated
Selectivity-at-age by fleet (S_a)	2	Estimated
Length-at-maturity (L_{mat})	1	Pre-specified
Discard-related (Ω, L_{50}^D, δ,)	3	Estimated
Age-composition variance determination, γ	1	Pre-specified
Catchability coefficient by fleet, q^i	n_I	Estimated
Residual standard deviations (σ_d , σ_q^i, σ_r)	2+n_I	Pre-specified

Table F.2 : Parameters related to estimation.

(a) Species-specific biological parameters

	Spotted warehou	Tiger flathead	Jackass morwong	Pink ling
Plus-group (yr)	13	20	15	20
Natural mortality (yr^{-1})	0.3	0.2	0.2	0.15
Growth parameters				
ℓ_∞ (cm)	52.93	88.23	37.48	122.27
κ	0.304	0.081	0.305	0.137
t_0 (yr)	-0.488	-1.346	-0.409	-0.965
e	3.00	3.31	3.00	3.14
w_∞ (kg)	2.51	3.92	0.94	13.31
ϕ_a	0.18	0.07	0.13	0.09
Length-at-maturity (cm)	40	30	22	72

(b) Harvest strategy-specific parameters

	Spotted warehou	Tiger flathead	Jackass morwong	Pink ling
Empirical Approach				
Age-at-recruitment, a_{rec} (yr)	3	5	3	4
Oldest regression age, a_{max} (yr)	10	16	13	14
Integrated analysis				
Landed age range (yr)	2-10	3-16	2-13	2-14
Discard age range (yr)	1-7	2-5	1-7	N/A
Landed length range (cm)	25-40	25-49	15-28	34-78
Discarded length range (cm)	19-25	14-25	12-21	N/A
Recruitment CV, σ_r	0.6	0.6	0.6	0.6
Catchability CV, σ_q	0.3	0.3	0.3	0.3
Discard CV, σ_d	0.3	0.3	0.3	N/A
Multinomial N: landed catch, $N_y^{age,land}$	100	100	100	100
Multinomial N: discarded catch, $N_y^{age,disc}$	20	20	20	N/A
Log-normal CV; landed catch, σ_w	0.2	0.2	0.2	0.2
Log-normal CV; discarded catch, σ_v	0.3	0.3	0.3	N/A
VPA / ADAPT				
Age-range (yr)	2-10	3-16	2-13	2-14
Recruitments to skip, y_{ig} (yr)	2	2	2	2

Appendix G : An overview of the SEFStock Fishery Management Software

SEFStock comprises two computer programs. The first program (SEFStock) implements the operating model (see Appendices D and E for technical details) and the other program (Harvestman) implements the stock assessment methods and the harvest strategies (see Appendix F for technical details).

The software was designed using object-oriented technology (Unified Modelling Language), and implemented using Microsoft Visual C++ 6.0. The use of OOA/D (Object-oriented analysis and design) and OOP (Object-oriented programming) methods enables the software to be modified / extended easily. Given the modular structure of the program, it is relatively straightforward, for example, for developers / analysts to add additional assessment methods and to extend the operating model to consider additional scenarios / species. The AD Model Builder™ libraries are included in the program Harvestman to allow for rapid and robust parameter estimation.

The overall software package is designed around five main sections: System interface, Operating model, Harvest strategies, Performance evaluation, and Data management. Figure G.1 shows the links among these sections.

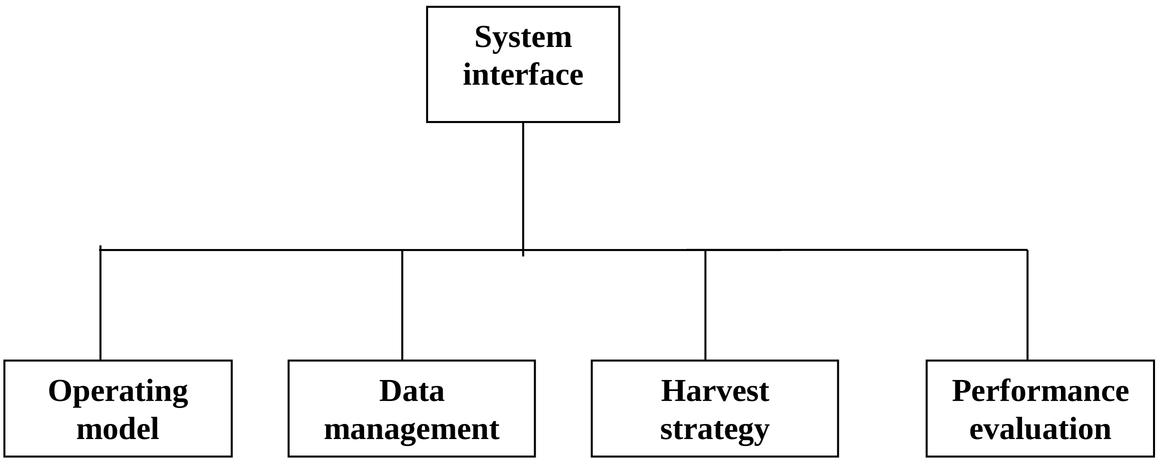


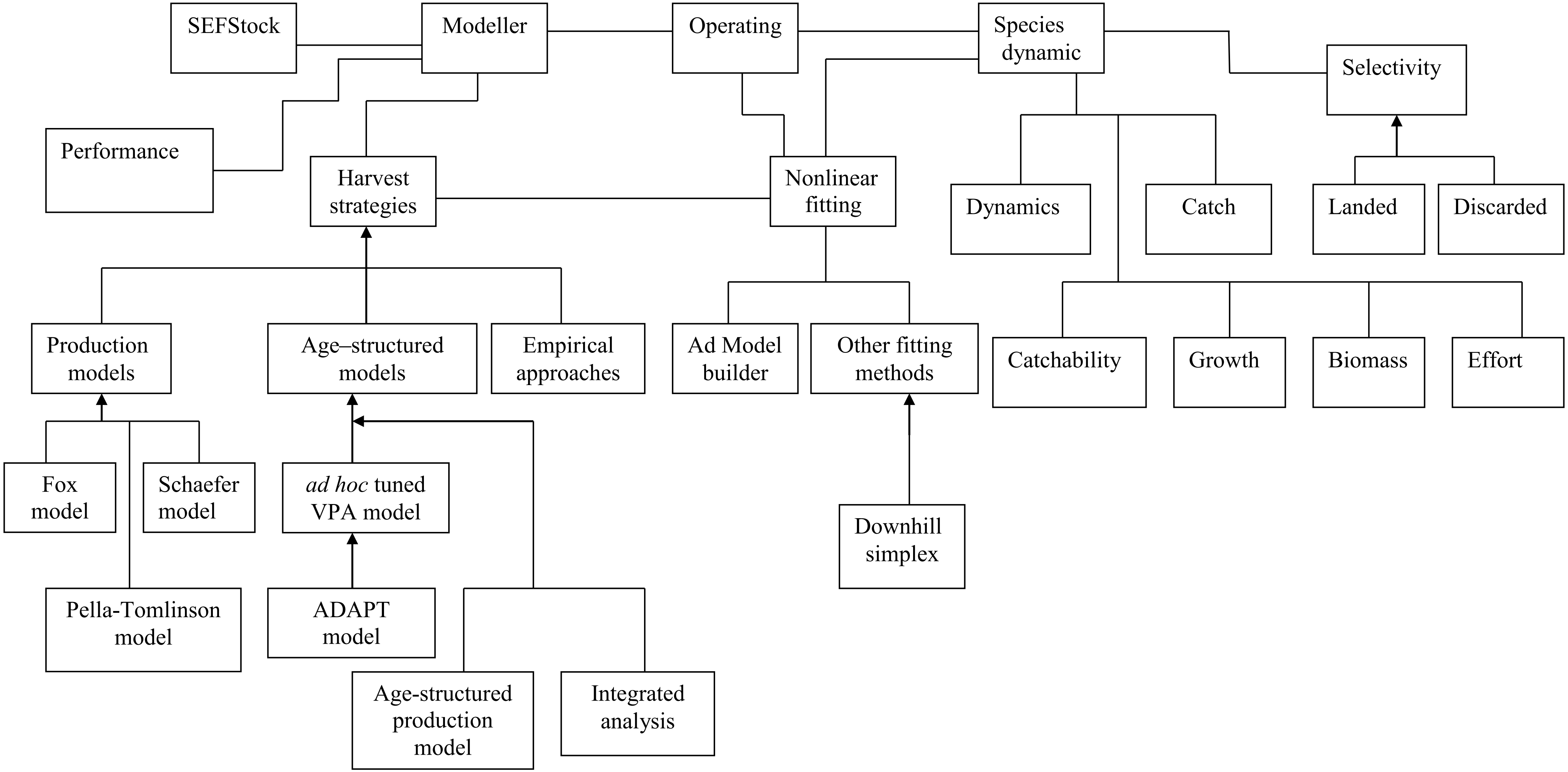
Figure G.1: The five main sections

Figure G.2 provides the links among the main modules of the software (noting that the harvest strategy modules are implemented in a separate program from the other modules). The following sections outline the main functions of and linkages among the sections.

G.1 System interface section

The system interface includes three system objects; the SEF management, the Modeller and the interface between the operating model and the assessment methods / harvest strategies. The SEF management module assigns tasks to Modeller, which implements these tasks and reports the results back to SEF management.

Figure G.2: The overall SEFStock software hierarchy.



Class SEF Management:
void main(): This main function receives specifications from the user and creates an instance of Modeller to perform tasks.

Class Modeller: This class first creates an instance of the Operating model class and maintains access to that class for each simulation trial. Once the simulations trials are completed, Modeller creates an instance of the Performance evaluation class and uses its functionality to generate the output files for each species. The key functions implemented in Modeller are:

bool check(*int isimu***)**: Checks if the *isimu*th simulation has been set up yet.
void initialization(*const char *file, const char* title***)**: Initialises the global data structures. ******file* is a pointer to the name of the input file that contains the global data, and **title* is the data header in the file.
void runHarvestStrategy(*int simu_idx, Performance &pf***)**: Conducts a simulation. *simu_idx* is the index to the simulation and *&pf* is a reference to the Performance object.
void startSimulation(): Starts the simulation process.

Class Offline: This class provides the interface between the operating model and the assessment methods / harvest strategies. It takes the information generated by the operating model and the specifications provided by the user and generates the files Harvest.dat, Harvest.rul and Harvest.pin for the selected assessment method / harvest strategy. It then makes a system call to apply the selected assessment method / harvest strategy. Once the application of the harvest strategy is completed, the output from the harvest strategy (e.g. any estimates of biomass, the updated *TAC*) is read in. Offline is created and used by Operating model. It is destroyed immediately after the updated *TAC* is passed to the Operating class. The key subroutines implemented in the Offline class are:

void run_quota(): Performs a system call to apply the selected assessment method / harvest strategy.
double getTAC(*int i, int y***)** : Returns the *TAC* for year *y* and species *i*.

G.2 The operating model section

The operating model section implements the age-, length-, and area-structured operating model. It is controlled by Modeller. The number of species included in the operating model is unrestricted, except by memory. The classes that form the operating model section, and the key functions implemented in each class are as follows:

Class Operating
int historic_generator(*int simu_idx***)**: Generates the historic biomass trajectory for simulation *simu_idx*. It first checks if this simulation has been set up before. If not, the value for the pre-exploitation equilibrium biomass is calculated to satisfy the specification in this regard.
double calibrate_historicB0(*int sp_i, int simu_idx***)**: Solves for the pre-exploitation equilibrium biomass for species *sp_i* to match the pre-specified depletion of the spawner biomass and returns this biomass.

double end_historic_sB(*int i ,double trial_B0, int simu, int iter***)**: Conducts a projection for a given pre-exploitation equilibrium biomass from 1958 until the first projection year.
v**oid species_creator()**: Creates all species objects for the current simulation.
void set_resumable(*int simu_i***)**: Checks whether the pre-exploitation equilibrium biomass for *simu_i* has already been calculated.
void run_harvest_strategy(*Offline *strategy, int sp_i***)**: Applies the specified assessment method / harvest strategy to the data for species *sp_i*.
void runHistoricModel(*int simu_idx, int *SeedBase***)**: Performs simulation trial *simu_idx*.

Class Species
void future_process (*int i***)**: Projects species *i* ahead one year.
void calibrate_fish_mortality(): Solves for fishing mortality given a catch.
bool load_fish_mortality(*int simu_idx***)**: Loads the fully-selected fishing mortalities by year and region for the current simulation.
void predictCatch(*double &dy***)**: Calculates the landed catch for a given level of effort.
void saveMortality(*int simu_idx***)**: Saves the fully-selected fishing mortalities for the current simulation.
void createAll(*int *seed, int *seed2, double RecrSD, double AvailSD***)**: Creates instances of all the other classes needed to implement the operating model.
double LCM(*int y, int f***)**: Returns the landed catch by mass for year *y*.
double LCMA*(int y, int A, int f***)**: Returns the landed catch by mass for year *y* and region *A*.
double historicProcess(*int is_noise, int simu_idx, int i***)**: Projects from 1958 to the current year.

Class Biomass
void calculate_maturity(*ARRAY1D &LC***)**: Sets up maturity as a function of length.
void begin_year_biomass(*ARRAY2D &w, ARRAY2D& L, ARRAY2D &sel, ARRAY3D &N***)**: Calculates the available biomass at the start of the year.
void mid_year_biomass(*ARRAY2D &w, ARRAY2D& L, ARRAY2D &sel, ARRAY3D &Z, ARRAY3D &N***)** Calculates the available biomass in the middle of the fishing season.
void calculate_spawner_biomass(*Growth &g, ARRAY3D &N***)**: Calculates the spawner biomass at the start of the year.
void init_spawner_biomass(*Growth &g, ARRAY3D &N***)**: Returns the pre-exploitation equilibrium spawner biomass.

Class catchability
void local_q(*ARRAY3D &B, ARRAY2D &vB0, ARRAY4D &obsE, ARRAY3D &FF***)**: Calculates the catchability coefficients by area.
void calcalate_qs(*ARRAY3D &B, ARRAY2D &vB0, ARRAY4D &obsE, ARRAY3D &FF, ARRAY4D &cat, ARRAY3D &qs***)**: Calculates the catchability coefficients by area and season.

Class DiscardSelectivity
void calculate_sel(*ARRAY2D &sel, ARRAY1D &LC, TArray &Lrat***)**: Calculates discard selectivity as a function of length.

Class Selectivity
void calculateSel(*int sel_curve_type, ARRAY1D *LC***)**: Controls the calculation of selectivity as a function of length.
void logistic_sel(*ARRAY1D &lc***)**: Implements logistic selectivity.
void uniform_sel(*ARRAY1D &lc***)**: Implements uniform selectivity.
void gamma_sel(*ARRAY1D& lc, ARRAY2D& sel***)** : Implements gamma selectivity.
void double_logistic_sel(*ARRAY1D &lc***)**: Implements double-logistic selectivity.
void add_sel_noise(): Adds noise to selectivity.

Class LandedSel
void calculateLSel(*Selectivity &s, DiscardSelectivity & ds***)**: Computes the selectivity pattern for the landed catch by subtracting the discard selectivity from the overall selectivity.

Class Dynamic
void calculateZeroDynamic(*double sB, double sB0, int i***)**: Generates the number of age 0 fish by region, accounting for the stock-recruitment relationship and the noise about that relationship.
void calculatePopulationDynamic(*Mortality &m***)**: Controls updating the population vector.
void initPopulationDynamic(*Mortality &m***)**: Finds the pre-exploitation equilibrium age-structure.
void movement(*ARRAY3D &XB***)**: Sets up the movement matrix.

Class Effort
void loadObsEffort(*const char *file_name, const char *title*): Loads the actual effort data.
void calculateEffort(*Biomass &b***)**: Converts from raw fishing effort to actual fishing effort, taking account of any non-linearity in the catch rate-abundance relationship and changes over time in efficiency.
void BackCalculateEffort(*Biomass &b, Mortality &m, Catchability &cb, int year***)**: Converts between observed and actual effort.

Class FCatch
void loadObsCatch(*const char *file_name, const char *title***)**: Loads the actual catch data.
void calculateFutureCatch(*Dynamic &dym, DiscardSelectivity &ds, LandedSelectivity &ls, Growth &g, Mortality &m***)**: Computes the landed and discarded catches as a function of fishing mortality by region.
void calculateDiscardFraction(): Computes the discard ratio.
void AccountTAC(*double TAC, int year***)**: Compares the *TAC* with the landed catch and adds the difference to the discarded catch.
ARRAY3D& getLandedCatchByNum(): Returns the landed catch by number.
ARRAY3D& getDiscardedCatchByNum(): Returns the discarded catch by number.
ARRAY2D& getLandedCatchByMass(): Returns the landed catch by mass.
ARRAY3D& getLandedCatchByMassArea(): Returns the landed catch by mass and region.
ARRAY2D& getDiscardedCatchByMass(): Returns the discarded catch by mass.
ARRAY4D& getLandedCatchLength(): Returns the landed catch by length-class.
ARRAY4D& getDiscardCatchLength(): Returns the discarded catch by length-class.
ARRAY3D& getAgeLengthKey(): Returns the age-length key.

void setDiscYears(*int _Y1, int _Y2, int _Y3***)**: Specifies the scenario regarding time-trends in discarding.

Class growth
void calculateGrowth(*Dynamic &dym***)**: Computes length as a function of age and mass as a function of length.

G.3 Harvest strategy section
This section implements four families of harvest strategy: production model, Integrated Analysis, VPA, and empirical. Some of these families include several harvest strategies. For example, the production model family includes the Schaefer, Fox and the Pella-Tomlinson forms of the surplus production function.

All of the assessment methods are implemented using the minimisation method included with the AD Model Builder™ package. This substantially reduces the time needed to apply some of the harvest strategies. It is relatively straightforward to add or extend assessment methods. In the general, developers only have to code how the data are entered and the function that is to be minimized; there is no need to be familiar with the details of how AD Model Builder™ implements its minimisation method. The following sub-sections outline each of the four families of harvest strategy.

G.3.1 The Production Model Family
This family (see Section 3 of Appendix F) includes two main classes. The class schaefermodel implements the Schaefer and Fox models, the selection between which is specified in the Harvest.dat file. The class pellamodel implements the Pella-Tomlinson surplus production model as a special class of the class schaefermodel.

G.3.2 The Integrated Analysis family
This family (see Section 4.4 of Appendix F) includes two key types of harvest strategy: Integrated Analysis and the age-structured production model (ASPM). Unlike the age-structured production model, Integrated Analysis can make use of the age- / length composition of the landed catches and the discards.

G.3.3 The VPA family
This family (see Sections 4.2 and 4.3 of Appendix F) includes *ad hoc* tuned VPA and ADAPT-VPA. As the objective function for ADAPT-VPA is not differentiable, the ADAPT-VPA method uses the downhill simplex method to find the maximum likelihood estimates for the parameters.

G.3.4 The empirical family
The empirical family (see Section 2 of Appendix F) includes several harvest strategies. These include changing *TAC*s is response to changes in catch rate, and in the mean size of the catch. Unlike the other families, none of the harvest strategies in this family involve formal application of a method of stock assessment.

G.4. Data Management Unit
The data management is based on the Façade principle that each object only interacts with its own database. A root DBClass is used to manage the requests of different objects. For all objects, their corresponding database object is named as class xxxxDB, where xxxx is the name of the entity, e.g. species, operating, etc.

G.5 Performance Evaluation Unit

The class Performance produces all the statistics for evaluating the performance of the assessment methods / harvest strategies (see Sections 4.5 and 4.6).

G.6 System Requirements

The software is compiled using VC++ 6.0 with the "no MFC" option switched on so that its does not have to run in the Windows environment. There must be at least 200 MB of free disk space for the software to store temporary files and to implement the necessary virtual memory.

Appendix H : Performance measures for the base-case trials and the base-case Integrated Analysis estimator

This appendix list the lower 5th, median and upper 5th percentiles of the relative (statistics R5%, R50% and R95%) and absolute value (statistics A5%, A50% and A95%) error distributions for each of the 12 management-related quantities (see Section 5.1) for the base-case trial and the base-case Integrated Analysis estimator (see also Figure 5).

Species	Statistic	Management-related quantities											
		a	b	c	d	e	f	g	h	i	j	k	l
Spotted warehou	R5%	28.2	43.9	30.4	21.4	-19.5	-23.5	-97.1	-55.9	-93.8	-99.2	-96.8	-97.4
	R50%	224.1	254.9	90.7	72.2	25.1	5.9	83.4	142.5	-43.9	48.7	34.3	21.0
	R95%	1635.5	1674.1	356.1	296.6	105.6	61.9	637.5	270.6	-1.0	138.3	429.5	410.1
	A5%	28.2	43.9	30.4	21.4	3.6	0.9	16.4	12.3	11.3	20.0	5.3	3.6
	A50%	224.1	254.9	90.7	72.2	27.6	14.4	97.3	142.5	43.9	77.8	76.3	73.0
	A95%	1635.5	1674.1	356.1	296.6	105.6	61.9	637.5	270.6	93.8	138.3	429.5	410.1
Tiger flathead	R5%	-63.6	-70.3	-64.6	-69.1	-28.2	-36.4	-89.3	-81.8	-97.4	-93.5	-89.4	-91.2
	R50%	-39.0	-47.6	-26.5	-33.2	-6.8	-8.2	-37.9	-37.0	48.8	-5.2	-33.0	-33.4
	R95%	5.7	-4.5	15.8	8.9	25.9	26.4	-2.4	9.1	182.6	5.6	5.3	7.7
	A5%	8.7	14.4	1.5	2.9	1.2	1.0	4.3	2.6	39.3	0.6	4.2	4.3
	A50%	39.0	47.6	26.5	33.2	12.8	14.2	37.9	37.0	93.2	6.7	33.0	33.4
	A95%	63.6	70.3	64.6	69.1	33.8	40.5	89.3	81.8	182.6	93.5	89.4	91.2
Jackass morwong	R5%	-78.5	-80.2	-70.9	-72.1	-29.0	-18.4	-81.5	-86.8	-97.3	-89.9	-82.2	-85.4
	R50%	-31.8	-30.7	-12.8	-10.7	20.0	21.7	-42.4	-42.5	-76.2	-55.5	-44.7	-50.0
	R95%	36.1	45.2	65.3	69.0	72.7	75.0	-10.1	108.4	48.6	33.5	-14.0	-13.7
	A5%	5.2	3.4	1.4	2.8	1.7	4.1	10.2	5.0	9.4	7.0	14.0	13.7
	A50%	35.3	34.5	35.1	35.8	24.5	28.0	42.4	60.0	79.3	55.5	44.7	50.0
	A95%	78.5	80.2	80.9	83.8	72.7	75.0	81.5	108.4	97.3	89.9	82.2	85.4
Pink ling	R5%	-83.4	-57.6	-54.3	-57.9	-35.6	-43.1	-63.1	-53.6	-86.0	-70.3	-53.7	-54.4
	R50%	-67.1	-12.6	-35.0	-34.8	-10.6	-17.2	-17.9	8.3	393.0	14.2	-13.6	-7.8
	R95%	-49.4	42.5	-9.5	0.2	11.1	19.1	23.6	73.2	619.4	17.9	29.6	38.0
	A5%	49.4	1.5	9.5	3.0	1.1	1.6	3.7	1.9	41.9	10.6	2.1	0.6
	A50%	67.1	21.2	35.0	34.8	13.3	19.4	19.6	26.3	393.0	15.3	18.2	18.2
	A95%	83.4	61.7	54.3	57.9	35.6	43.1	63.1	73.2	619.4	70.3	53.7	55.2