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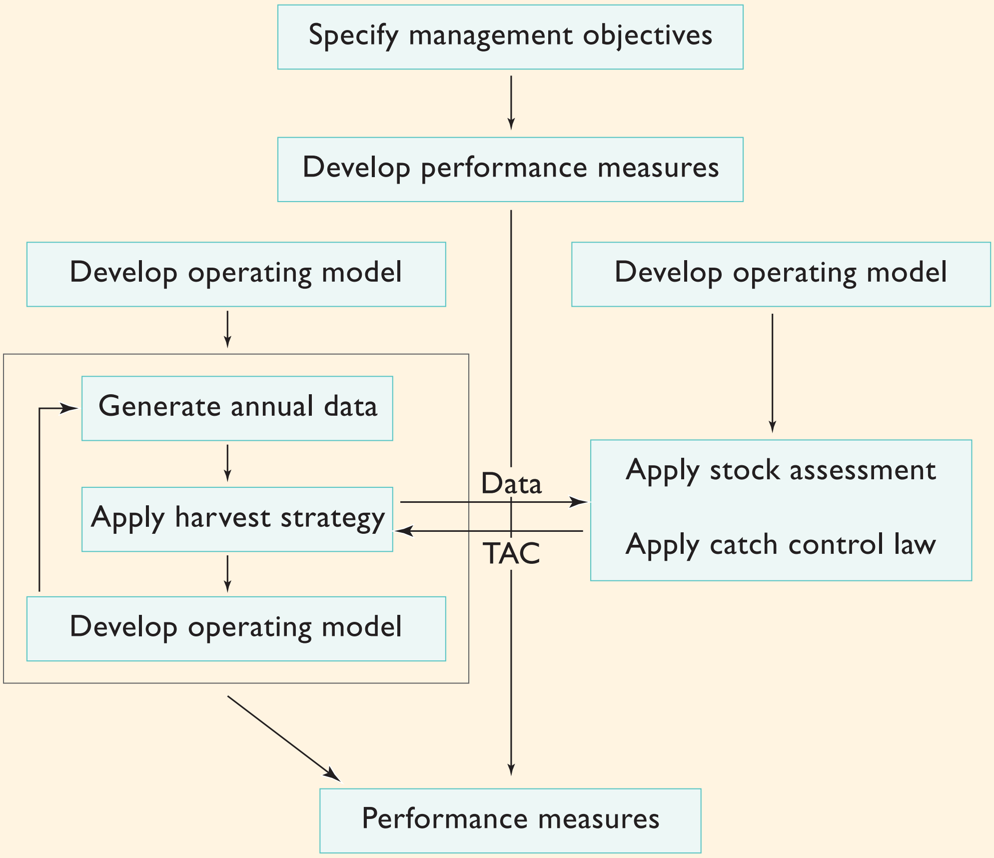
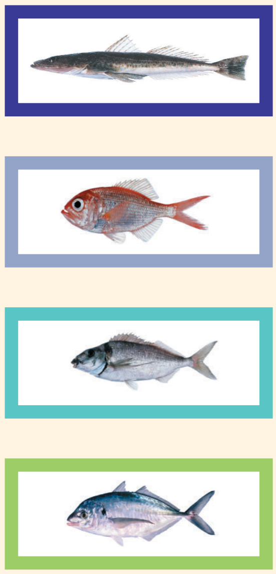
# Final Report for non-complete project:
# Development of harvest strategies for selected SEF species


Anthony D. M. Smith

Gurong Cui

André E. Punt


CSIRO MARINE RESEARCH

Australian Government

Fisheries Research and Development Corporation

# DEVELOPMENT OF HARVEST STARTEGIES FOR SELECTED SEF SPECIES


*Principal Investigator*

*Anthony D. M. Smith*


Australian Government

Fisheries Research and Development Corporation

CSIRO

MARINE RESEARCH


**Final report to the Fisheries Research and Development Corporation**
**FRDC Project 2001/101**
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**NON TECHNICAL SUMMARY**

**2000/ 101 Development of harvest strategies for selected SEF species**

**PRINCIPAL INVESTIGATOR**: Dr Anthony D. M. Smith
**ADDRESS**: CSIRO Marine Research
GPO Box 1538
Hobart, TAS 7001
Australia
Telephone 03 6232-5222 Fax 03 6232-5000

**OBJECTIVES**:
1. To extend the general SEF operating model for evaluating harvest strategies and performance indicators to deal with fisheries subject to exploitation using multiple gear-types / fleets.
2. To develop a user interface for the software used to conduct stock assessments and evaluate harvest strategies in the SEF, and to improve the presentation for non-experts (non-quantitative biologists, managers and industry) who wish to use the software.
3. To parameterise the operating model using the actual data for redfish, pink ling, tiger flathead, and spotted warehou and hence select robust assessment methods and harvest strategies for these species.
4. To evaluate the costs and benefits associated with different data aquisition strategies for these species (with particular reference to fishery-independent survey techniques).
5. To develop the modelling software in a manner which lends itself to tailoring (by CSIRO and other agencies) to suit Commonwealth or State fisheries.

**NON TECHNICAL SUMMARY**:

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 was to be used to compare the performances of a variety of harvest strategies for four of the species in Australia's South East Fishery (tiger flathead, *Neoplatycephalus richardsoni*, redfish *Centroberyx affinis,* spotted warehou, *Seriolella puncata*, and pink ling, *Genypterus blacodes*). The aim of the analyses of this project was to extend the analyses of Punt *et al.* (*Defining robust harvest strategies, performance indicators and monitoring strategies for the SEF. Report of FRDC 98/102*) in the following ways: (a) allow for multiple gear-types, (b) base the values for the parameters of the operating on the actual data for the four species.

This report outlines methodology to address objectives 1), 2), and 4). It summarizes the mathematical specifications for extending the operating model used by Punt *et al*. However, numerical problems precluded the ability to evaluate candidate harvest strategies. The numerical problems were: (a) how to allow for gear competition among multiple fleets within the context of a discrete-time population dynamics model, (b) difficulties achieving fits of the operating model to the data for which the Hessian matrix was positive definite given that the objective function includes constraints, and (c) conflicts between the way growth was included in the operating model and the actual data for the four species.

**KEYWORDS: harvest strategy, Monte Carlo simulation, South East Fishery**

# 1. BACKGROUND

The South East Fishery is a classic example of a fishery complicated by its multispecies and multigear nature. It is managed by setting total allowable catches (*TAC*s) for some individual species. However, the level of information differs for each species, and information on stock status provided to the SEF TAC Sub-Committee ranges from output from sophisticated assessments models evaluating alternative harvest regimes to cursory examinations of trends in catch and effort data (e.g. Smith and Wayte, 2002). However, *TAC*s have to be set for each quota species irrespective of the amount of available information. To date, however, no explicit account appears to have been taken when setting *TAC*s of the quality of the data on which scientific advice is based.

Each SEF species is required to have management objectives, management strategies and performance indices. For some of the SEF quota species, the management objectives have been conflicting. For example, the management objectives for blue grenadier used to include development of the spawning season fishery and prevention of declines in the catch-rates for the non-spawning fishery – objectives that were clearly in conflict. Industry and SEFAG have recognised that the performance indicators for several SEF species are inadequate and require revision. The species-specific assessment groups established by SEFAG at the time this project started (EGAG, BWAG, BGAG, ORAG and RAG) had started to address this issue. However, little progress had been made beyond noting that changes to the management objectives, management strategies and performance indices were required. No progress had been made at all on revising the objectives, strategies and performance indicators for species for which species-specific assessment groups had not been established, even though some members of the SEF TAC Sub-Committee had expressed substantial interest in clearly interpretable information that could be used to set *TAC*s.

If performance indicators are to be useful for setting TACs, it is necessary to link them to harvest strategies that specify what management actions are to be taken if a target or a limit for a performance indicator is approached or triggered. 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*. The results of FRDC 98/102 (Punt *et al*., 2001a, 2002a, 2002b) suggested that assessments (and hence harvest strategies) based on the Integrated Analysis approach to fisheries stock assessment (e.g. Fournier and Archibald, 1982; Methot, 1990; 2000) perform best.

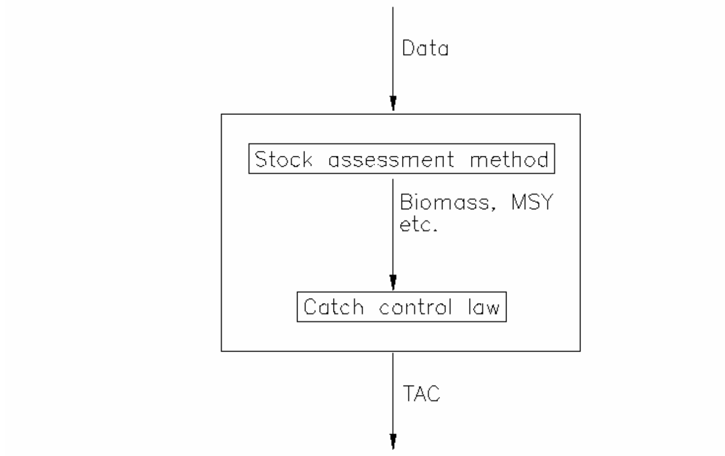


Figure 1 : A harvest strategy illustrating the difference between the assessment and catch control law components.

When this project commenced, a harvest strategy had been in place for eastern gemfish since 1996 and had substantially reduced the difficulty in setting TACs for this species. However, performance indicators were generally not linked to harvest strategies (the exceptions being orange roughy and eastern gemfish) so it was unclear what (if any) management actions were appropriate were the targets or limits for a performance indicator to be approached or triggered.

Dealing with uncertainty is one area where modelling of fisheries has expanded substantially in recent years (Francis and Shotton, 1997; Punt and Hilborn, 1997; Patterson, *et al*. 2001). 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 spatial factors. Such models are now increasingly being applied to provide management advice for Commonwealth-managed fish species. For example, the 1999 assessment of blue grenadier allowed for variability in recruitment, and explicitly modelled the process of discarding (Punt *et al*., 2001b) while the 1999 assessment of school shark (Punt *et al.*, 2000) explicitly modelled the dynamics of movement and migration. The assessment models that were tested as part of FRDC 98/102 (Punt *et al*., 2001a) incorporate many of these features and have been applied in actual assessments of SEF species (e.g. those of blue warehou *Seriolella brama* and eastern school whiting *Sillago flindersi*), substantially reducing the time and cost associated with conducting assessments for these species.

The robustness of alternative harvest strategies to uncertainties caused by, for example, misspecification of biological processes and model structure uncertainty can be evaluated using operating models. The general operating model developed as part of FRDC 98/102 allows for variability in growth, selectivity and natural mortality, discarding due to lack of quota, and the impact of depth on catchability, size-composition and data collection.

The opportunity for funding research for many 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.

# 2. NEED

Given AFMA's need to satisfy its ESD objective, there is a need to consider uncertainty explicitly 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.

The project also addresses to some extent two key 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".

FRDC project 98/102 (Punt *et al*., 2001a) has already identified several areas where there is considerable uncertainty. However, that project focused on 'generic' data-poor species (although tailored to some extent to the actual situation for jackass morwong *Nemadactylis macropterus*, pink ling *Genypterus blacodes*, tiger flathead *Neoplatycephalus richardsoni*, and spotted warehou *Seriolella puncata*, species that have been identified as 'high' and 'medium' priority by SEFAG). Ideally, harvest strategy calculations need to be tailored to the particular species to achieve optimal outcomes. This project aimed to evaluate harvest strategies for the four species that received initial focus in FRDC 98/102. FRDC 98/102 also focused on situations in which the fishery is based on a single gear-type only. However, it is increasingly being realized within SEFAG that even within the trawl sector there are sub-fleets, each of which differ substantially in terms of their selectivity. For example, for blue warehou, the trawl fishery off New South Wales has a selectivity pattern more similar to that of the non-trawl fleet based at Lakes Entrance than that of the trawl fleet based in Portland (Punt, 2000).

One of AFMAs legislative objectives relates to providing cost-effective fisheries management. Increasingly, industry is being expected to bear some of the costs associated with the monitoring on which stock assessments and hence TACs are based. There is therefore a need for an objective process for determining the trade-off between monitoring costs and the ability to which AFMAs management objectives are satisfied. The aim of this study is to examine this question within the scope of the trade-off between catch and risk.

Finally, there is a major need for stock assessment of more species in the SEF. However, although data for many species is poor, there are nevertheless fewer assessments than there could be due to a lack of software for conducting the increasingly complicated assessments demanded by stakeholders. FRDC 98/102 developed software modules for implementing several commonly applied stock assessment methods (including "Integrated Analysis" – the basis for the most recent assessments of blue grenadier, eastern school whiting, eastern gemfish *Rexea solandri*, orange roughy *Hoplostethus atlanticus*, and blue warehou). If the detailed output from the software that implements these assessments could be available in an easily useable and visual form, this software could provide a better basis for conducting routine stock assessments.

# 3. OBJECTIVES

The objectives for the study were:

1) To extend the general SEF operating model for evaluating harvest strategies and performance indicators to deal with fisheries subject to exploitation using multiple gear-types / fleets.
2) To develop a user interface for the software used to conduct stock assessments and evaluate harvest strategies in the SEF, and to improve the presentation for non-experts (non-quantitative biologists, managers and industry) who wish to use the software.
3) To parameterise the operating model using the actual data for redfish, pink ling, tiger flathead, and spotted warehou and hence select robust assessment methods and harvest strategies for these species.
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5) To develop the modelling software in a manner which lends itself to tailoring (by CSIRO and other agencies) to suit Commonwealth or State fisheries.

# 4. METHODS

This report focuses exclusively on the methods considered to address objectives 1), 2) and 4). In common with previous studies that aimed to evaluate harvest strategies[1] for marine renewable resources (e.g. Bergh and Butterworth, 1987; Butterworth *et al*., 1997; Butterworth and Punt, 1999; Cochrane *et al*., 1998; Geromont *et al*., 1999), the scientific approach on which the analyses would be based is the management strategy evaluation (MSE) approach (Smith, 1994; Punt *et al*., 2001c). Punt *et al*. (2001a) identify four questions that can be addressed using the Management Strategy Evaluation approach, viz.:

- 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*).

[1] Also referred to as 'management procedures' and 'decision rules'.

- 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.

The advantages of basing decisions regarding the selection of appropriate tools for use in the assessment and management of marine renewable resources on the results from the application of the Management Strategy Evaluation approach are detailed elsewhere (e.g. Smith, 1994; Cooke, 1999; Cochrane *et al*., 1998). However, in the context of the SEF, the primary advantage of the MSE approach is that it can explicitly take 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) into account.

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 five legislative objectives of the Australian Fisheries Management Authority (AFMA)[2], given that these objectives are contradictory to some extent (i.e. there are trade-offs among achieving different objectives). 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).

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 are as follows (Figure 2):

- Identification of the management objectives and representation of these using a set of quantitative performance measures.

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[2] AFMA’s five legislative objectives (Anon, 1998) are:

- implementing efficient and cost-effective fisheries management on behalf of the Commonwealth;
- ensuring that the exploitation of fisheries resources and the carrying on of any related activities are conducted in a manner consistent with the principles of ecologically sustainable development and the exercise of the precautionary principle, in particular the need to have regard to the impact of fishing activities on non-target species and the long term sustainability of the marine environment;
- maximising economic efficiency in the exploitation of fisheries resources;
- ensuring accountability to the fishing industry and to the Australian community in the Authority’s management of fisheries resources; and
- achieving government targets in relation to the recovery of the costs of the Authority.

- 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), 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.

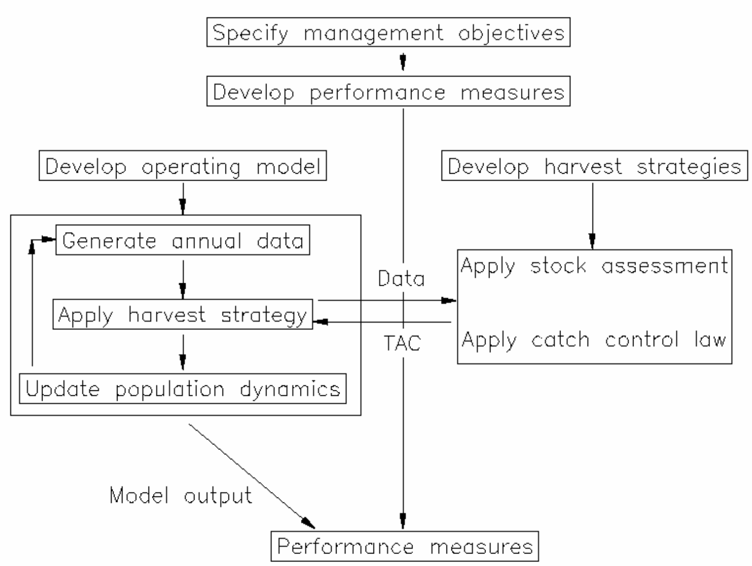


Figure 2 : Outline of the MSE approach.

The following two sections focus on: (a) the structure of the operating model and, in particular, how the operating model developed by Punt *et al*. (2001a) has been extended to allow for multiple fleets, and (b) how this operating model could be fit to the actual data for the species to be considered in the MSE evaluations.

## 4.1. The operating model

The operating model is a multi-gear-type (multi-fleet) and multi-region population dynamics model. It is based on the model developed by Punt *et al.* (2001a, 2002a) although it has been extended to allow for multiple gear-types. Some of the features of the operating model developed by Punt *et al.* (2001a) have been omitted from this operating model (e.g. density-dependence in growth and time-dependence in fleet selectivity) because these features were found by Punt *et al.* (op. cit.) to be largely inconsequential in terms of the performance of decision rules.

**4.1.1. 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 dynamics of the populations for the years $y > y_0$ (where year $y_0$ is the first year considered in the model) are therefore governed by the equation:

$$N_{y+1,a}^{i,l,A} = \begin{cases} N_{y+1,0}^{i,l,A} & \text{if } a = 0 \\ \sum_{A'} X_y^{i,A',A,\tilde{L}_a^{i,l}} \; N_{y,a-1}^{i,l,A'} U_{y,a-1}^{i,l,A'} e^{-M_{a-1}^i} & \text{if } 1 \le a < x \\ \sum_{A'} X_y^{i,A',A,\tilde{L}_x^{i,l}} \left[ N_{y,x-1}^{i,l,A'} U_{y,x-1}^{i,l,A'} e^{-M_{x-1}^i} + N_{y,x}^{i,l,A'} U_{y,x}^{i,l,A'} e^{-M_x^i} \right] & \text{if } a = x \end{cases} \tag{1}$$

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

$U_{y,a}^{i,l,A}$ is the fraction of fish of species *i* and age *a* in growth-group *l* and region *A* that survives fishing during year *y*:

$$U_{y,a}^{i,l,A} = 1 - F_{y,a}^{i,l,A} \tag{2}$$

$F_{y,a}^{i,l,A}$ is the exploitation rate on fish of species *i* and age *a* in growth-group *l* and region *A* during year *y*,

$M_a^i$ is the instantaneous rate of natural mortality on fish of species *i* and age *a*,

$\tilde{L}_a^{i,l}$ is, for a fish of species *i*, the length-class corresponding to age *a* and growth-group *l*,

$X_y^{i,A',A,\tilde{L}}$ 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*:

$$X_y^{i,A',A,\tilde{L}} = \frac{X_{y_0}^{i,A',A,\tilde{L}}\, e^{\varepsilon_{X,y}^{i,A',A,\tilde{L}}}}{\sum_{A''} X_{y_0}^{i,A',A'',\tilde{L}}\, e^{\varepsilon_{X,y}^{i,A',A'',\tilde{L}}}} \qquad \varepsilon_{X,y}^{i,A',A,\tilde{L}} \sim N(0;\sigma_X^2) \qquad (3)$$

$\sigma_X$ is the parameter that determines the extent of inter-annual variation in movement among regions, and

$x$ is the maximum (lumped) age-class.

**4.1.2. Recruitment and spawner biomass**

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

$$N_{y,0}^{i,l,A} = \pi^{i,l,A} \frac{(\tilde{B}_y^i / \tilde{B}_0^i)^{\gamma^i}}{\alpha^i + \beta^i (\tilde{B}_y^i / \tilde{B}_0^i)^{\gamma^i}} e^{\varepsilon_{r,y}^i - (\sigma_r^i)^2/2} \qquad (4)$$

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

$$\tilde{B}_y^i = \sum_A \sum_{a=1}^{x} \sum_l m_{\tilde{L}_a^{i,l}}^i \, w_{\tilde{L}_a^{i,l}}^i \, N_{y,a}^{i,l,A} \qquad (5)$$

$m_{\tilde{L}}^i$ 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*, $\varepsilon_{r,y}^i \sim N(0;(\sigma_r^i)^2)$,

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

$\sigma_r^i$ is the standard deviation of the logarithms of the multiplicative fluctuations in year-class strength for species *i*.

The form of the stock-recruitment relationship (Equation 4) 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). Appendix C describes how the values for α, β and γ are calculated from those for $\tilde{B}_0$, *h*, and $\tilde{q}$.

**4.1.3. Growth**

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

$$w^i_{\tilde{L}^{i,l}_a} = w^i_\infty (L^{i,l}_a / \overline{L}^i_\infty)^{e^i_2} \tag{6a}$$

$$L^{i,l}_a = L^{i,l}_\infty (1 - e^{-\kappa^{i,l}(a - t^i_0)}) \tag{6b}$$

where $L^{i,l}_\infty$ is the asymptotic length for a fish of species *i* in growth-group *l*,
$\overline{L}^i_\infty$ is the mean asymptotic length for a fish of species *i*,
$w^i_\infty$ is the mean asymptotic weight for a fish of species *i*,
$e^i_2$ is the mass-length exponent for species *i*,
$\kappa^{i,l}$ is the growth rate for a fish of species *i* in growth-group *l*, and
$t^i_0$ is the "age" at which a fish of species *i* has zero length.

Equations 6a and 6b are based on the assumption that length-at-age and mass-at-age are time-invariant. This assumption is known to be violated for some SEF species (e.g. Punt and Smith (2001)). However, there are insufficient data to quantify how growth rate might depend on, for example, the size of an incoming recruitment.

#### 4.1.4. Catches and discarding

The total landed catch in mass of fish of species *i* by fleet *f* during year *y* is given by:

$$C^{i,f}_y = \left(1 - D^{i,f}_y\right) \sum_A \sum_{a=0}^{x} \sum_l w^i_{\tilde{L}^{i,l}_a}\ p^{i,A,f}_{y,a}\ \tilde{S}^{L,i,f}_{\tilde{L}^{i,l}_a}\ k^{i,A,f}_y\ N^{i,l,A}_{y,a}\ e^{-M^i_a/2} \tag{7}$$

where $k^{i,A,f}_y$ is exploitation rate by fleet *f* in region *A* during year *y* on fully-selected fish of species *i*,
$p^{i,A,f}_{y,a}$ is the expected proportion of fish of species *i* and age *a* in region *A* that are available to fleet *f*,
$D^{i,f}_y$ is the fraction of the catch of species *i* that could potentially be landed by fleet *f* during year *y* but is discarded because operators lack sufficient quota,
$S^{L,i,f}_{\tilde{L}}$ is relative selectivity (landed catch) on fish of species *i* in length-class $\tilde{L}$ by fleet *f*:

$$\tilde{S}^{L,i,f}_{\tilde{L}} = S^{i,f}_{\tilde{L}} \left(1 - S^{D,i,f}_{\tilde{L}}\right) \tag{8}$$

$S^{i,f}_{\tilde{L}}$ is the relative selectivity on fish of species *i* in length-class $\tilde{L}$ by fleet *f*, and

$S_{\tilde{L}}^{D,i,f}$ is relative selectivity (discarded catch) on fish of species *i* in length-class $\tilde{L}$ by fleet *f*.

The total discarded catch of fish of species *i* by fleet *f* during year *y* is given by:

$$C_y^{D,i,f} = \sum_A \sum_{a=0}^{x} \sum_l w_{\tilde{L}_a^{i,l}}^i \; p_{y,a}^{i,A,f} \; \left( \tilde{S}_{\tilde{L}_a^{i,l}}^{D,i,f} + D_y^{i,f} \; \tilde{S}_{\tilde{L}_a^{i,l}}^{L,i,f} \right) k_y^{i,A,f} \; N_{y,a}^{i,l,A} \; e^{-M_a^i/2} \tag{9}$$

Equation (7) 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 (9) 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 $C_y^{L,i,f} + C_y^{D,i,f}$ is the total catch by fleet *f* according to the overall selectivity pattern.

The exploitation rate (all gear-types combined) on fish of species *i* and age *a* in growth-group *l* and region *A* during year *y* is given by:

$$F_{y,a}^{i,l,A} = \sum_f p_{y,a}^{i,A,f} \; S_{\tilde{L}_a^{i,l}}^{i,f} \; k_y^{i,A,f} \tag{10}$$

The exploitation rate on fish of species *i* by fleet *f* in region *A* during year *y* is computed using the equation:

$$k_y^{i,A,f} = \frac{C_y^{i,A,f,obs}}{\left(1 - D_y^{i,f}\right) \sum_{a=0}^{x} \sum_l w_{\tilde{L}_a^{i,l}}^i \; p_{y,a}^{i,f} \; \tilde{S}_{y,\tilde{L}_a^{i,l}}^{L,i,f} \; N_{y,a}^{i,l,A} \; e^{-M_a^i/2}} \tag{11}$$

where $C_y^{i,A,f,\text{obs}}$ is the observed catch (in mass) of species *i* by fleet *f* in area *A* during year *y*.

Selectivity is assumed to be a function of length and to be governed by a logistic curve:

$$S_{\tilde{L}}^{i,f} = \left( 1 + \exp\left[ -\ell n 19 \frac{L_{\tilde{L}} - L_{50}^{i,f}}{L_{95}^{i,f} - L_{50}^{i,f}} \right] \right)^{-1} \tag{12}$$

where $L_{50}^{i,f}$ is the length-at-50%-selectivity on fish of species *i* by fleet *f* ,

$L_{95}^{i,f}$ is the length-at-95%-selectivity on fish of species *i* by fleet *f* , and

$L_{\tilde{L}}$ is the midpoint of length-class $\tilde{L}$ .

Two key sources for discarding are considered in the operating model, viz, discarding due to the lack of quota, and discarding of unmarketable small animals. The 'discard' selectivity pattern is assumed to be a logistic decreasing function of size and to be independent of fleet:

$$S_{\tilde{L}}^{D,i,f} = \frac{\phi^{D,i}}{1+\exp\left[\left(\tilde{L}-L_{50}^{D,i}\right)/\delta^{D,i}\right]} \tag{13}$$

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

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

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

Quota-related discarding is defined as the fraction of the catch of species $i$ that could potentially be landed by fleet $f$ during year $y$ but is discarded because operators lack sufficient quota (Punt *et al*., 2001a):

$$D_y^{i,f} = \bar{D}_y^{i,f} e^{\varepsilon_{D,y}^f - \sigma_D^2/2} \qquad \varepsilon_{D,y}^f \sim N\left(0;\sigma_D^2\right) \tag{14}$$

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

$$\bar{D}_y^{i,f} \begin{cases} 0 & \text{if } y < 1992 \\ \bar{D}^{i,f} & \text{if } 1993 \le y \le 2000 \\ \max\left(\bar{D}^{i,f}\,\dfrac{(2020-y)}{20},\ \ 0\right) & \text{if } y > 2000 \end{cases} \tag{15}$$

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

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

Equation (15) reflects the fact that no quota-related (but some size-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-related discarding. The assumption that there will be no quota-related discarding in 2020 is optimistic but should be adequate for the purposes of this study.

The exploitable biomass for fleet $f$ and species $i$ in region $A$ at the start of year $y$ is:

$$B_y^{i,A,f} = \sum_a \sum_l w_{\tilde{L}_a^{i,l}}^i \, S_{\tilde{L}_a^{i,l}}^{i,l,f} \, N_{y,a}^{i,l,A} \tag{16}$$

**4.2 Projecting forward**

The projections beyond 2002 are based on the same equations as are used to model the period 1985-2002, except that the recruitment residuals (see Equation 4) are generated rather than being treated as estimable parameters.

The sizes of the annual landed catches by species and fleet are driven by the constraints imposed by the Total Allowable Catch, *TAC*, and by the ability to market catches. The *TAC* by species and fleet is determined by applying a harvest strategy to data generated by the operating model. Each species is assumed to have a threshold catch level, $\tilde{C}_y^{L,i,f}$. For species that are easy to market such as pink ling, the threshold is the *TAC* (i.e. $\tilde{C}_y^{L,i,f} = TAC_y^{i,f}$) while for species that can be difficult to market, $\tilde{C}_y^{L,i,f}$ is the minimum of the *TAC* and a value generated from the historical catch data (to reflect the "market demand"). Following Punt *et al*. (2001a), the fleet-and region-specific fishing efforts, $E_y^{A,f}$, are selected by minimizing the penalty function, *P*, i.e.:

$$P = P_1 + P_2 \tag{17}$$

$$P_1 = 100\left( E_y^{A,f} / \sum_{f'} \sum_{A'} E_y^{A',f'} - \bar{E}^{A,f} / \sum_{f"} \sum_{A"} \bar{E}^{A",f"} \right)^4$$

$$P_2 = \begin{cases} 4\sum_i \sum_f \left( C_y^{i,f} - \tilde{C}_y^{L,i,f} \right)^2 & \text{if } C_y^{i,f} < \tilde{C}_y^{L,i,f} \\ \sum_i \sum_f \left( C_y^{i,f} - \tilde{C}_y^{L,i,f} \right)^2 & \text{otherwise} \end{cases}$$

where $\bar{E}^{A,f}$ is the average effort by fleet *f* in region *A* over the years 1994-2000.

The exploitation rate by fleet *f* in region *A* during a future year *y* on fully-selected fish of species *i*, $k_y^{i,A,f}$ is related to the effective fishing effort in each region *A*:

$$k_y^{i,A,f} = q^{i,A,f}\, \tilde{E}_y^{A,f}\, e^{\varepsilon_{q,y}^{i,A,f} - (\sigma_q^{i,A,f})/2} \qquad \varepsilon_{q,y}^{i,A,f} \sim N(0;(\sigma_q^{i,A,f})^2) \tag{18}$$

where $q^{i,A,f}$ is the relative catchability of fully-selected animals of species *i* by fleet *f* in region *A*,
$\sigma_q^{i,A,f}$ is the extent of variability in catchability for species *i*, region *A* and fleet *f*,
$\tilde{E}_y^{A,f}$ is the effective fishing effort by fleet *f* in region *A* during year *y*:

$$\tilde{E}_y^{A,f} = E_y^{A,f}\, e^{\lambda y} \tag{19}$$

$\lambda$ is the parameter that determines changes over time in efficiency; the term $e^{\lambda y}$ allows for an exponential increase in catchability over time due to the possible impact of improved technology and skill in the fishery.

The term $P_1$ in Equation 17 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 for the control parameters in Equation 17 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 $C_y^{L,i,f}$ exceeds $\tilde{C}_y^{L,i,f}$, the difference between $\tilde{C}_y^{L,i,f}$ and $C_y^{L,i,f}$ is assumed to be discarded.

### 4.3 Conditioning the operating model

Conditioning involves specifying the values for the model parameters. The outcome of the ‘conditioning’ process is that the simulation trials are able to the mimic the available monitoring and research data ‘satisfactorily’. Table 1 lists the parameters of the operating model. Some of these parameters can be set based on auxiliary information, some are pre-specified (and sensitivity is examined to alternative values for these parameters), while the remainder are estimated by fitting the operating model to the available monitoring data.

The objective function minimized to estimate the “free” parameters of the operating model includes four sources of data and penalties on the recruitment residuals and on the depletion of the spawning biomass in 1985.

$$L^i = \sum_k L_k^i \tag{20}$$

where $L^i$ is the total objective function for species $i$, and

$L_k^i$ if the $k^{\text{th}}$ component of the total objective function (one component for each of the four data sources and the penalty on the recruitment residuals and on the depletion of the spawning biomass in 1985).

#### 4.3.1 Catch-rate data

The contribution of the catch-rate data for fleet $f$ in region $A$ to the objective function for species $i$ is based on the assumption that catch-rates are log-normally distributed about their expected values, i.e.:

$$L_1^i = \sum_f \sum_A \sum_y \left[ \ell\text{n}\sigma_q^{i,A,f} + \frac{1}{2\left(\sigma_q^{i,A,f}\right)^2}\left(\ell\text{n}I_y^{i,A,f,\text{obs}} - \ell\text{n}\left(q^{i,A,f} B_y^{i,A,f} e^{\lambda y}\right)\right)^2 \right] \tag{21}$$

where $I_y^{i,A,f,\text{obs}}$ is the catch-rate index for year $y$, species $i$, region $A$ and fleet $f$.

The values for $q^{i,A,f}$ and $\sigma_q^{i,A,f}$ are obtained using the equations:

$$q^{i,A,f} = \tfrac{1}{n_I^{i,A,f}} \sum_y \ell\text{n}\left( I_y^{i,A,f,\text{obs}} / (B_y^{i,A,f} e^{\lambda y})\right) \tag{22a}$$

$$\sigma_q^{i,A,f} = \sqrt{\tfrac{1}{n_a^{i,A,f}} \sum_y \left(\ell\text{n}I_y^{i,A,f,\text{obs}} - \ell\text{n}(q^{i,A,f}\ B_y^{i,A,f}\ e^{\lambda y})\right)^2} \tag{22b}$$

where $n_q^{i,A,f}$ is the number of years for which catch-rate data are available for species $i$, region $A$, and year $y$.

### 4.3.2 Discard rate data

The contribution of the observed mass of discards to the objective function is based on the assumption that the errors in measuring the fraction of the total catch of species $i$ that is discarded by fleet $f$ are log-normal with a coefficient of variation of $\sigma_d^{i,f}$, i.e.:

$$L_2^i = \sum_y \sum_f \left( \ell\text{n}\sigma_d^{i,f} + \frac{1}{2\left(\sigma_d^{i,f}\right)^2}\left(\ell\text{n}\rho_y^{i,f,\text{obs}} - \ell\text{n}\rho_y^{i,f}\right)^2 \right) \tag{23}$$

where $\sigma_d^{i,f}$ is the (pre-specified) residual standard deviation,

$\rho_y^{i,f,\text{obs}}$ is the observed fraction of the catch (in mass) of species $i$ by fleet $f$ that is discarded, and

$\rho_y^{i,f}$ is model-estimate of the fraction of the catch (in mass) of species $i$ by fleet $f$ that is discarded:

$$\rho_y^{i,f} = \frac{D_y^{i,f}}{C_y^{i,f} + D_y^{i,f}} \tag{24}$$

### 4.3.3 Catch-at-age data

The contribution of the catch-at-age data to the objective function is either based on the assumption that the catch proportions-at-age are multinomially distributed (Equation 25a) or log-normally distributed (Equation 25b), i.e.:

$$L_3^i = \begin{cases} -\sum_f \sum_A \sum_y \tilde{N}_y^{i,A,f,\text{land}} \sum_a \rho_{y,a}^{i,A,f,\text{land,obs}} \ell\text{n}\left(\rho_{y,a}^{i,A,f} / \rho_{y,a}^{i,A,f,\text{land,obs}}\right) & \text{(25a)} \\ \sum_f \sum_A \sum_y \sum_a \left( \ell\text{n}[\sigma_C^{i,A,\text{land}} (\rho_{y,a}^{i,A,f})^{-\gamma_C^i/2}] + \frac{\left(\rho_{y,a}^{i,A,f}\right)^{\gamma_C^i} \ell\text{n}(\rho_{y,a}^{i,A,f,\text{land,obs}} / \rho_{y,a}^{i,A,f})^2}{2\left(\sigma_C^{i,A,\text{land}}\right)^2} \right) & \text{(25b)} \end{cases}$$

where $\rho_{y,a}^{i,A,f,\text{land,obs}}$ is the observed fraction of the landed catch of species $i$ by fleet $f$ in region $A$ that is of age $a$,

$\rho_{y,a}^{i,A,f}$ is model-estimate of the fraction of the landed catch of species $i$ by fleet $f$ in region $A$ that is of age $a$:

$$\rho_{y,a}^{i,A,f} = C_{y,a}^{i,A,f} / \sum_{a'} C_{y,a'}^{i,A,f}$$

$\tilde{N}_y^{i,A,f,\text{land}}$ is effective sample size for species $i$, region $A$, fleet $f$ and year $y$,

$\sigma_C^{i,A,\text{land}}$ is overall coefficient of variation of the catch-at-age data for species $i$, fleet $f$ and region $A$, and

$\gamma_C^i$ is a parameter that determines the relationship between the coefficient of variation of a proportion-at-age and its expected value for species *i*.

The above formulation can be used to include information on the age-structure of the discarded catch in the objective function.

**4.3.4 Catch-at-length data**

The contribution of the catch-at-length data to the objective function is either based on the assumption that the catch proportions-at-length are multinomially distributed (Equation 26a) or log-normally distributed (Equation 26b), i.e.:

$$L_4^i = \begin{cases} -\sum_f \sum_A \sum_y \tilde{\tilde{N}}_y^{i,A,f,\text{land}} \sum_{\tilde{L}} \rho_{y,\tilde{L}}^{i,A,f,\text{land,obs}} \ell n\left(\rho_{y,\tilde{L}}^{i,A,f} / \rho_{y,\tilde{L}}^{i,A,f,\text{land,obs}}\right) & (26a) \\ \sum_f \sum_A \sum_y \sum_{\tilde{L}} \left( \ell n[\sigma_L^{i,A,\text{land}} (\rho_{y,\tilde{L}}^{i,A,f})^{-\gamma_L^i/2}] + \frac{\left(\rho_{y,\tilde{L}}^{i,A,f}\right)^{\gamma_L^i} \ell n(\rho_{y,\tilde{L}}^{i,A,f,\text{land,obs}} / \rho_{y,\tilde{L}}^{i,A,f})^2}{2\left(\sigma_C^{i,A,\text{land}}\right)^2} \right) & (26b) \end{cases}$$

where $\rho_{y,\tilde{L}}^{i,A,f,\text{land,obs}}$ is the observed fraction of the landed catch of species *i* by fleet *f* in region *A* that is in length-class $\tilde{L}$,

$\rho_{y,\tilde{L}}^{i,A,f}$ is model-estimate of the fraction of the landed catch of species *i* by fleet *f* in region *A* that is in length-class $\tilde{L}$:

$$\rho_{y,\tilde{L}}^{i,A,f} = \sum_{a,l} C_{y,a,l}^{i,A,f} / \sum_{a'} C_{y,a'}^{i,A,f}$$

where the summations of over age and growth group are restricted so that $\tilde{L}_a^{i,l}$ is in length-class $\tilde{L}$,

$C_{y,a,l}^{i,A,f}$ is the model-estimate of the landed catch of animals by fleet *f* of species *i* and age *a* in growth-group *l* and region *A* during year *y*:

$$C_{y,a,l}^{i,A,f} = \left(1 - D_y^{i,f}\right) p_{y,a}^{i,A,f} \tilde{S}_{\tilde{L}_a^{i,l}}^{L,i,f} k_y^{i,A,f} N_{y,a}^{i,l,A} e^{-M_a^i/2} \qquad (27)$$

$\tilde{\tilde{N}}_y^{i,A,f,\text{land}}$ is effective sample size for species *i*, region *A*, fleet *f* and year *y*,

$\sigma_{\tilde{L}}^{i,A,\text{land}}$ is overall coefficient of variation of the catch-at-length data for species *i*, fleet *f* and region *A*, and

$\gamma_{\tilde{L}}^i$ is a parameter that determines the relationship between the coefficient of variation of a proportion-at-length and its expected value for species *i*.

The above formulation can be used to include information on the length-structure of the discarded catch in the objective function.

**4.3.5 The penalty on the recruitment residuals**

The penalty placed on the recruitment residuals is based on the assumption that deviations about the stock-recruitment relationship are log-normally distributed:

$$L_5^i = \frac{1}{2(\sigma_r^i)^2} \sum_y (\varepsilon_{r,y}^i)^2 \tag{28}$$

**4.3.6 The penalty on the 1985 depletion**

The penalty placed on the model-estimate of the depletion of the spawning biomass in 1985 when scenarios involving pre-specified values for this depletion are considered is:

$$L_6^i = \frac{1}{2\sigma_{D_i}^2} \left( D_{\text{init}}^i - \tilde{B}_{y_0}^i / \tilde{B}_0^i \right)^2 \tag{29}$$

where $D_{\text{init}}^i$ is the pre-specified depletion of the spawning biomass in 1985, and

$\sigma_{D_i}$ is the parameter that determines the magnitude of the penalty.

**4.3.7 Specifying the initial state of the system**

Punt *et al*. (2001a) began their population projections in 1958 and assumed that the biomass of each species was at its pre-exploitation equilibrium level at that time. This is clearly an unrealistic assumption for the species to be considered in this report because: (a) reliable estimates of the catches prior to 1985 are not available for most of them, and (b) it is well-known that some of these species (e.g. tiger flathead) were fished well before 1957.

Therefore, instead of making the assumption of an unfished population at some point in time, the first year of the population projection is assumed instead to be 1985 and that the population was in equilibrium but with an age-structure that depends on an "initial level of fishing", i.e. for the case of one growth-group and region:

$$N_{y_0,a}^i = \begin{cases} 1 & \text{if } a = 0 \\ N_{y_0,a-1}^i \, e^{-\hat{Z}_{a-1}^i} & \text{if } 1 \le a < x \\ N_{y_0,x-1}^i \, e^{-\hat{Z}_{x-1}^i} / (1 - e^{-\hat{Z}_x^i}) & \text{if } a = x \end{cases} \tag{30}$$

where $\hat{Z}_a^i$ is the total mortality on animals of age *a* and species *i* prior to 1985:

$$\hat{Z}_a^i = \sum_f S_{\tilde{L}_a^i}^{i,f} \, \tilde{F}^{i,f} \, p_{y_0,a}^{i,f} + M_a^i \tag{31}$$

$\tilde{F}^{i,f}$ is fishing mortality by fleet *f* on species *i* prior to 1985.

The virgin stock size in Equation (29) represents the population size to which the stock would recover on average if all exploitation ceased. It may differ from the original pre-exploitation stock size for a variety of reasons including changes in overall species composition and in the environment. This virgin stock size may not be consistent with the estimates of historical (i.e. pre-1985) removals due to the impact of (unknown and now unknowable) changes in the environment and the impact of errors when reporting and recording catches. Estimating the pre-exploitation population size by back-projecting from the population size in 1985 is therefore subject to considerable uncertainty. For example, temporally-correlated environmental factors appear to have resulted in cyclic-like behaviour in catches of flathead.

# 5. SOFTWARE DESIGN

The code used to implement the specifications 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). The computer program used to implement the operating model was coded in C++ and the AD Model Builder package was used to condition the operating model.

# 6. OUTCOMES AND PROBLEMS ENCOUNTERED

Although this study ultimately failed to achieve its objectives due to technical difficulties, attempts to address these difficulties led to a thorough examination of two questions which will need to be addressed if future work along these lines is to be attempted and which have a bearing on how future stock assessments are conducted: (a) how to handle multiple fleets and consequently gear competition, and (b) how to parameterize a model in terms of the depletion in the first year of the population projection and so that the objective function remains differentiable with respect to all of the model parameters. These two issues are addressed further below.

### 6.1 Multiple fleets and gear-competition

It is self-evident that if the selectivity patterns for two fleets which fish the same area overlap there must be some form of “gear competition”. This competition can be included straightforwardly if fishing is assumed to occur continuously throughout the year (Murawski, 1984; Pikitch, 1987). However, implementing the assumption that the fishery operates continuously throughout the year would lead to a substantial increase in the number of estimable parameters (i.e. the fishing mortalities for each combination of species, fleet, region and year would need to be treated as estimable parameters). This would have lead to prohibitive computational requirements. Unfortunately, the alternative of simply treating each fleet as being independent of all the others can lead to the model predicting that more than all of the animals in an age-class are caught even when the fishing mortality on other age-classes is relatively low.

There are several ways to attempt to overcome this problem:

A) Ignore it, by including a constraint when conditioning the operating model that no age-class be rendered extinct at any time during the historical projection period by adding an extra penalty to the objective function. This approach risks creating a positive bias in population size estimation when there is an age-class that is highly selected by several fleets.

B) Use the approach outlined in Appendix D. This approach overcomes the problem of ‘gear-competition’ by partitioning each age-class among the various fleets. However, it requires that $p^f_{y,a}$ (see Equation D.9) be defined. Unfortunately, there is no obviously way to define $p^f_{y,a}$ so that simultaneously (a) the sum over fleets

C) of the catch-in-mass is the catch-in-mass for all fleets combined, and (b) there is an analytical solution for $k_y^f$ in Equation D.10.

D) Assume that each fleet operates sequentially (i.e. the catch by fleet 1 is removed, followed by that of fleet 2, etc. - this is the approach used when conducting assessments of shark species off southern Australia (e.g. Punt *et al*., 2000)). The disadvantage of this method is that if fishing mortality by one fleet is high on one age-class, the catch of that age-class by fleets that occur "after" it may be unrealistically low.

### 6.2 Conditioning the operating model

A single-species, single-region version of the operating model was fitted to the data for tiger flathead (see Table 2 for an overview of the data included in this exercise). The approach to dealing with gear-competition was A) above because the fishing mortality is never very high on any one age-class. The results of this application (Cui *et al*., 2003) are not provided in this report. Interested readers can consult Smith *et al.* (2003) which contains the extension to this analysis which now forms the basis for the actual stock assessment of tiger flathead.

Fitting the operating model to the data for tiger flathead highlighted a number of difficulties in addition to the problem of gear competition identified above:

- The approach used to estimate the age-structure at the start of 1985 involved satisfying a constraint related to the state of the population relative to the unfished state in order to develop different scenarios regarding the ratio $\tilde{B}^i_{1985} / \tilde{B}^i_0$ (see Equation 29). However, the ability to find the set of parameters which minimize Equation 20 for which the Hessian matrix is positive definite depends on the choice of the parameterization of the model (e.g. should the value of $F^i_{\text{init}}$ be solved for numerically on each function call or should $F^i_{\text{init}}$ be treated as an estimable parameter and an additional penalty term added).
- Parameterizing the matrix $\mathbf{X}_{y_0}$ (see Equation 3) is very non-trivial. It is clear that the model will be over-parameterized if all of the entries in the matrix $\mathbf{X}_{y_0}$ are treated as "free" parameters of the operating model. The solution to this problem is to impose some structure on the entries in this matrix (as has been done for the assessments of blue grenadier (*Macruronus novaezelandiae*) in New Zealand (Francis *et al*., 2002) and of school shark (*Galeorhinus galeus*) in Australia (Punt *et al.*, 2000)). However, there is currently insufficient information for the species considered in this report to select a plausible parameterization for the matrix $\mathbf{X}_{y_0}$.

Fitting the model to the data for tiger flathead highlighted a potential conflict between having growth-groups (see Equation 1) and fitting to actual length-frequency data. Unfortunately, it can (and did) arise that the match between the length-classes for which length-frequency data are available and those which are implied by the growth groups was poor. This led, for example, to predictions of zero catch for some length-classes for which the actual data suggest that there was some catch. This behaviour is very strongly penalized by objective functions such as Equation 26. Growth groups have been successfully included in operating models for other species (for example, the ELF simulation model – Mapstone *et al*. (in press), and the model used to test alternative indicators for swordfish - Punt *et al*. (2001d)). However, the operating model was not fitted to actual length-frequency data in these more successful cases. This problem could be overcome to replacing the growth-group structure by one in which a length-transition matrix is used to predict the length-structure of the catch. This approach has been used successfully in assessments of several species in Australia and elsewhere (e.g. Smith and Punt (1998); Ianelli *et al*. (2000); Cope *et al*. (in press)).

# 7. FURTHER DEVELOPMENT

1) The approach to dealing with ‘gear competition’ can have a major impact on the results of attempts to condition an operating model and on the results of actual stock assessments based on the Integrated Analysis paradigm when the operating model and assessment are based on a first-order Taylor series approximation to the continuous catch equation. Preliminary analysis (not shown in this report) indicates that the estimates of exploitable biomass can vary substantially depending on how the parameters related to the expected proportion of each age-class available to each fleet is modelled. Future research should be focussed on using Monte Carlo simulation to examine the likely magnitude of any bias arising from an inappropriate selection of a functional form for $p^f_{y,a}$ (Appendix D) and hence on how to select the most appropriate functional form for this quantity. The simulations would be based on the continuous multi-fleet catch equation and the models used for estimation purposes on each of the alternatives identified in Section 6.1.
2) All current Integrated Analysis assessments in Australia are based on approximating the continuous (and multi-fleet) catch equation by a first-order Taylor series approximation. This is primarily because this assumption avoids the needs for iterative methods to solve the catch equation. This is, however, not the only possible assumption and alternative assumptions may perform better. For example, it is possible to approximate the catch equation by a second-order Taylor series approximation (G. Stefansson, University of Iceland, pers. commn) or to use a Runga-Kutta integration method. To date, no attempts have been made to base Integrated Analysis assessments on second- or higher order approximations to the catch equation.
3) The attempts to condition the operating model were largely unsuccessful. However, the operating model considered for this report did not include all of the sources of process error included in the operating model developed by Punt *et al*. (2001a) [which was not fitted formally to the actual data for the species considered in that report unlike the aim of the analyses of this report]. In particular several of the sources of process errors (e.g. variability over time in natural mortality and selectivity) and spatial and temporal correlation in the recruitment residuals are not included in the operating model outlined in Section 4.1 of this report. Future research should consider basing the operating model projections on the results of Bayesian analyses as these have been shown to be able to capture several sources for process error simultaneously (e.g. Ianelli *et al*., 2000; Butterworth *et al*., 2003).

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Table 1. The parameters of the population dynamics model

| Parameter | Treatment |
|---|---|
| First year considered in the model, $y_0$ | Pre-specified |
| Natural mortality by species and age, $M_a^i$ | Pre-specified |
| Extent of variability in movement, $\sigma_X$ | Pre-specified |
| Maximum age-class, $x$ | Pre-specified |
| Spatial distribution of births, $\pi^{i,l,A}$ | Pre-specified |
| Average movement parameters, $\mathbf{X}_{y_0}$ | Estimated[a] |
| Proportion mature at length, $m_{\tilde{L}}^i$ | Auxiliary analyses |
| Extent of variability in recruitment, $\sigma_r^i$ | Pre-specified |
| Recruitment residuals, $\varepsilon_{r,y}^i$ | Estimated |
| Pre-exploitation equilibrium biomass, $\tilde{B}_0^i$ | Estimated |
| Steepness, $h^i$ | Pre-specified |
| Parameter determining depensation, $\tilde{q}^i$ | Pre-specified |
| Growth parameters, $L_\infty^{i,l}$, $\overline{L}_\infty^i$, $w_\infty^i$, $e_2^i$, $\kappa^{i,l}$, $t_0^i$ | Auxiliary analyses |
| Availability proportions, $p_{y,a}^{i,A,f}$ | Set to 1[b] |
| Length-at-50%-selectivity, $L_{50}^{i,f}$ | Estimated |
| Length-at-95%-selectivity, $L_{95}^{i,f}$ | Estimated |
| Discard selectivity-related parameters, $\phi^{D,i}$, $L_{50}^{D,i}$, $\delta^{D,i}$ | Auxiliary analyses |
| Expected amount of quota-related discarding, $\overline{D}^{i,f}$ | Pre-specified |
| Extent of variability in quota-related discarding, $\sigma_D$ | Pre-specified |
| Extent of increase in efficiency over time, $\lambda$ | Pre-specified |
| Exploitation rate in the year $y_0$, $F_{\text{init}}^i$ | Estimated |

a – see Section 6.2 for more details
b – see Section 6.1 for additional details

Table 2. Data sources included when modelling tiger flathead.

| Data | Source | Fleet | |
|---|---|---|---|
| | | Otter trawl | Danish seine |
| Catch | SEF1 | 1985-2002 | 1985-2002 |
| Discard ratio | Onboard Monitoring | 1992-2002 | 1994-95, 1998-2002 |
| Catch rate | SEF1 | 1985-2002 | 1985-2003 |
| Age-composition data | | | |
| Landed | CAF, ISMP | 1991-2002 | 1991-2002 |
| Discarded | - | - | - |
| Length-frequency data | | | |
| Landed | ISMP | 1991-2002 | 1992, 1994-2002 |
| Discarded | Onboard Monitoring | 1992-2002 | 1993-95, 1998-2002 |
| Age-length keys | CAF, ISMP | 1991-2002 | 1991-2002 |

## 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 75.77 : 24.33 between the Fisheries Research and Development Corporation and CSIRO Marine Research.

## Appendix B : Staff

| | | |
|---|---|---|
| Anthony D.M. Smith | Project Leader, CMR | 15% |
| Peter Cui | Modeller, CMR | 100% |
| André E. Punt | Senior Research Scientist, CMR | 5% |

## Appendix C : The parameterisation of the stock-recruitment relationship

The parameters of the stock-recruitment relationship are α, β and γ (Equation 4). The values for these parameters are determined from $\tilde{B}_0$ (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.:

$$R_0 = \frac{1}{\alpha+\beta}; \quad h\,R_0 = \frac{0.2^\gamma}{\alpha+\beta\,0.2^\gamma}; \quad \frac{0.1^\gamma}{\alpha+\beta\,0.1^\gamma} = \tilde{q}\frac{0.1}{\alpha^{'}+\beta^{'}\,0.1} \qquad \text{(C.1)}$$

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

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

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

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

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

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

$$\tilde{q} = \frac{0.1^\gamma\,(\alpha^{'}+\beta^{'}\,0.1)}{0.1(\alpha+\beta\,0.1^\gamma)} \qquad \text{(C.3)}$$

which simplifies to:

$$\tilde{q} = \frac{(1.8-h)(1-0.2^\gamma)}{0.8(2^\gamma(1-h)+h-0.2^\gamma)} \qquad \text{(C.4)}$$

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

## Appendix D : One approach to dealing with gear competition

Many of the assessments based on the Integrated Analysis approach to fisheries stock assessment involve approximating the Baranov catch equation by the first order Taylor Series approximation of Pope (1972) or the more accurate approximation derived by Allen and Hearn (1989). However, both of these approximations were derived for the catch by a single fleet of a single age-class. The extension of these approximations to the catch over several age-classes by a single fleet is straightforward but that to multiple fleets and ages simultaneously leads to problems owing to the impact of "gear competition".

The derivation below is based on a situation in which a single stock of a given species is found in a region. Information is available on the total catch (over several age-classes) by each fleet.

1) **Total population**

Consider the case of a single age-class when the catch of that age-class is known. By definition, the total catch is the sum over all fleets of the catch by fleet. Given the population dynamic equation:

$$\frac{dN}{dt} = \left.\frac{dN}{dt}\right|_F + \left.\frac{dN}{dt}\right|_M = -N(F+M) \tag{D.1}$$

where $F$ is the total annual instantaneous rate of fishing mortality, and
$M$ is the instantaneous rate of natural mortality.

and applying the operator splitting method (Yanenko, 1971; Chorin, 1967; Cui, 1993; Easton *et al*., 1997), leads to the following first order approximation to the solution of Equation (D.1):

$$N_{y+1} = N_{y+1/2}(1-F_y) = N_y(1-F_y)\,e^{-M} \tag{D.2}$$

Now, consider the case in where there are multiple fleets (or even multiple fishers) harvesting the age-class under consideration. By definition, each fleet can only take a fraction of the total population. If the fraction of the catch taken by fleet *f* is $p^f$ (where, by definition, $\sum_f p^f = 1$), then the fishing mortality by fleet *f* is:

$$F^f = p^f F \tag{D.3}$$

Substituting Equation (D.3) into Equation (D.1) leads to:

$$\frac{dN}{dt} = -(p^1F + p^2F + \cdots)N - NM = -FN\sum_f p^f - NM = -N(F+M) \tag{D.4}$$

The first-order approximation to the catch (in numbers) by fleet *f* is then:

$$C_y^f = N_y\; p_y^f\; F_y\; e^{-M} \tag{D.5}$$

2) **Age-specific dynamics**
Equations (D.1) – (D.4) can be extended to be specifically age-structured, i.e.:

$$\begin{aligned} \frac{dN_{y,a}}{dt} &= -(F_{y,a} \cdot p^1_{y,a} + F_{y,a} \cdot p^2_{y,a} + \cdots + M)N_{y,a} \\ &= -(F_{y,a} \sum_f p^f_{y,a} + M)N_{y,a} \\ &= -(F_{y,a} + M)N_{y,a} \end{aligned} \quad \text{(D.6)}$$

Applying the operator splitting method to Equation (D.6) leads to

$$N_{y+1,a+1} = N_{y,a}(1 - F_{y,a})\, e^{-M} \quad \text{(D.7)}$$

so that the catch (in mass) by fleet *f* of fish of age *a* during year *y* is:

$$\tilde{C}^f_{y,a} = w_a\, F_{y,a}\, p^f_{y,a}\, N_{y,a}\, e^{-M} = w_a\, F^f_{y,a}\, N_{y,a}\, e^{-M} \quad \text{(D.8)}$$

Now, assuming that $F^f_{y,a}$ can be decomposed into the product of three factors:

$$F^f_{y,a} = k^f_y\, p^f_{y,a}\, S^f_a \quad \text{(D.9)}$$

leads to the following equation for the total (i.e. aggregated over ages) catch (in mass) during year *y* by fleet *f*:

$$\tilde{C}^f_y = k^f_y \sum_a w_a\, p^f_{y,a}\, S^f_a\, N_{y,a}\, e^{-M} \quad \text{(D.10)}$$