Development of an operating model and evaluation of harvest strategies for the Eastern Tuna and Billfish Fishery

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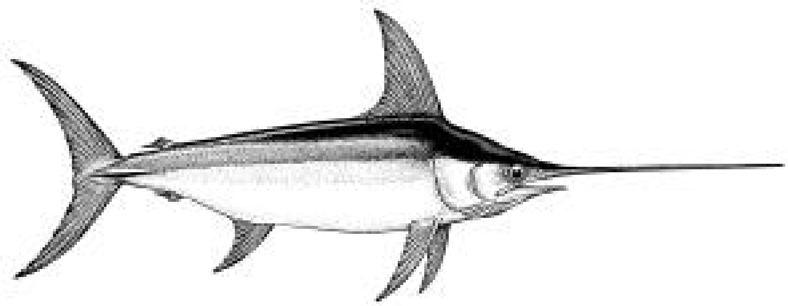
November 2003



FRDC Project 1999/107

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Published by CSIRO Marine Research

The Fisheries Research and Development Corporation plans, invests in and manages fisheries research and development throughout Australia. It is a federal statutory authority jointly funded by the Australian Government and the fishing industry.

Bibliography.
ISBN 1 876996 46 3.

1. Tuna fisheries - Australia - Evaluation. 2. Billfish fisheries - Australia - Evaluation. 3. Fishery management - Australia. 4. Fishery resources - Australia - Management. I. Dowling, Natalie Anne, 1975- . II. CSIRO. Marine Research. III. Title. (Series : FRDC Project ; 1999/107).

639.277830994

Preferred way to cite this publication:
Campbell, R. A. and Dowling, N. (2003). Development of an operating model and evaluation of harvest strategies for the Eastern Tuna and Billfish Fishery. Final report for Project 1999/107, Fisheries Research and Development Corporation, Canberra.

Printed by Piper Printing, Hobart

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Non-Technical Summary

1999/107 Development of an operating model and evaluation of harvest strategies for the Eastern Tuna and Billfish Fishery

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Objectives

1. To develop an operating model of the ETBF to be used in the evaluation of various harvest strategies for this fishery, in particular for broadbill swordfish and bigeye tuna.
2. To assist Eastern Tuna MAC and Eastern Tuna FAG quantify the management objectives for the ETBF by means of a range of performance measures.
3. To provide Eastern Tuna MAC and AFMA with an evaluation of the trade-offs associated with a range of harvest strategies for broadbill swordfish and bigeye tuna within the ETBF.

Non-Technical Summary

Outcomes Achieved to Date

This project provided the main source of quantitative advice to AFMA, Eastern Tuna MAC and other stakeholder groups to assist in the evaluation of appropriate harvest strategies for the Eastern Tuna and Billfish Fishery. In particular, the outcomes of this project played a major role in assisting AFMA determine an initial Total Allowable Effort (*TAE*) for the longline sector of the ETBF. It has also assisted AFMA identify and evaluate appropriate performance indicators and decision rules for the future adjustment of this *TAE*. Both of these are required for implementation of the new management plan for this fishery in 2004. This advice was conveyed to AFMA and other stakeholder groups through two ETBF Effort Setting workshops held in December 2002 and March 2003. The decision of the AFMA Board to set a preliminary *TAE* of 13.5 million hooks was announced on 2 June 2003.

The methodologies developed by this project have also been used to assist AFMA and other stakeholder groups determine initial Total Allowance Catches for the principal target species in the Southern and Western Tuna and Billfish Fishery. Finally, the outcomes of this project have been conveyed to a number of scientific and fishery forums, and provide the basis for further work on evaluating harvest strategies for the tuna and

In order to fulfill its legislative objectives the Australian Fisheries Management Authority (AFMA) is presently finalising a new management plan for the Eastern Tuna and Billfish Fishery (ETBF). The need for a new management plan was heightened by the rapid expansion of the longline sector of the ETBF in the mid-to-late 1990s, which saw an increase in annual effort levels from less than 3 million hooks in 1994 to over 10 million hooks in 1999, and concerns about over-capitalisation in the fishery. The management plan, which is to take effect from mid-2004, will include the introduction of input controls in the form of a total allowable effort (*TAE*), manifested as "hook days". With the introduction of the management plan there is a need to determine an appropriate initial *TAE* and to identify a range of performance indicators for the fishery and decision rules by which the *TAE* may be altered.

The Management Strategy Evaluation (MSE) approach was identified by the Fisheries Assessment Group for the ETBF as the most appropriate method for evaluating a range of candidate harvest strategies for the ETBF. This method allows evaluation of harvest strategies across a range of plausible stock and fishery scenarios based on the comparison of a range of performance measures. In turn, this allows the trade-offs among management objectives across a range of management actions to be explicitly identified. Furthermore, by allowing for the evaluation of harvest strategies across a range of possible stock scenarios, the uncertainties in our knowledge concerning the biology of the target species are explicitly incorporated into the process.

Of the three principal target species in the longline sector of the ETBF, broadbill swordfish was identified as the species most likely to possess a regional stock structure within the south-west Pacific and, consequently, the species most amenable to local management. On the other hand, the ocean-wide stock-structure of bigeye and yellowfin tuna, combined with the relatively small catches taken by Australian vessels, implies that local management of these resources to any meaningful level is unlikely. For these reasons, the MSE approach was only adopted for the evaluation of harvest strategies in relation to the catch of swordfish, while a different approach was adopted for the two tuna species.

The operating model for swordfish was an age-, length- and area-structured population dynamics model which assumes a single stock of swordfish within the SW Pacific. It also explicitly considered the dynamics of three principal fleets catching swordfish in this region - Australia, New Zealand and Japan - with the catch of swordfish taken by other fleets incorporated into the latter. A reference, or baseline, biology for the population dynamics of the swordfish population in the SW Pacific - based on research undertaken on swordfish in this region and elsewhere - was adopted for the evaluation of most harvest strategies. As the condition of the stock at the end of 2001 remained unknown, a range of assumed levels of depletion (*ie*. the reduction in the initial biomass level due to removals up until the year 2001) ranging between 15% and 50% were considered. Sensitivity of the results to alternative biological scenarios and assumed depletions were then considered. Each scenario, or alternative operating model, was conditioned on the available historical data.

Consideration of a range of fixed future effort harvest scenarios for the Australian longline fleet allowed a range of candidate initial *TAE* levels to be evaluated for the fishery. For this purpose, annual effort levels for the Australian longline fleet were allowed to range between 11 million and 28 million hooks. These harvest strategies were also evaluated against a range of alternative scenarios concerning both the future effort deployed by non-Australian vessels in the SW Pacific, increased gains in effective effort due to effort creep, and the population dynamics of the swordfish resource.

A range of economic and conservation based performance indicators - which included the rewards in the form of catches, the stability of these rewards and the risk to the stock - were identified for the ETBF and calculated for each harvest strategy over a 20 year projection period. As would be expected, the annual size of the Australian catch was found to generally increase with greater effort. However, with increased effort and catches there was a general decrease in the average size of fish caught, and an increased probability that the biomass would be fished down to levels below 50% and 30% of its initial level. As large fish generally return a higher price, a decrease in the proportion of large fish in the catch would result in a lower unit return across the total catch. If one adopts 30%B_o as a limit reference point then all scenarios where the Australian effort is increased above 16.8 million hooks were found to place the stock at high risk of being over-fished, while even an increase to 16.8 million hooks resulted in a moderate level of risk. The results indicated that large increases in effort would generally result in a poor conservation outcome, and illustrated the trade-offs between the achievement of both the economic and conservation objectives for the fishery.

The results were found to be sensitive to assumptions made about the natural mortality, recruitment and movement rates within the population, and were equally or more sensitive to the assumed depletion level at the end of the historical time-period used to condition the model. Examination of various fixed effort scenarios showed that as future effort was increased, the conservation objectives performed increasingly more poorly at higher assumed 2001 depletion levels. While the high (50%) depletion scenario may be considered unlikely, there may also be a high level of risk associated with the assumption that the depletion in 2001 was only 15%, since this assumption may not be seen as being precautionary.

Ideally, harvest strategies should incorporate feedback loops decision rules whereby the status of the fishery is regularly assessed, and harvest strategies are updated and applied depending on the results. By adjusting effort levels in this manner, the risk of not achieving either the conservation and/or economic objectives should be diminished. Two sets of harvest strategies that incorporated either a simple empirical-based decision rule or a model-based decision rule for adjusting annual effort for the Australian fleet during the 20 year projection period were evaluated. The empirical-based decision rules considered changes in the annual trends of either catch rates or the upper 95th percentile of individual fish weights in the catch, while the model-based decision rules used the results of a production model assessment. Both were found to be successful in arresting the declines in spawning biomass, but most did so by decreasing domestic effort until stability was attained in the monitored indicator variable used in the decision rule. Empirical approaches may be poor if the stock is already highly depleted, while the production model assessments were found to significantly underestimate true biomass levels, possibly because of a lack of contrast in the data and a confounding between the fitted parameters. Ultimately, more comprehensive data and a more sophisticated stock assessment are required if one is to better estimate sustainable yields.

Unlike the MSE approach adopted for swordfish, which assessed the performance of the ETBF based on input effort strategies, for bigeye and yellowfin tuna direct estimates of the sustainable catch of each species in the ETBF region were obtained. These were based on estimates of stock-wide MSY values and the distribution of each resource across the Pacific based on the distribution of catch rates for Japanese longliners. As with the MSE approach, several different estimates were obtained based on a range of alternative stock and productivity scenarios. Under the high productivity scenario, the results indicated that there may be considerable scope for increasing the catch of yellowfin tuna in the ETBF, while under the low productivity scenario, it remains possible that present catches may already exceed the sustainable yield for this region. On the other hand, the results for bigeye tuna under all scenarios indicated that there is little, if any, scope for increasing catches of bigeye tuna above their present levels either in the ETBF or elsewhere in the Pacific Ocean. This result is consistent with the current assessment of bigeye tuna in the WCPO which indicates that over-fishing of the bigeye stock in the WCPO is presently occurring.

The development of the operational model, together with the identification of performance indicators and future effort levels for evaluation, were undertaken in consultation with the Fisheries Assessment Group for the ETBF. All results were presented to two Effort Setting Workshops convened by AFMA to consider and discuss appropriate initial *TAE* levels for the ETBF. The results provided the only quantitative assessment of possible sustainable catch and effort levels for the fishery, and provided the basis for the decision on an initial *TAE* by the AFMA Board.

Keywords: Eastern Tuna and Billfish Fishery, harvest strategy, total allowable effort, performance indicators, decision rules, operational model, Monte Carlo simulations, bigeye tuna, broadbill swordfish, production models

Chapter 1: Harvest Strategies for the Eastern Tuna and Billfish Fishery

1.1. Background

The longline sector of the Australian fishery which operates off the east coast of Australia, known as the Eastern Tuna and Billfish Fishery (ETBF), underwent considerable expansion during the second half of the 1990s, with the number of hooks deployed increasing from less than 3 million in 1994 to over 10 million hooks in 1999 (Table 1.1). During this period the fishery also increased its targeting of both broadbill swordfish and bigeye tuna. As a result, the catch of swordfish increased from less than 50 tonnes (t) in 1994 to over 3,000 t in 1999, while the catch of bigeye increased from 120 t to around 1,200 t in 1998. While the catch of yellowfin tuna, which until 1995 had been the main target species, also increased over this period (from 1,300 t in 1994 to 2,000 t in 1999), the relative size of the increase was not as large.

The expansion witnessed during the period up until 1999 has slowed somewhat in recent years, with effort increasing to over 11 million hooks in 2001. Record catches of yellowfin tuna and bigeye tuna were also recorded in 2001, though there has been a continuous decline in the catch of swordfish in recent years.

Table 1.1 Total annual retained catch of yellowfin, bigeye and swordfish and associated effort for the Australian longline fleet operating off eastern Australia.

	Effort				Catch (tonnes)		
Year	Sets	Boats	Squares	Hooks	Yellowfin	Bigeye	Swordfish
1990	2,267	98	92	1,152,004	744	24	30
1991	3,256	96	138	1,793,913	765	29	76
1992	3,358	105	128	2,107,684	970	37	62
1993	2,947	84	95	1,678,445	689	23	41
1994	3,988	88	129	2,770,500	1,074	119	48
1995	5,057	104	155	3,834,553	1,380	196	87
1996	6,252	121	162	4,554,217	1,814	338	817
1997	8,759	138	170	6,283,371	1,835	1,063	2,338
1998	11,429	151	206	9,712,703	2,261	1,262	2,777
1999	11,548	152	246	10,281,973	2,060	973	3,077
2000	11,050	140	249	9,551,837	1,890	794	2,928
2001	12,511	141	233	11,262,305	2,845	1,346	2,420

The recent changes in the ETBF, together with the diversity and large spatial range and highly migratory nature of the targeted stocks and uncertainties in the information available to assess the status of the stocks in the ETBF, pose specific problems regarding the ability to provide specific scientific advice on resource status, sustainable catch levels and the trade off between risk and catch to the managers of the ETBF. For example, the 1997 catch of broadbill swordfish exceeded the 800 t 'trigger' level which Eastern Tuna MAC had placed on this species. While there was no biological basis for the setting of this trigger level (it was based on the average of historical catches), the purpose of the trigger was to alert the Australian Fisheries Management Authority (AFMA) that the fishery was expanding and that more attention would now need to be paid to this species. Unfortunately, at this time the stock structure of this resource remained uncertain and no stock assessments had been undertaken on broadbill swordfish within the eastern AFZ, or elsewhere in the Pacific. Consequently, AFMA was not able to assess whether the annual catches of this species were sustainable. It also had no identified harvest strategy for dealing with the future development of this component of the fishery.

As a further example, bigeye tuna, which are presently considered to represent a single stock across the entire Pacific Ocean, are targeted and caught by a large number of fisheries across this region. Furthermore, the catch of bigeye by a number of these fisheries greatly exceeds that taken within the ETBF. As a consequence, the catch of bigeye in the ETBF represents around half-of-one percent of the total catch (estimated to be around 200,000t in 2000) taken from the entire stock of bigeye in the Pacific Ocean. Hence, unless it can be shown that the bigeye tuna that occur within the ETBF are a largely self-recruiting sub-population of the Pacific-wide stock, management of the Australian fishery alone will not be able to ensure the sustainability of this fishery. This is because the status of the stock will be, to a large extent, determined by the size of catches taken outside the ETBF.

Despite these problems, AFMA is required to manage the ETBF in accordance with the legislative objectives set under the Fisheries Management Act 1991. These objectives include the ecologically sustainable development of the fishery and a precautionary (ie. risk averse) approach to setting harvest strategies for these resources, especially in light of scientific uncertainty about the status of the stocks.

In recent years various approaches have been developed in order to help identify appropriate management strategies in light of the uncertainties in the knowledge about a fishery. One such approach, known as Management Strategy Evaluation (MSE), has been developed and applied to the several fisheries within eastern Australia (Punt and Smith 1999, Punt et al 2001). The Eastern Tuna Fisheries Assessment Group identified the usefulness of this approach within the EBF, and a preliminary evaluation of performance indicators for the ETBF was undertaken in 1998 (Punt et al, 1999).

1.2 Need

At the time that this project was proposed, little information was available to AFMA to estimate the size of the catches of tunas and billfish which could be taken on a sustainable basis within the eastern AFZ. This was due to uncertainties in and/or absence of the necessary information on which this advice could be based. Nevertheless, given AFMA's need to satisfy its Ecologically Sustainable Development (ESD) objective, there was a need for Eastern Tuna MAC to identify appropriate management (or harvest) strategies for the continued and sustained development of this fishery.

During 1998 and 1999 the Eastern Tuna Fisheries Assessment Group (FAG), noted the rapid increase in the catches of bigeye tuna and broadbill swordfish taken in the fishery. It was also noted, that given the levels of investment being made in the fishery, these increases were likely to continue. The FAG was also informed of concern expressed by the Standing Committee on Tuna and Billfish over the current level of exploitation of bigeye tunas in the Pacific Ocean. Concern was also expressed over the susceptibility of broadbill swordfish to over-exploitation in light of the long-lived nature of this species and the declines seen in swordfish fisheries elsewhere (Ward and Elscot 2000). The FAG concluded that there was a need to identify and evaluate appropriate harvest strategies to allow for the controlled and sustainable development of this fishery. In particular, Eastern Tuna MAC needed to avoid a situation where there was an unsustainable level of investment in the fishery.

The Management Strategy Evaluation approach, mentioned above, was seen as the most appropriate method to adopt in achieving this outcome. In particular, this method allows evaluation and selection of appropriate harvest strategies across a range of possible stock scenarios based on the comparison of a range of performance measures which would typically include the risk to the stock, rewards in the form of catches and the medium to long-term stability of these rewards. By allowing for the evaluation of harvest strategies across a range of possible stock hypotheses, the uncertainties in our knowledge concerning the biology of the target species is explicitly incorporated into the process.

Of the three principal target species in the longline sector of the ETBF, broadbill swordfish was identified as the species most likely to possess a local or regional stock structure within the south-west Pacific (Reeb 2000, Bremer et al 2001). Furthermore, recent data indicates that Australian longliners take the largest catch from this regional stock (Campbell and Taylor 2000). Consequently, swordfish was identified as the species most amenable to local management. This may be considered somewhat fortuitous, as coincidentally swordfish has in recent years comprised the largest component of the total longline catches taken in the ETBF. However, as no recent stock assessments have been undertaken on broadbill swordfish in the Pacific Ocean, it remains unknown whether current catches of this species are sustainable. Nor is there an identified harvest strategy to deal with the any future developments within the fishery.

In 2000 the AFMA agreed to the introduction of a new Management Plan for the ETBF. This Plan will include the introduction of input controls in the form of a total allowable effort (*TAE*), manifested as “hook days”. The management plan is to take effect from mid-2004. With the introduction of the management plan there was a need to determine an appropriate initial *TAE*. Furthermore, concomitant with the setting of this *TAE* will be the need to identify a range of performance indicators for the fishery and decision rules by which, if required, the *TAE* may be altered. This project, which was jointly funded by the Australian Fisheries Management Authority (AFMA) and the Fisheries Research and Development Corporation (FRDC), provides a methodology for addressing these needs. In this report we outline the use of the Management Strategy Evaluation procedure to evaluate a range of initial *TAEs* and decision rules appropriate to the harvesting of the principal tuna and billfish species in the ETBF together with the results.

1.3 Project Objectives

The stated objectives of the project were as follows:

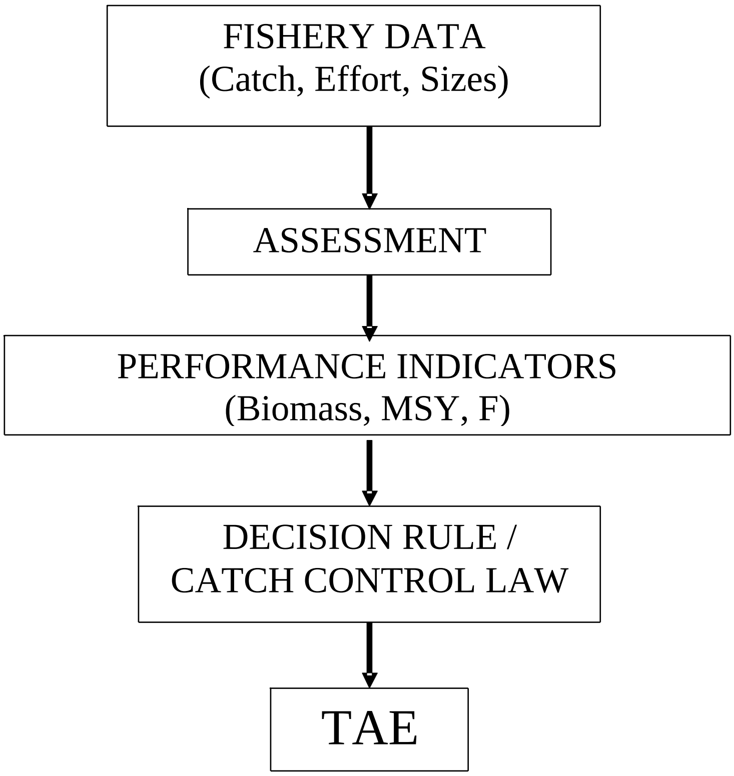
1. To develop an operating model of the ETBF to be used in the evaluation of various harvest strategies for this fishery, in particular for broadbill swordfish and bigeye tuna.
2. To assist Eastern Tuna MAC and Eastern Tuna FAG quantify the management objectives for the ETBF by means of a range of performance measures.
3. To provide Eastern Tuna MAC and AFMA with an evaluation of the trade-offs associated with a range of harvest strategies for broadbill swordfish and bigeye tuna within the ETBF.

1.4 Methods

1.4.1 Evaluating Harvest Strategies for the ETBF – The MSE Approach

A harvest strategy is a set of rules that is used to determine a management action. The set of rules should define the data to be collected from the fishery, how those data are to be analysed, and how the results of the data analyses are to be used to determine actions (Cochrane *et al* 1998). A schematic representation of the typical harvest strategy is shown in Figure 1.1. Harvest strategies may be very simple (eg. a constant catch/effort strategy) or extremely complicated (such as how *Total Allowable Catches* are being set for southern shark (Punt *et al* 2001b)). There is currently no harvest strategy being used in the ETBF, but future management actions are to be based on the setting of a Total Allowable Effort (*TAE*).

Figure 1.1 Components of a 'typical' harvest strategy.



Before any harvest strategy is adopted for the ETBF it should be evaluated against how well it is able to satisfy the management objectives for the fishery. An approach that has been developed to do this is known as Management Strategy Evaluation (MSE). This approach has been well described elsewhere (Smith 1994, Punt and Smith 1999, Punt *et al* 2001a) but a review of the major themes is given here.

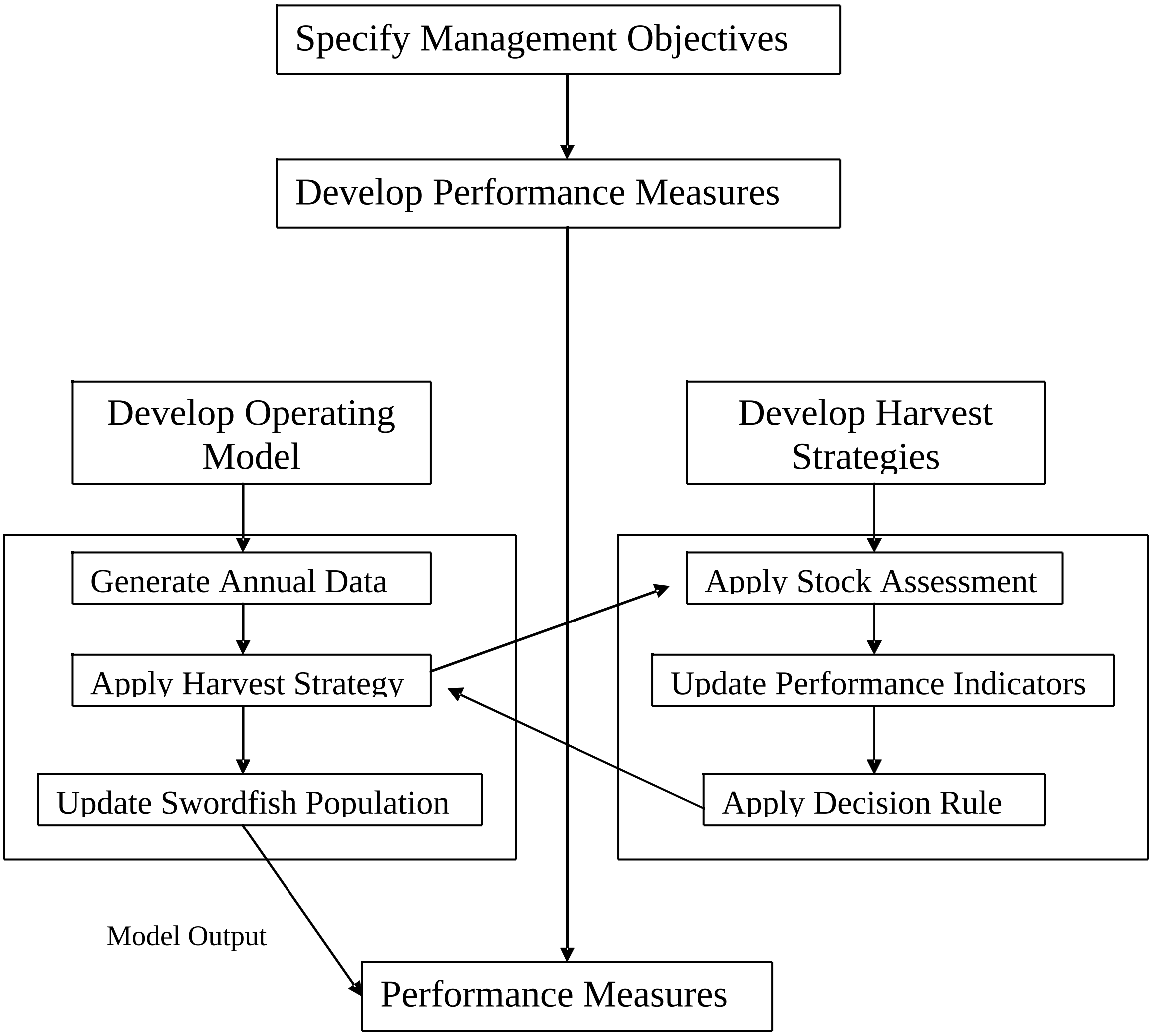
The primary goal of the MSE approach is to identify, in an objective and quantifiable manner, the trade-offs among the management objectives across a range of management actions. Note, it is never possible to perfectly satisfy all of the management objectives, and all harvest strategies consequently achieve some balance among them (eg. high catch, high risk; low catch, low risk). This information on the trade-offs among the management objectives is needed by the decision makers to make an informed decision about management actions, given the importance they assign to each of the objectives.

The key steps in the MSE approach are outlined in Figure 1.2 and involves five basic steps:

1) Identification of the management objectives and representation of these using a set of quantitative performance measures.
2) Identification of alternative harvest strategies
3) The development and parameterization of a set of alternative operating models that are used to represent the alternative realities in the calculations.
4) Simulation of the future using each harvest strategy to manage the system (as represented by each operating model).
5) The development of summary measures to quantify the performance of each harvest strategy relative to the management objectives of the fishery.

An operating model is a mathematical or statistical model of the population dynamics of the fishery being studied. Each operating model reflects an alternative (yet plausible) representation

Figure 1.2 Outline of the MSE approach.



of the status and productivity of the resource and the fishing dynamics of the fleets. The operating model is used to generate observations in the form of pseudo catch, effort and catch-at-length data sets which are then used in the management procedure. Several operating models are considered because the true situation for any fishery is never well known, and a broad range of input parameter values thus need to be examined to ensure the full range of possible resource and fleet dynamics are covered. In reality, we can only implement one strategy at a time, often with unknown results. The operating model component of the MSE framework enables a range of possible harvest strategies (e.g. *TAEs*) to be evaluated in terms of how well they can satisfy management objectives, prior to their actual implementation.

A key feature of the MSE approach is that it can explicitly take into account a wide range of uncertainties. In particular, it can be used to identify robust harvest strategies in light of the uncertainties in the information available for managing fish resources. This is achieved by incorporating into the MSE framework not only the uncertainty in the underlying dynamics of the resource in response to management actions, but also the uncertainty in the methods and data used to assess the status of the resource, and uncertainty in the ability to implement management actions. This uncertainty is modelled by constructing a range of operating models each based on the given set of parameter values. As such, the approach is based on recognition that it is the combination of the uncertainties about the dynamics of the system being managed, plus the ability to measure relevant information about the system, that determines the performance and robustness of a management decision-making framework.

In practice, the MSE uses Monte Carlo simulation techniques to evaluate candidate harvest strategies. The simulations iteratively model the current status of the resource, the collection of data with sampling errors, assessment of the data, management decisions based on the assessment and finally the consequences of the decision on the status of the resource. By constructing alternatives within each of these components, it is possible (at least in principle) to construct and evaluate management system models that encompass the full range of uncertainties that exist about a system.

In this report we describe the application of this approach to the swordfish resource within the SW-Pacific together with the principal longline fisheries catching swordfish within this region. The swordfish fishery is simulated using a range of "operating models", each of which is characterized by a unique set of input parameters and is ‘conditioned’ by fitting to data over the historical years of the fishery. This is required to estimate a number of free parameters in the model and to determine a range of initial starting values (eg. initial biomass) for the operating model that are consistent with the available historical information on the stock being evaluated. After conditioning the model, the general framework used to evaluate candidate harvest strategies consists of projecting the model forward using the following procedure:

- A sampling model that generates the data available for assessing the resource from the "true" state of the resource as simulated in the operating model.
- An assessment model that uses the data from the sampling model to provide estimates of resource status;
- A harvest strategy component that determines management actions based on the results of the assessment model and specified decision rules;
- A component for the calculation of an appropriate set of performance statistics for evaluation of the harvest strategy.

The first three components are sequentially iterated to simulate a time series of future population sizes, management actions and catches. The results can then be used to evaluate the performance of a particular management strategy (against predetermined management objectives) for a specific set of assumptions about the dynamics of the resource.

1.4.2 The Management Objectives and Performance Measures

The performance of the different harvest strategies should be considered relative to the management objectives of the ETBF, which are based on the five legislative objectives of the Australian Fisheries Management Authority. These are:

- Implementing efficient and cost-effective fisheries management on behalf of the Commonwealth
- Ensuring that the exploitation of fisheries resources and the undertaking 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 the 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.

Only the first three of these objectives need be considered, as the other two objectives are not related to how a *TAE* would be set for the ETBF.

It has been argued (Kaufmann *et al*, 1999) that the third objective (economic efficiency) is satisfied for the target species of a fishery if the *TAC* is implemented as individual Transferable Quotas. Thus, if quota trading actually works, the fishery will move over time to a situation in which the catch is taken with a minimum number of inputs. If this is the case, the complexities of trying to model investment behaviour can be avoided. It is hoped that the same comments would also hold for the fishery managed by a *TAE*.

Dealing with the "cost-effective management" objective is also complicated, but it should be possible to deal with this objective adequately by determining the "financial" cost associated with alternative harvest strategies as the cost of the data used for setting of *TAEs*.

Finally, a quantitative expression of how well the fishery performs relative to the stated management objectives is known as a performance measure. The performance measures for ESD need to consider two key issues when evaluating a harvest strategy: impact on the viability of the target species and the broader ecosystem, and impact on the profitability of the fishery. Further details on these performance measures are provided in Chapter 4.

1.4.3 Different approach for Bigeye Tuna

As explained in the following chapters, the MSE approach described earlier was only applied to evaluating harvest strategies for the swordfish fishery in the SW Pacific. This approach appears to be well suited to swordfish for two main reasons. First, recent genetic studies indicate, with high likelihood, a relatively isolated population of swordfish exists in the SW Pacific. Consequently, a biological model can be built for this species which can to a large extent ignore the degree of mixing with other swordfish populations in the Pacific. Secondly, the MSE is a useful approach for swordfish in the SW Pacific as the current status of the stock remains unknown. Hence, various current states of stock depletion can be examined via this approach.

The situation for bigeye tuna is, however, quite different. In the first instance, tagging and genetic studies indicate a single stock throughout the entire Pacific (Grewe and Hampton 1998). Additionally, although analysis of tagging data indicates the possibility of a degree of localised temporal residence by components of the stock, the fact that there is relatively high degree of mixing between different areas is not disputed (Hampton and Gunn 1998). Given, then, the fact that the stock range and potential areas of mixing are so large for bigeye, the utility of the MSE approach is likely to be compromised, as the uncertainty due to these factors is likely to dominate any attempt to understand the dynamics of the resource solely within the SW Pacific. Despite this, basin wide stock assessment models for bigeye tuna in the Pacific have now been developed and the results, together with MSY estimates, have been reported to recent meetings of the Standing Committee on Tuna and Billfish (Hampton et al, 2003). Given, this situation, a different approach was developed to identify potential sustainable catches of bigeye tuna (and yellowfin tuna) in the ETBF and SW Pacific regions. This approach is outlined in Chapter 8.

1.5 Consultation with Eastern Tuna FAG

The ETBF Fisheries Assessment Group (FAG) provides advice to AFMA and Eastern Tuna MAC on the status of target and by-catch species taken in the ETBF and the annual performance of the fishery. During the development of the management plan for the ETBF, this group also provided a forum for the discussion of issues of relevance to that plan. In particular, with the adoption of the MSE approach for the evaluation of harvest strategies, it was important that the FAG be kept informed and educated on the project and its results. Consequently, the project team has solicited advice from the FAG on a number of issues related to the development of the operational model and other needs of the project and reported progress back to the FAG at subsequent meetings. Due to the complexity of the model and the range of issues involved in the evaluation of harvest strategies, this has been a lengthy process, and there has been a ongoing need to educate members of the FAG on all aspects of the project. In return, the FAG has provided a useful forum for the discussion of aspects of the project and has been a vital source of information on details of the fishery required for development of the operational model, the types of performance indicators to be considered, and the range of harvest strategies to be evaluated. Below, we briefly outline the interactions between the project team and the FAG during the life of the project. Full descriptions of discussions are contained within the relevant minutes of each meeting.

April 2001

The project was initially outlined to the FAG. Tony Smith (CSIRO) gave a presentation on Management Strategy Evaluation (MSE) and how the MSE approach works in fisheries management. The FAG was informed that the MSE approach allows the performance of alternative candidate harvest strategies to be compared relative to the objectives for the fishery. The actual harvest strategy for a fishery is then selected by all stakeholders from those harvest strategies that achieve satisfactory performance relative to the management objectives for the fishery. The process of comparing and selecting harvest strategies is therefore transparent to all participants, and allows stakeholders to be pro-active when dealing with future management of a resource.

Robert Campbell gave a presentation on needs related to the development of the operational model. The FAG discussed a number of issues relevant to modeling the swordfish resource in the SW Pacific, including stock structure, movement dynamics, natural mortality rates and other biological parameters relevant to the population dynamics of swordfish. Historical data needed to condition the operational model was also discussed, including data that is available from catch and effort logbooks, size monitoring programs, and tagging results.

March 2002

A number of presentations reporting progress on the project were given. First, details on development of the operating model were explained and discussed, including the current uncertainties in our knowledge and how these uncertainties would need to be incorporated across a range of operational models. It was also explained that the process of conditioning uses the data and information at hand to identify those parameter combinations or assumptions which are most compatible with historic observations. Secondly, some preliminary results were presented and used to illustrate the manner in which a range of values for some biological processes (ie. the steepness parameter in the stock-recruitment relation) are required to model uncertainty. It was also explained how a number of stochastic simulations (usually 100) are carried out during each projection period, and how the results are summarized in terms of quantities such as mean (or median) and the 5th and 95th percent quantiles. There was also a discussion about which variables are most appropriate for reporting the results (ie. total catches, year-to-year variability in catches, spawning biomass, etc).

Finally, a brief overview of the relationships and differences between performance indicators, performance measures, decision rules and management objectives was provided. Discussion focused on the need to have both economic and conservation based management objectives and related performance measures. Several types of conservation performance measures were reviewed, such as the probability that the SSB remains above 30% of the unexploited SSB. It was also suggested that some measure of size of fish in the catch may be more informative as an economic performance measure than aggregated catch. The FAG also noted that issues relating to economic objectives, as contained in AFMA's list of objectives, are complex, and ways in which economic objectives could be incorporated into an MSE framework may be a topic for consideration by the AFMA Economics Group.

July 2002

An interactive session was conducted to obtain feedback from the FAG regarding the final parameterization of the operational model, the choice of performance indicators and measures, and a range of future effort scenarios to be tested.

Industry members provided information relevant to the parameterization of retention practices and predation of hooked fish. It was suggested the 5-10% of the total catch was lost to shark or cetacean mauling, with larger (>50kg) fish being more susceptible to mauling. Mauling was considered to be seasonal, and there may be some information on mauling rates from observer data. It was agreed that all fish less than 10-15kg in weight were discarded, whether alive or not, and that fish from 15-25kg and above were retained. The biological uncertainty in the population dynamics of swordfish was also reviewed and a range of parameters to model this uncertainty was agreed on. It was also agreed that in order to model the uncertainty in the current status of the swordfish stock, that the range of depletions to consider at the end of the historical conditioning period should be 15%, 30% and 50%.

A document providing an illustrative example of aspects of various decision rules and reference limits was also circulated and discussed. The aim of this document was to explain how decision rules could be used within a management framework. The industry members of FAG were asked for CPUE levels below which they would not wish to drop in an economic sense. It was explained that the size of the fish is also important in such decisions (catching three large fish per set may be acceptable while three small fish may not). It was suggested that 55kg is the average mean weight fishers would desire when targeting swordfish, and that 8-10 swordfish of this size per 1000 hooks would be the minimal acceptable catch rate, with less that 8 swordfish per 1000 hooks a marginal CPUE. In order to develop economic performance indicators based on size of fish, it was agreed that three size classes would be appropriate: 0-25kg, 25-50kg and 50+ kg. In the middle of the moon (i.e. on an average market), prices corresponding to each size class are approximately $4-5/kg, $6-7/kg and $10-12/kg, respectively.

Finally, the FAG was requested to consider a range of future effort scenarios to be evaluated. This needed to include future effort scenarios for both the foreign and domestic fleets. A number of scenarios were discussed, together with the need to model effort creep (increases in effective effort due to the introduction of new fishing practices or equipment). An agreed list of future effort scenarios (including an effort creep of 5% per annum – later adjusted to 2%) was chosen for evaluation. This list formed the basis of the fixed effort scenarios described in Chapter 6.

Based on the above agreed outcomes, several illustrative model runs were completed and discussed over the course of the meeting. Time series plots of i) relative spawning biomass and ii) mean and upper 95th percentiles of average fish weight, and histograms of i) the average annual catch, ii) final spawning biomass relative to initial spawning biomass, and iii) the probability that the spawning biomass dropped below 30% of its initial level, were presented.

December 2002

A full summary of the operating model and the approaches used for evaluating alternative harvest strategies was presented to the FAG. A number of technical issues were also explained in some detail in order to help clarify aspects of the modeling process. A presentation and discussion of preliminary results completed to date for a number of alternative biological and future fixed effort scenarios was also given and discussed These results were also presented to the ETBF Effort Setting Workshop which was held during the following two days. (Note: these results were included in the presentation made by the chair of the *TAE* Setting Workshop to the AFMA Board during February 2003 on the outcomes of the workshop.) A final presentation and discussion then focused on aspects of the decision rules which will be evaluated by the model. Two types of decision rules were explained and illustrated. The first is based on empirical observations (such as changes in nominal or standardised CPUE) while the second is based on outputs of an assessment model (eg. estimates of current biomass). Due to the current lack of an age-structured assessment model for swordfish in the SW Pacific, and the difficulties of constructing such a model in the short term, the assessment model used in the operating model is a simple production model.

March 2003

A full presentation of the results of the evaluation of fixed effort harvest strategies was given to the 2nd ETBF Effort Setting Workshop. These results were also an important input into the FAG meeting held on the following two days to review advice on determination of an initial *TAE* in the ETBF. Again, these results were also part of the summary presentation to the AFMA Board on the outcomes of the workshop and the FAG.

July 2003

An outline of the project, the methods and a sample of results were presented to the 16th meeting of the Standing Committee on Tuna and billfish, held 9-17th July in Mooloolaba, Queensland.

A listing of working papers generated during the course of the project is given in Appendix C.

1.6 Outline of Report

Given the different approaches for assessing sustainable harvest strategies for swordfish and bigeye tuna, this report is divided into several independent sections. The first section, presented in Chapter 2, contains an overview of the biology of swordfish and bigeye tuna. The evaluation of harvest strategies for the capture of swordfish in the SW Pacific is then presented in the second section. This consists of a detailed summary of the available data (Chapter 3) and a detailed description of the operating model for swordfish in the SW Pacific (Chapter 4). An evaluation of the robustness of harvest strategies to uncertainty in our present knowledge about the population dynamics and status of the swordfish population is given in Chapter 5, while the evaluation of a range of fixed effort harvest strategies is given in Chapter 6. This section concludes with a discussion of various decision rules in Chapter 7. In the third section, a presentation of the methodology and results for assessing sustainable catch levels across several regions of the Pacific Ocean is presented (Chapter 8). Finally, the report concludes with a short summary of the main results and suggestions for future research in Chapter 9.

Chapter 2: Review of Species Biology

2.1 Introduction

The first stage in developing an operational model for the swordfish fishery off eastern Australia involves specifying the population dynamics of the swordfish resource in the SW Pacific region and identifying those aspects about which there exist uncertainties. In order to account for these uncertainties, a suite of operational models will be required in order to encompass the range of biological hypotheses which are considered plausible for the population dynamics of this species. In this chapter we therefore provide a review of the stock structure and biology of swordfish in the Pacific and in light of this review consider the spatial framework of the operational model. We also review the stock structure and biology of bigeye tuna and explain why an alternative approach (described in Chapter 8) was adopted for this species.

2.2 Distribution and Stock Structure

The spatial distribution and stock structure of each species is used to define the spatial domain of the operational model and impose restrictions on the interchange and movements of each species between sub-regions in the model.

2.2.1 Broadbill swordfish

Broadbill swordfish are widely distributed, occupying the tropical, temperate and sometimes cold waters of all oceans. They occur between 50°N and 45°S in the western Pacific. They have a broad temperature tolerance of 5°C to 27°C, and are usually associated with surface temperatures is excess of 13°C (Nakamura 1985). They appear to concentrate in areas where food is abundant, commonly along frontal zones where ocean currents or water masses intersect to create turbulence and sharp gradients of temperature and salinity. The fisheries for swordfish usually occur in these regions (Palko et al, 1981, Sakagawa 1989).

A daily movement cycle, where they swim close to the surface at night before returning to depths of up to 600m during the day, imposes daily temperature changes of up to 19°C (Cary and Robinson 1981, Carey 1990). Spawning generally takes place in tropical and sub-tropical waters where surface temperatures are above 20^{o}C. Juveniles are confined to the tropical or sub-tropical regions for at least their first year, and migrate to higher latitudes as they grow (Gorbonova 1969, Yabe et al, 1959). Females attain a larger maximum size than males (most fish longer than 180cm are female). Consequently they tolerate colder water and hence occupy the highest latitudes of the range. The smaller adult males have a more tropical and sub-tropical distribution.

Off eastern Australia, swordfish predominately occur in oceanic waters where the warm East Australian Current meets intrusions of the cold Southern West Wind Drift Current (Sakagawa 1989). The existence of frontal zones and associations with seamounts are also important in determining distributions within the eastern AFZ. Catch rates of swordfish off southern Queensland are highest in the third quarter (July-September). Peak catch rates display a southerly movement over the summer months with catch rates south of Sydney being highest during the first quarter (January-March) (Campbell 2000). Although the 13^{o}C isotherm is well south of Tasmania at the end of summer, swordfish catches in this region are not common. Larvae have been found off northeastern Queensland and at the edge of the AFZ between 20-30^{o}S (Nishikawa et al 1985). In some years, small juveniles (1-15kg) have been reported from continental shelf waters off central and southern NSW (Caton et al 1998).

Across the Pacific Ocean, swordfish have three areas of high catch rate: in the north-west, east and south-west Pacific (cf. Figure 2.1). Seasonal distributions can be inferred from catch rates, but little is known of swordfish movement patterns (Campbell and Miller, 1998). No large scale tagging studies have been undertaken for swordfish in the Pacific Ocean, and until recently little work has been done to investigate the Pacific stock structure; however, larvae have been found in a number of widely distributed areas. There are two major stock hypotheses: (i) three separate stocks centred on the regions of high catches, and (ii) a single Pacific-wide stock. Identification of spatially or temporally discrete spawning areas has been difficult because of the long spawning season, the widespread areas in which larvae have been found, and the variety of methods used to survey the ichthyoplankton (Grall et al 1983). Nonetheless, seasonality in the abundance of larvae and reproductive adults is evident in the northern and southern Pacific and suggests some population subdivision (Palko et al 1981, Grall et al 1983, Young et al 2000, Sun et al 2000).

Results of a recent genetics study support population subdivision within the Pacific Ocean (Reeb et al 2000). The results indicates a -shaped pattern of genetic connectivity in the Pacific with northern and southern populations in the eastern Pacific being genetically continuous while those in the west (Japan and eastern Australia) having diverged. This pattern outlines a system of equatorial currents in the Pacific around which swordfish appear to migrate. However, the results leave two hypotheses that involve very different strategies of fisheries management. The first hypothesis states that there are at least two distinct populations of swordfish in the Pacific with range overlap in the east. The second hypothesis suggests that the six sampled populations are representative of several subpopulations interconnected by gene flow among neighbours. While the first hypothesis requires the two stocks be separately managed, the second leaves open the possibility that stock depletion through overfishing would be eventually overcome through migration from neighbouring sub-populations. However, the distribution of larvae and catch data lends stronger support to the first hypothesis.

Further subdivision of the swordfish populations into three or more stocks under the first hypothesis remains uncertain. However, the spatial distribution of Japanese longline catch rates may indicate at least three populations. Indeed, the apparent separation of the region of high catch rates in the SW-Pacific from the other regions supports a hypothesis of a separate regional stock of swordfish in the this region. This is also supported by a separate genetics study reported by Bremer et al (2001) and the spatial and temporal separation of high densities of larval swordfish found in this region (Nishikawa et al, 1985) However, genetic studies have been unable to distinguish the swordfish occurring off the west and east coasts of Australia (Reeb, pers comm). Longline catch data indicate a relatively continuous distribution of swordfish around southern Australia though the low catch rates despite substantial longlining effort suggest that there may be little interchange between the eastern and south-western AFZ (Campbell and Miller, 1998; Campbell et al., 1998). The interchange of swordfish across northern Australia is less likely due to the warm and shallow waters within this region.

2.2.2 Bigeye tuna

Bigeye tuna inhabit the tropical and temperate waters of the Pacific Ocean between 40°N and 40°S. In the western and central Pacific, Japanese catch rates indicate several east-west bands of high abundance in temperate waters around 35°N and in the tropics between 10°N and 10°S. Bigeye tuna can tolerate a lower dissolved oxygen concentration than other tunas and hence are more tolerant of lower temperatures and are caught in deeper waters. Temperatures above 17°C are preferred, but provided the dissolved oxygen concentration exceeds 1.0mg/l, temperatures down to 10°C can be tolerated (Hanamoto, 1987). Indeed, adults tend to inhabit the thermocline (~150-200m in tropics) where temperatures are approximately 10°C. Generally, bigeye are found at depths of at least 250m during the day, but make regular brief

Figure 2.1. Mean distribution of annual nominal swordfish CPUE within each 5x5-degree square of latitude and longitude for Japanese longliners for the years 1962-2000.

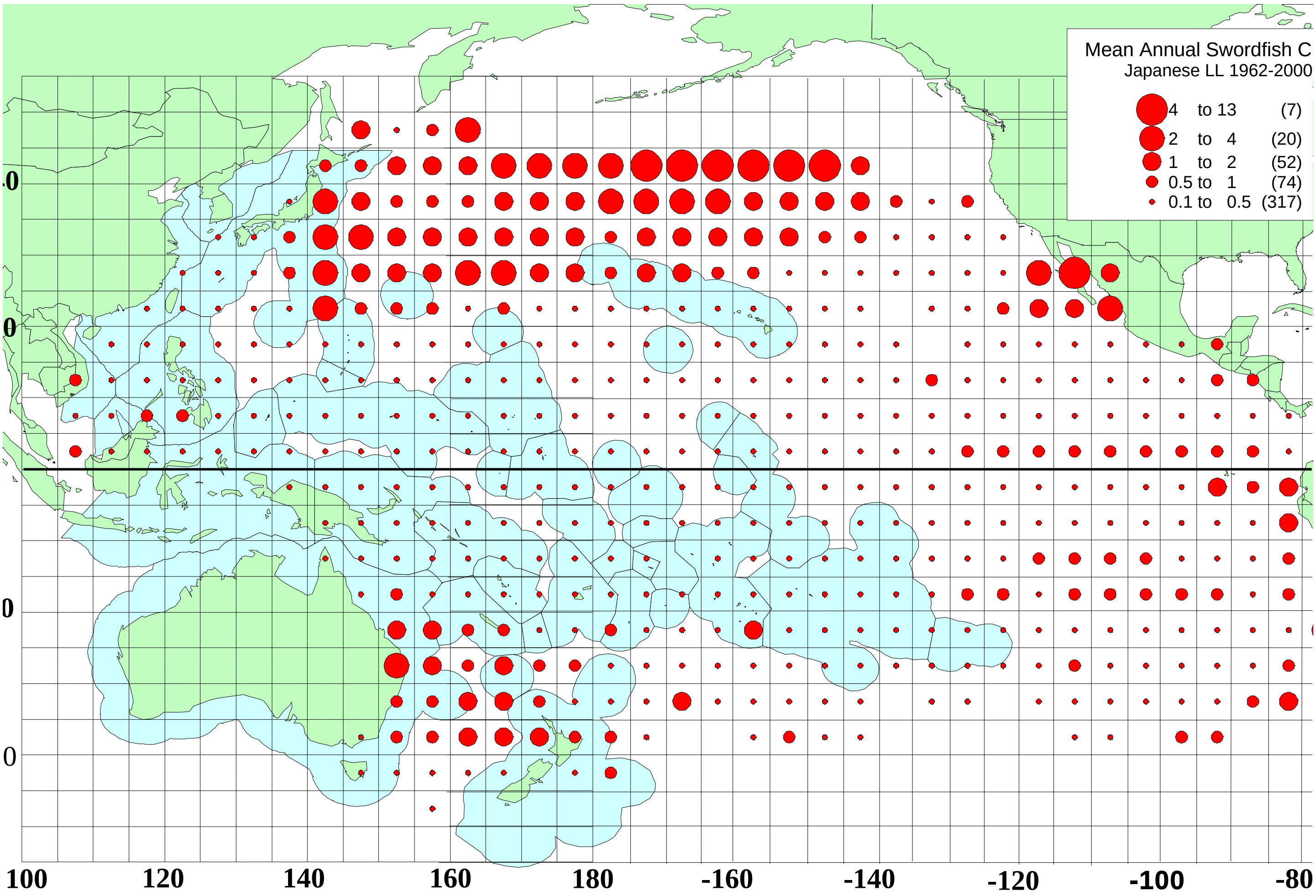
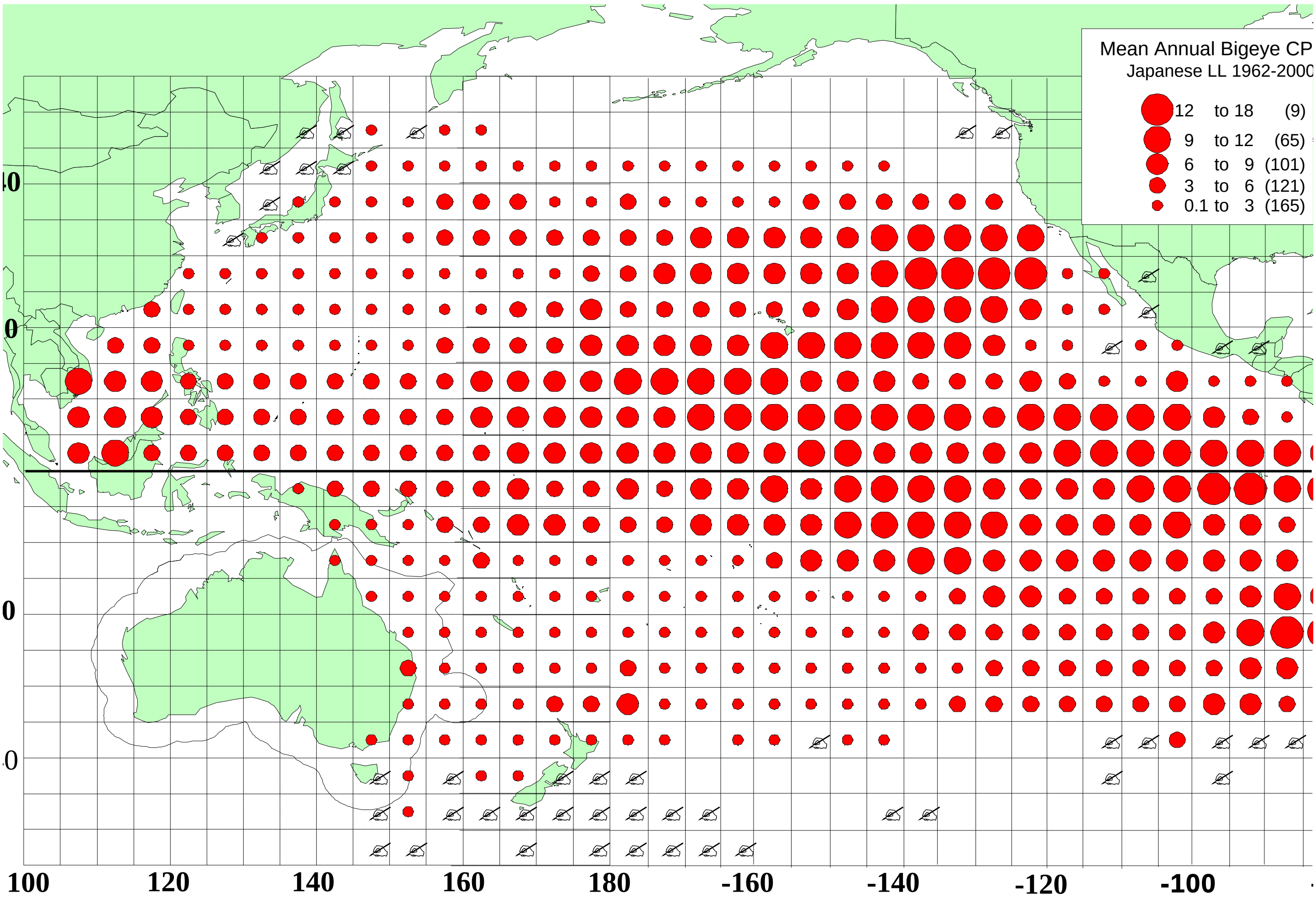


Figure 2.2. Mean distribution of annual nominal bigeye CPUE within each 5x5-degree square of latitude and longitude for Japanese longliners for the years 1962-2000.



excursions to the bottom of the mixed layer during the day to thermoregulate (Holland et al 1990).

The majority of the WCPO bigeye catch is taken in two longitudinal bands: equatorial waters between 15°S and 15°N, and temperate waters north of 25°N (cf. Figure 2.2). In these areas shallow thermoclines, in association with optimal water temperatures at the thermocline, render bigeye more vulnerable to longline gear (Hampton et al 1998b). Off eastern Australia bigeye show a distinct seasonal cycle in availability to the longline fishery. The movement of fish south from northern NSW appears to the related to the seasonal movements of the East Australia Current. They are rarely caught south of 40°S.

The degree of stock structure of bigeye tuna in the Pacific presently remains uncertain and two possibilities are hypothesized: i) a single Pacific-wide stock, and ii) overlapping (western/central and eastern) sub-populations. The overlapping stocks hypothesis is supported by the existence of three larval concentration areas and an apparent scarcity of larvae in the central Pacific. Also, the tagging data suggest that movement of bigeye from the western Pacific to the eastern Pacific is not extensive. On the other hand, the lack of a strong discontinuity in longline catch rates for bigeye across the Pacific and genetic studies suggest little differentiation across the Pacific basin and favour a Pacific-wide hypothesis (Grewe and Hampton, 1998, Hampton et al, 1998b).

2.3 Population Dynamics

2.31 Broadbill swordfish

The operating model will explicitly consider the age-structure of the swordfish population together with the reproductive dynamics of the stock. Here we outline the source of the parameter values that will be used in the model. A summary listing of relevant population dynamics parameters adopted for swordfish in the SW Pacific is given in Table 2.1.

Age and Growth

Due to the lack of tagging studies on broadbill swordfish, age and growth rates are poorly understood. One-year old fish range from 50-60cm in eye-fork length, and beyond 2 years of age females grow faster than males. Most fish longer than 180cm are female. While the maximum age of swordfish in the Indo-Pacific remains unknown, fish have been recorded up to 445cm and 540kg (Nakamura, 1985). In the Atlantic Ocean, life-span estimates are 14 and 32 years for males and females respectively (Radtke and Hurley, 1983).

Joseph et al (1994) provide information on length-at-age. For the purposes of this study the estimates based on the study by Berkely and Houde (1983) using anal fin spine sections from fish caught in the Straits of Florida were used. Separate male and female von-Bertalanffy parameters were used in Punt et al (1999) and this difference is retained in the present study (*see section 4.1*).

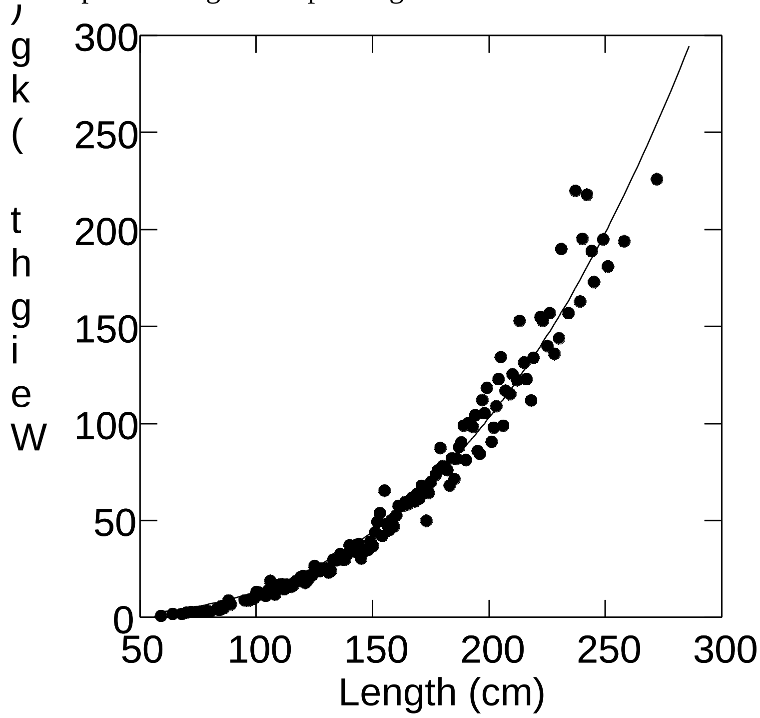
Weight-length relationship

Information on length versus weight for swordfish was obtained from the data collected by Australian observers placed on board Japanese longliners fishing within the eastern AFZ, and stored in the database on tuna fisheries managed by CSIRO Marine Research (Betlehem et al 1998). While data on a range of length and weight measurements are available, the largest amount of data related lower jaw to fork length and whole weight, and was available for 416 fish. A plot of the relation between these measurements is shown in Figure 2.3. The parameters in the relation $W=aL^b$ were obtained by fitting this curve to the data by least squares.

Table 2.1 Values for the biological parameters relating to broadbill swordfish.

Quantity	Values	Reference
Growth parameters		Berkely and Houde, 1993
- Male: L_∞	217.36	
k	0.1948	
t_o	-2.0444	
- Female: L_∞	340.04	
k	0.09465	
t_o	-2.5912	
Weight-at-Length		Punt *et al*, 1999
$\tilde{a}$	$2.1355\ 10^{-5}$	
$\tilde{b}$	2.902	
Natural mortality - *M*	Age-specific See Table 2.2	Yabe *et al*, 1959: Joseph *et al*, 1994 Preece (pers comm.)
Maturity Ogive - Females		
a	8.129	Young and Drake, 2002
b	-0.041	
- length at 50% mature	199.8 cm OFL	
- age at 50% mature	9-10 years	Young, 2003
Steepness	0.9	Punt et al, 1999
Sex ratio	1:2.5	Young and Drake ,2002

Figure 2.3 Length-weight relationships for swordfish based on data collected by Australian observers on board Japanese longliners operating within the eastern AFZ.



Natural mortality

Information on the annual natural mortality was obtained from a recent review of the biology and fisheries for swordfish in the Pacific Ocean (Joseph et al 1994). A range of estimates of natural mortality rates are given (0.12 to 0.43), though most of these studies relate to swordfish caught in the Atlantic Ocean. The average annual rate from these studies is 0.24. Yabe et al (1959) provide the only estimate of natural mortality (0.22) for swordfish in the Pacific Ocean.

More recent studies also indicate that natural mortality rate for tropical tunas and billfish are size or age specific (Hampton, 2000). Age-specific mortality vectors estimated for southern bluefin tuna also support this (A. Preece, pers. comm.). Based on the age-independent value reported by Yabe *et al* (1959) and age-specific natural mortality vectors for southern bluefin tuna, and given that swordfish are a long-lived species like southern bluefin tuna, the natural mortality vector assumed for swordfish in the SW-Pacific is given in Table 2.2.

Table 2.2 Assumed natural-mortality-at-age assumed for swordfish in the SW Pacific.

Age	Natural mortality
1	0.3
2	0.285
3	0.27
4	0.255
5	0.235
6	0.22
7+	0.2

Reproduction

Spawning is believed to occur year-round in equatorial regions and during spring-summer in higher latitudes, generally occurring in waters above 24°C (Nishikawa and Ueyanagi 1974). Within the SW-Pacific, larval have been observed off Queensland (up to PNG), northern NSW and extending further offshore to Vanuatu (Caton *et al* 1998). A recent study undertaken by CSIRO on the spawning dynamics of swordfish occurring off eastern Australia indicated an extended spawning season over summer (October-May), with an increase in the average size of fish during this period as larger females migrate into the region (Young and Drake, 2002).

Figure 2.4 Maturity ogive for female swordfish (Young and Drake, 2002).

According to Yabe et al (1959), swordfish first reach maturity at 5 to 6 years of age, when they are 150 to 170 cm in length, while a plot of gonad index versus length for female swordfish indicates a sharp increase in the gonad index for fish between 160-170 cm in length (Nakano and Bayliff, 1992). Di Martini (1999) gives an age-at-first maturity for females of 140-180cm. The results from the detailed study off eastern Australia indicated a minimum size of maturity for females at 156cm (Young and Drake, 2002). This study also obtained maturity ogives for female broadbill swordfish by fitting a logistic equation, $p(L) = 1/(1+exp(a+bL))$, to a scatterplot of percent mature, *p versus* orbital fork length, *L* (Figure 2.4). Sexual maturity was determined using histology to evaluate the state of the gonads, which is a more reliable method than the use of a gonad somatic index. The results found that the length at which 50 percent of females reached maturity was 199.8cm. A more recent aging study indicates that these fish are around 9-10 years old (Young, pers. comm.).

<u>Sex ratio</u>

There are few data describing the sex ratios of swordfish from commercial catches in the Pacific or elsewhere. For the Hawaiian longline fishery, the overall sex composition of catches sampled across all areas and seasons was indistinguishable from unity (0.495 males: 0.505 females), though swordfish sex ratios (males as percentage of total fish) decreased with latitude. Due to the sexual dimorphism in growth and distribution, the sex ratio is female biased (0.46) north of 26°N, but male biased (0.62) at and below 26°N (DeMartini, 1999). Data from 2,331 swordfish sampled by Australian observers on board Japanese longliners fishing within the eastern AFZ indicated a male to female ratio of close to 1:3, while results from the CSIRO study off eastern Australia indicate that for fish of length >90cm, the sex ratio is approximately 1:2.5, though there is some variation between seasons (Young et al 2002). While the proportion of males to females was found to be relatively constant up to 170cm, the proportion of males decreased for larger fish.

2.3.2 Bigeye tuna

A summary listing of relevant population dynamics parameters adopted for bigeye tuna in the SW Pacific is given in Table 2.2.

<u>Age and Growth</u>

Bigeye tuna can achieve lengths in excess of 200cm, however, bigeye longer than 180cm are rarely caught in Australia. Aging processes are uncertain, but studies suggest that their lifespan may be greater than 10 years (Hampton et al, 1998b), although a 6-7 year lifespan was suggested for bigeye around Hawaii (Whitelaw and Unnithan, 1997).

A range of von-Bertanffy growth parameters for the Pacific Ocean are summarised by Miyabe and Bayliff (1998). However, more recent analysis of the incremental growth of 264 bigeye recovered as part of the Regional Tuna Tagging Program (RTTP) undertaken by SPC, together with daily otolith readings from another 149 fish, has resulted in a modified von-Bertalanffy (MVB) growth model, with evidence of a slowing of growth at 60cm (Lehodey et al., 1999). The MVB model introduces a variation of K according to a normal distribution. This is achieved by replacing K by K-N(t) where:

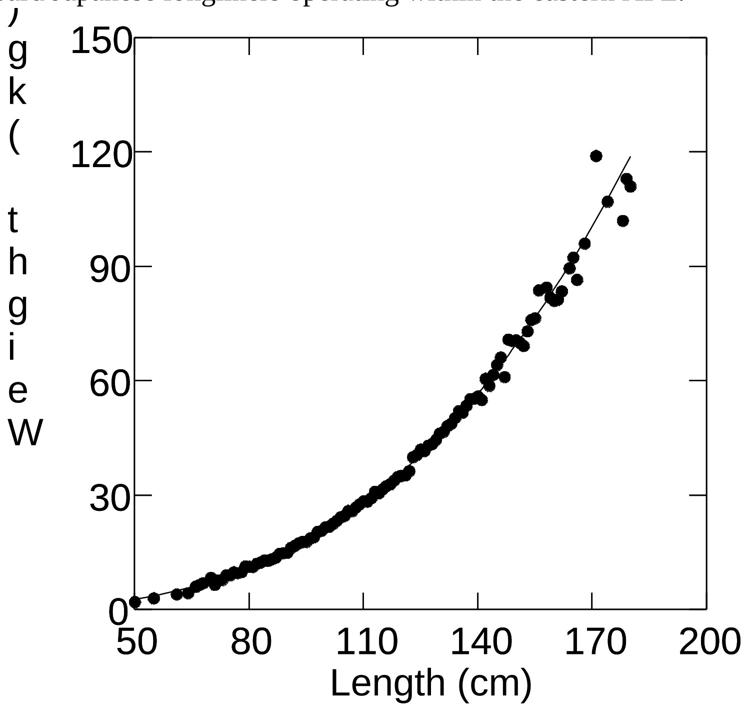
$$N(t) = \frac{a}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(t - t_m)^2}{2\sigma^2} \right]$$

and where a = 0.02, σ = 0.25 and tm = -0.28. The other parameters in the von-Bertalanffy model are given in Table 2.2.

Table 2.2 Values for the biological parameters relating to bigeye tuna.

Quantity	Values	Reference
Natural mortality - *M*	0.4 – 0.8	Anonymous 1998, Hampton 2000
Selectivity – S_L		I-ATTC 2000, Hampton and Fourier 2000
Growth parameters		Lehodey *et al*, 1999
L_∞	166.3	
k	0.349	
t_o	-0.389	
Weight-at-Length		Observer data
$\tilde{a}$	2.6696 10^{-5}	
$\tilde{b}$	2.948	
Sex ratio	1:1	Observer data
σ_r	0.4	Punt et al, 1999
Steepness	0.9	Punt et al, 1999
Age-at-maturity	2-3 years	Yabe *et al*, 1959
Length-at-maturity	100 cm	Lehodey *et al*, 1999
Plus-group age, *x*	10 yr	

Figure 2.4 Length-weight relationships for bigeye tuna based on data collected by Australian observers on board Japanese longliners operating within the eastern AFZ.



Weight-length relationship

Information on length versus weight for bigeye tuna was obtained from the data collected by Australian observers placed on board Japanese longliners fishing within the eastern AFZ, and stored in the database on tuna fisheries managed by CSIRO Marine Research (Betlehem et al, 1998). Data relating caudal fork length to whole weight was available for 1,892 fish. After the removal of some outliers in the data, a plot of the relation between these measurements is shown in Figure 2.4. The parameters in the relation $W=aLb$ were obtained by fitting this curve to the data by least squares. These parameters can be compared with those summarised for the Pacific Ocean by Miyabe and Bayliff (1998).

Natural mortality

Estimates of natural mortality for bigeye tuna in the Pacific have been summarised by Miyabe and Bayliff (1998). An early estimate of M = 0.361 yr^{-1} was obtained by Suda and Kume (1967) based on analysis of catch-at-age data for the longline fishery during 1957-64. More recently, several estimates of natural mortality have been obtained from analyses of RTTP tagging data (Hampton et al 1998b). An order of magnitude decline in M was found between small (21-40cm) and larger sizes and suggests that natural mortality may be age-dependent. Natural mortality was found to vary between 0.15 and 0.90 yr^{-1} for size-classes >40cm, which compares with the range of 0.4-0.8 most often used in bigeye tuna stock assessments (Anon 1998). Estimates of natural mortality have also been obtained from the application of the Multifan-CL stock assessment model to bigeye tuna in the Pacific, with the results being similar to those obtained from the tagging data alone.

Reproduction

Bigeye tuna spawn in the tropics of the eastern and western Pacific. Larvae are found between 30°N and 20°S in the western Pacific and between the equator and 20°N in the eastern Pacific. Bigeye are serial spawners, spawning every 1-2 days over several months. Females are sexually mature at 100-125cm (3+ years) in the north-west Coral Sea, but there have been reports from other regions of maturity at 67cm (Whitelaw and Unnithan, 1997). They spawn in the summer months (ie April-September in the northern hemisphere and January-March in the southern hemisphere).

In the north-west Coral Sea, they aggregate and spawn at full moon periods from October to January. However, an extended spawning season with peaks in March and June, with daily spawning intervals, has been postulated. The spawning aggregations are associated with myctophid spawning in frontal regions with sea surface temperatures of 25-26°C. The Coral Sea spawning may be a major internal source of recruits to the SW-Pacific region. No spawning is known to occur along the southern AFZ, and hence replenishment depends on migrations which are usually associated with the seasonal movement of the East Australia Current (Campbell and Miller, 1998).

Sex ratio

There is no evidence of sexual dimorphism in bigeye tuna. However, an examination of sex ratio data from the Pacific longline fishery shows a general predominance of male fish over most of the size range studied, with the dominance of males becomes more prominent as the size increases (see Hampton et al, 1998b). However, a study of bigeye caught in the South China Sea found a sex ratio close to 1:1, with the proportion of males increases for fish greater than 146cm (Sun et al, 1999). Also, data from 4,035 bigeye tuna sampled by Australian observers on board Japanese longliners fishing within the eastern AFZ indicates a male to female ratio of close to 1:1.

2.4 Oceanographic Influences

The two major current systems influencing the eastern AFZ are (i) the western Pacific circulation (which brings warm, nutrient poor tropical water onto the NE coast and supplies the southerly flowing East Australia Current); and (ii) the sub-antarctic water of the West Wind Drift (which brings cool, nutrient rich water into southern region). The region off eastern Australia, therefore, covers a diverse oceanography ranging from tropical oligotrophic waters of the Coral Sea in the north to a mixture of tropical and sub-antarctic waters in the south. Linking much of the waters of the fishery is the East Australia Current (EAC), which has its origin as an offshoot of the Coral Sea and extends as far south as the east coast of Tasmania. The strength of this current is determined by both seasonal and interannual factors. In the Australian summer the EAC is at its strongest and pushes as far south as the southern tip of Tasmania where it finally dissipates into the waters of the subtropical convergence. In the winter it retreats northward as the winter westerly winds drive sub-antarctic waters northwards. Interannual variations can be more pronounced. El Nino years produce relatively weak currents as the equatorial waters feeding the western Pacific are at their weakest. In contrast, La Nina years appear to be characterised by higher temperatures along the eastern seaboard and extent further south.

Although the linkages and mechanisms are not well understood, it is considered that oceanography primarily determines (i) the timing and extent of seasonal movement of fish; (ii) the location, timing and possibly the intensity of breeding by bigeye and swordfish off eastern Australia; and (iii) the extent of transportation and movement of fish between the AFZ and the wider western Pacific (Campbell and Miller, 1998). Studies relating seasonal changes in abundance, as inferred from catch rates, and changes in the regional oceanography need to be undertaken to better understand the above linkages.

Critical habitats for bigeye tuna and broadbill swordfish in the SW-Pacific remain uncertain, but the interaction of oceanic circulation and nutrient input from coastal rivers drives the productivity of the Continental Shelf, and hence the aggregation of prey. ENSO events are also important, as they periodically strengthen and weaken the tropical influence on the east coast. El Nino event imply a weakly developed tropical influence so that cool water extends further north, while La Nina years confer a strong flow of tropical water, strengthening the EAC and extending warm water further south (Campbell and Miller, 1998). There also appears to be an 11-year cycle associated with the strength of westerly winds.

Fronts and convergence zones are also important in determining species distributions. Large persistent eddies and fronts (ie the Tasman Front) are sites of prey production/aggregation and commonly used by fishers as a targeting strategy. The seabed topography (even at hundreds of meters depth) also has a strong influence on tuna and billfish abundance, presumably via the generation of local circulation structures (Campbell and Hobday, 2003). There is also a positive correlation between CPUE and geostrophic velocitites, whereby high catch rates occur in proximity to eddies and meanders which constitute the frontal zone (Olson and Polovina, 1999).

2.5 Tagging and Movement Data

Due to the spatially explicit nature of the operating model, it will be important to understand the seasonal movement patterns of the fish resources within the SW-Pacific region. Tagging fish allows the direct observation of the movement of fish. However, there has been limited tagging of bigeye tuna within the eastern AFZ, and to date there has been only a small industry based tagging project for swordfish with only 3 returns. Consequently, there is currently limited knowledge of movement of tuna and billfish off the east-coast of Australia. Nevertheless, movement of fish can also be inferred from seasonal changes in catch rates. In this section we briefly summarise the information that will be helpful in ascertaining movement patterns both within the eastern AFZ ands the larger SW-Pacific region.

2.5.1 Tagging data for Bigeye Tuna

The SPC tagged 8,074 bigeye from 1990-1992 as past of the Regional Tuna Tagging Program (RTTP) within the western central Pacific Ocean. By September 30 1996, 937 recaptures had been reported, mostly from 3 locations: the Philippines (small fish), the Coral Sea and the Gilbert Islands (medium-sized fish). Many fish moved extensively throughout the WCPO; several tagged in the Coral Sea were recaptured in the central Pacific east of 180°, and 2 individuals had displacements >4000 nm in 4 years. Approximately 25 percent of displacements were >200nm, and about 5 percent were >1000nm. In some locations, most notably the Coral Sea, 82 percent of recaptures were in the release area up to 5 years later. Thus there appears to be some residency despite the capacity for long-distance movement (Hampton et al 1998b, Sibert and Hampton 2003). Interestingly, none of the bigeye tagged within the equatorial Pacific were recaptured with the eastern AFZ. Whether this is due to a lack of movement of fish into the eastern AFZ from the equatorial WCPO, or due to the limited amount of effort in this region, remains unclear.

As part of the RTTP, 4,277 bigeye were tagged and released in the Coral Sea during October to November of 1991 and November 1992. By the end of 1996, 192 recaptures had occurred, most of which were in the release area (Hampton and Gunn 1998). Recapture data also showed radial movement of fish from the north-west Coral Sea into adjacent WCPO areas, supporting the hypothesis of a single pan-Pacific stock, as well as southerly movement by a portion of bigeye. Thus clear links between tuna stocks in the western tropical Pacific were demonstrated.

A combined CSIRO/SPC conventional/archival tagging project for bigeye tuna commenced in the Coral Sea in 1999. Tagging was carried out over two seasons (1999/2000 and 2001/2002) and to date 56 conventional tags have been returned from a total of 269 releases and 14 archival tags have been returned from a total of 161 releases. While both eastward and north/south movements have been observed, the latter predominate. Observations from the archival tags indicate an initial rapid southward movement at around the time of the spring equinox and then a corresponding northward movement at around the time of the autumn equinox. While the data indicates movement from the tagging grounds to areas around New Britain, the Solomon Islands and New Caledonia, no tags have yet been returned from fish which have moved out of the broader Coral Sea region, unlike returns reported during the RTTP (Gunn and Clear, 2003)

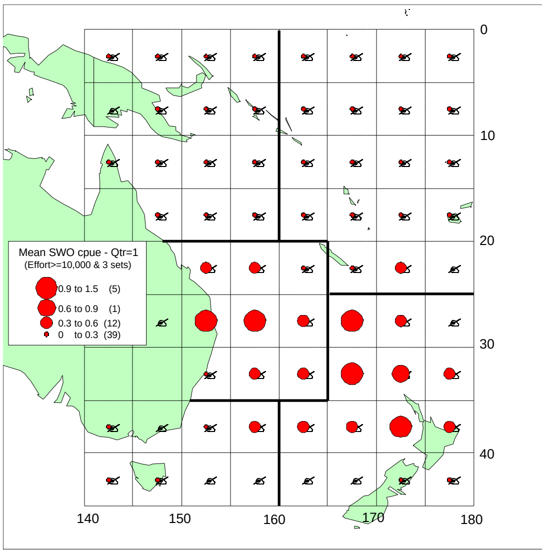
2.5.2 Distributions of CPUE

Quarterly 5-degree square nominal catch rates for both swordfish and bigeye tuna obtained by the Japanese longliners operating in the SW-Pacific are shown in Figures 2.5 and 2.6 respectively. For each quarter, the data are averaged over all years between 1971-99. Shifts in the spatial distribution of the populations may be inferred by shifts in the spatial distributions of catch rates. For example, the region of highest catch rates for swordfish is located within the eastern Tasman Sea (off north-west New Zealand) between April and June, and shifts to the central eastern AFZ during October to December. The catch rates are more evenly distributed between these two regions during the other seasons. From this seasonal pattern of catch rates, one may infer a seasonal movement of swordfish across the Tasman Sea, though the reasons for these migrations presently remain unknown.

The spatial and temporal distributions of catch rates for bigeye tuna (Figure 2.6) also show some seasonal patterns. Higher catch rates are found in the south-eastern Tasman Sea between October and December, shifting to the south-western Tasman Sea during January-

Figure 2.5 Nominal swordfish CPUE by quarter and 5-degree square (aggregated over the years 1971–1999) for Japanese longliners operating in the region [0,45]^{o}S and [140,180]^{o}E

(a) January-March



(b) April-June

(c) July-September

(d) October-December

March. The highest catch rates are then found in the northern Tasman and Coral Seas between April to June. This pattern of catch rates coincides to the temporal pattern of catch rates obtained by the domestic fleet, where the highest catch rates of bigeye tuna in the mid-latitudes (20-29^{o}S) are obtained during the second quarter and the lowest catch rates during the fourth quarter. As for swordfish, one may infer a seasonal movement of bigeye tuna around the Tasman/Coral Sea regions. However, the relationship of the bigeye tuna in these regions with those in the equatorial regions remains more difficult to discern.

Figure 2.6 Nominal bigeye tuna CPUE by quarter and 5-degree square (aggregated over the years 1971–1999) for Japanese longliners operating in the region [0,45]^{o}S and [140,180]^{o}E.

(a) January-March

(b) April-June

(c) July-September

(d) October-December

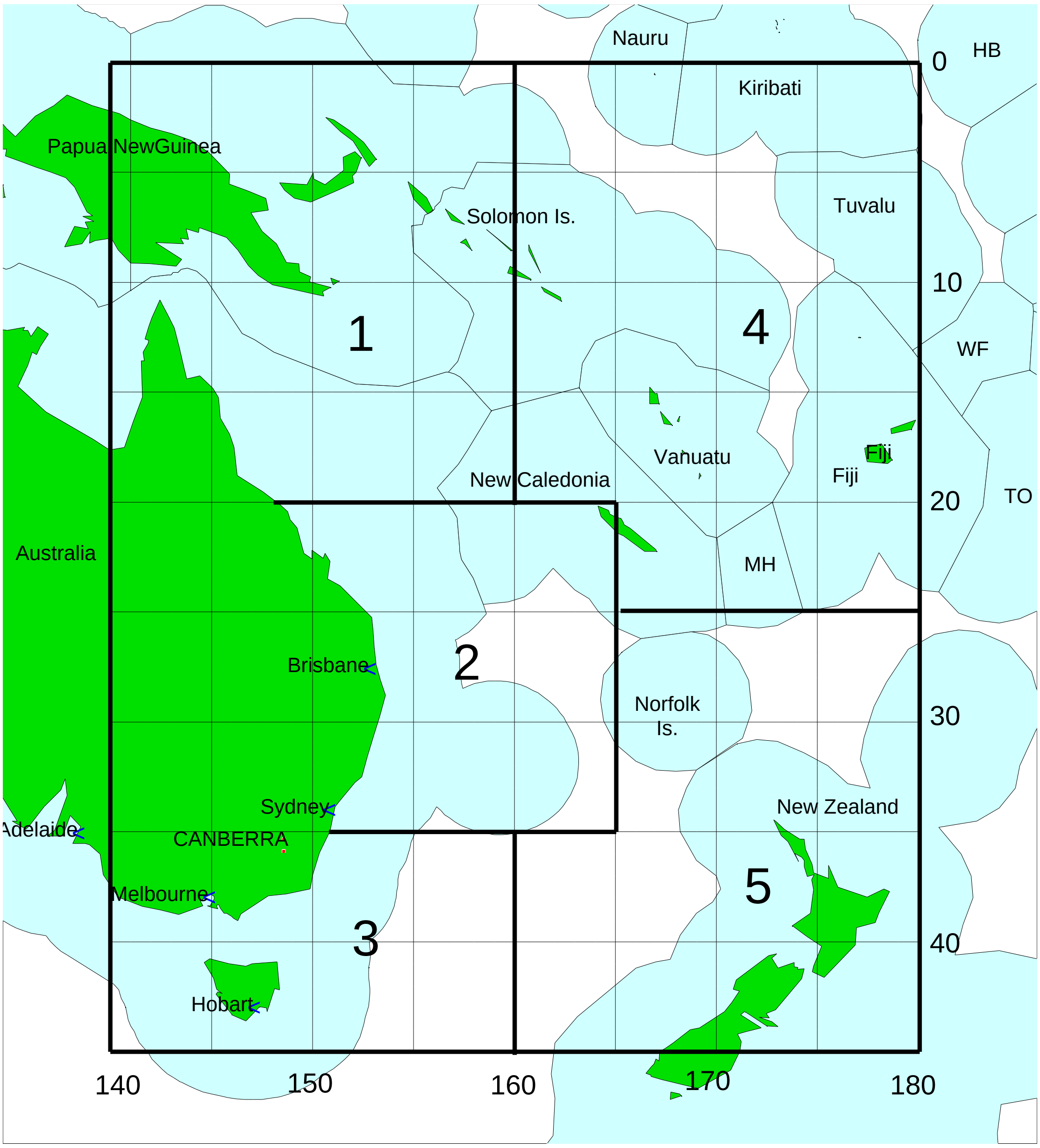
2.6 Spatial Domain and Regions for the Swordfish Model.

2.6.1 Swordfish

Based on the results of genetic studies and the distributions of catch rates described above (cf. Figures 2.1 and 2.5) it would appear that the swordfish resource in the SW Pacific belongs to a population which is to a high degree separate from the swordfish populations found elsewhere within the Pacific Ocean. Hence, for the purpose of this study we assume that there is little exchange, if any, between the swordfish population in the SW Pacific and populations elsewhere. Furthermore, the distribution of catch and catch rates indicate that few swordfish are caught south of 45^{o}S and east of 180^{o}E, so we take these lines as representing the southern and eastern limits of the swordfish resource in this region. The western boundary of the model was taken to be the east-coast of Australia, extending back to 140°E. This is the same of the western boundary of the ETBF. Finally, the northern boundary was taken to be the equator. These limits therefore defined the domain of the swordfish model as that region within the boundaries [0-45]°S and [140-180]°E.

The SW-Pacific region was further sub-divided into five sub-regions, or Areas. These Areas were identified by referring to the spatial distribution of fishing effort and swordfish catches and catch rates in the SW-Pacific in order to identify the areas of high and low seasonal abundance. Furthermore, three areas along the eastern boundary of Australia was deemed an appropriate spatial structure which would account for the three main concentrations of fishing effort in the ETBF, namely, the Coral Sea region, the Brisbane Grounds fishery, and southern NSW. The spatial structure adopted is shown in Figure 2.7. All of these Areas have been fished by the Japanese fleet. The Australian domestic fleet has fished mainly in Areas 1, 2

Figure 2.7. Map of the SW-Pacific region indicating the five spatial areas used in the operational model for swordfish. The EEZ of each nation is also indicated. International waters are represented by the unshaded areas.



and 3. Low levels of effort have been recorded for the Australian fleet in Area 5 in recent years but for the purposes of modeling this was combined with the data in Area 2. The New Zealand domestic fleet has fished only in Area 5.

2.6.2 Bigeye Tuna

Unlike the situation for swordfish, the information for bigeye tuna indicates that the bigeye population found in the SW Pacific is to a high degree contiguous with the bigeye tuna populations found throughout the Pacific Ocean. However, the rates and timing of the exchange of fish between the SW Pacific and the larger WCPO remain unknown, as does the degree of fidelity of bigeye in the SW Pacific. It should be noted that the Coral Sea tagging study undertaken as past of the RTTP, and described above, could only examine dispersal and, as such, the extent of movement into the Coral Sea remained unknown. However, the results are not inconsistent with alternative hypotheses of sub-population structure that need to be explored. For example, the bigeye tuna resource in the eastern AFZ may be principally derived from the broader WCPO stock, and as such the recruitment base would be large. At the other extreme, the Coral Sea may source the majority of the eastern AFZ bigeye resource, and so the recruitment base would be much smaller. At an intermediate level, recruits to the fishery may be supplied by fish from both the WCPO and the Coral Sea.

The management options available to AFMA in relation to the ETBF will depend critically on which one of these stock scenarios is correct. If recruitment is largely driven by events external to the ETBF (and the SW Pacific) then management of this region as an autonomous unit does not make sense biologically. Options for management will, to a large extent, be dependent on actions taken outside this region. For this reason, it was decided that instead of undertaking an MSE for bigeye tuna based on an operational model, an alternative approach would be adopted. This alternative is described in Chapter 8.

Chapter 3: Review of Fisheries Catch and Effort Data used in the Swordfish Model

In this chapter we review and summarise the available fishery data for the fleets catching swordfish in the SW Pacific. This data will be used to condition the operational model.

3.1 Longline Fleets in the SW Pacific

Japan began pelagic longlining off Australia's east coast in the early 1950s and the fishery was well established by 1960 (Ward and Whitelaw, 1999). A major increase in longline catch and effort occurred during the 1970's as a result of the development of both deep-freezing methods and deeper longlines (Fonteneau, 1998). The latter resulted in increased targeting of bigeye tuna from the late 1970's (Suzuki et al 1977, Hampton et al 1998a). Since the declaration of the Australian EEZ on 1 November 1979, progressive access restrictions were imposed on the activities of Japanese vessels fishing within the AFZ. By 1991, Japan was not permitted to longline within 50nm of the coast, near the Great Barrier Reef, or between 35°S and 39°S of south-east Australia (Caton and Ward, 1996). These and other restrictions, together with temporal seasonal changes in the distribution of the main target species, resulted in there being considerable inter-annual variation in the spatial and temporal distribution of Japanese longline effort within the AFZ, (Ward and Whitelaw, 1999). Japanese longliners ceased fishing in the AFZ in November 1997 when the annual bilateral agreements ceased (Ward, 1996). However, Japanese vessels continue to fish outside the AFZ in international waters of the Coral and Tasman Seas.

Whilst Australian vessels had sporadically longlined for yellowfin tuna off New South Wales since the 1950s, it was only after local operators began air-freighting fresh-chilled tuna to Japan in the mid-1980s that the fishery expanded. By 1987, about 1,000 tonnes (t) of yellowfin were landed and 240 operators had been granted a longline endorsement. Yellowfin tuna remained the principal target species during the first half of the 1990s, with the catch averaging around 750 t between 1987 to 1994. During the second half of the 1990s the fishery expanded rapidly, initially in northern Queensland where catch rates of yellowfin and bigeye were high. In 1996 a shift to targeting broadbill swordfish lead to a major increase in effort in the region off southern Queensland (operating out of Mooloolaba) and northern NSW. In recent years around 140 to 150 vessels have been active in the fishery.

3.1.1 Domestic Australian Data

A logbook program for the ETBF commenced in 1986 and the catch and effort data from these logbooks is currently stored in the AFZIS (Australian Fishing Zone Information System) database managed by AFMA. The use of logbooks was not mandatory for the first few years and less than 50 percent of permit holders are believed to have had logbooks before 1989. Field support of logbooks lapsed in 1993, and AMFA subsequently made logbook maintenance a condition of the license and instituted monthly auditing of logbook returns (Ward and Whitelaw, 1999).

Based on the AFMA logbook data, estimates of the annual catch and effort for the longline component of the ETBF are given in Table 3.1. The AFMA data have been adjusted to take into account a number of factors which may introduce a bias into the raw logbook data. First, for those logbook records with a catch but no associated effort, the effort (number of hooks) for that record was set equal to the average effort across all sets for the associated year. Second, an attempt has been made to correct for a possible bias in the AFZIS data due to the assumption made by AFMA that all catch weights reported in the ALO4 logbook were whole

Table 3.1 Catch and effort data for the domestic longline fishery off eastern Australia. The logbook data is considered to be incomplete for the early years of the fishery, and the estimated coverage rates are indicated. The data have been raised in order to account for these coverage rates. Note: Catch is whole weight (tonnes).

Year	Number of Vessels	Logbook Coverage	Number of Hooks	Yellowfin Tuna	Bigeye Tuna	Broadbill Swordfish	Striped Marlin
1987	67	50%	2,000,516	1,697	79	37	116
1988	69	50%	2,188,513	1,338	67	34	135
1989	94	70%	1,090,580	987	22	25	12
1990	98	85%	1,355,299	875	29	35	119
1991	96	90%	1,993,237	850	33	84	57
1992	105	85%	2,479,628	1,142	43	73	43
1993	84	85%	1,974,641	810	27	48	53
1994	88	100%	2,770,500	1,074	119	48	87
1995	104	100%	3,834,553	1,380	196	87	143
1996	121	100%	4,554,217	1,814	338	817	243
1997	138	100%	6,283,371	1,835	1,063	2,338	334
1998	151	100%	9,712,703	2,261	1,262	2,777	705
1999	152	100%	10,281,973	2,060	973	3,077	799
2000	140	100%	9,551,837	1,890	794	2,928	944
2001	141	100%	11,262,305	2,845	1,346	2,492	940
2002*	132	100%	8,391,760	2,428	821	1,735	444
avg(98-01)	146	100	10,202,204	2,264	1,094	2,818	847

* Incomplete

weights, when in fact it is believed that a large proportion of these weights were dressed weights. The procedure for accounting for this bias is explained in detail in Appendix D.

Finally, as mentioned previously, the logbook data is considered to be incomplete for the early years of the fishery. It is estimated that the coverage by logbooks was 50% of actual landings during 1987 and 1988, 70% during 1989, rising to 85%, 90% and 85% in 1990, 1991 and 1992 respectively (Dendrinos and Skousen 1991, Lawson 1993). The catch and effort data has been raised in proportion to these estimated coverage rate. The logbook coverage after 1992 remains uncertain. Despite this, the coverage for 1993 has been assumed to be 85%, while the coverage after 1993 has been assumed to be 100%.

The quality of data remains uncertain. A logbook review undertaken by AFMA in 1995 identified a number of areas of concern relating to the collection of logbook data and provided several options for improving the logbook program (Anon, 1995). Data collected during 1995 and 1996 by scientific observers on domestic longliners also found instances of major inconsistencies between observer and vessel-recorded data. As a consequence of the AFMA review, a series of new logbooks was introduced into the fishery in 1997. The new logbooks were method-specific, requiring specific catch data on a shot-by-shot basis including provision for data on discards, wildlife interactions, lengths and weights, and verified weights for fish landed. With the introduction of the new logbooks, an extensive education program was also undertaken to ensure the completion of logbooks. This program, together with the introduction of caution and infringement notices, resulted in a substantial improvement in the timely completion and submission of logbooks.

Since the introduction of the new logbooks in 1997 there has been no formal validation of the data recorded in logbooks. However, several comments by industry representatives and meetings convened by the Fisheries Assessment Group for the ETBF have indicated instances of mis-reporting of catch and effort, mainly as a reaction to possible future management arrangements. For example, by recording a catch (or effort) that is greater than that actually obtained, an operator may gain an increased share of any quota introduced into the fishery. The extent of this mis-reporting remains unknown. In order to address some of these concerns, AFMA undertook an audit of randomly selected landed catch records declared by operators in the fishery against records held by the first receivers of the declared fish (ie. holders of Fish Receiver Permits – introduced in February 1997).

The audit undertook to review the 688 landings of fish, made by 83 vessels, between 1 April to 31 July 1997 (Marrington 1998). However, due to the fact that there was usually more than one first receiver of fish, and that the weight or name of the species sent to each receiver had not been individually recorded, the audit was reduced to reviewing only those landings where there was only a single receiver of fish (168 landing from 58 boats). The audit found that for the 779 individual landings of different species, logbook recorded weights matched with the weights held by fish receivers on 360 occasions, were under-declared on 55 occasions, were over-declared on 83 occasions. Fish receiver records were unable to be found for the remaining 281 landings. This result indicates that the percentage of landings where the weight of fish recorded on logbooks matches with that recorded by fish may be as high as 72 percent, but possibility as low as 46 percent. The results also indicate a greater tendency to over-report the weight of fish on logbooks than under-report. However, the audit did not report discrepancies by species types and so it remains unclear whether the mis-reporting of weights is the same for all species.

3.1.2 Japanese data

After the declaration of the AFZ in November 1979, Japanese longliners were required by the Australian government to complete logbooks and/or radio report their daily position and catch. In 1996 a satellite-based vessel monitoring system (VMS) replaced the logbook and radio reporting systems. The data, dating from 1979 to 1997, is stored in the AFZIS database. Beginning in 1980, Australian observers collected information on Japanese vessels fishing within the AFZ. During the 1990s, observers covered around 10-15% of all Japanese fishing operations. A comparison on the data collected by observers with the data recorded in the logbooks indicated that the quality of the logbook data was good (Campbell, 1999b).

Japanese vessels also maintain a Japanese logbook, and the data from these logbooks is stored at the National Research Institute of Far Seas Fisheries (NRIFSF) in Shimizu, Japan. Catch and effort data for Japanese longline vessels operating within the region bounded by 0-50°S and 140-170°E, aggregated by month, 1-degree square and hooks-per-basket, covering the period 1971-2001 have been provided to the authors. Due to the longer time-series, and larger spatial extent of this data, it is used in preference to the data stored in the AFZIS database. The NRIFSF data also provides information of gear configuration which is missing in the AFZIS data.

3.1.3 Other Nations

Fishing vessels from several other nations also catch bigeye and swordfish in the SW-Pacific. These nations form into two groups: Pacific Island and Coastal Territories (PICT, such as Fiji, New Caledonia, Papua New Guinea, and the Solomon Islands), which have domestic longline fleets that usually fish within their own EEZ, and distant-water fishing nations (DWFN - Japan, Taiwan, Korea), which have large fleets of vessels that fish over a large spatial range. This latter group of vessels normally catches the majority of fish in foreign EEZs (if permitted) and international waters.

<u>Fiji</u>

Domestic longlining is the main component of the Fiji tuna fishery, with around 101 longline vessels operating in 2002. Fishing mainly occurs within Fijian waters, but around 25% of the catch is now taken in Vanuatu and adjacent high seas. The 2002 total catch is estimated at 16,472 mt, based on 90% logsheet coverage, of which 10,906 mt was tuna (albacore, followed by yellowfin and bigeye). Albacore comprised 50% of the total landed catch and over 70% of the tuna catch. The National Tuna Development and Management Plan came into operation in

2002, and a *TAC* of 15,000 mt of target tuna species has been established for the Fiji longline fishery, with a vessel limit of 110 (J. Amoe, 2003).

New Caledonia

Since 2000, the New Caledonia tuna fleet has increased considerably, with 25 longliners active in 2002 compared to only 14 boats two years before. This is mainly due to the establishment of new fishing companies operating in the Northern Province. Catches have also increased, however this has been slower than expected because of a reduction of the average size of the vessels. Furthermore, whereas yellowfin and bigeye were preferentially targeted until recently, since the construction of a processing plant in Nouméa, inaugurated in March 2002, albacore is being more actively targeted (and already represents more than 50 per cent of the total catch in 2002). Swordfish is currently not a target species and catches remain small.

New Zealand

New Zealand tuna fisheries began in the early 1960s with troll landings of skipjack and albacore, and developed during the 1970s into the summer albacore troll and skipjack purse seine fisheries. During the 1980s domestic handline and troll fisheries for southern bluefin tuna in winter developed. Since 1991 domestic longlining progressively expanded and today purse seine, troll and longline fisheries target all commercially valuable tuna species present in the EEZ year-round. The number of longline vessels operating in 2002 was around 158. Although swordfish comprises the second largest component of the longline catch (after albacore), the targeting of this species is currently prohibited.

Papua New Guinea

The Papua New Guinea (PNG) fishery is significant in both the regional and global sense. It typically produces 20% of the regional purse-seine catch and in some years, 10% of the global tuna catch is taken in the PNG EEZ. Over 120 bilateral and multilateral vessels fish under access agreements in PNG waters. The smaller longline catch is taken entirely by domestic vessels (around 40 in 2002), under a domestication policy in place since 1995. A separate shark longline fishery comprising 9 vessels has recently been recently established. Catch estimates for the longline fishery were 3,800 mt for all vessels for 2002, with yellowfin (70%), and bigeye (14%) comprising the majority of the catch.

Solomon Islands

In recent years the Solomon Islands' domestic tuna fishery, comprised of pole-and-line, purse seine and longline fleets, has continued to struggle due to continuing social unrest. Before that the Solomon Islands had one of the largest domestic tuna fisheries in the region. The longline catch fell from 1,197 t in 2000 to around 407 t in 2001, with the number of vessels falling from 14 to 8. Yellowfin and bigeye tunas are the main target species, with very few swordfish recorded caught.

Taiwan

Taiwan has a large longline fleet which fishes in a number of regions across the WCPO, including the waters in the Coral and Tasman Sea. The main target species for this fleet has traditionally been albacore, but in more recent years the fishery has increased its targeting of bigeye tunas in the equatorial regions. This change has also resulted in an increased catch of swordfish which has increased ten-fold (to around 3,700 t) over the last 3 years.

Korea

The Korean longline fleet operating in the Pacific Ocean in 2002 comprised 162 vessels and caught a total of 60,300 mt. Between 1998 and 2001 catches in the WCPO averaged around 30,000 t, but increased significantly to around 47,000 t in 2002. Bigeye comprised around

53% of the catch, with yellowfin and albacore together comprising another 37%. The catch of swordfish in the WCPO increased to around 1300 t in 2002 (J. Koh et al, 2003).

Each fishing nation has its own logbook which is processed by that country. Data is then provided to the Secretariat for the Pacific Community (SPC) in Noumea, which collates total catch and effort data for whole WCPO. For the PICT fleets, data is provided for each individual fishing operation, while for the DWFN fleets data is usually aggregated (5x5-degree square and month for longline data and by 1x1-degree square and month for purse-seine data). Data relating to DWFN operations within national EEZs is also provided for each individual set.

It should be noted that broadbill swordfish are generally not the principal target species in most WCPO fisheries but occur as incidental bycatch. As such, some degree of error may be associated with broadbill data due to poor reporting of bycatch species by many vessels (Campbell and Miller, 1998).

3.2 Catch and Effort Data Summaries

Catch and effort data pertaining to the various longline fleets operating in the SW Pacific were obtained from the following sources:

1. Australia: Individual set-by-set data, covering the years 1985-2001, obtained from AFMA. Tim Skousen is thanked for supplying this data.
2. New Zealand: Individual set-by-set data, covering the years 1989-2001, was obtained from the NZ Ministries of Fisheries. Talbot Murray is thanked for supplying this data.
3. Japan: Aggregated 1-degree, month data stratified by the number of hook-per-basket was obtained from the National Research Institute of Far Seas Laboratories. This data covers the years 1971-2001. Naozumi Miyabe is thanked for supplying this data.
4. DWFNs (Japan, Korea, Taiwan): Aggregated 5x5-degree month data for each fleet was obtained from the Oceanic Fisheries Program in SPC. Tim Lawson is thanked for supplying this data.
5. PICT Nations: Annual estimates of catch by domestic longline fleets operating in the SW-Pacific were obtained from National Reports tabled at recent meetings of the Standing Committee on Tuna and Billfish.

A summary of the estimated annual effort by Australian, New Zealand and the three DWFNs (Japan, Taiwan and Korea) is given in Table 3.2. Effort data for the other nations fishing in the region (principally PNG, Solomon Islands, New Caledonia and Fiji) is not shown, but is presently believed to total around 36 million hooks per annum. This consists of 5.9 million hooks reported for the PNG fleet in 2002 (Kumoru and Lewis, 2003), 4.2 million for the New Caledonian fleet in 2002 (R. Etaix-Bonnin, pers. comm.), and estimates of around 25 and 1 million hooks respectively for the Fijian and Solomon island fleets in 2002. This would indicate that around one-third of the total longline effort in the SW Pacific is being deployed by these nations.

The effort by the three DWFNs generally dominates the total longline effort in the region, though a distribution of this effort (Figure 3.1) indicates that considerable proportion of this effort is in the northern equatorial region, especially for the Taiwan and Korean fleets. The effort for PNG, Solomon Islands, New Caledonia and Fiji is also confined to the region north of 25^{o}S, and accounts for the general absence of Japanese and Korean effort in these respective EEZs. Whilst the effort by both the Australian and New Zealand fleets has increased significantly over the past decade, the Japanese effort has decreased with effort levels in recent years (approx 23 million hooks) being less than half the mean annual effort

Figure 3.1 Spatial distribution of the mean annual longline effort for Japanese, Taiwanese and Korean longline fleets between 1981 and 2000.

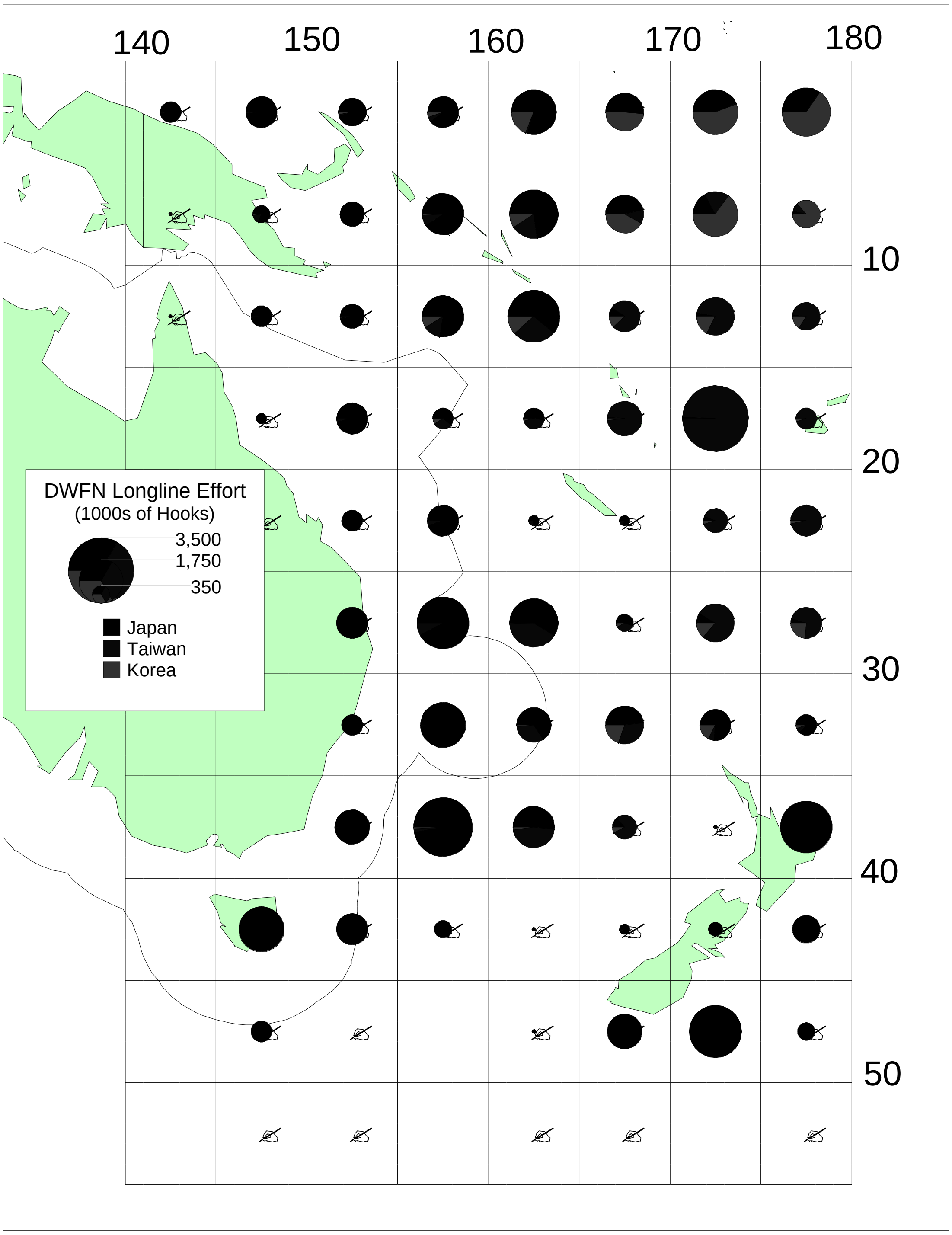


Table 3.2 Annual effort (1000s of hooks) deployed by Australian, New Zealand and Distant Water Fishing Nations longline fleets in the SW Pacific since 1971. Note: na = not available, while blank means either zero or not available.

YEAR	Australia	NZ	Japan	Taiwan	Korea	Total
1971			56,372	16,369		72,741
1972			50,144	12,681		62,825
1973			43,312	17,269		60,581
1974			43,208	16,890		60,098
1975			29,879	10,942	458	41,279
1976			49,050	11,814	12,668	73,532
1977			36,844	18,076	20,762	75,682
1978			28,000	19,548	14,373	61,921
1979			42,766	19,829	17,824	80,419
1980			70,761	20,056	21,338	112,155
1981			84,419	18,289	16,181	118,889
1982			80,826	11,128	12,963	104,916
1983			56,277	9,483	7,648	73,408
1984			46,555	13,848	6,502	66,905
1985	13		52,619	9,016	11,277	72,924
1986	33		42,983	5,785	5,436	54,237
1987	1,000		35,491	6,715	2,146	45,352
1988	1,094		51,205	12,987	13,235	78,520
1989	763	1,699	51,686	16,573	14,396	85,116
1990	1,152	3,483	47,059	24,551	13,931	90,175
1991	1,794	2,391	38,216	21,663	2,973	67,038
1992	2,108	2,361	30,096	78	6,978	41,621
1993	1,678	3,179	38,264	10,075	5,390	58,587
1994	2,771	2,587	44,025	15,521	1,221	66,124
1995	3,835	3,969	41,969	25,662	9,295	84,729
1996	4,554	2,498	30,032	19,048	7,570	63,702
1997	6,283	3,907	29,280	21,884	5,034	66,388
1998	9,713	4,978	29,286	17,971	9,748	71,697
1999	10,282	7,684	20,484	29,666	5,674	73,789
2000	9,552	8,139	20,386	35,749	8,125	81,951
2001	11,262	9,844	22,869	na	na	na
Avg 98-01	10,202	7,661	23,256	27,795	7,849	75,812

deployed during the 1980s (57 million hooks). This is likely to be due to the fact that the Japanese fleet is now excluded from fishing within the Australian Fishing Zone, where historically most of the effort by this fleet below 15^{o}S was targeted. Since the 1980s effort by Korean longliners in the SW Pacific region has also decreased by around one-third. On the other hand, the Taiwan effort in the SW Pacific has increased throughout the 1990s, with annual effort levels in recent years (approx 28 million hooks) being more than twice the mean annul effort during the 1980s (12.4 million hooks).

Estimates of annual retained catch of swordfish taken by longline vessels in the SW Pacific are given in Table 3.3 and Figure 3.2. For swordfish, the annual catches in recent years have been the greatest recorded, being around 75% higher than the average annual catch taken during the 1980s (which averaged around 2,700 t). Much of this increase in the total catch of swordfish in the region is due to the large increases in catches by Australia, and to a lesser extent by New Zealand. However, these increase have occurred during a period when the catches taken by Japanese vessels have decreased significantly, from over 3,000 t during several years in the 1980s to less than 500 t since 2000. Since 1998, Australian longliners have accounted for around 58% of the total swordfish catch in the region, with New Zealand and Japan each accounting for 19% and 14% respectively. Catches taken by all other fleets are small in comparison.

Table 3.3 Annual catch (whole weight) of swordfish retained and recorded by Australian, New Zealand and Distant Water Fishing Nations longline fleets in the SW Pacific since 1971. Note: na = not available, while blank means either zero or not available.

YEAR	Australia	NZ	Japan	Taiwan	Korea	Fiji	New Cal	Solomon	P
1971			1,372	80	0				
1972			1,427	81	0				
1973			1,102	88	0				
1974			1,352	68	0				
1975			667	68	4				
1976			1,236	81	58				
1977			345	51	50				
1978			479	61	26				
1979			893	164	43				
1980			2,306	93	47				
1981			3,166	64	62				
1982			3,377	28	27				
1983			2,099	28	20		2		
1984			2,032	45	12		6		
1985			2,385	22	56		5		
1986			2,670	13	15		14		
1987	19		2,649	12	9		17		
1988	17		3,727	16	69		5		
1989	18	12	1,910	19	79	1	7		
1990	30	80	1,684	66	99	5	13		
1991	76	38	1,535	44	34	17	15		
1992	61	29	2,043	0	62	25	9		
1993	41	93	1,416	7	39	39	9		
1994	48	93	1,622	116	7	0	9		
1995	87	108	1,265	91	51	211	10		
1996	817	178	1,596	77	23	167	10		
1997	2,336	281	1,752	110	12	78	9		
1998	2,777	554	1,130	63	28	92	26	1	
1999	3,077	1,004	657	124	9	104	17	1	
2000	2,928	973	465	37	45	118	17	1	
2001	2,492	1,029	387	na	na	115	15	2	
Avg 98-01	2,819	890	660	75	27	107	19	1	

Figure 3.2 Annual catch (tones) of broadbill swordfish in the SW Pacific by principal longline fishing fleets. Other nations include Taiwan, Korea, New Caledonia, Fiji, Solomon Islands, PNG and Vanuatu.

The mean annual distribution of swordfish catches taken by the three DWFNs between 1981 and 2000 is shown in Figure 3.3. Three features are notable. First, catches have been dominated by those taken by Japanese longliners. Second, the large majority of the catch has been taken in the Tasman Sea region off eastern Australia extending over to and around New Zealand. This coincides with the regions where both the Australian and New Zealand fleets catch swordfish. Third, the catches outside the Tasman Sea region are small, and reinforces the research that suggests that the swordfish found in the SW Pacific region are likely to form a single stock for management purposes.

Figure 3.3 Distribution of the mean annual swordfish catch taken by Japanese, Taiwanese and Korean longline fleets between 1981 and 2000.

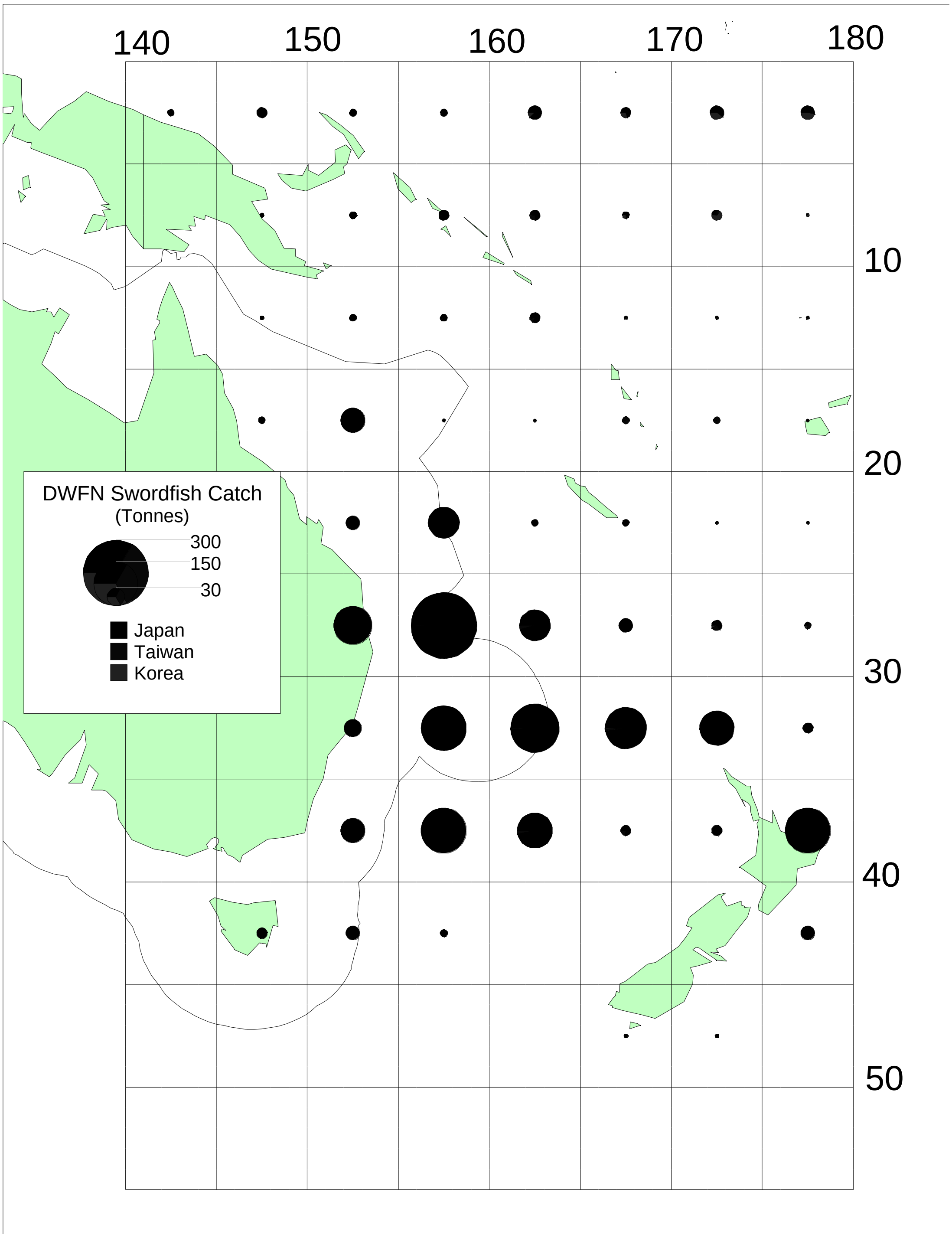


Figure 3.4 Annual catch (tonnes) of bigeye tuna in the SW Pacific by principal longline fishing fleets. Other nations include New Caledonia, Fiji, Solomon Islands, PNG and Vanuatu.

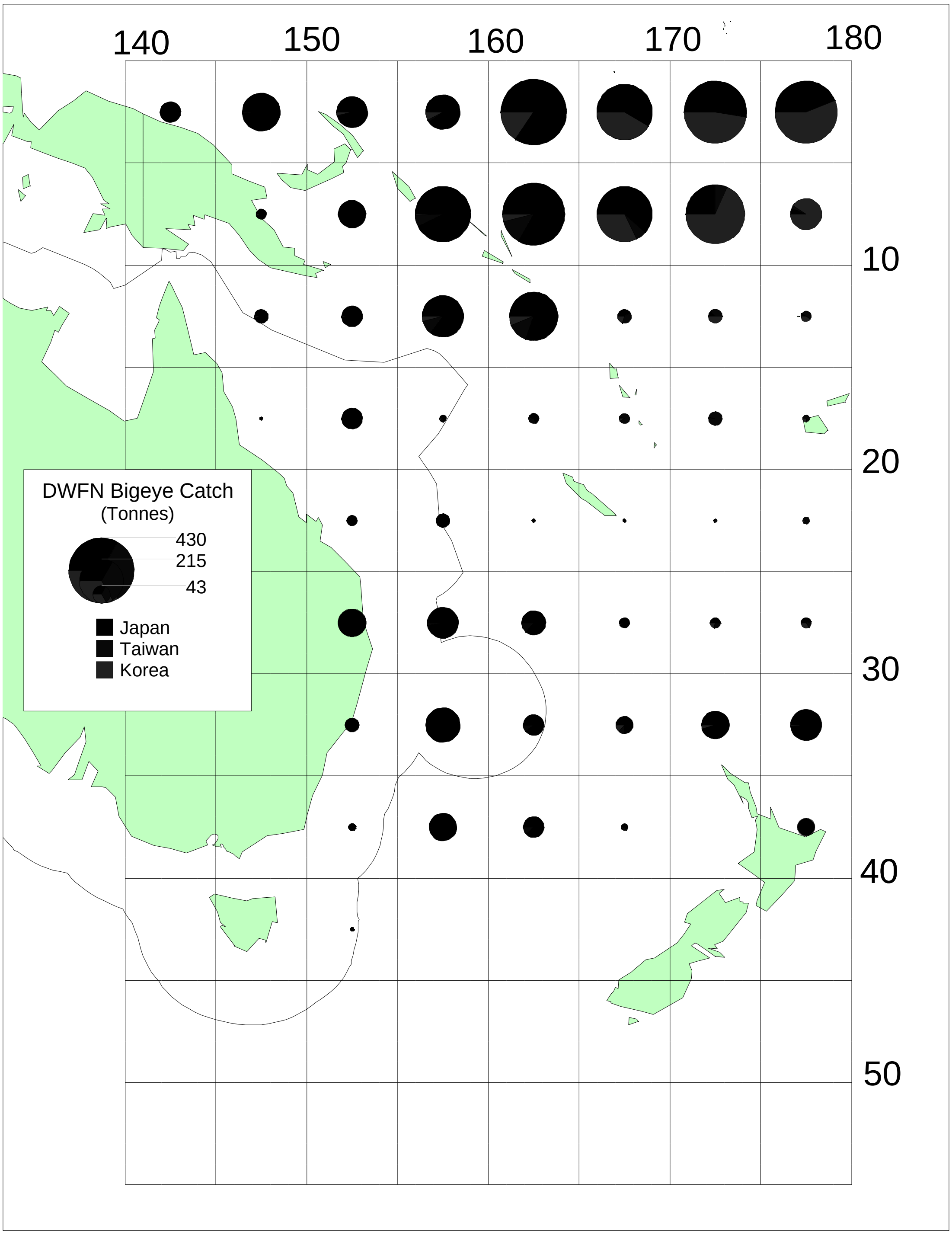
Estimates of annual retained catch of bigeye taken by longline vessels in the SW Pacific are given in Table 3.4 and Figure 3.4. Total catches in recent years are around 27% higher than the average annual catch taken during the 1980s (6,345 t). While some of this increase is influenced by the high catch taken in 2000, this trend is also influenced by the significantly increased catches taken by Australia and New Zealand, increasing from less than 100 t in the early 1990s to around 1,400 t in recent years. Annual catches by both Japan and Korea in recent years have declined by around one-third since the 1980s, though catches by Taiwan has increased several-fold. Catches by the three DWFNs are also seen to be highly variable, with catches often varying by a factor of 3-5 fold between years. Unlike the situation for swordfish, the domestic fleets of the Pacific Island Nations in the regions have accounted for a significant portion (around 20%) of the total bigeye catch in recent years.

The spatial distribution of mean annual bigeye catches taken by the three DWFNs between 1981 and 2000 is shown in Figure 3.5. Catches have been predominately taken within two broad latitudinal bands, one in the equatorial regions, generally north of 10^{o}S, and the other in the temporal region between 25-40^{o}S. This pattern highlights the presumably more complex stock structure of bigeye tuna in comparison to swordfish, with it currently believed that the bigeye tuna found in the SW Pacific region being part of the population found across the entire Pacific Ocean. The absence of catches around some of the Pacific Island nations (eg. New Caledonia, Fiji) is, however, somewhat misleading, as in more recent years the domestic fleets of these nations have been taking a total catch of around 1,500 t per annum. Recent development of the Australian and New Zealand longline fisheries has also led to large increases in the catch of bigeye tuna in the western Coral Sea and eastern Tasman Sea respectively. Accounting for these extra catches would make the spatial spread of catches across the entire region more continuous than it appears in Figure 3.5.

Table 3.4 Annual catch of bigeye tuna retained and recorded by Australian, New Zealand and Distant Water Fishing Nations longline fleets in the SW Pacific since 1971. Note: na = not available, while blank means either zero or not available.

YEAR	Australia	NZ	Japan	Taiwan	Korea	Fiji	New Cal	Solomon	Pl
1971			1,994	958					
1972			2,006	873					
1973			1,980	1,074					
1974			1,650	1,095					
1975			1,350	238	38				
1976			2,003	470	2,466				
1977			2,522	455	3,019				
1978			2,250	534	1,990				
1979			3,266	699	2,160				
1980			5,652	706	2,382				
1981			4,404	385	1,012				
1982			5,518	200	748				
1983			4,714	117	651				
1984			4,262	199	264				
1985			7,473	175	1,185				
1986			4,873	78	203				
1987	40		2,720	64	541				
1988	34		4,588	129	2,963				
1989	15	9	4,450	155	2,541				
1990	24	30	4,581	325	3,238				
1991	30	44	3,505	337	640				
1992	37	39	2,162	11	1,913				
1993	23	74	3,849	36	1,382				
1994	119	69	4,935	304	172				
1995	196	60	4,386	229	1,716				
1996	338	86	2,474	161	779				
1997	1,063	140	3,548	835	723	409	234		
1998	1,262	388	2,747	709	1,060	460	498	726	
1999	973	420	1,071	1,296	283	462	553	469	
2000	794	421	6,282	421	1,099	687	517	364	
2001	1,307	480	2,524	na	na	662	128	187	
Avg 98-01	1,084	427	3,156	808	814	568	424	436	

Figure 3.5 Distribution of the mean annual bigeye tuna catch taken by Japanese, Taiwanese and Korean longline fleets between 1981 and 2000



Data on catches taken by non-longline fishing methods (purse-seine, pole-line and troll) indicate that swordfish are not caught by these other methods (or, at least, are not separately identified in the catch) in the SW-Pacific. Consequently, the operational model for the swordfish fisheries in this region needs only to consider the catches taken by the longline fleets. On the other hand, around 20,000 t of bigeye tuna were caught by purse-seiners operating in the SW-Pacific in 1999. (Since 1962, around 123,000t of bigeye tuna has been caught by purse-seines in this region compared with around 209,000 t taken by longline). The catch of bigeye tuna by pole-line and troll appear to be small. As such, any model of bigeye tuna catches in the SW-Pacific will also need to consider the catches taken by purse-seine fleets in the region (and the catches taken by all fleets outside the region).

3.3 Standardisation and Adjustment of Data for Operational Model

3.3.1 Standardisation

For any single species assessment model, it is important to standardize fishing effort so that the measure of effort which is used in the model is an accurate reflection of the level of effort directed at the species of interest. If there have been changes in targeting practices, or adoption of gears which increase (or decrease) fishing efficiencies, then these changes need to be accounted for.

The longline fleets which catch swordfish and bigeye tuna in the SW Pacific generally target a range of tropical tunas and billfish. For the Australian longline fleet, the principal target species are yellowfin and bigeye tuna, broadbill swordfish and striped marlin, whilst yellowfin, bigeye, albacore and southern bluefin tuna together with swordfish are the principal target species of the New Zealand longline fleet. For the DWFN longline fleets , the tropical tuna species are the principal target species, with several billfish species perhaps being targeted only opportunistically by the Japanese fleet. For the Pacific Island Nations, albacore tuna together with yellowfin and to a lesser extent bigeye tuna are the principal target species. As with the DWFNS, billfish species are usually only taken as a bycatch.

The nominal catch rates for the Australian and New Zealand fleets within each of the five areas used in the operational model are shown in Figures 3.6a&b. Despite the significant seasonal variation seen in catch rates, for both fleets and all areas the nominal catch rates are seen to increase over time. Indeed, the increase for the Australian fleet in Area 2 after 1995 is seen to be quite dramatic and is believed to be associated with the rapid development of the swordfish fishery in this area. The increases in catch rates in the other areas and for the New Zealand fleet were less dramatic, and are likely to reflect the slower switch to targeting swordfish in these areas. (Note, fishery regulations in New Zealand prohibit the targeting of swordfish and the swordfish catch is assumed to be a bycatch taken by vessels which principally target bigeye tuna. However, the significant increases in swordfish catch rates seen in the New Zealand fishery would indicate that some practices within the fishery have changed which has had the effect of increasing the catch rates of swordfish). As sufficient auxiliary information was not available to account for the changes in both targeting practices and changes in gear efficiencies, it was not possible to formally standardize either the Australian or New Zealand effort. However, in order to account for these temporal shifts, a suitable parameterization of the relationship between fully-selected fishing mortality and nominal effort for these fleets was used in the model. The details of this parameterization are described in Chapter 4.

The nominal catch rates for the Japanese fleet within each area are shown in Figures 3.6c. Again, significant seasonal variation is seen in the catch rates. However, unlike the temporal increases seen in the catch rates for the Australian and New Zealand fleets, the time-series of Japanese catch rates in most areas display either no overall trend or a slight decline, though there are periods when higher than average catch rates were obtained. Although it is well known that Japanese longliners increased their targeting of bigeye with the introduction of deeper longlines in the mid-1970s, it remains unknown whether the Japanese have significantly altered their targeting practices in relation to swordfish. As stated previously, swordfish are believed not to be a principal target species for the Japanese, but may be targeted opportunistically when regions of high abundance are encountered. This behaviour may account for the large spikes in the times-series of catch rates seen in Figure 3.6c. While problems remain in attempting to standardise effort for a non-target species, the Japanese effort was standardized to account for changes in gear configurations (ie. the number of hooks

Figure 3.6a Quarterly time-series of nominal swordfish catch rates (number of fish per 1000 hooks) for the Australian longline fleet within each of the three spatial areas used in the operating model.

Figure 3.6b Quarterly time-series of nominal swordfish catch rates (number of fish per 1000 hooks) for domestic New Zealand longline fleet within Area 5.

Figure 3.6c Quarterly time-series of nominal and standardised swordfish catch rates (number of fish per 1000 hooks) for the distant water Japanese longline fleet within Areas 1-3.

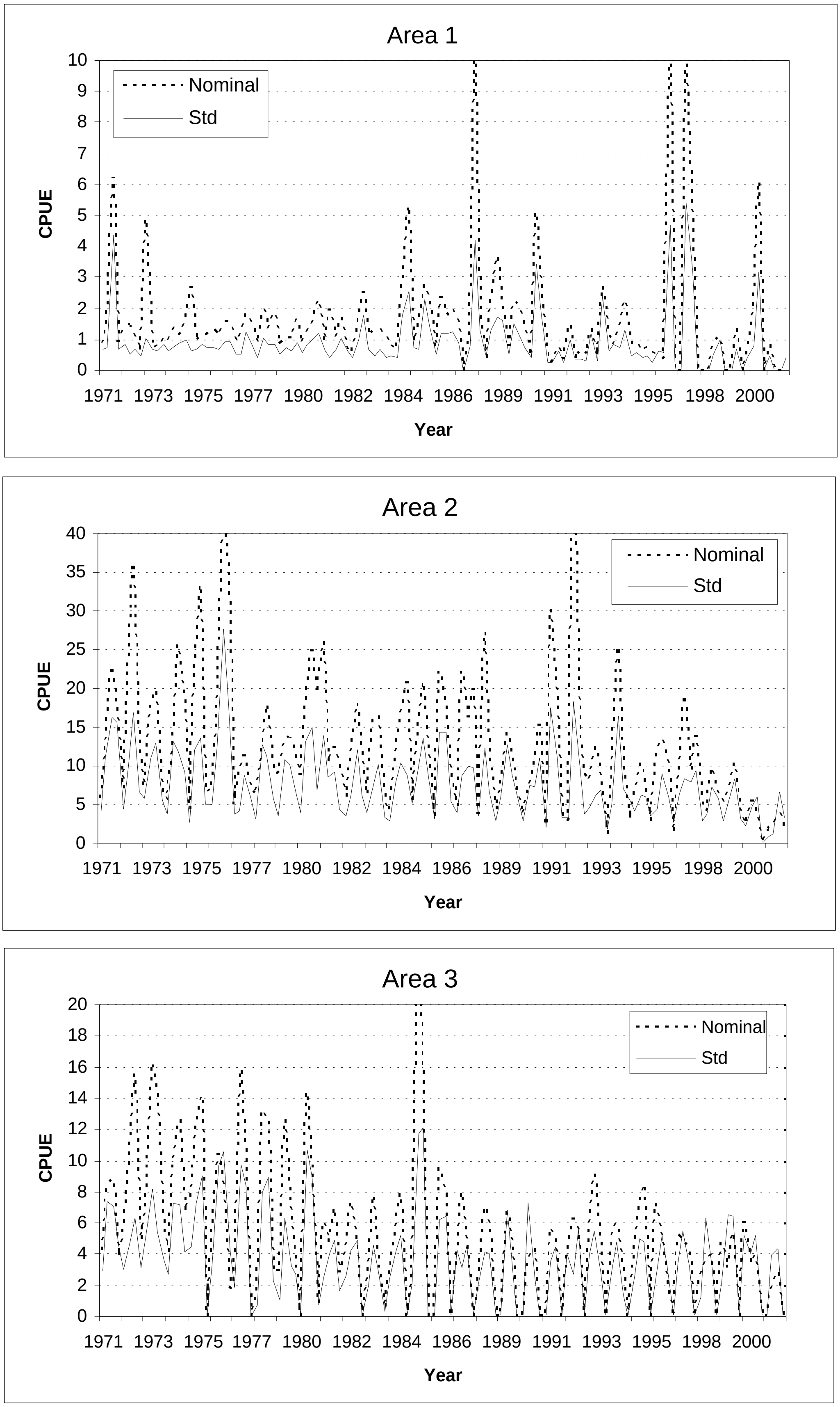
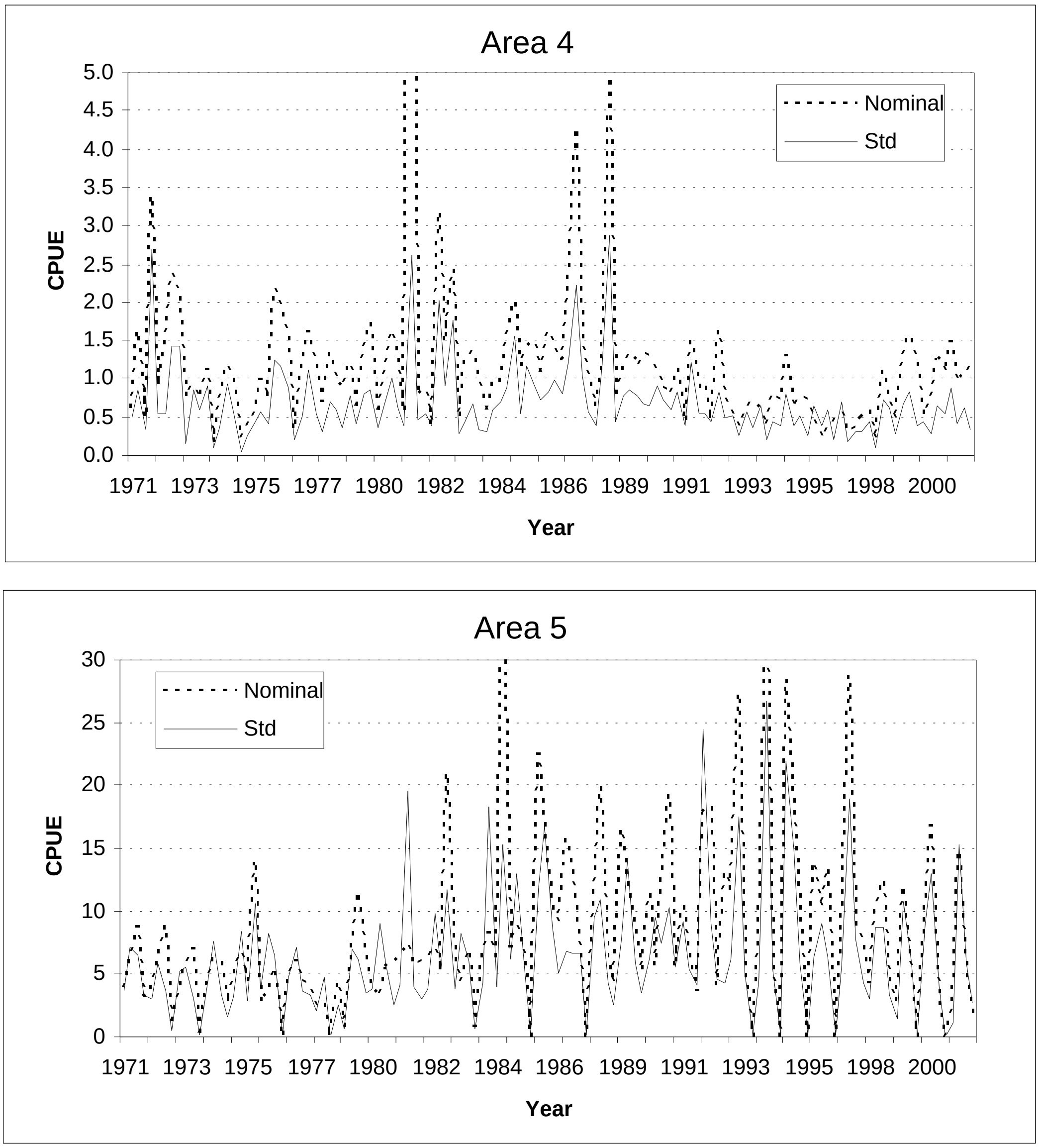


Figure 3.6c (cont'd) Quarterly time-series of nominal and standardised swordfish catch rates (number of fish per 1000 hooks) for the distant water Japanese longline fleet in Areas 4 and 5.



set per basket) as well as other temporal and spatial shifts in the distribution of fishing effort throughout the SW Pacific. The details of this analysis are outlined in Appendix F. The resulting time-series of standardized Japanese effort within each area is compared with the nominal effort in Figures 3.6c.

3.3.2 Adjustment of Japanese Data

In order to limit the number of fleets which needed to be included in the operational models, only the three main fleets catching swordfish in the SW Pacific were included. The combined catch from these fleets (Australia, New Zealand and Japan) have accounted for over 90% of the annual catch in recent years. The catch by any other fleet is usually small, and as the catch information for these other fleets is often difficult to obtain and/or unreliable, and their selectivity remains unknown, they are not included in the model. As such, the fleet dynamics of the operational model was limited to that of Australia, New Zealand and Japan.

Figure 3.7 Annual raising factors used for each area to raise the Japanese catch in each area for account for catches by other fleets not included in the operating model. Note, the raising factor of 34.3 for area 1 in 2001 is off the scale shown.

Nevertheless, it is important to condition the population dynamics of the model using the total known historical catches taken from the population. For this reason, it was necessary to pro-rata the catch and effort of at least one of the included fleets to account for the catch taken by the non-included fleets. The Japanese fleet was chosen for this purpose, as most of the catch taken by the other fleets occurred in Area 4 and only the Japanese fleet fished in this area. The procedure followed for raising the Japanese catch and effort was as follows:

1. For each year and area, the total catch (by weight) was calculated for the Japanese fleet and the other fleets (Taiwan, Korea and the other Pacific Island Nations, cf Table 3.3).
2. A raising factor, equal to the ratio of the combined catch of the Japanese and other fleets to the Japanese catch alone, was calculated for each year and area. The time-series of raising factors for each area is shown in Figure 3.7.
3. The Japanese catch and effort for each area and quarter of each year was multiplied by the appropriate raising factor for that area and year. (Note, there was not sufficient data to calculate the raising factor for each area/quarter.)

As implied previously, and as seen in Figure 3.7, only the data for Area 4 was subject to any significant adjustment, though the raising factor for Area 1 was large for the last few years – this being due to the small size of the Japanese catches in this area during this period.

In summary, catch and effort data was available by region and quarter for the Japanese fleet from 1971 to 2001, the New Zealand fleet from 1991 to 2001 and the Australian fleet from 1987 to 2001. However, as the Australian effort before 1990 was very small only the data since this year was used. The time-series of total effort (nominal Australian and New Zealand effort plus standardized Japanese effort) and catch (nominal Australian and New Zealand catch plus adjusted Japanese catch) within each of the five spatial areas in the operational models is shown in Figures 3.8 and 3.9 respectively, while a total listing of the catch and effort data for each fleet, quarter and area is given in Appendix E.

Figure 3.8 Annual time-series of total longline effort within each of the five areas in the operational model. Total effort is a combination of nominal effort for the Australian and New Zealand fleets and the Japanese effort which has been standardized and adjusted to account for the catch by other DWFN fleets and Pacific Island fleets operating in the SW Pacific.

Figure 3.9 Annual time-series of total longline catch of swordfish within each of the five areas in the operational model. Total catch is a combination of the catch for Australian and New Zealand fleets and the Japanese fleet which has been adjusted to incorporate catches taken by other DWFN fleets and Pacific Island fleets operating in the SW Pacific.

3.4 Size Data.

Since mid-1997, weight data pertaining to individual yellowfin tuna, bigeye tuna and broadbill swordfish caught and landed by Australian vessels within the ETBF have been collected and collated by WW Fisheries and forwarded to CSIRO Marine Research. An extensive summary of this data, together with a preliminary analysis of time trends, is given elsewhere (Campbell et al, 2002). A feature of this sampling program is the large number of fish that have been sampled and the corresponding high sampling fraction across the fishery. For example, between July-1997 and June 2001, weight data for 88,202 swordfish were collected, representing around 80 percent of the 110,309 swordfish recorded in logbooks as having been retained in the ETBF.

For this purposes of this study, representative histograms (ie. aggregated across all years of the available size data) of the weight of swordfish caught within each of three areas fished by Australian longliners (Areas 1-3) were determined for each quarter of the year. These distributions are shown in Figure 3.10. They indicate differences in the size of fish within each region, which infers, to some extent, that the movement rates of fish between regions varies with size. If this were not so, the size distributions would be invariant across all regions.

For vessels fishing within New Zealand's EEZ (within Area 5), observers have obtained length samples of swordfish caught by both Japanese and New Zealand vessels. For Japanese vessels data are available since 1987, while for New Zealand vessels data is available since 1992. A summary of the number of fish sampled by fleet and quarter is given in Table 3.5 below. No fish were sampled from Japanese vessels during the first or fourth quarters, while sample sizes are small across all quarters for the New Zealand vessels. Distributions of lengths, aggregated across all years, for all fleet/quarters where more than 100 fish have been sampled are shown in Figure 4. Due to the paucity of data from the New Zealand fleet, only the data for the Japanese fleet is used in conditioning the operating model. Again, differences in the distributions between the two quarters shown indicate differential movement rates based on size.

Table 3.5 Number of swordfish lengths obtained by observers from Japanese and New Zealand longline vessels fishing within Area 5.

Quarter	Japanese	New Zealand	Total
1	0	326	326
2	1409	163	1572
3	1143	19	1162
4	0	22	22
Total	2552	530	3082

A complete listing of the size data used in the operating model is given in Tables D.3 and D.4 in Appendix E. As described in Chapter 4, the size data was used to help condition the model so that the predicted size of fish caught in the model was similar to the observed size of fish caught.

3.5 Temporal and Spatial Distributions of CPUE

To assist the estimation of the movement parameters in the model, the predicted and observed temporal and spatial distributions of the swordfish resource were compared. For this purpose, the observed catch rates were used to mimic the actual temporal and spatial distributions of the swordfish resource. Furthermore, two sets of data (which are not entirely consistent) were used in order to infer these distributions.

Figure 3.10 Distributions of swordfish weights retained and landed by Australian longline vessels by area and quarter.

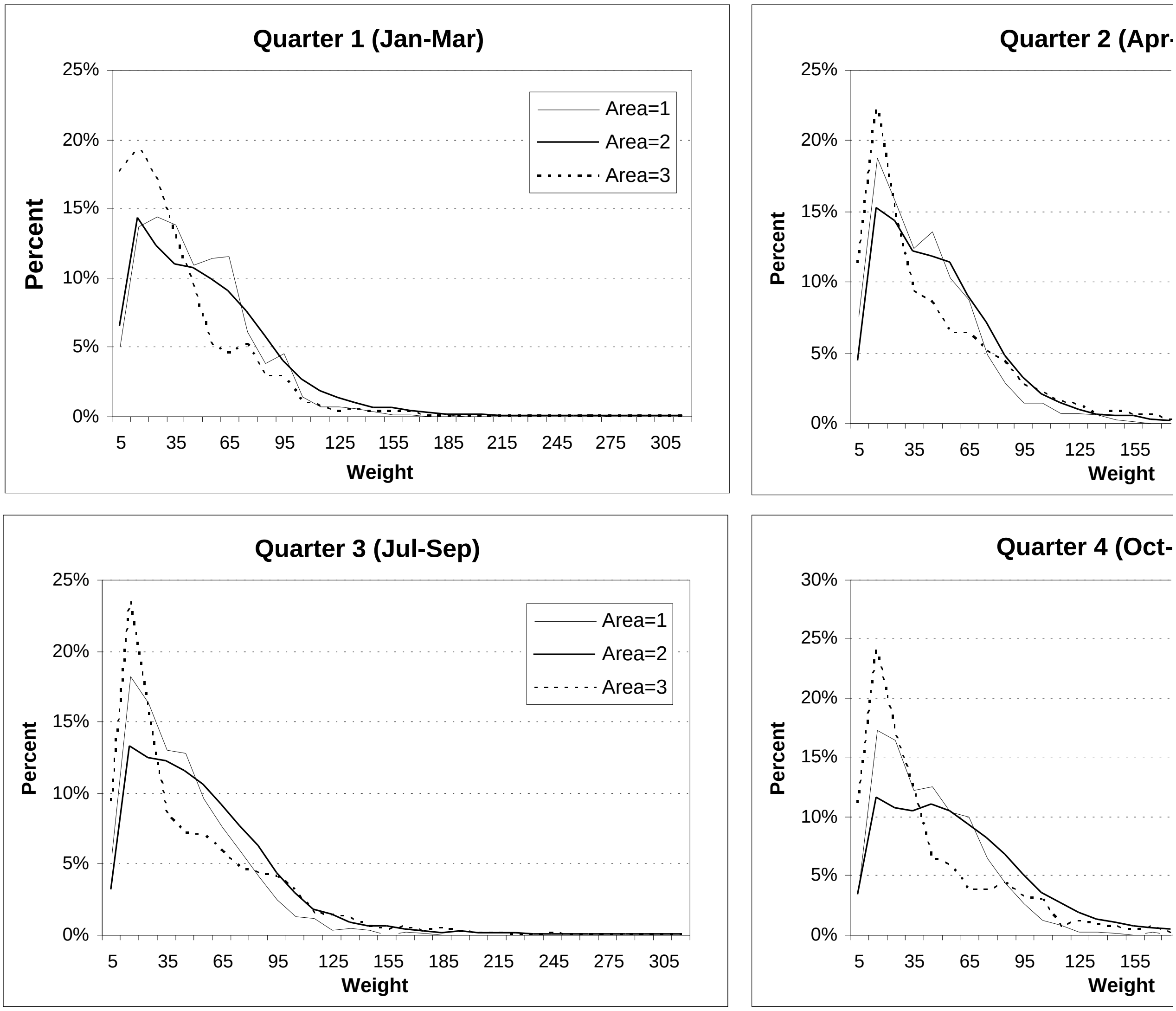
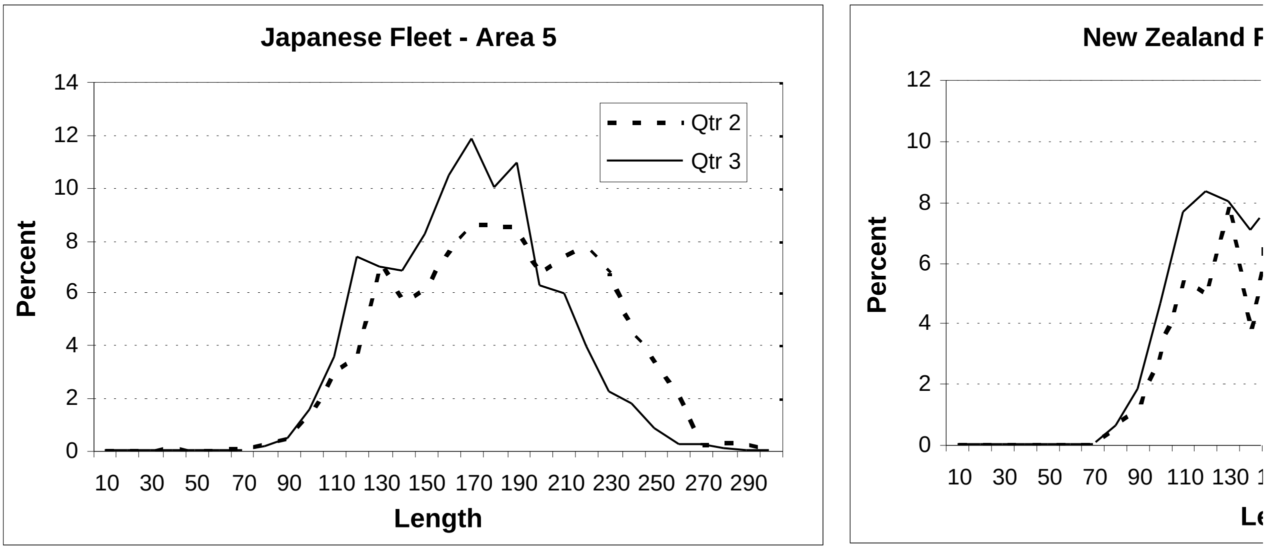


Figure 3.11 Distributions of swordfish lengths retained by Japanese and New Zealand vessels fishing within Area 5 by quarter.



In the first instance, the indices of selected biomass within each region for each year and quarter calculated during the standardisation analysis of the Japanese catch rates across the entire SW-Pacific were used. For each quarter, the index of selected biomass within each of the five regions was expressed as a percentage of the total index across all regions and the average of these percentages was then calculated across all years. The results, given in Table 3.6, give an estimate of the average distribution (across all years) of the relative selected population size within each region for each quarter.

Table 3.6 Proportion of selected swordfish populations within each region and quarter, averaged over all years.

Quarter	Region 1	Region 2	Region 3	Region 4	Region 5
1	8.8%	25.2%	10.3%	11.2%	44.4%
2	3.2%	31.9%	10.1%	6.3%	48.6%
3	6.7%	35.3%	9.4%	11.4%	37.2%
4	13.6%	32.0%	7.7%	17.5%	29.3%
Average	8.1%	31.1%	9.4%	11.6%	39.9%

In the second instance, the distribution of selected biomass across each quarter of the year within each region was inferred from the quarterly distributions of catch rates. For regions 1-3 and region 5 the catch rates for the domestic fleets were used. In particular, for regions 1-3 the quarterly nominal catch rates for the Australian fleet for the years 1996-1999 were used, while for region 5 the nominal catch rates for the New Zealand fleet for the same period were used. For region 4 the standardised catch rates for the Japanese fleet for all years were used. Within each region and for each year, the catch rate in each quarter was expressed as a percentage of the sum of the catch rates across all quarters for that year. Then for each quarter, the average of the percentages across all years was calculated. The results are given in Table 3.7.

Table 3.7 Quarterly distributions of selected swordfish populations within each region, averaged over all years.

Quarter	Region 1	Region 2	Region 3	Region 4	Region 5
1	12.7%	28.4%	13.8%	16.6%	31.4%
2	29.1%	21.7%	36.4%	21.5%	39.9%
3	33.5%	23.8%	38.7%	33.3%	19.6%
4	24.8%	26.0%	11.2%	28.7%	9.1%
Total	100%	100%	100%	100%	100%

An examination of the distributions in Tables 3.6 and 3.7 indicates a degree of inconsistency between the two results. These inconsistencies are no doubt linked to observational errors and the different nature of the two sets of catch rates data. For the purposes of obtaining an initial guess of the movement parameters, a synthesis of the two results was used. First, for a given region, the average level of population size across all quarters shown in Table 3.6 was adjusted to reflect the quarterly distributions of population shown in Table 3.7 (such that the average level across all quarters remained the same). These levels were then adjusted so that for each quarter the total of the percentages within each region was 100%. The final distribution, shown in Table 3.8, was then used as the initial guess for the movement matrix.

Table 3.8. Synthesis of the distributions shown in Tables 3.6 and 3.7 used to form the initial guess for the movement matrix.

Quarter	Region 1	Region 2	Region 3	Region 4	Region 5
1	4.0%	34.5%	5.1%	7.5%	48.9%
2	7.6%	21.9%	11.0%	8.0%	51.5%
3	10.6%	29.2%	14.2%	15.2%	30.7%
4	11.1%	44.7%	5.8%	18.4%	20.1%

Note, in calculating the data in Tables 3.6 and 3.7, averages were taken across all years as the movement rates were assumed to show no inter-annual variation. This is a approximation as it is possible that there are changes between years, driven by changes in oceanographic conditions.

Chapter 4: Technical Description of the Operating Model

This chapter provides the technical details of the operating models, describes the data used to fit the model parameters, and discusses the use of performance indictors and harvest strategies to be evaluated within the management framework.

4.1. Population and Fishery Dynamics

The operating model used for characterising the dynamics of the swordfish resource targeted by the ETBF is based on a single stock and explicitly considers the age-structure and sex-structure of the population. Individual variability in growth (and hence the length-structure of the population) is accounted for by dividing each cohort into several groups, each of which grows according to a different growth curve. The time-step used is a quarter of the year. The model assumes that natural and fishing mortality occur continuously through a year whereby values are updated every quarter, and that movement (which is assumed to be a function of size) occurs at the end of each quarter. The model is fleet-specific for the Japanese, Australian and New Zealand longline fleets, and fishing and movement occurs across five regions (see section 5).

4.1.1 Basic Population Dynamics

The basic dynamics of the population, which are based on standard catch and population dynamics, are governed by the equation (4.1):

$$N_{t,a}^{k,A} = \begin{cases} N_{t,0}^{k,A} & \text{if } a = 0 \\ \sum_{A} X_{t,L_{k,a-0.5}}^{A',A} \; (N_{t-1,a-1}^{k,A'} e^{-M_{a-1}/2} - C_{t-1,a-1}^{k,A'}) \; e^{-M_{a-1}/2} & \text{if } 1 \leq a < x \\ \sum_{A} X_{t,L_{k,x-0.5}}^{A',A} \; (N_{t-1,x-1}^{k,A'} e^{-M_{x-1}/2} - C_{t-1,x-1}^{k,A'}) \; e^{-M_{x-1}/2} + \sum_{A} X_{t,L_{k,x+0.5}}^{A',A} \; (N_{t-1,x}^{k,A'} e^{-M_{x}/2} - C_{t-1,x}^{k,A'}) \; e^{-M_{x}/2} & \text{if } a = x \end{cases}$$

where $N_{t,a}^{k,A}$ is the number of animals of (3-monthly) age a in growth group k in region A at the start of quarterly time step t,

$X_{t,L}^{A',A}$ is the probability that animals in length-class L_i in region A' at the end of quarterly time step t will move to region A.

$C_{t,a}^{k,A}$ is the catch by numbers of animals of (3-monthly) age a in growth group k in region A at the start of quarterly time step t,

M_a is the instantaneous rate of age-specific natural mortality,

$L_{k,a}$ is the 5cm length class of a fish of age a in group k, and

x is the maximum age (chosen so that selectivity, fecundity, movement and natural mortality for ages x-1 and greater can reasonably be assumed to be the same).

4.1.2 Births

The number of 0-year-olds in group k (females only; $5 \leq k < 10$) at the start of quarterly time step t is given by:

$$N^k_{t,0} = K^k \tilde{B}_t \, (\alpha + \beta \, \tilde{B}_t)^{-1} e^{\varepsilon^s_t - \sigma_r^2/2} \qquad \varepsilon^s_t \sim N(0;\sigma_r^2) \tag{4.2}$$

where $\tilde{B}_t$ is the female spawning biomass at the start of time step t:

$$\tilde{B}_t = \sum_A \sum_{k=5}^{10} \sum_{a=1}^{x} f_{L_{k,a}} \, w_{L_{k,a}} \, N^{k,A}_{t,a} \tag{4.3}$$

f_L is the proportion of female animals of length L that are mature,

K^k is the fraction of zero-year-olds in group k,

α , β^s are the parameters of the stock-recruitment relationship, where:

$$\alpha = \tilde{B}_0 \frac{1-h}{4h} \qquad ; h = \text{steepness}$$

$$\beta = \frac{5h-1}{4hR_0}$$

$$\tilde{B}_0 = \sum_{a=1}^{x} \sum_{k=5}^{10} V_a K^k f_{L_{k,a}} w_{L_{k,a}}$$

$$V_a = \begin{cases} 0 & ; a = 0 \\ 1 & ; a = 1 \\ e^{-\sum_{i=1}^{a-1} M_i} & ; a > 1 \end{cases}$$

R_0 is the initial number of fish (fitted as a model parameter)

and σ_r is the standard deviation of the logarithms of the fluctuations in births.

Within each year, recruitment occurs only in quarters 1 and 2, and recruits are spatially distributed according to a distribution matrix represented by the proportions, $P^{tot}_{q,A}$, of the selected population within each region A in quarter q. These proportions are based on the distribution of catch rates averaged across all quarters and years from 1971 to 2001 (*see section 3.6*). The values for the parameters of the stock-recruitment relationship are calculated from values for the steepness of the stock-recruitment relationship and the virgin biomass, as described in the above equations (Francis, 1992).

4.1.3 Growth

The size of an individual is assumed to be governed by the von Bertalanffy growth equation:

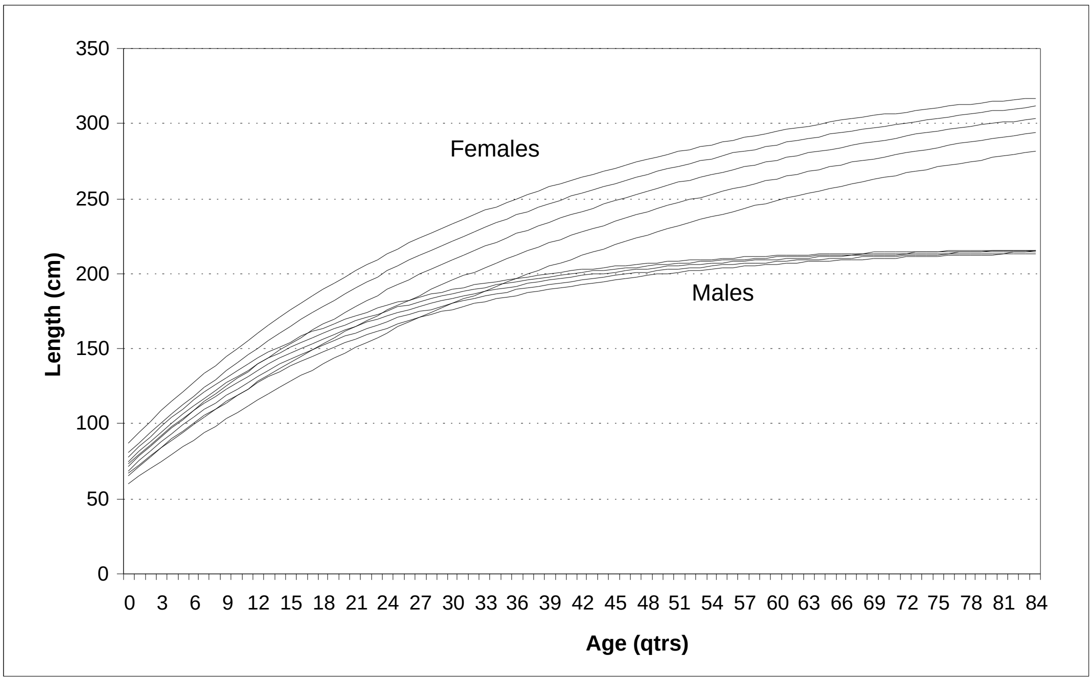
$$L_{k,a} = L^k_\infty (1 - e^{-\kappa^k (a - t^k_0)}) \tag{4.4}$$

Estimates for von-Bertalanffy growth parameters were taken from Berkely and Houde (1983). Individual variability in growth is accounted for by dividing each cohort into ten groups, each of which grows according to a different growth curve. This was achieved by varying the growth parameter, _ .Five of these groups are based on growth curves derived for females while the other five are based on growth curves derived for males. The central curve for each sex reflects the "best estimate" of growth. The proportion of 0-year-olds that are in each group is selected so that the division of 0-year-olds by sex is 1 : 5 : 9 : 5 : 1. The individual growth curves for each growth-group are shown in Figure 4.1.

The mass of an animal of length L is given by:

$$w_L = \tilde{a} \, L^{\tilde{b}} \tag{4.5}$$

Figure 4.1 Growth curves for the 10-growth groups used in the operational model.



4.1.4 Catches

The catch (in mass) from region A for fleet f during quarter t, $C^A_{t,f}$, is determined by the selectivity of the gear, the retention rate, and the amount of effort directed towards region A:

$$C^A_{t,f} = \sum_k \sum_a w_{L_{k,a+0.5}} R_{L_{k,a+0.5}} P_{L_{k,a+0.5}} S_{t,L_{k,a+0.5}} F^A_{t,f} N^{k,A'}_{t,a} e^{-M_a/2} \qquad (4.6a)$$

where

$S_{t,L}$ is the selectivity of the fishing gear on a fish of length L, and assumed to be the same for each fleet (with a random error specific to each fleet f and time step, t), calculated as:

$$S_{t,L} = 1/(1+e^{(A_t - B(5L-2.5)})$$

where $A_t = A' e^{\varepsilon_{t,f} - \sigma^2_S/2}$, $\varepsilon_{t,f} \sim N(0,\sigma^2_S)$

A', B are the parameters of the logistic selectivity curve

σ_S is the standard deviation of the logarithms of the fluctuations in selectivity parameter A'

$F^A_{t,f}$ is the fully-selected fishing mortality for fleet f in region A during quarter t,

R_L is the knife-edged retention rate (due to discarding, high-grading or fish freeing themselves from a hook) for a fish of length L, calculated as:

$$R_L = \begin{cases} 1/3 & L \le L_R \\ 1 & L > L_R \end{cases}$$

where L_R is the retention length threshold, corresponding to a weight threshold of 12.5kg, and

P_L is the 1-(the rate of fish loss due to predation by sharks, cetaceans and birds), calculated as:

$$P_L = \begin{cases} 0.95 & ; L \le L_{Plow} \\ \left[0.05/(L_{low} - L_{high})\right](L - L_{high}) + 0.9 & ; L_{Plow} < L < L_{Phigh} \\ 0.9 & ; L \ge L_{Phigh} \end{cases}$$

where L_{Plow} = lower predation loss length threshold, corresponding to a weight threshold of 25kg, and

L_{Phigh} = higher predation loss length threshold, corresponding to a weight threshold of 50kg.

Note: The retention rates and predation loss functions were based on discussions with industry members at the Fisheries Assessment Group meeting held in July 2002. It was suggested the 5-10% of the total catch was lost to shark or cetacean mauling, with larger (>50kg) fish being more susceptible. It was also agreed that the majority of swordfish less than 10-15kg in weight were discarded, whether alive or not, and that fish from 15-25kg and above were retained. As port monitoring indicates that fish less than 15kg are landed, the retention rate for fish less than 12.5kg was set at one-third. The retention and predation loss relationships with fish mass are shown in Figure 4.2.

Figure 4.2: Proportion retained and proportion not lost to predation *versus* fish mass (kg)

The catch (in numbers) in region A for fleet f during quarter t of fish in length-class $\tilde{L}$ (in number), $C^A_{t,\tilde{L}}$, is given by:

$$C^A_{t,\tilde{L},f} = \sum_k \sum_a R_{L_{k,a+0.5}} P_{L_{k,a+0.5}} S_{t,L_{k,a+0.5}} F^A_{t,f} N^{k,A}_{t,a} e^{-M_a/2} \qquad (4.6b)$$

where the summation over age and group in Equation (4.6b) is restricted to those combinations of age and group for which $L_{k,a+0.5} \quad \tilde{L}$.

For the historical time series, the fishing mortality for each area, fleet and quarterly time step, $F^{A}_{t,f}$, is calculated analytically using the observed catches and Pope's Approximation:

$$F^{A}_{t,f} = C^{obs,A}_{t,f} / \sum_{k} \sum_{a} R_{L_{k,a+0.5}} P_{L_{k,a+0.5}} S_{t,L_{k,a+0.5}} N^{k,A}_{t,a} \, e^{-M_a/2} \tag{4.6c}$$

where $C^{obs,A}_{t,f} = C^{obs',A}_{t,f} \quad Bias \quad e^{\varepsilon^C_t - \sigma^2_C/2}$, $\varepsilon^C_t \sim N(0;\sigma^2_C)$

$Bias$ is the bias in reported observed catch

$C^{obs',A}_{t,f}$ is the reported observed catch

σ_C is the standard deviation of the logarithms of fluctuations in reported observed catch

For the projection time steps, the fully selected fishing mortality is calculated using catchability parameters fitted using the historical observed effort data, as described in section 4.3.1 below.

4.1.5 Movement

Fish are assumed to move among regions according to a matrix of transition probabilities, $X^{A,A'}_{q,L}$, where:

$$X^{A,A'}_{q,L} = \begin{cases} \sigma^{A}_{q} \delta^{A}_{L} \overline{X}^{A,A'}_{q} / \sum_{A''} \left(X^{A'',A'}_{q,L} \right) & \text{if } A = A' \\ \overline{X}^{A,A'}_{q} / \sum_{A''} \left(X^{A'',A'}_{q,L} \right) & \text{otherwise} \end{cases} \tag{4.7}$$

where $X^{A,A'}_{q,L}$ is the probability that a fish of length L in region A' at the start of quarter q moves to region A at the end of that quarter given that it survived that quarter.

$\overline{X}^{A,A'}_{q}$ is an initial guess for the probability that an animal will move from region A' to region A in quarter q.

$\sigma^{A'}_{q}$ is an adjustment for quarter q for region A' (fitted as model parameters for 3 quarters and 3 areas).

$\delta^{A'}_{L}$ is an adjustment for a fish of length L in region A', given by:

$$\delta^{A'}_{L} = \begin{cases} 1 + \partial^{A'} \quad L / L_{\infty} & ; L < L_{\infty} \\ 1 + \partial^{A'} & ; L \geq L_{\infty} \end{cases}$$

where ∂^{A} are fitted as model parameters for 3 areas.

Equation (4.7) allows the initial movement matrix to be modified in two ways. First, the probability of not moving from a given region in a given quarter can be adjusted (thereby increasing or decreasing all the other rates of movement). Second, the probability of not moving from a given region is dependent on the size of a fish.

The elements of the initial movement matrix are determined by the proportions, $P_{q,A}^{tot}$, of the selected population within each area *A* in quarter *q*. These proportions are based on the distribution of catch rates averaged across all quarters and years from 1971 to 1999 (cf. Tables 3.7 and 3.8).

A log-normal random error is applied to the movement array each year *y* to account for inter-annual variation in movement, and the matrix is then re-normalised:

$$X_{t,L}^{A,A'} = X_{q,L,y}^{A,A'} = X_{q,L}^{A,A'} \; e^{\varepsilon_{L,y}^{A,A'} - \sigma_X^2/2} \Big/ \left[\sum_{A''} X_{q,L}^{A'',A'} \; e^{\varepsilon_{L,y}^{A'',A'} - \sigma_X^2/2} \right] \qquad \varepsilon_{L,y}^{A''} \sim N(0;\sigma_X^2)$$

where σ_X is the standard deviation of the logarithms of annual fluctuations in the movement probability array elements, and *t* is the quarterly time step described uniquely by *q* and *y*.

4.1.6 Input Parameter Values

Apart from the initial biomass and movement parameters, fitted as estimable parameters, a number of other input parameters are required to specify the dynamics of both the resource and the fishing fleets. All parameter values are summarized in Table 4.1. The biological parameters are based values described previously in Chapter 2 while the procedures used to ascertain the values of the technological parameters are described here.

<u>Selectivity Ogives</u>

No information on the selectivity at length for swordfish caught in the ETBF is currently available. Instead, selectivity-at-length was estimated as follows (Punt et al, 1999):

a) The fleet-aggregated selectivity pattern (by age) for swordfish captured in the Atlantic (Table 13 of Anon (1997)) was converted into age-specific selectivity for the Japanese longline fishery in the Atlantic. The selectivity for age 9 obtained in this manner was much lower than expected (0.31) and was therefore excluded from further analyses.
b) An average growth curve was obtained by averaging the “central” sex-specific growth curves,
c) A length-specific logistic selectivity curve (see below) was fitted to the longline selectivity calculated at step a).
d) The curve parameters, *a* and *b*, were adjusted until the modelled length- and weight-frequency distributions closely matched the observed distributions.

The shape of the resulting selectivity curve is shown in Figure 4.2. An error term was applied to the parameter *a* of the selectivity curve enabling alternative selectivity curves for each model iteration, i.e.

$$S_L = 1/(1 + e^{(\hat{a} - b\,(5L - 2.5)})$$

where $\hat{a} = a e^{\varepsilon_f^L - \sigma_S^2/2}$, $\varepsilon_f^L \sim N(0, \sigma_S^2)$

Alternative values of the error term, σ_S, were investigated *a priori* to determine which generated a range of selectivity curves without frequently obtaining unrealistic scenarios (e.g. 100% selectivity at a small length). Based on this investigation a value of σ_S =0.4 was selected. Samples of selectivity ogives based on this value are shown in Figure 4.2.

Table 4.1: Biological and technological parameters of the operating model

Parameter/quantity	Value	Source	Location	Comment
Plus-group age	40 years			
Natural mortality, *M*	0.2-0.3 (age-specific)	Yabe *et al.* (1959) Preece, *pers.comm*	Pacific Ocean	Would be preferable to have age/sex specific values from east Australian fishery
Growth: Male: L_∞ k t_0	217.36 0.1948 -2.0444	Berkely and Houde (1983)	Straits of Florida	Would be preferable to have parameters from Australian fishery
Female: L_∞ k t_0	340.04 0.09465 -2.5912			
Weight-at-length ($W=aL^b$): a b	 $2.1355\text{x}10^{-5}$ 2.902	Data collected by Australian observers on Japanese vessels	Eastern AFZ	
Steepness, *h*	0.9-0.4	Punt et al (1999).		Based on the advice from Andre Punt.
σ_r = coefficient of variation for recruitment fluctuations	0.4	Punt, pers. comm..		This assumes relatively low recruitment variability.
Length at which 50% mature (fecundity ogive) Female Male	 199.8 cm 85.9 cm	Young *et al.* (2002)	ETBF	State of gonad development (from histology) used to ascertain sexual maturity
Selectivity - S_L a= b=	Sigmoid curve: 5.5 0.042	Anon (1997)	Atlantic Ocean	Curve parameters were adjusted until the modelled length- and weight-frequency distributions closely matched the observed distributions
σ_s = coefficient of variation for fluctuations in selectivity parameter *a*	0.4			Based on investigation of appropriate value.
Retention-at-length R_L	See Fig 4.2	ETBF Fisheries Assessment Group	ETBF	Based on views expressed by industry.
Predation loss-at-length P_L	See Fig 4.2	ETBF Fisheries Assessment Group	ETBF	Based on views expressed by industry.
Bias in catch	1	Campbell (2001)	ETBF	
σ_c, coefficient of variation associated with reported catch	0	Campbell (2001)	ETBF	For simplicity.

Figure 4.2 Sample of selectivity ogives used in the model. The dashed line gives an indication of the range of selectivites for each length.

Recruitment Variability

The parameter σ_r (which approximates the coefficient of variation of the fluctuations in recruitment) was set to 0.4. This corresponds to an assumption of relatively low recruitment variability about the stock-recruitment curve.

A listing of all parameters and their initial values is given in Table 5. Note, however, in order to encompass the full range of possible resource and fleet dynamics, the values of many of these parameters will be varied about the values shown. This is described in the next chapter.

4.2 Model Conditioning

The population and fishery dynamics within the operating model are uniquely determined for each set of input parameters. However, not all possible model dynamics will be consistent with the historical data collected from the fishery. For example, if the initial biomass is set too low, it is likely that the modelled population dynamics will not be able to explain the complete sequence of historical catches taken from the stock. While it is not possible to simultaneously estimate all parameters given the historical data available, it is desirable to estimate some of the parameters which otherwise would be difficult to determine from the available data - for example, the initial biomass. The set of non-estimated parameters can be varied independently as fixed inputs, where each variant is one of the range of scenarios examined later. The process of determining a range of initial starting values for the operating model that are consistent with the available historical data is known as conditioning.

4.2.1 Parameter Estimation

For the present model, the values of *Ro* (the steady state number of recruits in the pre-exploitation stock), and the parameters of the movement probability matrix were chosen to be estimated. All other parameters were input as fixed values for each scenario. The model was then conditioned to the 31 years (1971-2001) of catch, CPUE and size data (described in the previous chapter) by minimising the following objective function:

$$SS = w_1 SS_1 + w_2 SS_2 + w_3 SS_3 + w_4 SS_4 + w_5 SS_5$$

where:

$$SS_1 = \left(B_{32} / B_1 - D_{32}\right)^2 \tag{4.8}$$

where B_t is the spawning biomass at the start of the *n-th* year and D_{32} is the assumed level of depletion at the start of the 32nd year, ie. the ratio of the size of the spawning biomass at the end of the historical period to the size of this biomass at pre-exploitation equilibrium is compared with a given level of depletion.

SS_2 and SS_3 relate to fitting the size histograms of the predicted catches to the size histograms of the observed catches (described in section 3.4). Multinomial log likelihoods are used in fitting to the length- and weight-frequency data (the negative is taken so that the likelihood is maximized when the objective function is minimized):

$$SS_2 = \tfrac{1}{2}\sum_{q=1}^{4}\sum_{A=1}^{Na}\sum_{W=1}^{Nwt}\ln[2\pi(\xi'_{qAW} + \tfrac{0.1}{Nwt})\tau^2] - \sum_{q=1}^{4}\sum_{A=1}^{Na}\sum_{W=1}^{Nwt}\ln\left[\exp\left\{\frac{-\left(P^{Aus}_{q,A,W} - \hat{P}^{Aus}_{q,A,W}\right)^2}{2(\xi'_{qAW} + \frac{0.1}{Nwt})\tau^2}\right\} + 0.01\right] \tag{4.9}$$

where $\hat{P}^{Aus}_{q,A,W}, P^{Aus}_{q,A,W}$ are the modelled and observed proportions, respectively, of the total catch retained by Australian longliners during quarter q in region A during the years 27-31 (1997-2001) that lie in weight-class W,

$\xi_{qAW} = (1 - P^{Aus}_{q,A,W})P^{Aus}_{q,A,W}$

Na is the number of areas,

Nwt is the number of weight categories in the weight frequency for each year,

$\tau^2 = \min(S,1000)^{-1}$, and

S is the effective weight frequency sample size

$$SS_3 = \tfrac{1}{2}\sum_{q=2}^{3}\sum_{A=4}^{Na}\sum_{L=1}^{Nlen}\ln[2\pi(\xi'_{qAL} + \tfrac{0.1}{Nlen})\tau^2] - \sum_{q=1}^{4}\sum_{A=4}^{Na}\sum_{L=1}^{Nlen}\ln\left[\exp\left\{\frac{-\left(P^{Jap}_{q,A,L} - \hat{P}^{Jap}_{q,A,L}\right)^2}{2(\xi'_{qAL} + \frac{0.1}{Nlen})\tau^2}\right\} + 0.01\right] \tag{4.10}$$

where $\hat{P}^{Jap}_{q,A,L}, P^{Jap}_{q,A,L}$ are the modelled and observed proportions, respectively, of the total catch retained by Japanese longliners during quarter q in region 5 (assumed also to be representative of region 4) during the years 21-29 (1991-1999) that lie in length-class L,

$\xi_{qAL} = (1 - P^{Jap}_{q,A,L})P^{Jap}_{q,A,L}$

Na is the number of areas,

$Nlen$ is the number of length categories in the length frequency for each year,

$\tau^2 = \min(S,1000)^{-1}$, and

S is the effective length frequency sample size.

SS_4 and SS_5 relate to fitting the predicted spatial and temporal distributions of the selected swordfish biomass to the observed spatial and temporal distributions of CPUE as described in section 3.5.

$$SS_4 = \sum_{q=1}^{4} \sum_{A=1}^{NA} \left(\hat{P}^{tot}_{q,A} - P^{tot}_{q,A} \right)^2 \qquad (4.11)$$

where: $\hat{P}^{tot}_{q,A}, P^{tot}_{q,A}$ are the modelled and observed number of swordfish selected by Japanese longliners in quarter q in region A expressed as a proportion of the total across all regions for that quarter (averaged over all years - *cf.* Table 3.8 in section 3.5).

Error terms are applied to each element of the Table 3.8 matrix ($P^{tot'}_{q,A}$), and the matrix is re-normalised as follows:

$$P^{tot}_{q,A} = P^{tot'}_{q,A} \; e^{\varepsilon_{q,A} - \sigma^2_{tot}/2} \Big/ \sum_{A'} P^{tot'}_{q,A'} \; e^{\varepsilon_{q,A'} - \sigma^2_{tot}/2} \; ; \qquad \varepsilon_{q,A} \sim N(0, \sigma^2_{tot}) \qquad (4.12)$$

where: σ_{tot} is the standard deviation of the logarithms of the fluctations in the within-quarter spatial distribution.

$$SS_5 = \sum_{q=1}^{4} \sum_{A=1}^{NA} \left(\hat{P}^{area}_{q,A} - P^{area}_{q,A} \right)^2 \qquad (4.13)$$

where $\hat{P}^{area}_{q,A}, P^{area}_{q,A}$ are the modelled and observed number of selected swordfish in quarter q in region A expressed as a proportion of the sum across all quarters for that year and for that region (averaged over all years - *cf.* Table 3.7 in section 3.5).

Error terms are applied to each element of the Table 3.7 matrix ($P^{area'}_{q,A}$) and the matrix is re-normalised as follows:

$$P^{area}_{q,A} = P^{area'}_{q,A} \; e^{\varepsilon_{q,A} - \sigma^2_{area}/2} \Big/ \sum_{A'} P^{area'}_{q,A'} \; e^{\varepsilon_{q,A'} - \sigma^2_{area}/2} \; ; \varepsilon_{q,A} \sim N(0, \sigma^2_{area}) \, , \qquad (4.14)$$

where σ_{area} is the standard deviation of the logarithms of the fluctations in the between-quarters spatial distribution.

To summarise, component SS_1 is used to fit the pre-exploitation stock size parameter while components SS_2 to SS_5 constrain the movement parameters. The weights, w_i, (determined by trial and error) are such that the contribution to each component to the sums of squares are comparable.

4.2.2 Conditioning Procedure

The observed catches are used in the model to determine the total fishing mortality in each region for each quarter (as described by equations 4.6a-c). Given an initial biomass estimate, this time series of fishing mortalities (together with the modelled natural mortality and recruitment) is then used to project the population biomass forward in time. At the end of the historical time period (2001) a number of predicted features of the swordfish population (eg. depletion level at the end of 2001) are then compared with the corresponding assumed or observed values (eg. the assumed depletion level at the end of 2001). This process is repeated until the values of *Ro* and the movement parameters which minimise the objective function described previously are found. At this stage, the parameters which describe the functional form of the catchabilities required for the calculation of the fishing mortalities used in the projection phase (and described in the next section) are determined.

More precisely, the specification of initial conditions and the model conditioning involves the following steps, repeated for each simulation:

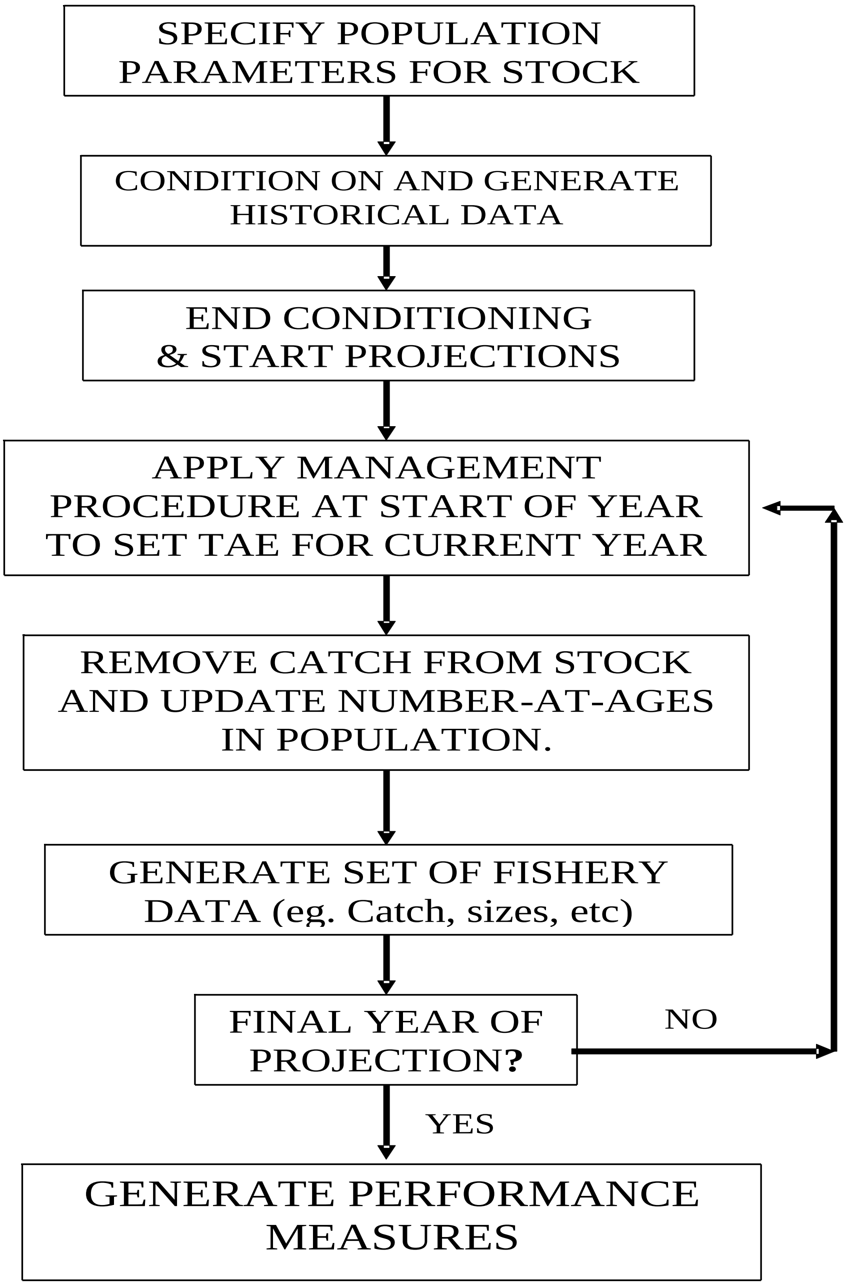
a) Values for the biological parameters (e.g. growth rates, natural mortality, steepness, length- and weight-frequency histograms) and the technological parameters (e.g. selectivity) are specified as fixed inputs.
b) The level of depletion of the spawning biomass at the start of the 32^{nd} year (relative to the corresponding pre-exploitation equilibrium) is specified.
c) The deviations about the stock-recruitment relationship (see Eqn. 3.3), selectivity parameter A (see Eqn. 3.2), the movement array (see Eqn. 3.9) and the elements of Tables 3 and 4 are generated
d) Starting values for the fitted parameters (pre-exploitation size of the stock and the movement parameters) are guessed.
e) The population is projected from deterministic equilibrium (that is, the first year of fishing) to the start of the 32^{nd} year (the first year of future projection) by removing the known catches from 1971 to 2001.
f) Using the objective function, corresponding values predicted from the operating model are compared with the historical observations and the estimated level of depletion at the start of the 32^{nd} year. If the difference is not small (SS<0.00001), steps d)-f) are repeated. The optimisation is achieved using AD Model Builder.
g) Values for the parameters of the relationship between fishing effort and fishing mortality are then determined by maximum likelihood.
h) Steps c) – f) are then repeated for each simulation run.

Therefore, each simulation run involves a single choice for the model inputs (the biological and technological parameters (Table 4.1) and the initial depletions). The output consists of different values for the pre-exploitation equilibrium biomass, the movement parameters, the catchability parameters, and the time-sequence of deviations about the stock-recruitment relationship and the observed catches. This approach to ‘conditioning’ the simulations is similar to that applied by the International Whaling Commission (IWC) (1993, 1994).

4.3 Projections

After conditioning the operational model, the model is then used to project the swordfish population forward for a further 20 years (ie. from the start of 2002 to the start of 2022). During the projection years, the fishery dynamics is controlled by the levels of fishing effort set for the each fleet. For example, for the fixed effort harvest strategies described in Chapter 6, the fishing effort for each fleet in each quarter and region is pre-determined at the start of each projection. Given this time-series of fishing effort, equations 4.6a-b are then used to calculate the corresponding time-series of catch and size-composition data. Together with the effort, these data are then used for constructing performance indicators and, were required, for input into the annual assessment. Note: the catches are assumed to be measured without error (although the model has the facility to impose a stochastic error on the observed catches). This assumption is thought to be reasonably realistic as a study which compared the numbers of fish reported in logbooks with the number of fish measured by processors found that the annual totals agreed to within a few percent (Campbell, 2001).

Figure 4. Flow chart of the procedural steps in the MSE process.



Unlike the situation for historical years, where the observed catch was used to calculate the corresponding fishing mortality using equation 4.6c, during the projection years the catch needs to be determined given a level of fishing effort. It follows from the catch equation ($C = FB = qEB$) that this requires knowing the values of q, the catchability function. The procedure for estimation of the catchability function is described here.

4.3.1 Catchability parameters

The fully-selected fishing mortality for region A during projection time step t, F_t^A, is calculated using catchability parameters, which are obtained at the end of the model conditioning by fitting predicted to observed catches, where the predicted catches by numbers, C_{pred} are calculated as:

$$C_{pred} = \sum_{A} \sum_{\tilde{L}} \sum_{f} C^{A}_{t,\tilde{L},f}$$

For the Japanese fleet, the fully-selected fishing mortality for the projection time series is assumed to be related to the observed fishing effort for region *A* and year by quarter, *t*, E_t^A, as follows:

$$F_{t,1}^{A} = \tilde{Q}_{q,1}^{A} \, (E_{t,1}^{A})^{\gamma_q} \, e^{\lambda_q t} \, e^{\varepsilon_{t,1}^{A} - \sigma_{A,1}^{2}/2} \tag{4.15a}$$

where $\tilde{Q}_{q,1}^{A}$ is the catchability coefficient for area *A* and quarter *q* (corresponding to time step *t*) for Japan (fleet 1)

γ_q is the non-linearity factor for quarter *q*

λ_q is a factor to account for changes over time in effectiveness in quarter *q*, and

$\varepsilon_{t,1}^{A}$ is a factor to account for random variation in catchability ($\varepsilon_{t,1}^{A} \sim N(0;\sigma_{A,1}^{2})$).

This equation can be log-transformed and solved for $\tilde{Q}_{q,1}^{A}$, γ_q and λ_q as a system of linear equations (ignoring the random variability term).:

$$\log F_{t,1}^{A} = \log \tilde{Q}_{q,1}^{A} + \gamma_q \log E_{t,1}^{A} + \lambda_q \; t \tag{4.15b}$$

This is done for the historical time series, using the observed effort, so that the fitted values for $\tilde{Q}_{q,1}^{A}$, γ_q and λ_q at the end of the historical period may be used in equation 4.15 for the projection time series. It should be noted, that while γ_q and λ_q vary between quarter, they are similar for all regions. As such, temporal changes in catchabilities are assumed to be the same across all regions. This is based on the belief that factors which influence temporal changes in Q impact in a synchronized manner across all regions.

For the Australian and New Zealand fleets, targeting progressively shifted onto broadbill swordfish after 1995 and fishers have learnt how to more efficiently target this species. Furthermore, unlike the situation for the Japanese fleet, the temporal changes in targeting practices for the Australian and New Zealand fleets were different for each region. To describe these shifts, the following equation was used to describe the relationship between fully-selected fishing mortality and observed effort for each fleet, *f*, for the projection time series:

$$F_{t,f}^{A} = \tilde{Q}_{t,f}^{A} \left(E_{t,f}^{A} \right) e^{\varepsilon_{t,f}^{A} - \sigma_{A,f}^{2}/2} \tag{4.16a}$$

where

$$\tilde{Q}_{t,f}^{A} = \begin{cases} Q_{q,f}^{A} \; ; t \le t' \\ Q_{q,f}^{A} \left(1 + \gamma_{q,f}^{A} (1 - e^{-\lambda_{q,f}^{A}(t-t')}) \right) ; t > t' \end{cases} \tag{4.16b}$$

and *t'* is the time at which the increase in targeting commenced (set to quarter 100 for the Australian fleet in all areas, and quarter 108 for the New Zealand fleet)

$\gamma_{q,f}^{A}$ is the amplitude of the asymptote for the catchability curve for each region, quarter and fleet (constrained to be between 0 and 4)

$\lambda^{A}_{q,f}$ is the rate of learning/increase in targeting for each region, quarter and fleet (currently constrained to be between 0 and 2, although data suggests it could well be greater than 2, especially for the Australian fleet in region 2) and

$Q^{A}_{q,f}$ is the baseline catchability prior to time step *t'*, for each region, quarter and fleet.

The observed effort time series was applied in equation 4.16a, and the least-squares difference between this and the fishing mortality obtained using equation 4.6c, was used to determine $\gamma^{A}_{q,f}$, $\lambda^{A}_{q,f}$ and $Q^{A}_{q,f}$, for each fleet, area and quarter. These parameters could then be fed into equation 4.2a for the projection time series.

4.3.2.Catch size-composition data

The catch size-composition data for region *A* during a given quarter *t* are assumed to be a simple (but large: 1000 fish) random sample of fish from the catch-at-size for that year (see Eqn 4.6b). The mass-frequency data are computed from the catch size-composition data by converting the length of each fish to mass according to the length-mass relationship (Equation 4.5) and adding multiplicative error with a coefficient of variation of 3.6%. This level of variability is based on the fit of a length-mass relationship to the actual data for broadbill swordfish (Punt et al, 1999). Note, while no length measurements for swordfish are presently being obtained from the fishery, the frequency of weight sampling is very high, with around 75 percent of all landed swordfish being individually weighed in recent years (Campbell et al, 2003).

4.3.3 Projection Runs

As described in the previous section, each conditioning simulation run involves the input of a single choice for the model parameters (including the assumed depletion level at the end of the historical period) and the historical time-series of catches, while the output consists of the estimated value for the pre-exploitation equilibrium biomass, the movement parameters, and the catchability parameters. On the other hand, each projection run involves the input of the same set of model parameters (together with the estimated values for the pre-exploitation equilibrium biomass, the movement parameters, and the catchability parameters) and the time-series of future efforts for each fleet, while the output consist of the predicted catches and population biomass within each quarter and region. For each biological and future effort scenario, the operational model therefore allows predictions to be made of the corresponding annual catches for each fleet and the response of the swordfish population to these catches.

For each scenario, the model was run 100 times and the various quantities of interest predicted by the model were summarized. While a large number of quantities of interest are calculated during each model run, prudence suggests that the selected quantities should be those of most interest and relevance to the industry and managers associated with the fishery. As such, based on discussion with the ETBF Fisheries Assessment Group, the following quantities were selected:

i) time-series plot, and 95th confidence limits, of the spawning biomass in Area 2 (expressed as a percentage of the original biomass),
ii) time-series plot of the mean and upper 95th percentiles of average weight of fish caught by the Australian fleet in Area 2
iii) time-series plots of the percentage of fish in Area 2 (by number) within each of three size classes (< 25kg, 25 ≤ processed weight ≤ 50kg, > 50kg),
iv) histogram of the average annual Australian catch over the projection years,
v) histogram of the final total spawning biomass relative to initial total spawning biomass,

vi) histogram of the probability that the total spawning biomass drops below 30% of its initial level

vii) histogram of the probability that the total spawning biomass drops below 50% of its initial level

The three size classes included in (iii) above were considered appropriate from an economic perspective, as there is a differential market price corresponding to each size class - approximately \$4-5/kg, \$6-7/kg and \$10-12/kg, respectively (B. Taylor, pers. comm.).

4.4 Performance Indicators and Performance Measures

In order to summarise the information pertaining to the performance of both the swordfish resource and the fishery during the projection years, a number of performance indicators and performance measures were used. A performance indicator conveys information about some aspect of the system under study (eg. the size of the swordfish population in the SW Pacific) while a performance measure conveys information about how well the system is performing relative to some management objective (eg. it compares the performance indicator with some reference value or benchmark, say 30%B_o). Performance measures are usually based on quantities estimated during the assessment and are generally useful only if a stock assessment method can estimate them reliably. The reference values or benchmarks could be target values that identify desirable conditions at which management should aim (target reference points) and/or threshold or limit values that identify critical levels which if exceeded result in potentially adverse fishery situations (limit reference points) (see, for example, Caddy and McGarvey 1996).

Desirable properties of indicator variables are that they change linearly with the quantity for which they are indicators, and that they are precise. Indeed, an ideal performance indicator is one that provides accurate and precise information about the quantity it is designed to mimic. For example, if CPUE is used as an index of abundance, it is hoped that changes in CPUE are proportionally related to changes in the abundance of the resource on which it is based.

Performance measures can be used to link future management actions with particular outcomes of regular assessments. This process uses an agreed decision rule that relates management outcomes with the values of the performance measures, or where a model based assessment is not available, to changes in the empirical based performance indicators themselves. For example, the annual *TAE* may be related to observed changes in the performance indicators such as catch rates or size composition of the catch. Alternatively, if a particular target is met, then stakeholders can agree beforehand on what management action is required. In such a situation the use of a decision rule allows the process to be proactive rather than reactive, and is transparent to all stake holders.

Performance indicators, performance measures and decision rules should be incorporated into the overall management procedure that is to be evaluated. As such, the management procedure needs to include the types of data to be used to assess the state of the fishery, how the data will be collected, the models which will be used to analyse the data, and the ‘decision’ rule which will be used to turn the output of the model (from the stock assessment) into the annual decision on the management measures to be adopted (such as the annual effort quota in the case of a *TAE* controlled fishery).

For the present study, a number of performance indicators and measures were considered in order to summarise the performance of the fishery during the projection period under each effort scenario. Again, in consulation with the ETBF Fisheries Assessment Group, the following eight performance indicators and measures were chosen. These performance indicators and measures were grouped into two broad classes - economic and conservation –

to help understand the trade-offs involved between these two broad management objectives for the fishery:

Economic

1. Mean annual catch taken by the Australian fleet over the 20 year projection period.
2. Mean change in the total catch between years (expressed as a percentage of the catch in the previous year).
3. Mean weight of fish caught by the Australian fleet in Area 2 over the 20 year projection period.
4. Mean percentage of large fish (>50kg) in the Australian catch in Area 2 over the 20 year projection period.
5. Mean annual economic value of the catch over the 20-year projection period (based on small, medium and large fish receiving a price of $4.50, $6.50 and $11.00 respectively).

Conservation

6. Final spawning biomass relative to the initial ("virgin") spawning biomass (expressed as a percentage).
7. Average probability that the spawning biomass drops below 30% of its initial value, (the average proportion of quarterly time steps over the 20 year projection period in which the spawning biomass is less than 30% of its initial value).
8. Average probability that the spawning biomass drops below 50% of its initial value, (the average proportion of quarterly time steps over the 20 year projection period in which the spawning biomass is less than 50% of its initial value)

These criteria were selected because collectively they broadly represent three broad management objectives for the fishery: maximise the present value of the catch subject to the constraint that the harvest regime is sustainable and the change in the catch from year to year is minimised (ie. maximise industrial stability is achieved), (Walters and Pearse 1996, Butterworth and Punt 1999). Note, it is never possible to perfectly satisfy all of the management objectives, and all harvest strategies consequently achieve some balance among them (eg. high catch, high risk; low catch, low risk). This information on the trade-offs among the management objectives is needed by the decision makers to make an informed decision about management actions, given the importance they assign to each of the objectives. Finally, it is also important the performance criteria should also be easy for managers and stakeholders to interpret (Francis and Shotten 1997).

Chapter 5: Comparison of Biological Scenarios

5.1 Introduction

In developing an operating model for broadbill swordfish, it must be acknowledged that there remain major gaps in our understanding of the biology and behaviour of broadbill swordfish in the south west Pacific Ocean. While reproductive studies have been undertaken by Young *et al.* (2002), little other biological work has been directed at broadbill swordfish in this region (however, CSIRO is presently undertaking an ageing study). In order to overcome this deficiency, information on growth, natural mortality rates, and the stock-recruitment relationship has generally been based on published research undertaken on broadbill swordfish in other oceans. The biology adopted in this manner form what is known as the reference or base-case biological model for swordfish in the SW Pacific. However, given the uncertainty surrounding the population dynamics, it is important to examine the sensitivity of the MSE outputs to a range of plausible biological scenarios for swordfish in the SW Pacific. For this purpose, a range of operating models, each with a different suite of assumed biological inputs, needs to be considered.

Ideally, all alternative harvest strategies should be assessed against each alternative biological scenario. However, as it is impractical to do this, in this chapter we compare a range of biological scenarios (operating models) using only four fixed effort strategies. If the performance of these strategies is robust to the range of biological scenarios, then this range of scenarios and operating models can be excluded from further analysis and harvest strategy evaluation. Moreover, determining the biological inputs to which the model results are sensitive helps with prioritising and focusing areas for future research. The focus for this chapter is thus on sensitivity analysis rather than evaluation of harvest strategies.

5.2 Selected Scenarios

The reference operating model, based on the input parameters listed in Table 4.1, represents the “best guess” for the population dynamics and biology of broadbill swordfish in the south-west Pacific. The proportion of females mature at length were taken from the recent CSIRO study on swordfish reproduction in the eastern tuna and billfish fishery (Young and Drake 2002), and are considered an accurate representation of reproductive dynamics. Similarly, the weight-at-length relationship is based on data collected by Australian observers on Japanese vessels in the ETBF. However, all other biological inputs are derived from the literature, or at best, are educated guesses.

5.2.1 Biological Scenarios

The alternative biological scenarios were chosen to represent what would be assumed to be extremes in the population dynamics and behaviour of the swordfish population, so that the outputs would provide upper or lower bounds for the population responses. These alternative scenarios are described as follows:

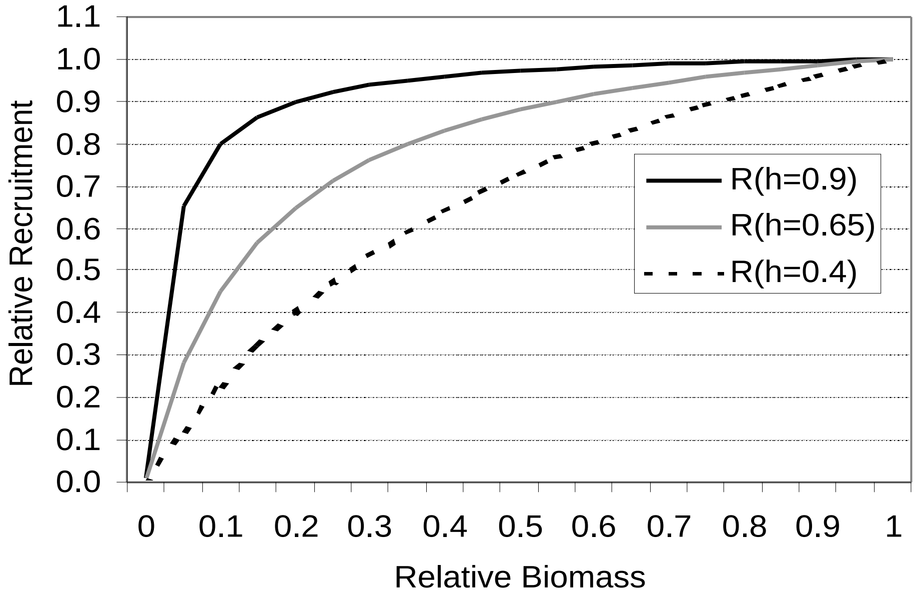
<u>1. Reference model</u>

Refer to above text.

<u>2. Steepness = 0.65.</u>

This model is the same as the reference model, except that steepness, *h,* is set to 0.65 rather than 0.9. This implies that recruitment is more sensitive to changes in biomass. Specifically, recruitment will be 35% lower, rather than only 10% under the reference scenario, when the total egg production is reduced to 20% of its pristine level (Figure 5.1). This indicates a

Figure 5.1 The stock-recruitment relationship for steepness h = 0.9, h = 0.65 and h = 0.4.



population more vulnerable to the effect of heavy fishing.

3. Steepness = 0.4

This model is the same as the baseline model, except that steepness, *h*, is set at 0.4 rather than 0.9. This implies that recruitment is more sensitive to changes in biomass, so that it will be 60% lower when the total egg production is reduced to 20% of its pristine level (Figure 5.1). This is considered to be a lower limit for steepness in the swordfish stock-recruitment dynamics (Punt, *pers. comm*.).

4 Natural mortality x 1.5:

This model is the same as the reference model, except that the baseline age-based natural mortality vector is multiplied by 1.5. This scenario indirectly implies a more productive stock in order to compensate for the loss of fish due to higher natural mortality.

5. Natural mortality x 1.5 and steepness = 0.65.

This model tests the effect of changing the natural mortality and the steepness simultaneously. While a higher natural mortality imposes a higher productivity, recruitment is lower than the baseline scenario for a given biomass. Thus the changes in these variables are likely to have opposing implications for the population, and the question is whether either will predominate over the other.

6. Intermediate movement

Fish are initially distributed and subsequently recruit according to the D_{init}, matrix given in Table 3.8. Subsequently, the movement probabilities of all fish are defined by taking the square root of the diagonal of the reference movement matrix and re-normalising. As such, fish have a lower probability of remaining within their current region, relative to the reference movement matrix. Quarterly and length-based movement parameters are still fitted.

7. No movement:

Unlike the baseline model, this scenario assumes there is no movement or exchange of fish between the five regions. Fish are initially equally distributed across the five regions but subsequently do not relocate. Thus heavily fished areas receive no replenishment from other regions, except in the form of recruits.

8. Equal (random) movement.

Fish are initially distributed and recruit according to the D_{init}, matrix given in Table 3.8. However, all fish subsequently have an equal (20%) probability of moving to any region (including remaining within their current region). This implies that movement is totally random. Unlike the baseline model, there are no quarterly or length-based movement parameters.

9. No movement and steepness = 0.4

This model tests the effect of stock more sensitive to changes in biomass (less productive), when no movement is permitted between regions. That is, there is no "source" replenishment of fish. If the biomass in any area is reduced, recruitment will decrease to a greater extent than it would under the reference scenario.

10. Depletion = 0.5 and steepness = 0.4

This model is a "conservative cross" to test the more extreme scenario of a less productive and less robust stock. A steepness of 0.4 is considered a lower bound for the species, and indicates that recruitment will be 60% lower when the total egg production is reduced to 20% of its pristine level (Figure 5.1). A higher level of assumed depletion implies that the swordfish population has been less robust to the historical levels of fishing effort.

5.2.2 Projected effort scenarios

The response of the swordfish population under each of the alternative biological scenarios is likely to vary according to the level of fishing intensity. If this change is not linearly proportional to the change in effort, an interaction between the level of effort and the change in the biological input is inferred. A population subject to low fishing pressure may be robust to an alternative biological scenario, but when it is more heavily fished it may show greater sensitivity. This is likely to be the case for the alternative stock-recruitment scenarios, since at high relative levels of biomass, and hence egg production, there is little difference between recruitment irrespective of steepness. Differences in steepness only begin to have an impact as biomass decreases.

In order to provide an opportunity to detect any interaction between effort and biological scenarios, if they exist, model projections under each biological scenario were undertaken using four effort scenarios taken from the range of low, intermediate and high Fixed Effort Scenarios evaluated in the next Chapter. The details of the four effort scenarios are as follows.

Scenario 1: Status quo:

- Domestic effort within each quarter/region strata remains at the 2001 level (Annual total of 11.2 million hooks).
- Foreign effort within each quarter/region strata remains at the average level of effort in that strata over the last 3 years 1999-2001.

Scenario 2: Domestic effort x 1.0, doubling of foreign increase, plus effort creep:

- Nominal domestic effort stays at 2001 level, but effective effort increases at 2% p.a. for all projection years,
- Nominal foreign effort doubles over the first 5 years, with effective effect increasing at 2% p.a. for the first five years, i.e. after the fifth year, both nominal and effective foreign effort remain constant.

Scenario 3: Domestic effort x 1.5, doubling of foreign effort, plus effort creep

- Nominal domestic effort increases by 1.5 over the first 5 years, with an effective effect increasing at 2% p.a. for all projection years, i.e. after the fifth year nominal domestic effort remain constant, but effective effect continues to increase.
- Nominal foreign effort doubles over the first 5 years, with effective effect increasing at 2% p.a. for the first five years, i.e. after the fifth year, both nominal and effective foreign effort remain constant.

Scenario 4: Domestic effort x 2.5, doubling of foreign effort, plus effort creep

- Nominal domestic effort increases by 2.5 over the first 5 years, with an effective effect increasing at 2% p.a. for all projection years, i.e. after the fifth year nominal domestic effort remain constant, but effective effect continues to increase,
- Nominal foreign effort doubles over the first 5 years, with effective effect increasing at 2% p.a. for the first five years, i.e. after the fifth year, both nominal and effective foreign effort remain constant.

5.3 Results

In order to first illustrate the difference in performance of the fishery under each biological scenario, time series and histogram results for the ten different biological scenarios listed above are presented for the status quo effort projection scenario only (Figures 5.2-5.7). The relative performance under each effort scenario will be investigated later.

5.3.1 Relative performance under Status Quo Effort Scenario

The time series plots of the predicted spawning biomass in Area 2 under each biological scenario are shown in Figure 5.2. (Note that the plots are annual values based on averages over the four quarters, and are expressed as proportions relative to the first quarterly time step.) The size of the final spawning biomass in Area 2 relative to the initial spawning biomass is also indicated in each plot. These values can be compared to the relative depletions predicted for the total spawning biomass across all regions given in Figure 5.6.

Under the reference biological scenario, the average spawning biomass in Area 2 is reduced to 49% of its initial value. This value decreases to 47% when steepness is reduced to 0.65 and to 43% when steepness is 0.4. This decrease is expected, as the average recruitment, and the rate at which the stock can rebuild, is reduced as the steepness of the stock-recruitment relation is reduced. On the other hand, when natural mortality is increased the final spawning biomass is slightly higher than under the reference biological scenario. This response is likely to be due to the fact that with a higher natural mortality, the stock needs to compensate by increasing its productivity in order to sustain the historical time-series of catches. Interestingly, when both the steepness and natural mortality are changed together, the final spawning biomass is found to be very similar to the reference value, indicating that in these two biological parameters tend to have opposite (and in this situation compensating) impacts on the overall productivity of the stock.

Intermediate movement makes minimal difference with respect to the reference scenario, with the final spawning biomass in Area 2 under this scenario also being 49% of its initial value. However, under the scenario of no movement the average final spawning biomass drops to 18% of its initial value. Furthermore, whereas similar levels of depletion for the spawning biomass in Area 2 and the total spawning biomass are predicted for the scenarios considered previously, in this situation the spawning biomass in Area 2 is predicted to be significantly more depleted than elsewhere (the total biomass is only depleted to 54%B_o, *cf.* Figure 5.6).

Figure 5.2 Time-series plot of the expected spawning biomass (expressed as a percentage of the original biomass), together with the 95th confidence limits, under the ten biological scenarios described in the text.

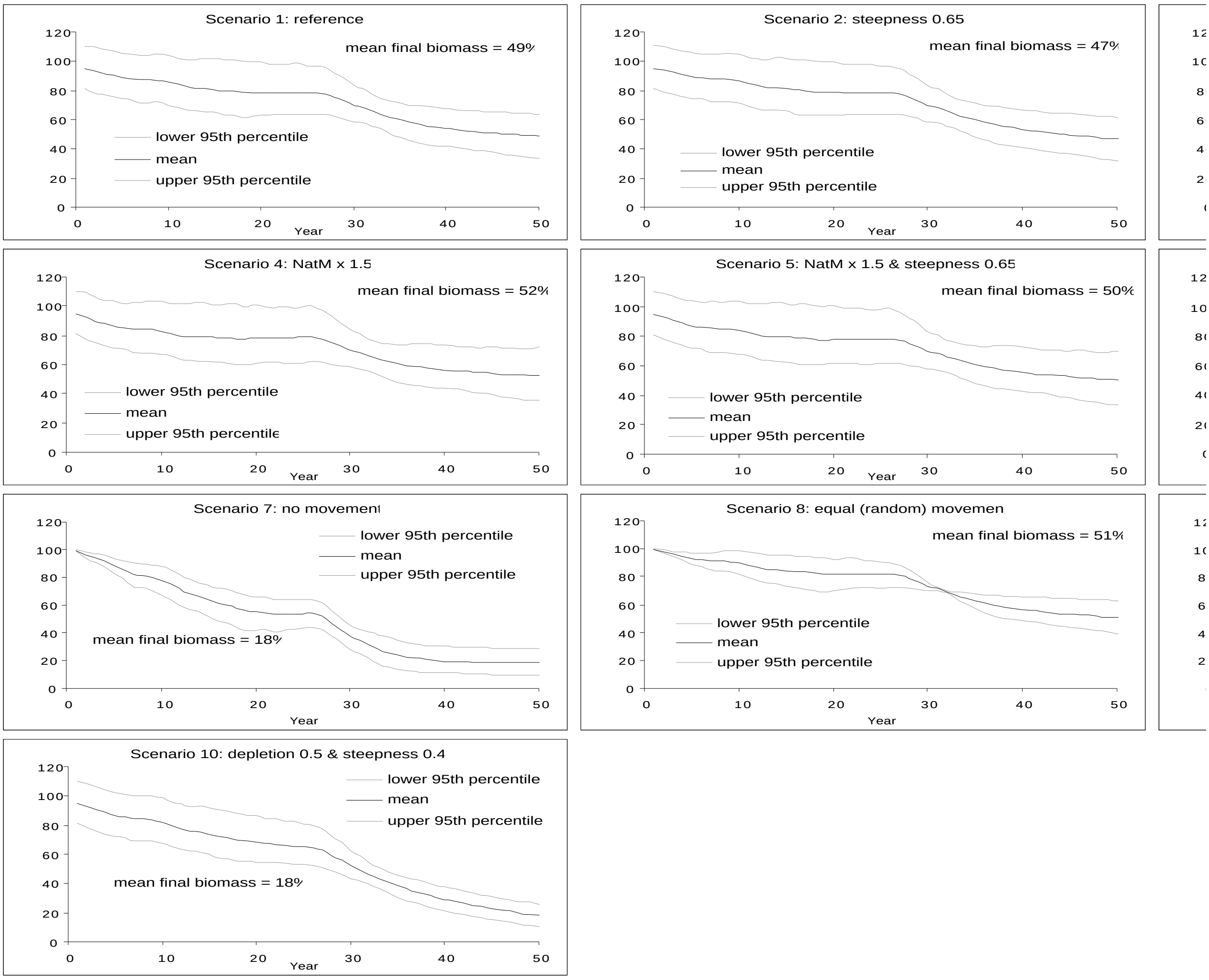


Figure 5.3 Time-series plot of the expected mass, together with the upper 95th confidence limit, under the ten biological scenarios described in the text.

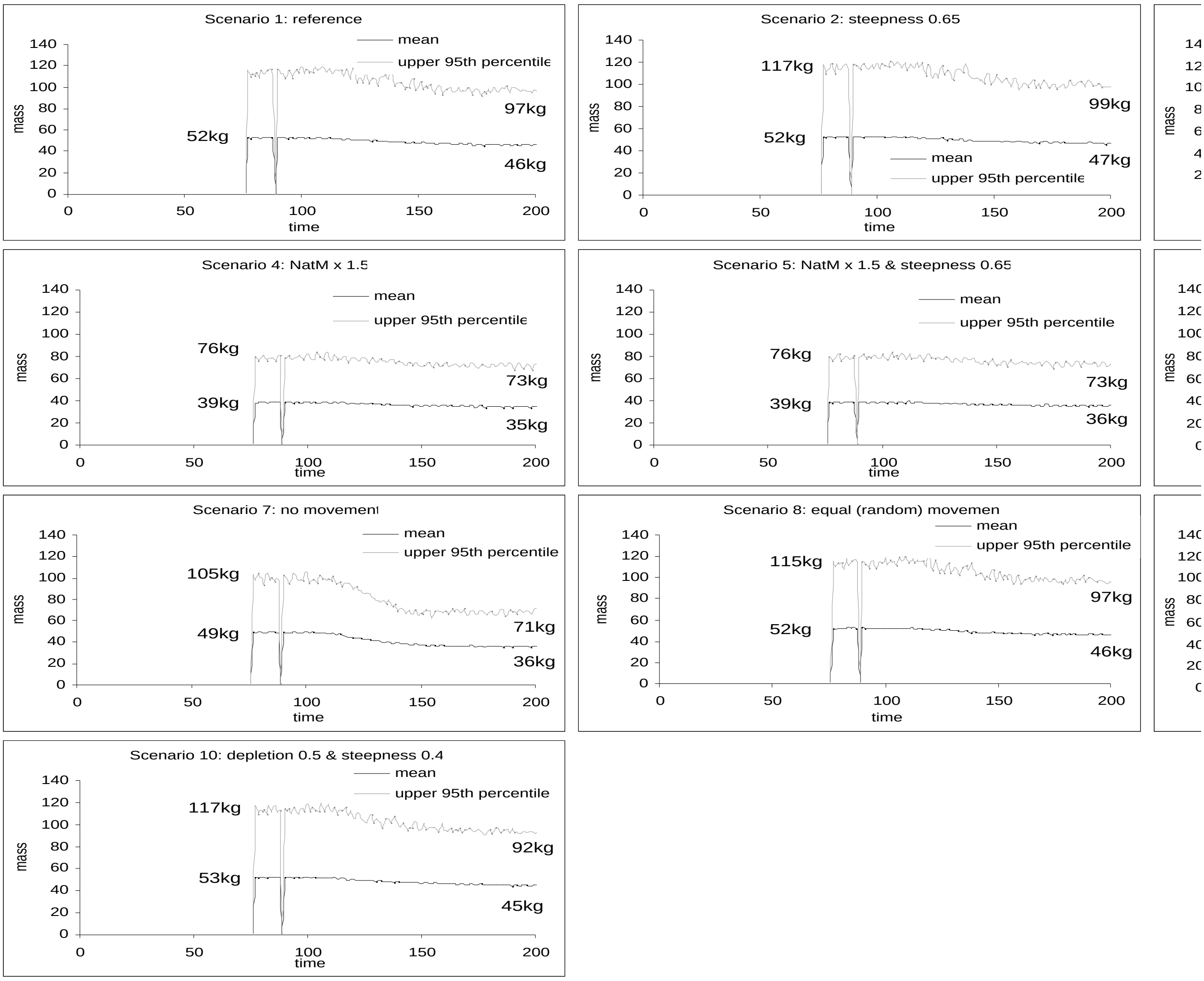


Figure 5.4 Time-series plot of the expected percentage of total catch by size class, under the ten biological scenarios described in the text.

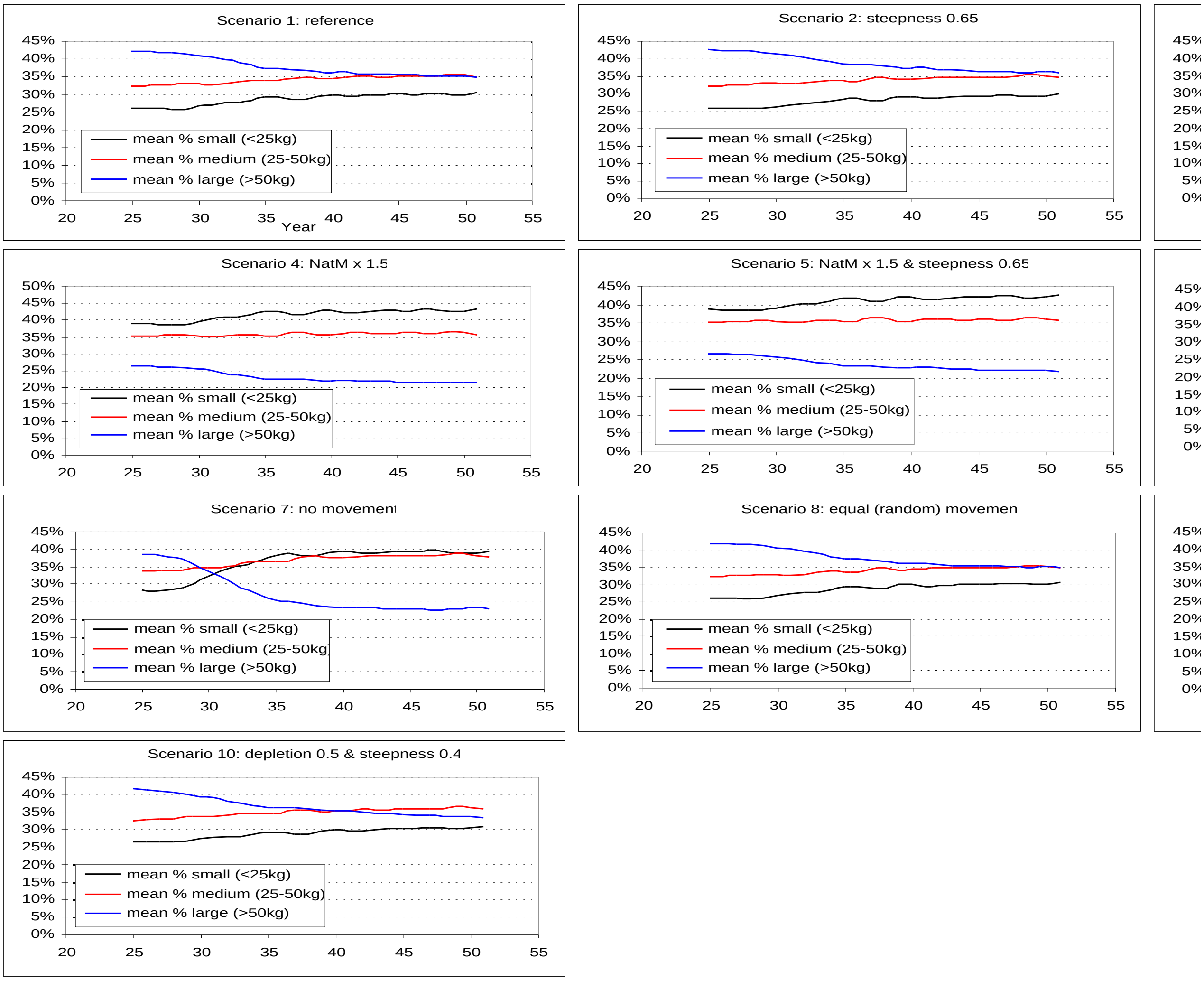


Figure 5.5 Histograms (over 100 simulations) of the mean annual catch (t) over the projection years, under the ten biological scenarios described in the text.

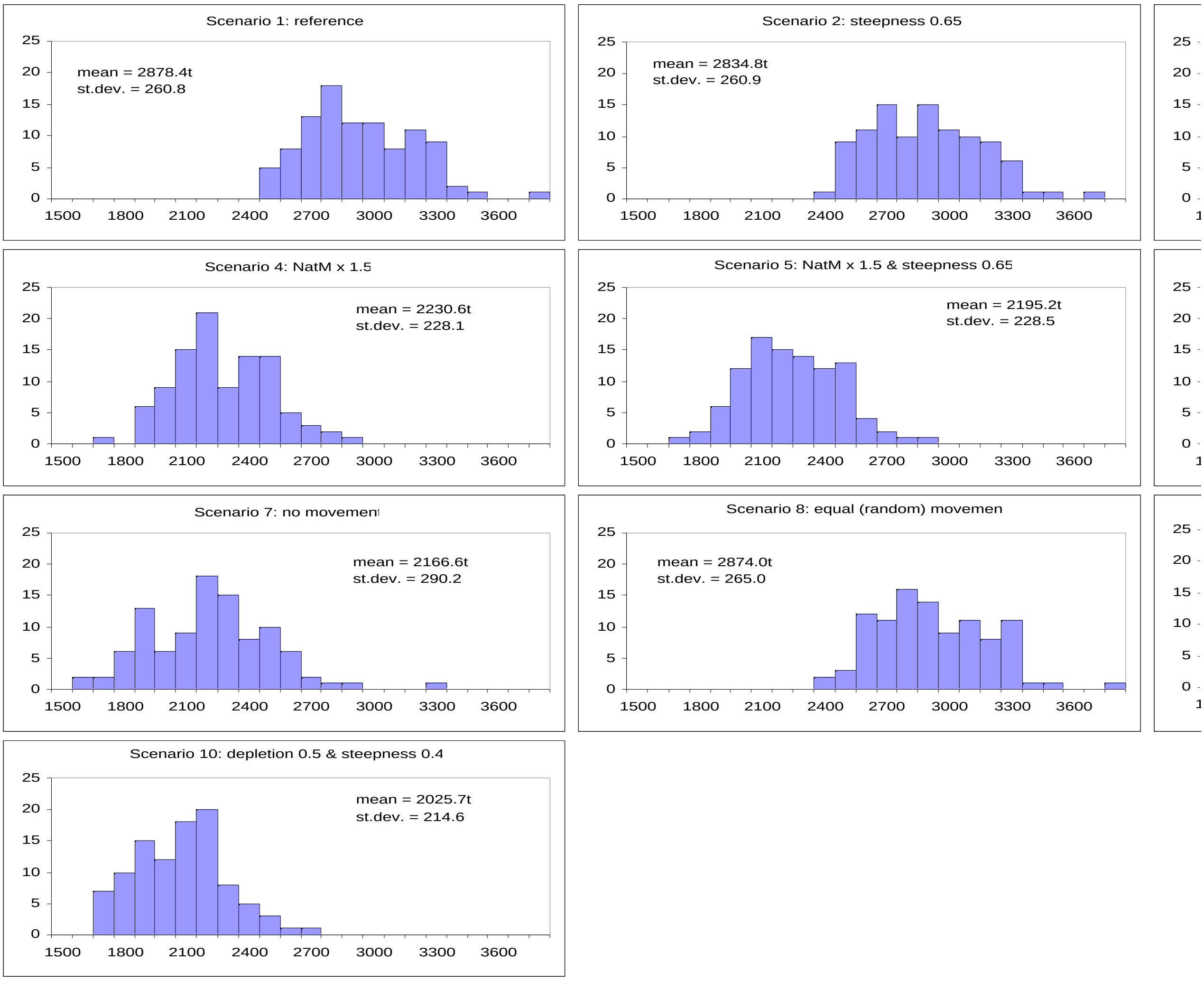


Figure 5.6 Histograms (over 100 simulations) of the ratio of the final to initial spawning biomass, under the ten biological scenarios described in the text.

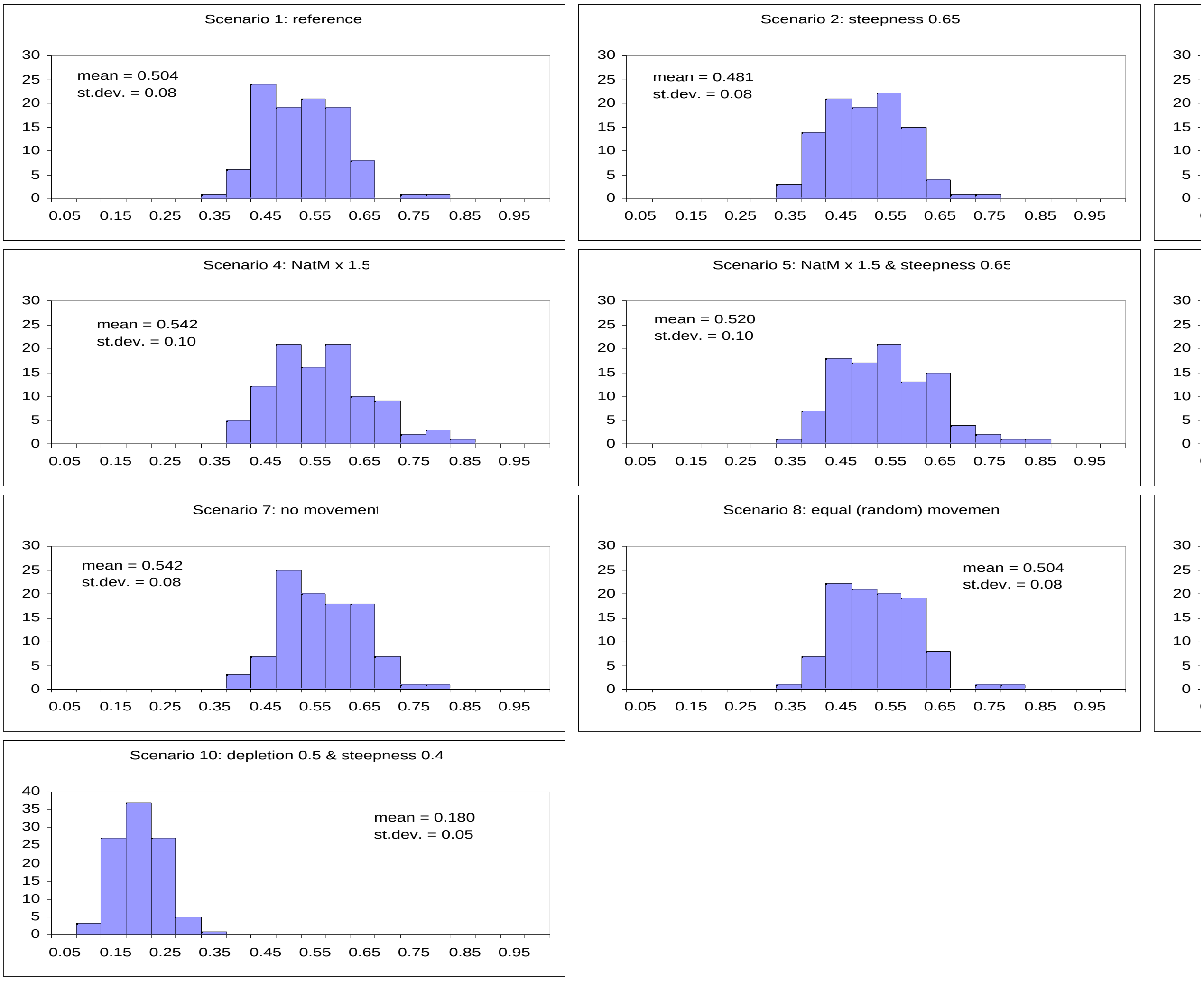


Figure 5.7 Histograms (over 100 simulations) of the probability that the spawning biomass dropped below 50% of its initial level, under the ten biological scenarios described in the text.

This is a consequence of the continuation of the relatively large catches taken by the Australian fleet in this region, and the fact that there is no replenishment of the resource in this area from other regions which by comparison are less heavily impacted. Under this scenario, this result would indicate that this area is presently being heavily fished. The size of this depletion effect also appears to be relatively insensitive to the value of the steepness parameter, as the final spawning biomass has a similar value when steepness is 0.4. Under the scenario where there is equal (random) movement between all regions, the average final biomass in Area 2 is estimated to be 51% of its initial value, and similar to the reference scenario. Hence, while the results are sensitive to whether there is movement or no movement, they are relatively insensitive to the two different movement scenarios considered. It also follows from these results that Area 2 is acting as a “sink” for the entire swordfish population in the SW Pacific, as catches in this region are being supported through fish moving into the region from other areas.

The time series plots of average mass of fish caught by the Australian fleet in Area 2 are shown in Figure 5.3. Two results are of particular note. First, the size of fish is seen to vary between the different scenarios, with the mean size of fish at the start of the time series being around 52kg for the reference scenario and around 39kg for the scenario where natural mortality was increased. Secondly, comparison of the changes in the mean and upper 95th mass percentile over the time period shown indicate that for most scenarios the 95th mass percentile is a more sensitive indicator of changes in the underlying stock biomass than the mean mass. For example, for the reference scenario, the change in mean mass is around 11.5% while the change for the 95th percentile is around 15.6%. As with the spawning biomass, change in the steepness parameter resulted in very little difference to the predicted mean mass, with the final mean mass ranging from 46.3kg for the reference scenario up to 49.2kg when steepness was set to 0.4. The slight increase in mass for those scenarios with a lower steepness is a result of the lower recruitments, thus increasing the relative proportion of larger fish in the population. The scenarios with equal (random) and intermediate movement also gave very similar results to that for the reference scenario. On the other hand, when natural mortality was increased (irrespective of the value for steepness), the mean and upper 95th mass percentiles were both appreciably lower over the time series, though the change in the upper 95th was relatively small – only 4%. This is due to the fact that fewer fish survive to older ages and correspondingly larger sizes. When there is no movement between areas, the final mean and 95th percentile masses undergo the greatest relative change, decreasing by 26% (to 36kg) and 32% (to 71kg) respectively. Combining no movement with a steepness of 0.4 raises the final mean mass to 40kg and the upper 95th percentile mass to 77kg. Finally, for the 50% depletion scenario with steepness 0.4, the mean and 95th percentile mass have similar values to the reference scenario but undergo a greater change over the period shown, declining around 15% and 21% respectively.

The time series plots of average percentage fish caught by the Australian fleet in Area 2 by size class are shown in Figure 5.4. As with the pattern displayed by the mean and 95th percentile of mass, the results for the scenarios with equal (random) and intermediate movement yielded almost identical results to the baseline scenario. Over the final 25 years of the time series, the proportion of large fish was predicted to decline from 42% to 35% while the proportion of small and medium fish increased (from 26%-30%, and 32%-35%, respectively). Hence, at the end of the projection period, large and medium sized fish were predicted to occur in about equal proportions in the Australian catch in Area 2. Changing steepness to 0.65 gave a similar result, but for steepness set to 0.4 there was less decline in the large size class and less increase in the small and medium size classes, such that the large size class continued to be dominant. For the no movement scenario, the catch in Area 2 was predicted to become dominated by small and medium fish (with each of these size classes comprising around 38% of the catch by the end of the projections, with large fish comprising less than 25%). The transition from predominantly large to predominantly small and medium fish is predicted to occur over a ten year period around the end of the historical time series.

Decreasing steepness to 0.4 with no movement showed a similar but less pronounced result, with the small and medium size classes each comprising around 37% of the total catch by the end of the projection time series, while large fish comprised around 27%. The transition in the dominant size classes occurred slightly later in the projection years. Increasing natural mortality (irrespective of the value for steepness) resulted in a predominance of small fish (39%-42%) well before the end of the historical time series, with large fish consistently comprising the smallest proportion of the catch. Again, this would be expected since at a higher natural mortality fewer fish survive to become large. The 50% depletion and 0.4 steepness scenario gave very similar results to the reference scenario, with the exception of a switch in the dominant size class from large to medium fish around about the 9th projection year. Final values were still relatively even, however, with small fish comprising 31%, medium 36%, and large 33% of the total Australian catch in Area 2.

Histograms of predicted mean annual Australian catch over the projection years across each of the 100 realisations are shown in Figure 5.5 and suggest little difference both in terms of mean catch and its associated variability between the reference scenario and those with equal (random) or intermediate movement. Furthermore, the mean catch was also relatively insensitive to changes in the stock-recruitment steepness parameter, ranging from 2749t (steepness = 0.4) to 2878t (steepness = 0.9). However, the mean catch was predicted to be around 22% lower when natural mortality was increased and around 25% lower under the no movement scenario (but both changes were again relatively insensitive to changes in the steepness parameter). The reduction in catch when natural mortality was increased was likely to have been due to a reduction in average individual fish mass, rather than to any large reduction in fish abundance, while the reduction under the no movement scenario was more likely to have resulted from a downturn in biomass resulting from a lack of replenishment from surrounding areas. Finally, when the depletion level at the end of the historical period was set to 50% and the steepness to 0.4, the average annual Australian catch was predicted to be around 2026 t, or 30% lower than for the reference scenario. This was due to the fact that biomass at the start of the projection years is lower while recruitment over the projection years is expected to be smaller.

Histograms of predicted mean final spawning biomass relative to the initial spawning biomass (across all areas) for each of the 100 realisations are shown in Figure 5.6. Except for those scenarios with a smaller steepness or higher assumed depletion, the results do not display a large degree of variation between biological scenarios, with the final biomass ranging from 50%-54%B_o. The final biomass is predicted to be lower for a lower steepness (48% for h=0.65, and 43% for h=0.4), while for the initial depletion of 50% scenario (and a steepness of 0.4) the final biomass falls to around 18%Bo. Final biomass was highest when natural mortality was increased or no movement was assumed (without a reduction in steepness). Under a higher natural mortality, the population is inherently more productive, while when no movement is allowed fish are not moving to (and being caught) in areas with high levels of fishing effort. For the scenarios involving changes in natural mortality or steepness, or alternate depletion regimes, these trends are similar to those for the spawning biomass from Area 2 alone (cf. Figure 5.2). However, for the no movement scenarios, the mean total final biomass, and its distribution across the 100 simulations, is equivalent to that of the baseline scenario, while for Area 2 the final relative spawning biomass was much lower (18%). This reinforces Area 2 as a “sink” with respect to fishing effort reducing the biomass unless it is replenished from other areas.

For the status quo effort scenarios, none of the alternative biological scenarios resulted in the spawning biomass dropping below 30% of its initial value, with the exception of the two scenarios where steepness was set to 0.4. For the reference scenario where the assumed depletion at the end of the historical period is 30%, the biomass dropped below 30% of its initial value, on average, only 0.3% of all time steps over the projection period, but this increased to 54% when the assumed depletion level was increased to 50%. Histograms indicating the probabilities of the spawning biomass dropping below 50% of its initial value during the 20 year projection period are shown in Figure 5.7. For the reference scenario, the spawning biomass dropped below 50% of its initial value, on average, 20.2% of all quarters, and similar results were obtained for the equal (random) and intermediate movement scenarios. Decreasing steepness resulted in an increase in the average probability that the biomass dropped below 50%B_o (to 24.0% when steepness was 0.65 and 34.2% when steepness was set to 0.4), while increasing natural mortality lowered the probability (to 14.4% or 17.2% when steepness was also changed to 0.65). The lowest probability (9.4%) was obtained under the no movement scenario, though when steepness was set to 0.4 with no movement, the probability of biomass dropping below 50% of its initial value increased to 21.2%.

A summary of the relative effect of each alternative biological scenario on each performance indicator for the reference scenario, ie. Indicator(Alternative Scenario)/Indicator(Reference Scenario), is shown for the status quo future effort strategy in Figure 5.8a. Due to the large relative effect for scenario 10, (50% depletion, steepness=0.4) the results for this scenario are not included. Overall, most indicators show a relative decrease in relation to the reference values. Furthermore, the smallest relative change occurs in relation to the final biomass indicator, while the largest relative change occurs in relation to the Prob($B<0.5B_o$). In particular, the greatest increase occurred when steepness was 0.4 (scenario 3) and the greatest decrease was when there was no movement (scenario 7). The proportion of large fish in the Australian catch in Area 2 also showed significant change across each of the scenarios, with the greatest decrease occurring when the natural mortality was increased (scenarios 4 and 5). There was little relative effect across all performance indicators under the intermediate (# 6) and equal (random) movement (#8) scenarios.

5.3.2 Comparison across future effort levels

The relative effect of each alternative biological scenario on the performance indicators for the reference scenario across the four different future effort scenarios are given in Table 5.1 and displayed in Figure 5.8, while a comparison of the absolute values of each performance indicator is given in Figure 5.9. (Note that spawning biomass is now the total across all areas, rather than that for Area 2 only, as was the case with the previous time series plots).

The pattern of absolute change in each of the performance indicators is the same across each combination of biological and effort scenarios (Figure 5.9). Increasing effort resulted in higher Australian catches, lower average mass and proportion of large fish in the Australian catch in Area 2, lower final spawning biomasses, and higher probabilities of driving the spawning biomass below 30% and 50% of its initial level.

Across each of the biological scenarios, the three economic indictors (catch, mean weight and proportion large fish) vary in a relatively consistent manner between the different future effort scenarios, while the relative behaviour of the three conservation indicators (those measuring biomass) is seen to vary across these effort scenarios (Figure 5.8). The proportion of large fish in the Australian catch from Area 2 is the most sensitive economic performance measure for all effort levels, while the most sensitive conservation indicator differed according to the level of future effort. For the status quo effort scenario, the proportion of time the spawning biomass is less than 50% of its initial value was the most sensitive, while for the highest effort scenario the final size of the spawning biomass was the most sensitive (with the former indicator now being the least sensitive). On the other hand, for a given future effort scenario, the equal (random) and intermediate movement scenarios showed little difference from the reference performance indicator values, while the greatest variation was seen for the alternative scenarios where steepness was set to 0.4 or no movement was assumed (Figure 5.8).

Table 5.1 Performance indicator values for each biological scenario and effort level, relative to the corresponding baseline scenario (expressed as proportions, unless otherwise stated), to illustrate the degree of consistency in trends between effort levels.

		Value relative to referen				
Effort Scenario	**Reference**	**Steepness h=0.65**	**Steepness h=0.40**	**NatMort Mx1.5**	**Mx1.5 h=0.65**	**Intermed Movement**
Mean Annual AUS catch (t)						
Status Quo	2878	0.98	0.96	0.77	0.76	1.00
Domestic(11.2m), Foreign(x2), ec	2993	0.97	0.93	0.80	0.77	1.00
Domestic(16.8m), Foreign(x2), ec	3885	0.96	0.92	0.81	0.78	1.00
Domestic(28.0m), Foreign(x2), ec	5154	0.94	0.89	0.84	0.78	0.99
Mean Fish Weight (kg)						
Status Quo	47.5	1.02	1.06	0.75	0.76	1.00
Domestic(11.2m), Foreign(x2), ec	44.8	1.03	1.09	0.75	0.77	1.00
Domestic(16.8m), Foreign(x2), ec	43.4	1.03	1.10	0.75	0.78	1.00
Domestic(28.0m), Foreign(x2), ec	40.9	1.05	1.13	0.76	0.79	1.00
Mean % Fish>50kg						
Status Quo	36.2%	1.03	1.09	0.61	0.63	1.00
Domestic(11.2m), Foreign(x2), ec	33.0%	1.05	1.14	0.60	0.63	1.00
Domestic(16.8m), Foreign(x2), ec	31.2%	1.06	1.17	0.59	0.63	1.00
Domestic(28.0m), Foreign(x2), ec	28.1%	1.09	1.24	0.58	0.63	1.00
SpBio(final)/Bo						
Status Quo	50.4%	0.95	0.86	1.08	1.03	1.00
Domestic(11.2m), Foreign(x2), ec	32.8%	0.92	0.81	1.13	1.05	1.00
Domestic(16.8m), Foreign(x2), ec	26.1%	0.90	0.76	1.17	1.06	1.00
Domestic(28.0m), Foreign(x2), ec	17.1%	0.83	0.66	1.25	1.05	1.01
Mean Pr(SpBio < 0.3Bo)						
Status Quo (see Note below)	0.0%	0.0%	0.3%	0.0%	0.0%	0.0%
Domestic(11.2m), Foreign(x2), ec	9.4%	1.30	1.77	0.54	0.88	1.01
Domestic(16.8m), Foreign(x2), ec	24.1%	1.13	1.34	0.70	0.85	1.00
Domestic(28.0m), Foreign(x2), ec	52.8%	1.00	0.99	0.80	0.86	0.99
Mean Pr(SpBio < 0.5Bo)						
Status Quo	20.2%	1.19	1.70	0.71	0.86	1.02
Domestic(11.2m), Foreign(x2), ec	63.0%	1.00	1.01	0.87	0.90	1.00
Domestic(16.8m), Foreign(x2), ec	71.0%	1.00	0.99	0.95	0.96	1.00
Domestic(28.0m), Foreign(x2), ec	77.5%	0.99	0.98	0.99	0.98	1.00

Note: As reference value is 0.0%, results for all scenarios are absolute values.

Figure 5.8 Relative effect of each biological scenario (relative to the reference scenario) within each of the 4 future effort scenarios. (Scenarios: 1=Reference, 2-(*h*=0.65), 3-(*h*=0.4), 4-(*M*x1.5), 5-(*M*x1.5 & *h*=0.4), 6-(Intermediate movement), 7-(No movement), 8-(Equal movement), 9-(No movement & *h*=0.4), 10-(Depletion=50% & *h*=0.4).

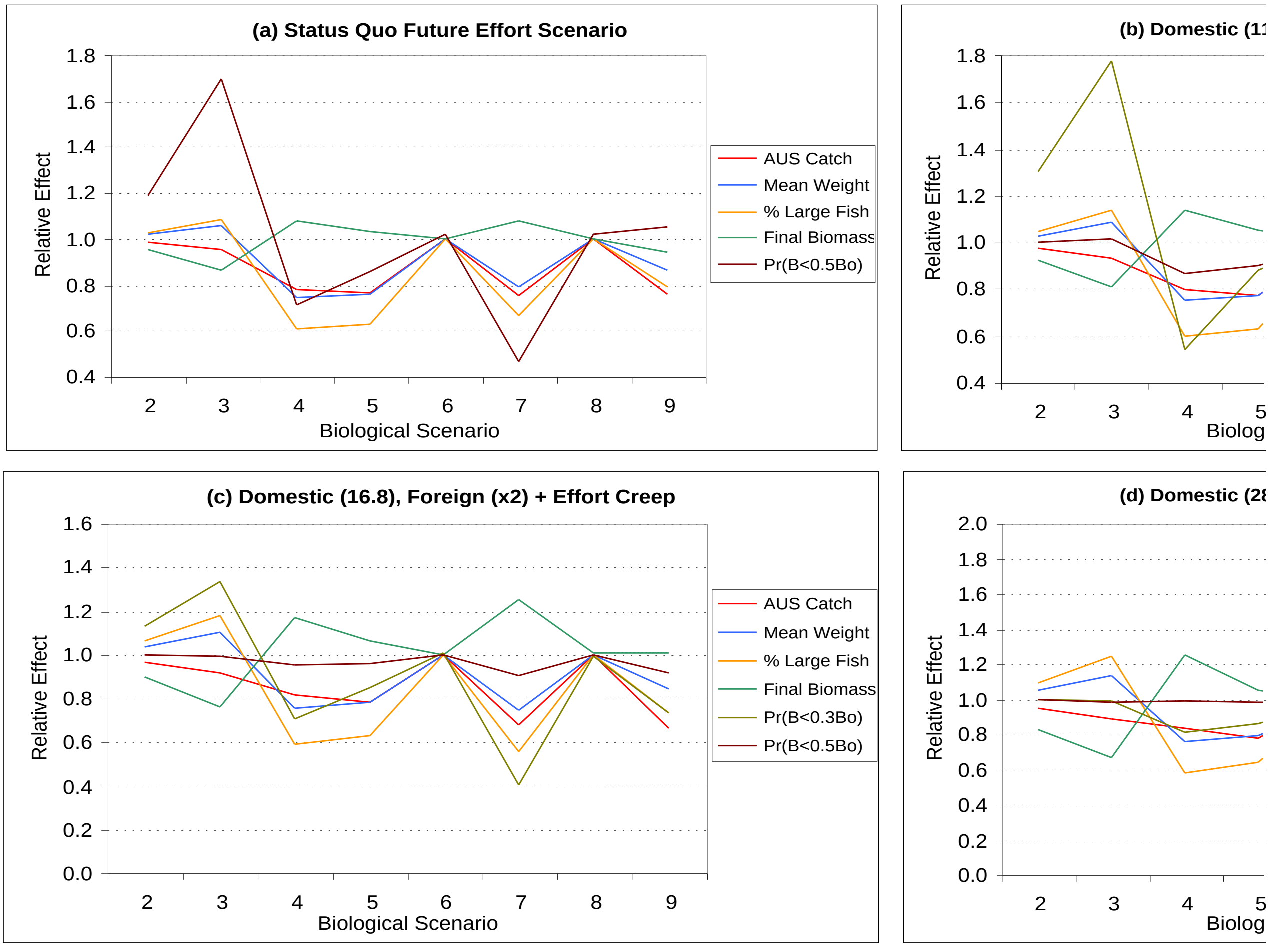
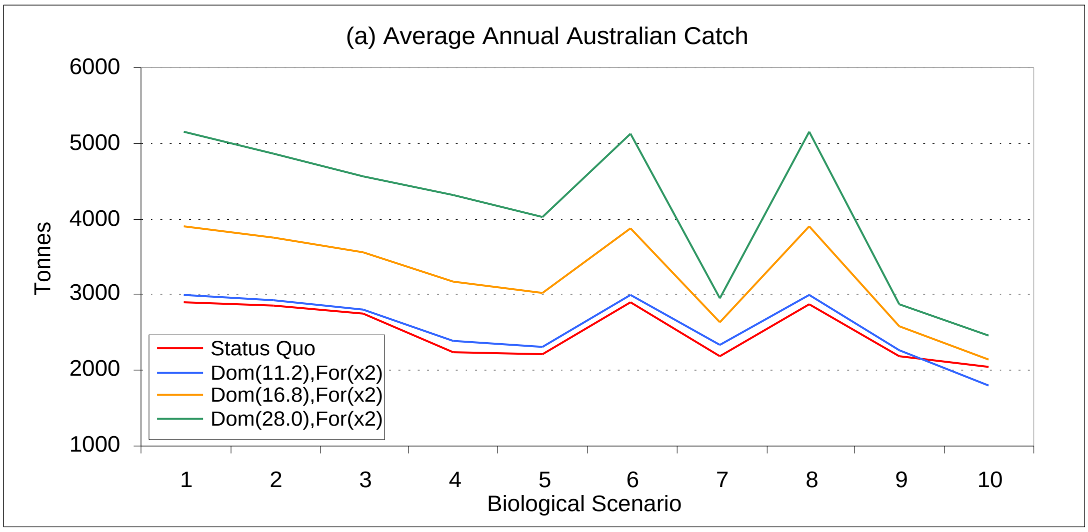
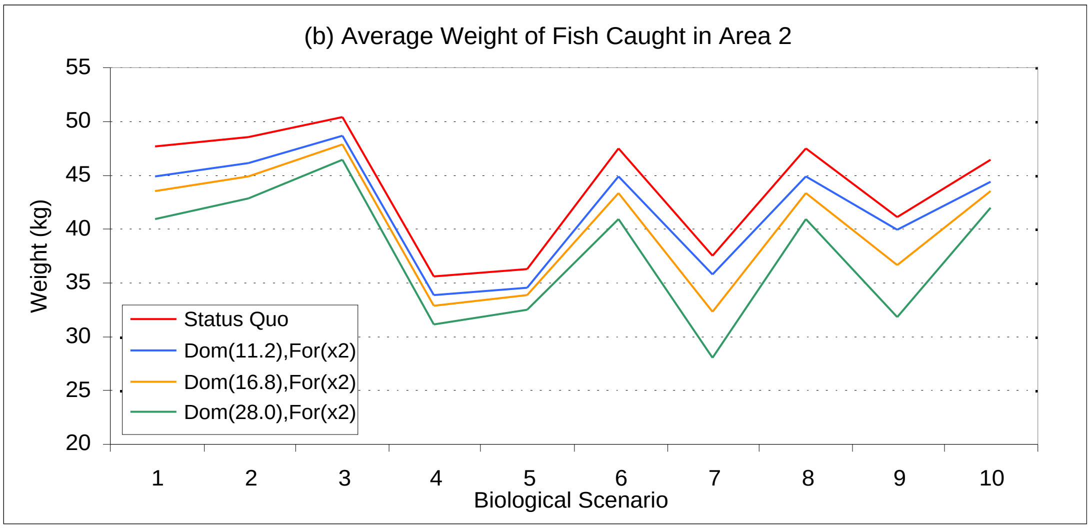


Figure 5.9 Comparison of performance indicators for each biological and future effort scenario. (Scenarios: 1=Reference, 2-(h=0.65), 3-(h=0.4), 4-(Mx1.5), 5-(Mx1.5 & h=0.4), 6-(Intermediate movement), 7-(No movement), 8-(Equal movement), 9-(No movement & h=0.4), 10-(Depletion=50% & h=0.4).





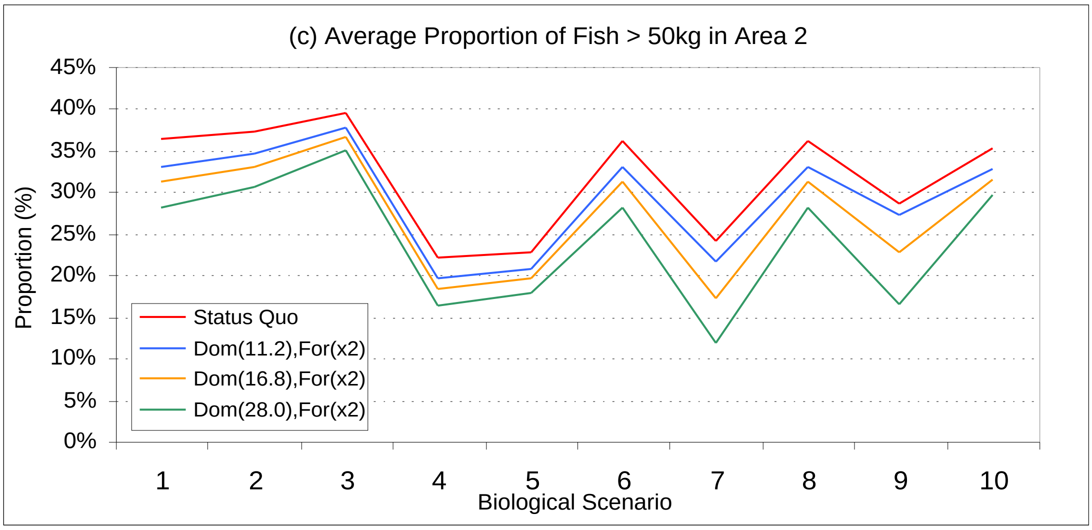
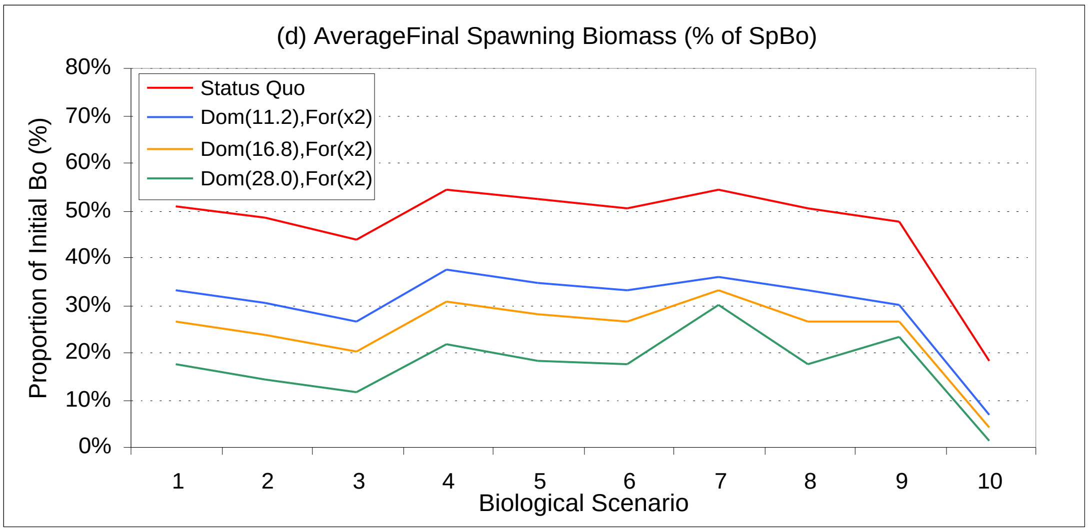
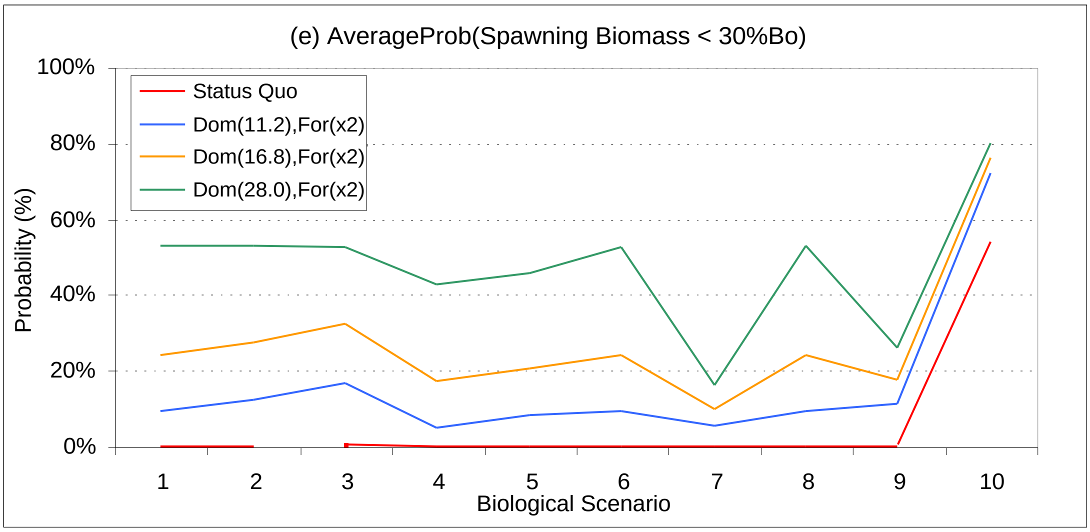
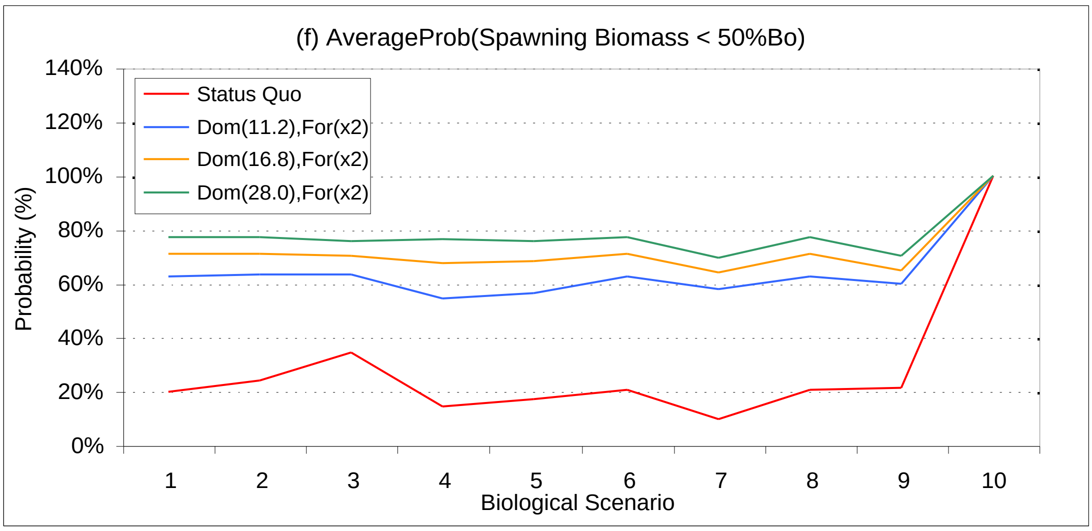


Figure 5.9 (cont'd) Comparison of performance indicators for each biological and future effort scenario. (Scenarios: 1=Reference, 2-(*h*=0.65), 3-(*h*=0.4), 4-(*M*x1.5), 5-(*M*x1.5 & *h*=0.4), 6-(Intermediate movement), 7-(No movement), 8-(Equal movement), 9-(No movement & *h*=0.4), 10-(Depletion=50% & *h*=0.4).







The relative sensitivity of the average annual Australian catch to the alternative biological scenarios increased with the higher effort levels, with performance most sensitive to the no movement and depletion scenarios (Figure 5.8). For the no movement scenario, the catch relative to the reference biological scenario changed from 75% to 56% when the future effort was increased from the status quo to the highest level , while for the 50% depletion scenario the change was from 70% to 47%. For the other two economic indicators, the sensitivity to each alternative biological scenario was similar for each future effort level, though there was a slight increase with increasing effort.

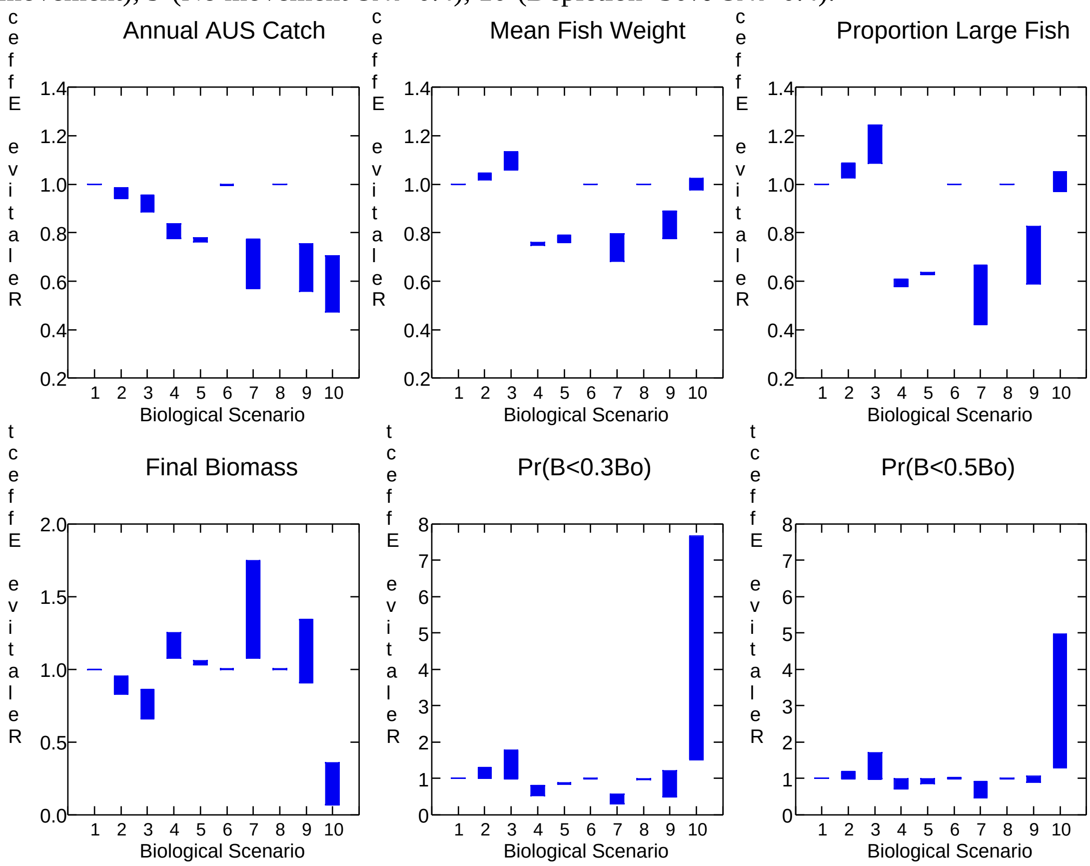
Except for scenario 10 (depletion 50%), the relative sensitivity of the average final spawning biomass to the alternative biological scenarios also increased with the higher effort levels, with performance most sensitive to the no movement scenario (Figure 5.8). Under the highest future effort level, final spawning biomass was 74% higher for the no movement scenario than for the reference. This is due to that fact the highest levels of effort are concentrated in Area 2 and under the reference scenario this region acts as a sink for the entire biomass, while under the no movement scenario only this region becomes heavily depleted, leaving the remainder of the stock relatively less depleted. For the probability that the biomass drops below 30%B_o, change relative to the reference biological scenario also varied across effort levels. This indicator was sensitive to a range of alternative biological scenarios (lower steepness, increased natural mortality and no movement) under the second lowest effort level, but was less sensitivity to these scenarios under the highest effort level, except for the no movement scenario where relative change was greater (0.30 as compared to 0.56). This change in relative sensitivity of this indicator is due to the fact that for the lower effort levels, the proportion of time the biomass is less than 30% is usually small (less than 10 percent, cf. Figure 5.9), so that relatively small absolute changes in this proportion can correspond to large relative changes. The same situation also holds for the probability that the biomass is less than 50%B_o, as this indicator is most sensitive to changes in the biological assumptions for the lowest effort levels and is relatively insensitive for the highest effort level.

When depletion was set to 50% and steepness to 0.4, the average annual Australian catch had its lowest value across all of the biological scenarios for all future effort levels, but particularly when only effort creep and an increase in foreign effort was applied. The average weight of fish and the average percentage of fish greater than 50kg showed little difference from the reference scenario at all effort levels. Spawning biomass was substantially lower than that for all other biological scenarios, as was the probability of spawning biomass dropping below 30% or 50% of its initial value. The latter was insensitive to the effort level, since the depletion was such that the spawning biomass dropped to below 50% of its initial level at a certain point in time and never recovered. Otherwise, for all performance indicators and measures, there was interaction between the effort level and the 50% depletion and steepness 0.4 scenarios, whereby the differential with respect to the reference scenario was greater at higher effort levels (Table 5.1).

5.4 Discussion

The above results indicate that the indicators of fishery performance are sensitive to a number of assumptions concerning the biology and population dynamics of the swordfish resource in the SW Pacific. A summary of these sensitivities is given in Figure 5.10, which displays the range of relative effects across the 4 future effort scenarios for each performance indicator and biological scenario. This plot may be interpreted as follows. First, the greater the relative effect for any indicator diverges from a value of 1, the greater the sensitivity of that indicator to the corresponding biological scenario. Second, the greater the actual range of relative effects for a given biological scenario, the greater the corresponding interaction between that biological scenario and the four assumed future effort levels.

Figure 5.10 Range of relative effects across the 4 future effort scenarios for each performance indicator and biological scenario. In order to help compare results, the scale of the y-axis scale is the same for the three economic indicators but is the same only for the last two biological indicators. Biological scenarios: (Scenarios: 1=Reference, 2-(*h*=0.65), 3-(*h*=0.4), 4-(*M*x1.5), 5-(*M*x1.5 & *h*=0.4), 6-(Intermediate movement), 7-(No movement), 8-(Equal movement), 9-(No movement & *h*=0.4), 10-(Depletion=50% & *h*=0.4).



The most consistent result is that all performance indicators showed little sensitivity (or interaction with the effort level) to scenarios 6 and 8 – the intermediate movement scenario and random movement scenario respectively. On the other hand, apart from scenario 10, nearly all indicators were most sensitive to, and displayed the greatest interaction with the effort levels, for scenarios 7 and 9 – those assuming no movement. It would appear, then, that as long as there is reasonable movement of fish between the five regions on an annual time-scale, the performance of the fishery is relatively independent of having precise knowledge of the nature of this movement. However, if there is no movement, or the movement dynamics are slow, then this will likely have an important bearing on the future performance of the fishery. Furthermore, the importance of this issue increases as the effort levels increase.

The results for the no movement scenario also highlight the usefulness of area-specific performance indicators. Under this scenario, the largest relative changes were seen in the performance indicators which were specific to Area 2, ie. there were large changes in the catch and size of fish in Area 2 under several effort strategies, while the change in the performance indicators across the whole stock were much less. Hence, if one were only to monitor indicators which related to the entire stock, significant changes in stock status in sub-regions may be overlooked. Differential declines in the catch rates of swordfish observed in the inshore regions off eastern Australian already suggest that such area-specific changes are possible (Campbell and Hobday, 2003). Given that Area 2 is of high relative importance to the Australian fleet, this result suggests that area-specific performance indicators will need to be an important component of the ongoing monitoring of the performance of the fishery.

Of the three economic indicators, all were relatively insensitive to changes in the steepness parameter (scenarios 2 and 3); however, sensitivity increased with increases in future effort, especially for the proportion of large fish in the Australian catch in Area 2. On the other hand, all three economic indicators were quite sensitive to the assumption of an increased natural mortality (scenario 4), though there was little interaction with the level of future effort. An interesting feature was that the Australian catch is predicted to be lower under all alternative biological scenarios, except scenarios 6 and 8 for which there is no change. For the three conservation indicators, a slightly different pattern was apparent. These indicators were more sensitive to changes in steepness and less to natural mortality, though there was a reasonable level of interaction associated with each. For all indicators the relative effect of scenario 5 was similar to that for scenario 4, though the extent of interaction is smaller in most instances. This was despite the fact that greater sensitivity was shown when each of these biological factors was changed independently. As explained previously, this result was due to the comparatively inverse effects that lower steepness and increased natural mortality had on the overall productivity of the stock –as indicated by the opposite relative effects for scenarios 2 and 4 shown in Figure 5.10.

Biological scenarios 1-9 all assumed a level of stock depletion at the start of the projection period of 30%. Sensitivity to this assumption was tested by scenario 10, which assumed a 50% depletion level. All the biological indicators, and the Australian catch, were seen to be the most sensitive to the assumed level of depletion, and there was also a large interaction with the level of future effort, especially for the biological indicators. This result indicates that although the range of biological hypotheses investigated in the first 9 scenarios were intended to provide upper or lower bounds for the population biology, the responses of many of the performance indicators across this range of biological scenarios are likely to be amplified if the assumed depletion level is increased. This result is not unexpected, as by changing the level of depletion the biomass trajectory is forced through a given value instead being dictated solely by the observed data and the assumed biology. This effectively enforces an assumed level of productivity on the stock – ie. the historical levels of catch have resulted in a given level of depletion. Hence, given this situation, and the more extreme behaviour of the performance indicators to differences in assumed depletion, different depletion levels can be considered as proxies for different levels of biological productivity in the swordfish stock. Hence, in the next chapter where a more comprehensive range of fixed future effort scenarios is evaluated, in order to consider sensitivity to uncertainty in the known biology of the stock, these effort scenarios are tested across a range of assumed depletion levels only. This negates the need to consider a large range of alternative biological scenarios, as each level of depletion can be considered to act as a proxy for a given stock productivity.

Finally, in this chapter we have investigated the sensitivity of a range of indicators concerning the performance of the swordfish fishery over the next 20 years to uncertainty in our understanding of the underlying biology of the swordfish stock in the SW Pacific. For this purpose we have compared the results across 10 different biological scenarios. While the reference biological scenario is based on the most informed biological research, the range of scenarios investigated are assumed to provide a reasonable set of bounds for alternative yet plausible population dynamics. Given this situation, it is nevertheless informative to ask whether there exists auxiliary data which may help discern which of these ten scenarios is the most plausible. For this purpose, we calculated the sum-of-squared errors obtained after comparing the catch-at-size histograms predicted by the model under each biological scenario with the observed catch-at-size-frequency data for the Australian fleets in Area 2 and the Japanese fleet in Area 5 (see section 3.8 for more details). The results of this comparison are shown in Table 5.2. The smallest sum–of-squares was obtained for scenario 6, the intermediate movement scenario. The next smallest sum-of-squares was for the reference scenario, together with that which assumed a steepness of 0.65. The no movement scenarios

Table 5.2 Sum-of-squared errors obtained after comparing the catch-at-size histograms predicted by the model under each biological scenario with the observed catch-at-size-frequency data.

Scenario	1	2	3	4	5	6	7	8	9	10
Australian size data	0.170	0.170	0.172	0.252	0.249	0.169	0.178	0.172	0.176	0.171
Japanese size data	0.011	0.011	0.011	0.026	0.025	0.011	0.011	0.011	0.011	0.011

had a significantly worse fit to the Australian size data, while the worst fits to both sets of size data were obtained for scenarios 4 and 5, which assume a higher natural mortality. The poor fit for these last two scenarios was also reinforced by the low mean weight of around 39kg predicted under these two scenarios for fish in the Australian catch in Area 2 (*cf*. Figure 5.3) – whereas all other scenarios predicted the mass of fish to be the range 49-53kg. The actual mean weight of fish sampled in this region is around 53kg. Hence, this auxiliary data provides some information to help discriminate between several of the biological scenarios and reinforces the preferred choice for the reference biology, or that with a steepness of 0.65.

Chapter 6: Evaluation of Fixed Effort Strategies

6.1 Introduction

With the development of the new Management Plan for the ETBF, based on the introduction of the *TAE*, much of the discussion and questioning about the MSE approach within the ETBF Fishery Assessment Group has been based around how the stock responds under certain fixed effort scenarios. This discussion is based on the premise that the initial *TAE* set for the fishery should be based on an effort value that is considered sustainable in the long term. Under the MSE framework the proposed effort levels can be evaluated by applying them without a feedback loop. Thus, projections using fixed effort regimes are a logical starting point for investigations using the MSE framework.

6.2 Fixed Effort Scenarios

In consultation with ETBF Fisheries Assessment Group, which includes representatives from a range of stakeholder groups including industry and management, a range of future effort scenarios were developed for consideration. As well as developing scenarios for the Australian fleet, consideration also had to be given to future scenarios for the two foreign fleets included in the operational model, as well as any future increases in fishing power (often known as effort creep). Although the future remains inherently uncertain, the following future effort scenarios were agreed upon for evaluation. While the number of scenarios was kept to a manageable number, these effort scenarios nevertheless cover a diverse range of possibilities and will hopefully bracket future changes in domestic and foreign effort.

Domestic Effort:

1. Status quo: effort stays at 2001 level (11.2 million hooks) for all years.
2. Increase in nominal effort over five years to 1.5 x 2001 level (16.8 million hooks) after which time no further increase.
3. Increase in nominal effort over five years to 2.0 x 2001 level (22.4 million hooks) after which time no further increase.
4. Increase in nominal effort over five years to 2.5 x 2001 level (28.0 million hooks) after which time no further increase.

Foreign Effort

1. Status quo: effort stays at average level over the last 3 years 1999-2001.
2. Increase in effort over five years to 2.0 x status quo level, after which time no further increase.

Effort Creep

1. No increase in effective effort due to effort creep.
2. Increase in effective effort due to effort creep of 2% per annum. Applied for all years to domestic fleet and for first five years only for the foreign fleets (to account for the possible entry of new and less skilled fishing fleets).

Crossing each domestic effort scenario with each effort creep scenario gives a total of 8 domestic scenarios. Each of these is displayed in Figure 6.1a. Under these scenarios, domestic effort ranges between 11.2 million and 31 million hooks by 2006 (*ie*. after the first five projection years) and between 11.2 and 41.7 million hooks by 2021 (*ie*. at the end of the 20 year projection period). Similarly, crossing each foreign effort scenario with each effort creep scenario gives a total of 4 foreign scenarios, each of which is displayed in Figure 6.1b. Under these scenarios, total foreign effort reaches between 60.7 million and 133.9 million by 2006, after which time it is held constant. Finally, crossing each domestic scenario with each foreign effort gives a total of 32 different future effort scenarios. However, in order to reduce

Figure 6.1 Time series of annual (a) domestic effort, (b) foreign effort, and (c) total effort, under each of the scenarios described in the text. Note; only the two extreme scenarios (with and without effort creep, EC) are shown for the total.

Table 6.1 List of future fixed effort scenarios used for evaluation purposes. Note: sq = status quo, m=million hooks and ec= effort creep applied.

Effort Scenario	Domestic Effort Increase first five Years	Foreign Effort Increase first five Years	Effort Creep Applied	Scenario Name
1	1	1	No	Domestic 11.2m, Foreign sq
2	1	2	Yes	Domestic 11.2m+ec, Foreign double+ec
3	1.5	1	Yes	Domestic 16.8m+ec, Foreign sq
4	1.5	2	No	Domestic 16.8m, Foreign double
5	1.5	2	Yes	Domestic 16.8m+ec, Foreign double+ec
6	2	1	Yes	Domestic 22.4m+ec Foreign sq
7	2	2	No	Domestic 22.4m, Foreign double
8	2	2	Yes	Domestic 22.4m+ec, Foreign double+ec
9	2.5	1	Yes	Domestic 28.0m+ec, Foreign sq
10	2.5	2	No	Domestic 28.0m, Foreign double
11	2.5	2	Yes	Domestic 28.0m+ec, Foreign double+ec
12	2.5*	2	No	Domestic 28.0m (15yrs), Foreign double

* After 15 Years

the reporting requirements, not all scenarios are presented here. The list of scenarios which were selected for presentation is given in Table 6.1 while several of the extreme scenarios are shown in Figure 6.1c. Effort ranges between 71.9 and 149.4 million hooks by 2006 and between 71.9 and 175.6 million by 2021. Note: the average of the total effort over the historical period (1971 to 2001) is 73.6 million hooks.

Scenarios 1 and 2 consider two variations on the 'status quo'. In the first, all effort levels remain at their present 2001 levels, and no increase in fishing power is assumed, while under the second scenario nominal domestic effort remains at present levels, nominal foreign effort doubles over the first 5 years, and an increase in fishing efficiency is assumed for both fleets. These two scenarios bracket the two extremes situations which may be encountered if nominal domestic effort remains unchanged. Scenarios 5, 8 and 11 consider a range in increases in domestic effort and assume a doubling of foreign effort within the first five years and an increase in fishing power for all fleets. Scenarios 4, 7 and 10 show the effect of the same increases in domestic and foreign effort but without any effort creep, while scenarios 3, 6 and 9 approximate the situation where the domestic fleet "out-competes" the foreign fleets to the effect that foreign effort levels remain at status quo, while the domestic fleet increases it effort and efficiency. Of the twelve scenarios listed, scenario 11 could be considered the most extreme, in that the 2.5 times increase in domestic effort is achieved in 5 years, foreign effort doubles over this time and there is effort creep in both the domestic and foreign fleets. As a less extreme alternative, scenario 12 considers the situation where the increase in domestic effort is spaced over 15, rather than 5, years and there is no effort creep.

As before, the operating model was conditioned on historical data (catch, effort, size data from the three fisheries) for the years 1971 to 2001. However, due to the lack of a stock assessment for swordfish in the south-west Pacific, the condition of the stock at the end of 2001 remains unknown. Hence, for scenario testing, we consider a range of assumed levels of depletion. This subset is chosen to include upper and lower extremes as well as the assumed "baseline" value. We thus consider the following three scenarios:

Upper scenario	B(2001) = 85% B_o
Baseline scenario	B(2001) = 70% B_o
Low scenario	B(2001) = 50% B_o

Finally, in all calculations we assume the reference biological regime discussed in the previous chapter.

6.3 Results

6.3.1 Time series and histograms

Examples of time series and histogram results for the 12 future effort strategies listed in Table 6.1 are presented in Figures 6.2-6.8. These are based on the baseline conditioning scenario, which assumes a stock depletion at the end of 2001 of 30% (i.e. total spawning biomass at end of 2001 is equal to 70% of initial total spawning biomass).

Time-series plots of the mean annual estimates, and upper 95th confidence limits, of the predicted spawning biomass in Area 2 under each of the 12 future effort strategies are shown in Figure 6.2. The steeper decline seen in the biomass trajectories after the 25th year is in response to the significant increase in catches of swordfish taken by Australia and New Zealand after the mid-1990s. The tightening of the 95th percentile ranges at the end of the conditioning years is due to the level of spawning biomass depletion being constrained at 30% after 31 years. (Indeed, plotting total spawning biomass across all areas shows bottlenecking at the end of this historical period.) The standard deviations for the total spawning biomass ranged from 6% to 8% for all effort scenarios.

Under the status quo scenario, the spawning biomass in Area 2 was predicted, on average, to decline to around 50% of its initial level by the end of the 20 year projection period (Figure 6.2). The assumption of a 2% annual effort creep and a doubling in foreign effort (scenario 2) further reduced the predicted spawning biomass to around 32% of its initial level. As stated earlier, these two scenarios potentially bracket the impact on the stock under the situation where current domestic effort levels remain unchanged. Under the alternative scenarios where Australian effort was increased to 16.8, 22.4 or 28 million hooks over 5 years (with associated effort creep) and where foreign effort remained at the status quo (scenarios 3, 6 and 9), the final spawning biomass was estimated to be depleted to around 35%, 28% and 22%B_o respectively. If there is a doubling of foreign effort with associated effort creep (scenarios 5, 8 and 11), the final spawning biomass is further depleted to around 26%, 21% and 17% respectively. As expected, the final spawning biomass, both in Area 2 and overall, decreased with increasing effort. However, the importance of effort creep alone on both the higher levels of future effort and on the resulting depletion levels was significant, and can be seen by comparing the last results with those for scenarios 4, 7 and 10 where there was no assumed effort creep. In all situations the final spawning biomass was considerably higher (at 41%, 34% and 29% respectively) and, indeed, higher than under the situation where there was no increase in foreign effort. Hence, for a given increase in nominal domestic effort, continuing increases in effective effort due to effort creep can have a larger impact on the stock than a doubling of nominal foreign effort. Finally, increasing effort to 28 million hooks over 15 years (scenario 12) rather than over 5 years (scenario 11) resulted in only a small difference (29% versus 31%) in the final level of depletion.

Time-series plots of the mean, and upper 95th percentile, weights of fish caught by the Australian fleet in Area 2 under each of the 12 future effort strategies are shown in Figure 6.3. (Note, the gap at time step 89 is due to a zero recorded catch at this time.) Declines in both the mean and upper 95th weight of fish caught are seen for all scenarios, though the decline for the status quo scenario is relatively minimal. As with the spawning biomass, the mean weight of fish tends to decrease with increasing effort. While the change in the mean weight is not large in most instances, the change in the upper 95th percentile weight is more pronounced A similar result was also noted by Punt et al., (2001). Under the most extreme scenario, where Australian effort is increased to 28 million hooks over 5 years, foreign effort

Figure 6.2 Time-series plot of the average spawning biomass in Area 2 (expressed as a percentage of the original biomass), together with the 95th confidence limits, across 100 simulations under each of the 12 effort scenarios described in the text.

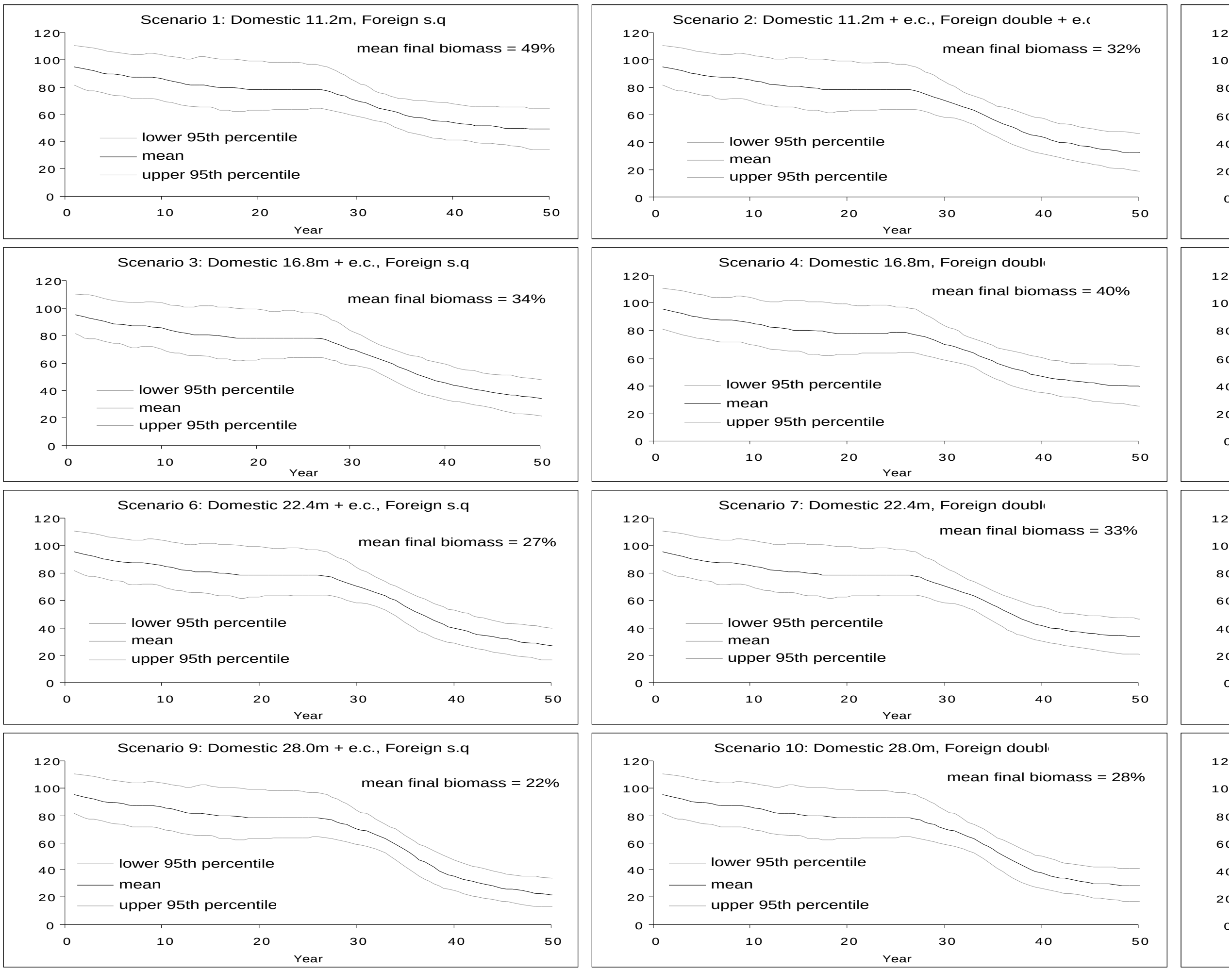


Figure 6.3 Time-series plots of the average, and upper 95th percentile, weight of fish caught by Australian vessels in Area 2 across 100 simulations under each of the 12 effort scenarios described in the text.

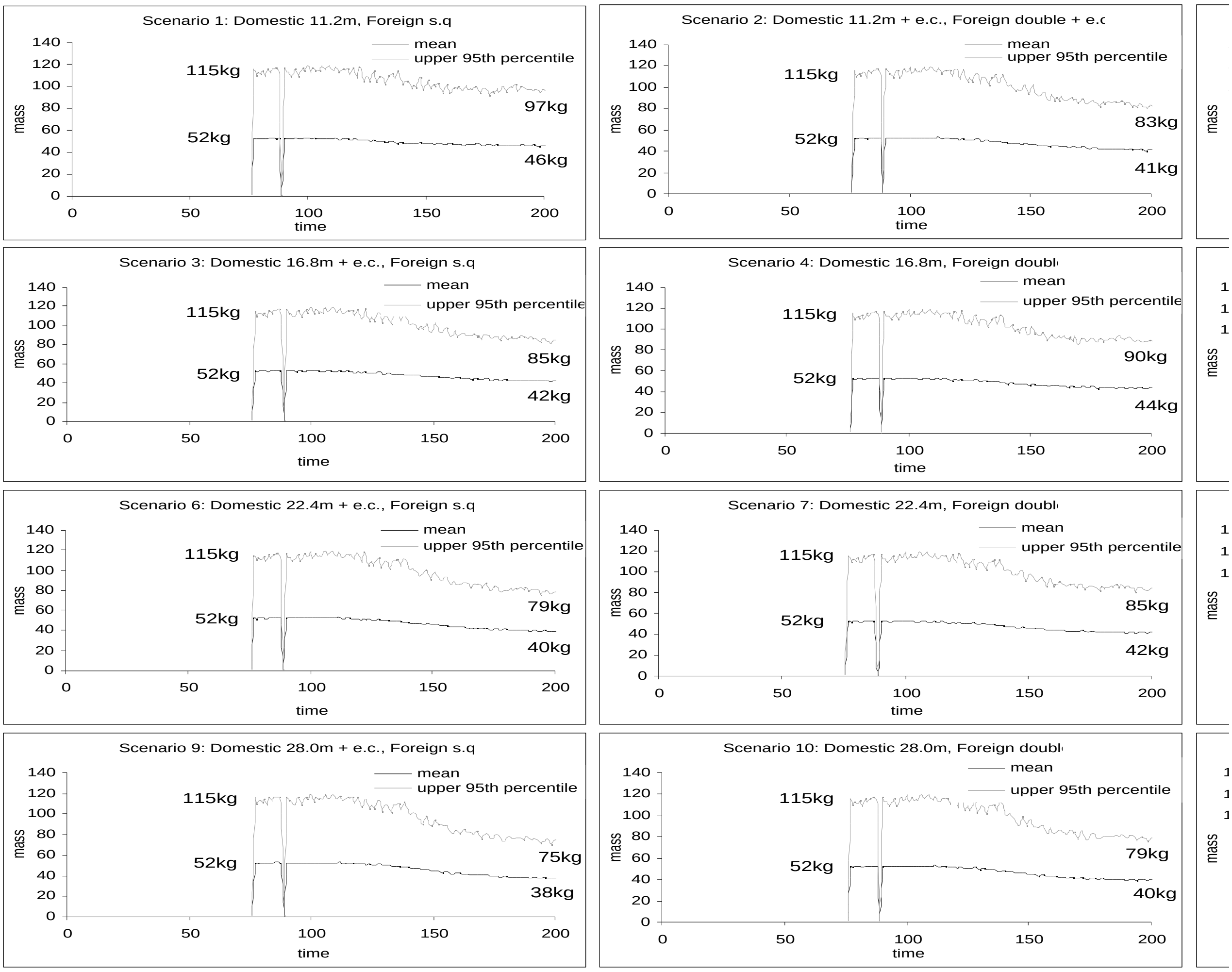


Figure 6.4 Time-series plots of the average proportions of small, medium and large sized fish caught by Australian vessels in Area 2 across 100 simulations under each of the 12 effort scenarios described in the text.

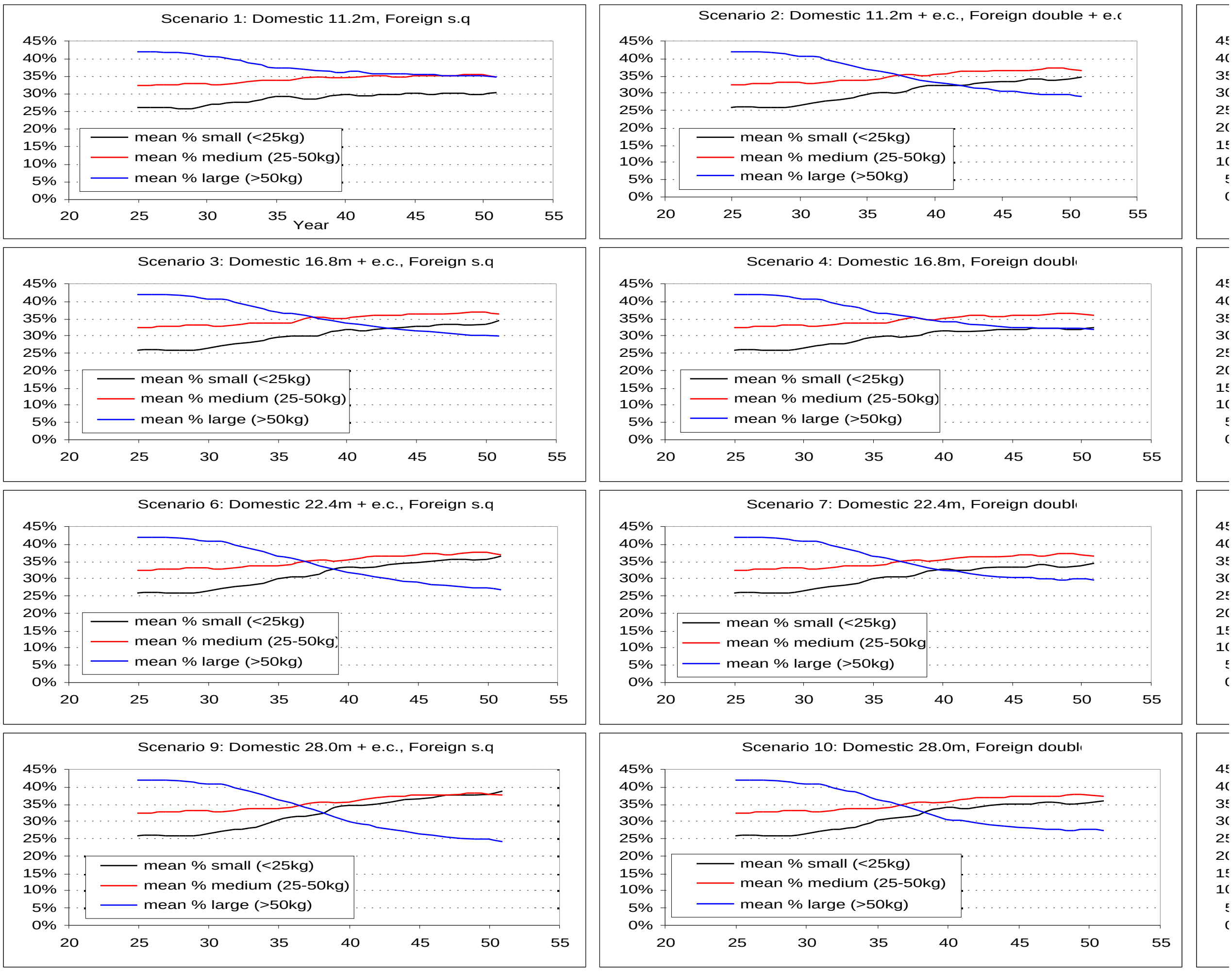


Figure 6.5 Histograms (across 100 simulations) of the average annual catch (tonnes) by Australian vessels over the projection years, under each of the 12 effort scenarios described in the text.

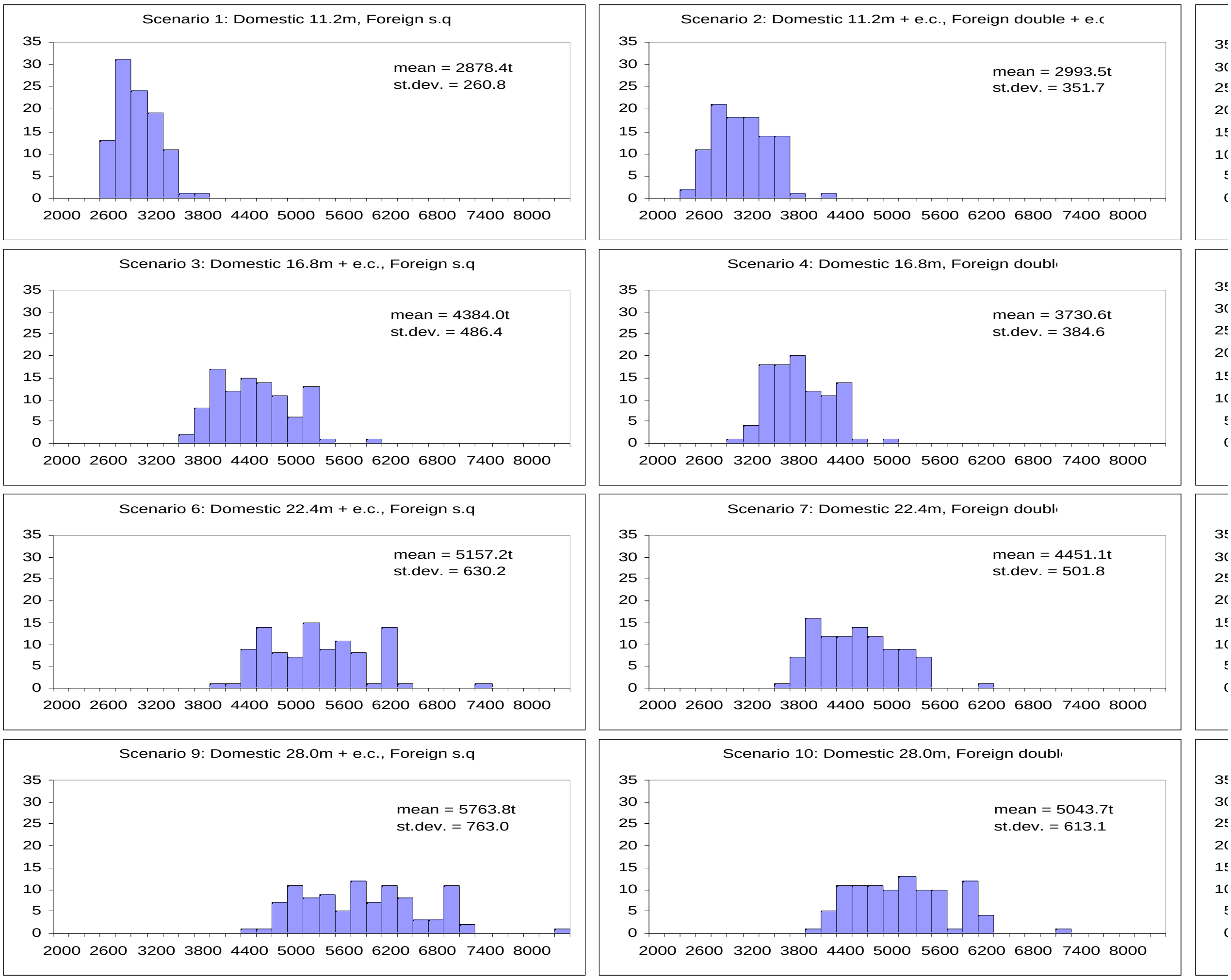


Figure 6.6. Histograms (across 100 simulations) of the final spawning biomass (ie. at the end of the projection period) relative to initial spawning biomass, under each of the 12 effort scenarios described in the text.

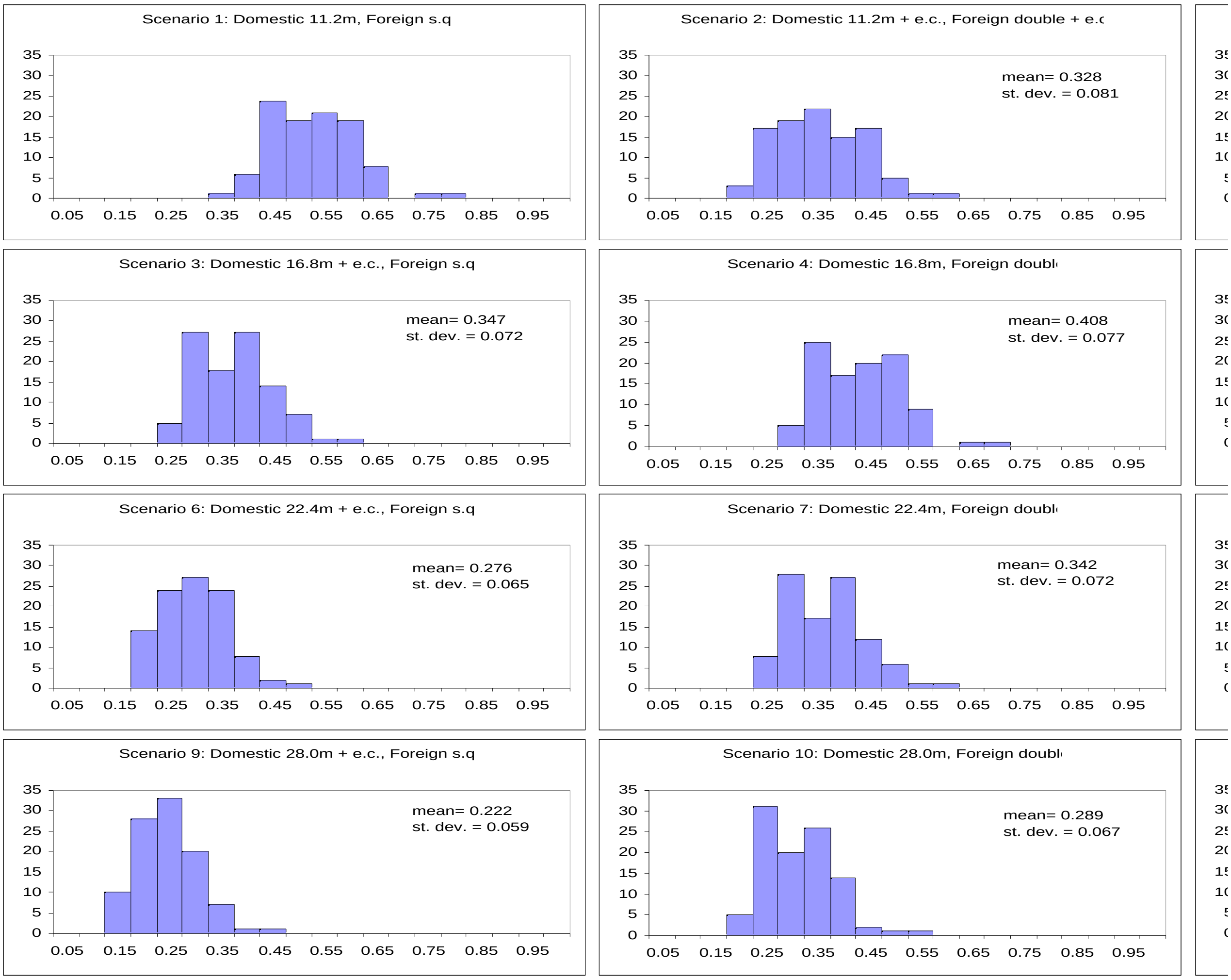


Figure 6.7 Histograms (over 100 simulations) of the probability that the spawning biomass dropped below 30% of its initial level, under each of the 12 effort scenarios described in the text.

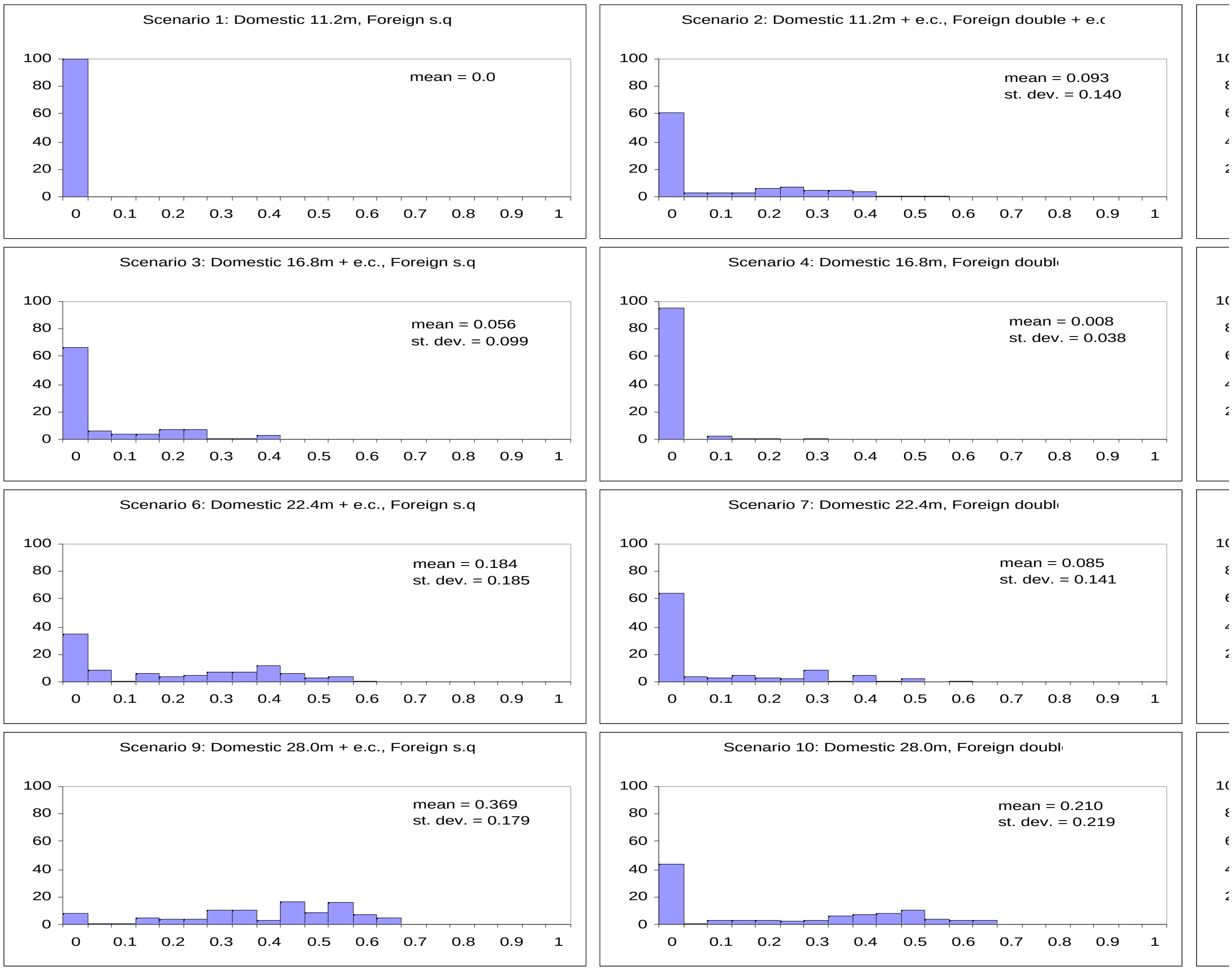
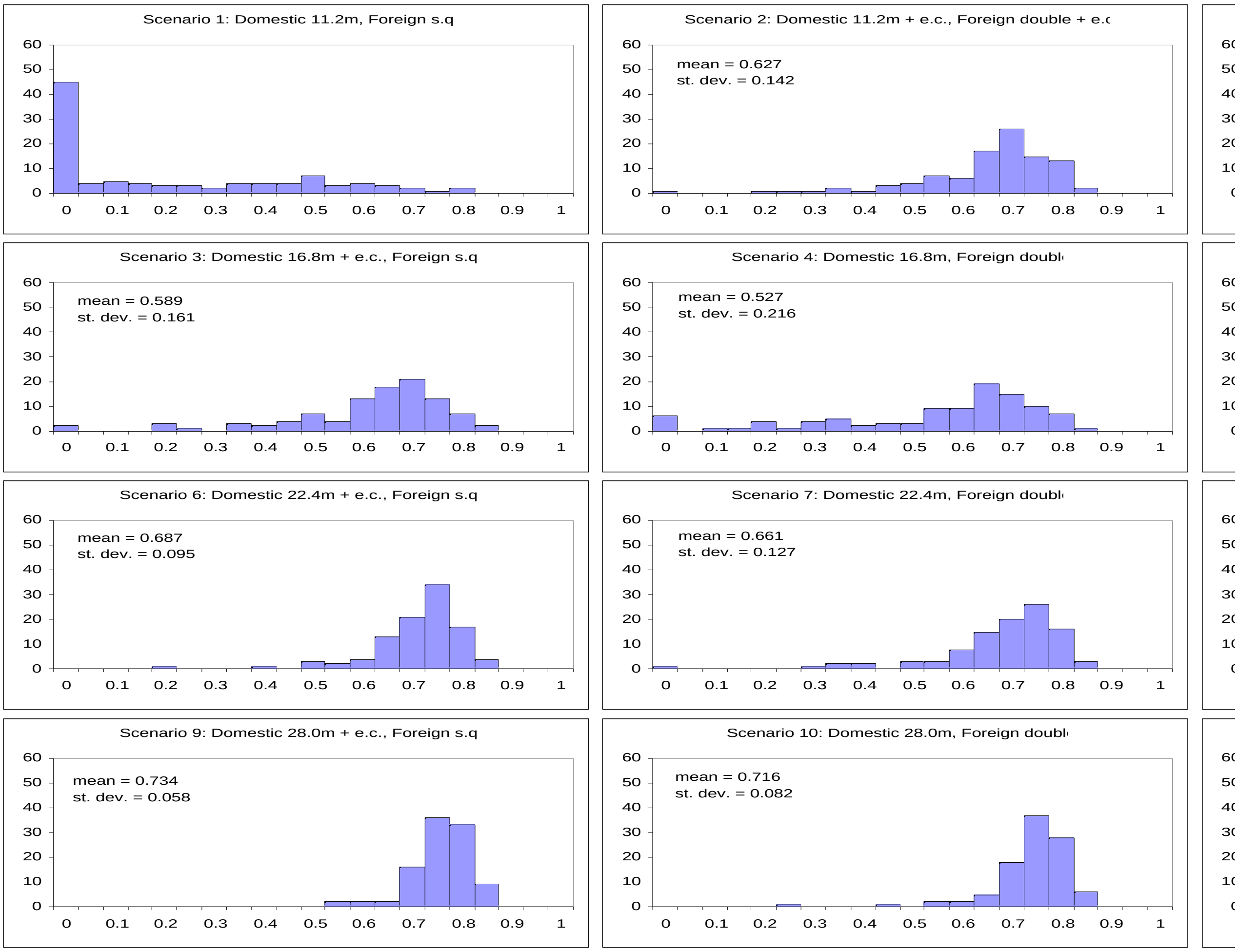


Figure 6.8 Histograms (over 100 simulations) of the probability that the spawning biomass dropped below 50% of its initial level, under each of the 12 effort scenarios described in the text.



doubles and effort creep applies to both fleets, the upper 95th weight percentile declined from approximately 115kg to approximately 68kg.

A better indicator of the change in size of fish caught was provided by the time-series plots of the percentage, by weight, of small, medium and large fish caught by the Australian fleet in Area 2 (Figure 6.4). Under all future effort strategies it is predicted that there will be a switch in the dominant size class of fish in the catch. At the start of the projection period, fish greater than 50kg dominated the catch, comprising around 40% of the catch (the proportion of medium fish (25-50kg) was 33% and the proportion of small fish (<25kg) was 27%). However, for nearly all effort strategies, by the end of the projection period large fish were predicted to comprise the smallest proportion of the catch, with either medium sized fish or small fish dominating (comprising between 32% and 41% of the catch respectively). The greatest relative increase was apparent for the small size category. The only exception to the above result was for the status quo scenario, where the medium and large-sized fish were equally dominant at the end of the projection period. The transition in size dominance in the catch from large to small and medium fish generally occurred between the 4th and 7th projection years for the scenarios where domestic effort was doubled or increased by 2.5 times (to 28 million hooks) over 5 years, and between the 6th and 13th projection years for those scenarios where domestic effort increased by 1.5 times (to 16.8 million hooks), or only effort creep was applied, or when domestic effort was increased by 2.5 times over 15 years with no effort creep. The decrease in the proportion of large fish in the catch became more substantial the larger the future effort. For example, under the most extreme scenario (#11) the proportion of large fish decreased to around 22% by the year 2021. The impact of effort creep was also seen to be significant, with the proportion of large fish at the end of the projection period generally being around 6% higher for those scenarios where no effort creep was assumed (eg. compare scenarios 4 and 5, 7 with 8, 10 and 11).

Histograms of the predicted average annual Australian catch over all projection years, together with the overall mean and standard deviation, for each future effort strategy are shown in Figure 6.5. As would be expected, the annual size of the Australian catch over the projection years is generally greater with greater effort. Additionally, the spread of the catch about the mean across the 100 simulations increases with increasing effort and effort creep. Mean catches ranged from 2,878 tonnes under the status quo scenario, to 5,764 tonnes when Australian effort was increased to 28 million hooks with effort creep while foreign effort was held at the status quo. Note that, for the same effort, Australian catches were 12% to 13% higher when foreign effort was held at status quo (scenarios 3, 6 and 9), as compared to when foreign effort doubled. This indicates that there exists a significant interaction between these different fleets and that increased effort levels in either will have a negative impact on the catch rates (and catches) of the other fleet.

As a corollary to the previous result, with increased effort and catches there was an increased probability that the biomass would be fished down to levels below 30% and 50% of its initial level (Figures 6.7 - 6.8). However, within each set of future effort creep / foreign effort scenarios, the increase in the average probability that the spawning biomass dropped below 50%B_o as domestic effort increased was only moderate (maximum range of 7.4%). For the status quo scenario, spawning biomass never dropped below 30%B_o (Figure 6.7), and for 55 of the 100 simulations, the spawning biomass never dropped below 50% of its initial level, and on average dropped below 50%B_o in only 20 percent of all time steps (Figure 6.8). Otherwise, for all other future effort scenarios, the spawning biomass was predicted to drop below 50% of its initial level between 53 % (scenario 4) and 77% (scenario 11) of all time steps. For the three scenarios when domestic effort was increased and foreign effort doubled, with effort creep, the biomass, on average, dropped below 30% its initial level in 24% (increase to 16.8 million domestic hooks in 5 years), 41% (increase to 22.4 million domestic hooks in 5 years) and 53% (increase to 28 million domestic hooks in 5 years) of all quarters. Under the corresponding scenarios when foreign effort was held at the status quo, the proportion of quarters in which the spawning biomass dropped below 30% were reduced to, on average, 5.6%, 18% and 37% (Figure 6.7).

These results indicate that large increases in the combined effort of both the Australian and foreign fleets would place pressure on the swordfish population. For the most extreme fishing scenario (increase to 28 million domestic hooks in 5 years, doubling of foreign effort, effort creep), the probability that the population drops below 30% of the initial biomass was estimated to be greater than 50%. Indeed, the combined effect of increased domestic effort, doubling of foreign effort and effort creep yielded the worst-case scenario for the fishery, in terms of spawning biomass, weight of fish in the Australian catch, and the average Australian catch.

6.3.2 Performance indicators and measures: comparison across effort scenarios and assumed depletions

Table 6.2 gives the results for each of the performance indicators and measures under each of the effort scenarios and across the range of assumed depletions. The results for six of performance indicators are displayed graphically in Figures 6.9a&b. The median annual change in Australian catch between years was not plotted as it is seen to be relatively insensitive to both the effort scenario and assumed depletion, ranging only between 12.6% and 16.3%. It decreased slightly with increased depletion, and increased with increasing Australian effort. Trends in average annual value of the Australian catch generally tracked the changes in the average annual Australian catch, and so were also not plotted. However, it is interesting to note that as effort and total catch levels increased, the relative increase in the value of the catch became smaller. This can be attributed to the corresponding decrease in the proportion of large (higher valued) fish in the catch. Hence, collectively the two indicators of total catch and proportion of large fish are a better indicated the economic performance of the fishery than the value of the catch alone. To assist in presentation and comparison, the above results are further summarized in Table 6.4 where the indicators have been grouped into either economic or biological indicators. In addition, the values of the economic indicators under each effort scenario have been expressed relative to the value obtained under the status quo future effort scenario.

Predictably, the results indicate that the performance of the fishery improved (ie. greater catches, lower depletion of the swordfish biomass) as the assumed depletion level at the end of 2001 is reduced. Furthermore, from Figures 6.9a&b it is seen that the relative trends of the performance indicators across the 12 future effort scenarios were generally consistent across each assumed depletion regime. The status quo scenarios gave the best fishery across all three conservation indicators and for several of the economic indicators (average size and proportion of large fish in the Australian catch), but the worst in terms of average catch. On the other hand, the scenario with 28 million hooks, a doubling of foreign effort and assumed effort creep resulted in the worst performance in terms of the conservation indicators, while it yielded the second-highest domestic catch within the 15% and 30% depletion regimes, and the 4^{th} highest within the 50% depletion regime. However, average Australian catches were consistently higher for corresponding levels of effort when foreign effort was held at the status quo, such that an increase to 28 million domestic hooks over 5 years, with effort creep, but foreign effort at status quo gave the highest average catches within each depletion regime. For the 50% depletion regime, and for each level of domestic effort, higher Australian catches were achieved when foreign effort was held at the status quo than when foreign effort was doubled.

Indeed, the relative size of the Australian catch showed a strong interaction between a subset of effort scenarios and the assumed regime. For example, when 15% and 30% depletion is

Table 6.2 Comparison of a range of performance measures under a suite of biological and future effort scenarios.

	Effort scenario (see below for description)	Average annual Australian catch (tonnes)		Median annual change in Australian catch (%)		Average weight of fish in Australian Area 2 catch (kg)		Average % fish in Australian Area 2 catch >50kg		Average annual value of Australian catch ($million)	
		mean	st. dev.	mean	st. dev.	mean	st. dev.	mean	st. dev.	mean	st. dev.
15% Depletion	1	3267	289	14.4	3.4	51.7	0.9	40.7	1.0	31.0	2.8
	2	3655	422	14.5	3.4	50.0	2.0	38.8	2.1	34.4	4.2
	3	5311	597	14.9	3.4	50.2	1.8	39.1	1.9	50.0	5.9
	4	4152	493	14.8	3.3	49.5	2.2	38.3	2.3	38.9	4.9
	5	4950	648	14.9	3.4	49.0	2.6	37.7	2.7	46.2	6.5
	6	6514	826	15.7	3.6	49.3	2.5	38.0	2.5	60.9	8.2
	7	5131	670	15.4	3.5	48.7	2.7	37.4	2.8	47.9	6.7
	8	6079	881	15.6	3.7	48.1	3.2	36.7	3.3	56.4	8.8
	9	7564	1063	16.3	3.6	48.4	3.0	37.0	3.2	70.2	10.6
	10	6011	852	15.9	3.5	48.0	3.1	36.6	3.2	55.8	8.5
	11	7071	1117	16.3	3.6	47.2	3.7	35.7	3.9	65.2	11.1
	12	5114	701	15.1	3.6	49.0	2.8	37.7	2.9	47.7	7.0
30% Depletion	1	2878	261	13.7	3.3	47.5	1.4	36.2	1.5	26.7	2.5
	2	2993	352	13.8	3.3	44.8	3.1	33.0	3.4	27.2	3.4
	3	4384	486	14.3	3.3	45.3	2.9	33.5	3.1	39.9	4.7
	4	3731	385	14.3	3.3	45.9	2.3	34.3	2.5	34.1	3.7
	5	3885	502	14.5	3.3	43.4	3.9	31.2	4.4	34.8	4.8
	6	5157	630	14.9	3.5	43.8	3.7	31.7	4.1	46.3	6.1
	7	4451	502	14.7	3.4	44.7	3.1	32.8	3.3	40.3	4.8
	8	4590	639	14.9	3.5	42.1	4.6	29.6	5.3	40.6	6.1
	9	5764	763	15.2	3.5	42.5	4.5	30.1	5.1	51.1	7.3
	10	5044	613	15.2	3.4	43.5	3.7	31.3	4.1	45.2	5.9
	11	5154	765	15.3	3.4	40.9	5.3	28.1	6.1	45.1	7.3
	12	4456	522	14.3	3.4	45.2	3.3	33.3	3.6	40.4	5.0
50% Depletion	1	2326	227	12.6	3.0	41.4	2.0	29.1	2.2	20.5	2.1
	2	2175	278	13.1	3.0	37.7	4.1	24.2	4.9	18.5	2.5
	3	3231	364	13.2	3.2	38.4	3.7	25.1	4.5	27.6	3.3
	4	2460	305	13.5	2.9	37.3	4.2	23.6	5.0	20.9	2.8
	5	2666	361	13.5	3.0	36.0	4.9	21.9	6.0	22.2	3.2
	6	3593	433	13.7	3.3	36.7	4.7	22.7	5.7	30.1	3.9
	7	2813	366	14.0	3.1	35.9	4.8	21.8	5.8	23.5	3.3
	8	2993	424	14.1	3.1	34.6	5.6	20.0	6.9	24.5	3.7
	9	3817	487	14.4	3.3	35.2	5.4	20.7	6.7	31.4	4.3
	10	3066	415	14.5	3.2	34.7	5.3	20.2	6.6	25.2	3.7
	11	3205	473	14.7	3.2	33.4	6.1	18.3	7.7	25.9	4.0
	12	2778	379	12.9	3.1	36.5	5.1	22.5	6.2	23.2	3.4

Table 6.3 Comparative summary of mean values for the main economic and biological performance indicators, for each fixed effort scenario, grouped by the assumed depletion level. Values for the economic indicators are expressed relative to those obtained for the status quo effort scenario.

		Management Objectives							
Scenario		Economic					Conservation		
B(2001) = 85% Bo		Total Catch	Annual Change	Fish Weights	Proportion Large	Economic Value	Final Spawning Biomass	Time (%) Biomass < 30% Bo	Time (%) Biomass < 50% Bo
		Relative to Status Quo							
1	D=11.2m, F=sq	1.00	1.00	1.00	1.00	1.00	71.0	0.0	0.0
2	D=11.2m+ec, F=double+ec	1.12	1.01	0.97	0.95	1.11	56.1	0.0	9.1
3	D=16.8m+ec, F=sq	1.63	1.04	0.97	0.96	1.61	57.7	0.0	6.7
4	D=16.8m, F=double	1.27	1.03	0.96	0.94	1.25	54.4	0.0	13.1
5	D=16.8m+ec, F=double+ec	1.51	1.04	0.95	0.93	1.49	49.2	0.2	19.1
6	D=22.4m+ec, F=sq	1.99	1.09	0.95	0.93	1.96	50.5	0.0	16.0
7	D=22.4m, F=double	1.57	1.07	0.94	0.92	1.54	49.4	0.3	22.0
8	D=22.4m+ec, F=double+ec	1.86	1.08	0.93	0.90	1.82	43.4	2.2	29.5
9	D=28.0m+ec, F=sq	2.31	1.13	0.94	0.91	2.26	44.5	1.3	26.4
10	D=28.0m, F=double	1.84	1.10	0.93	0.90	1.80	45.0	1.6	30.8
11	D=28.0m+ec, F=double+ec	2.16	1.13	0.91	0.88	2.10	38.5	6.7	40.4
12	D=28.0m(15yrs), F=double	1.57	1.05	0.95	0.93	1.54	46.9	0.5	19.6

		Management Objectives							
Scenario		Economic					Conservation		
B(2001) = 70% Bo		Total Catch	Annual Change	Fish Weights	Proportion Large	Economic Value	Final Spawning Biomass	Time (%) Biomass < 30% Bo	Time (%) Biomass < 50% Bo
		Relative to Status Quo							
1	D=11.2m, F=sq	1.00	1.00	1.00	1.00	1.00	50.4	0.0	20.1
2	D=11.2m+ec, F=double+ec	1.04	1.01	0.94	0.91	1.02	32.8	9.3	62.7
3	D=16.8m+ec, F=sq	1.52	1.04	0.95	0.93	1.50	34.7	5.6	58.9
4	D=16.8m, F=double	1.30	1.04	0.97	0.95	1.28	40.8	0.8	52.7
5	D=16.8m+ec, F=double+ec	1.35	1.06	0.91	0.86	1.31	26.1	24.0	70.7
6	D=22.4m+ec, F=sq	1.79	1.09	0.92	0.88	1.74	27.6	18.4	68.7
7	D=22.4m, F=double	1.55	1.07	0.94	0.90	1.51	34.2	8.5	66.1
8	D=22.4m+ec, F=double+ec	1.59	1.09	0.89	0.82	1.52	21.1	41.3	74.8
9	D=28.0m+ec, F=sq	2.00	1.11	0.89	0.83	1.92	22.2	36.9	73.4
10	D=28.0m, F=double	1.75	1.10	0.92	0.86	1.70	28.9	21.0	71.6
11	D=28.0m+ec, F=double+ec	1.79	1.12	0.86	0.77	1.69	17.1	52.6	77.1
12	D=28.0m(15yrs), F=double	1.55	1.04	0.95	0.92	1.51	30.8	9.5	56.8

		Management Objectives							
Scenario		Economic					Conservation		
B(2001) = 50% Bo		Total Catch	Annual Change	Fish Weights	Proportion Large	Economic Value	Final Spawning Biomass	Time (%) Biomass < 30% Bo	Time (%) Biomass < 50% Bo
		Relative to Status Quo							
1	D=11.2m, F=sq	1.00	1.00	1.00	1.00	1.00	27.9	28.4	99.9
2	D=11.2m+ec, F=double+ec	0.94	1.04	0.91	0.83	0.90	13.4	70.6	100.0
3	D=16.8m+ec, F=sq	1.39	1.05	0.93	0.86	1.34	15.0	68.0	100.0
4	D=16.8m, F=double	1.06	1.07	0.90	0.81	1.02	13.5	73.9	100.0
5	D=16.8m+ec, F=double+ec	1.15	1.07	0.87	0.75	1.08	9.3	76.0	100.0
6	D=22.4m+ec, F=sq	1.54	1.09	0.88	0.78	1.46	10.3	74.4	100.0
7	D=22.4m, F=double	1.21	1.11	0.87	0.75	1.14	10.3	77.2	100.0
8	D=22.4m+ec, F=double+ec	1.29	1.12	0.84	0.69	1.19	6.5	78.6	100.0
9	D=28.0m+ec, F=sq	1.64	1.15	0.85	0.71	1.53	7.3	77.4	100.0
10	D=28.0m, F=double	1.32	1.15	0.84	0.69	1.23	8.0	79.1	100.0
11	D=28.0m+ec, F=double+ec	1.38	1.17	0.81	0.63	1.26	4.7	80.3	100.0
12	D=28.0m(15yrs), F=double	1.19	1.02	0.88	0.77	1.13	8.7	72.6	100.0

Figure 6.9a. Pictorial comparison of selected economic performance measures for each future effort scenario and depletion regime described in the text. Note, in the legend D=Domestic, F=Foreign and ec=effort creep applied.

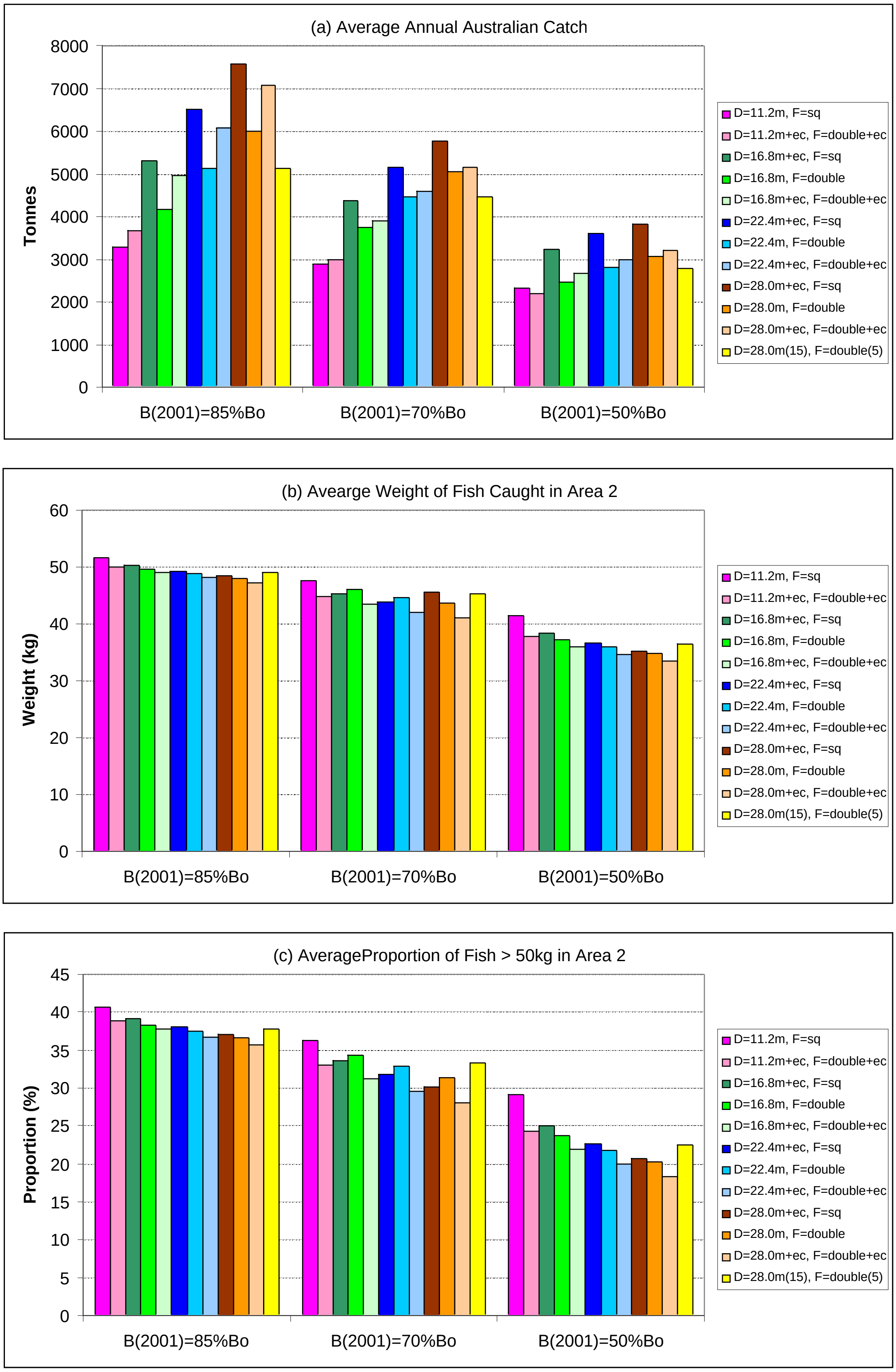
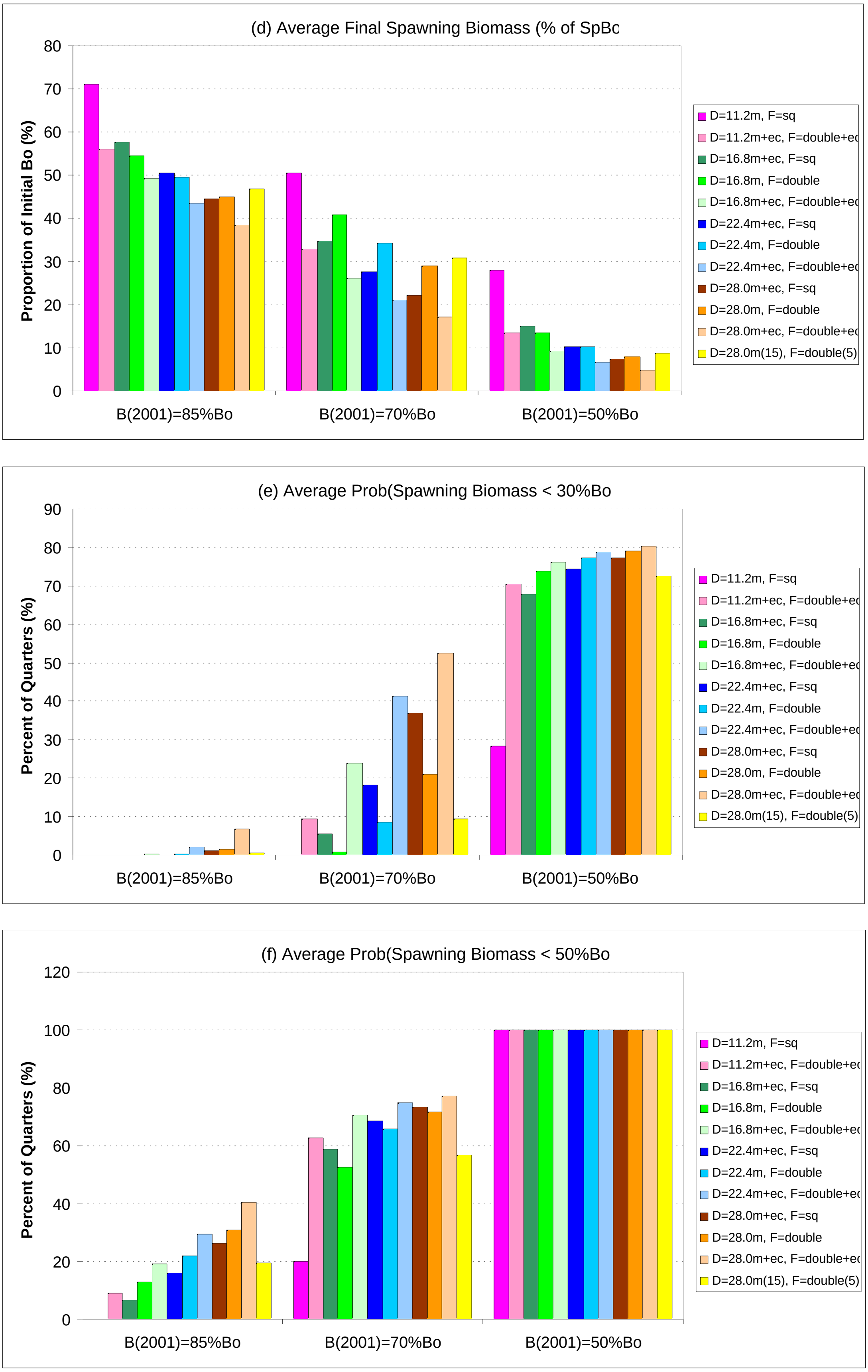


Figure 6.9b. Pictorial comparison of selected conservation performance measures for each future effort scenario and depletion regime described in the text. Note, in the legend D=Domestic, F=Foreign and ec=effort creep applied.



assumed, a lower average catch was achieved for scenario 3 (increase to 16.8 million domestic hooks over 5 years, effort creep, foreign status quo) than for scenarios 8 and 11 (increase to 22.4 and 28 million domestic hooks over 5 years, foreign effort doubled, effort creep). However, for 50% depletion, the average catch for scenario 3 was higher than that for scenarios 8 and 11. Additionally, average catch for scenarios 11 (increase to 28 million domestic hooks over 5 years, effort creep, foreign effort doubled) and 2 (foreign effort doubled, effort creep applied to all fleets) showed a greater relative decrease with increasing assumed depletion levels. When 15% depletion was assumed, scenario 11 yielded higher average catches than scenarios 3 and 6 (increase to 16.8 million and 22.4 million domestic hooks respectively over 5 years, effort creep, foreign status quo), but lower average catches for both scenarios 3 and 6 when 50% depletion was assumed. Scenario 2 resulted in higher average Australian catches than the status quo scenario when 15% or 30% depletion was assumed, but lower catches than the status quo scenario when 50% depletion was assumed.

Correspondingly, it is noted that the final spawning biomass for scenarios 8 and 11 dropped to less than 7% of the initial value when a 50% depletion level was assumed, while for scenario 3 the final spawning biomass was around 15%. That is, when 50% depletion was assumed, larger domestic catches were achieved for a smaller domestic effort when the total effort was reduced. This shows that the population is less resilient to increases in total effort when the assumed depletion is high. Lowered resilience with increasing total effort was evident to a lesser degree across all depletion regimes, in that greater domestic catches were taken for the same level of effort when the foreign effort was held at status quo.

When domestic effort was increased to 28 million hooks over 15 rather than 5 years (scenario 12 versus scenario 11), there was a significant increase in the final spawning biomass for the 15% and 30% depletion regimes, but only a slight improvement under the 50% depletion regime. Furthermore, the proportion of time that the biomass dropped below 30% of its initial level was greatly reduced for the lower depletion regime, but again only showed a slight improvement for the 50% depletion regime.

For all assumed depletion levels, applying effort creep (2% p.a. for the Australian fleet, and for the foreign fleet in the first 5 projection years) and a doubling of foreign effort (scenario 2) had a reasonably similar effect to scenario 4, where Australian effort increased by 1.5 times to 16.8 million hooks over 5 years and foreign effort doubled, but there was no effort creep. Thus the effect of domestic and foreign effort creep can be considered most comparable in magnitude to a 1.5 times increase in domestic effort. When effort creep was applied together with an absolute increase in Australian effort, a comparison of the results of scenarios 5, 8 and 11 (domestic increases and foreign doubling, with effort creep) with those from 4, 7 and 10 (domestic increases and foreign doubling, no effort creep), indicates that the impact of effort creep was greater when the assumed depletion was lower.

Apart from the medium change in annual catch, the average individual weight of fish caught by the domestic fleet in Area 2 was the least sensitive / most robust performance indicator to the range of assumed depletions and to the effort scenarios. There was a 4.4 kg range within the 15% depletion regime, which equates to a maximum of 9.3% variation between the effort scenarios. The variability increased with assumed depletion, with a maximum 8.0 kg (24%) variation for the 50% depletion regime. Consistent with the time series plots of mean weights (Figure 6.3), the upper weight percentiles were more sensitive to the effort scenarios and to the assumed depletion regime. For example, for the status quo scenario the average percentage of large fish in the Australian catch from Area 2 decreased from 41% for the 15% depletion regime to 29% for the 50% depletion regime. Furthermore, the variation across effort scenarios ranged from 4% for the 15% depletion regime to 10.7% for the 50% depletion regime.

Final spawning biomass was the most sensitive performance indicator between effort scenarios and across depletion regimes. For the 15% depletion regime, the relative final spawning biomass ranged from 38% for scenario 11 (increase to 28 million domestic hooks over 5 years, doubling of foreign effort, effort creep) to 71% for the status quo scenario. On the other hand, for the 50% depletion regime, final spawning biomass ranger from 30% of its initial value for the status quo scenario, to 4.7% under scenario 11. Indeed, for the 50% depletion regime, all but the status quo scenario resulted in final spawning biomasses less than 16% of the initial level, while for the 30% depletion regime all but two effort scenarios (1 and 4) gave a final spawning biomasses less than 35% of the initial level. However, for the 15% depletion regime, the final spawning biomass was predicted to always remain above 38% of its initial value.

The probability that, or proportion of quarterly time steps in which the spawning biomass drops below 30% of its initial value, was also found to be highly sensitive to the assumed level of depletion at the start of the projection period. For the 50% depletion regime, this probability was between 26% and 32% for all future effort scenarios (except the status quo effort scenario for which this probability is around 11 percent) and is relatively insensitive to the effort level. This is likely to be due to the fact that once the biomass drops below 30% it remains below this value for the remainder of the projection period. Hence, the associated probability is just a indicator of how early in the projection period the biomass reaches this reference level. For the 30% depletion regime these probabilities are more sensitive to the effort scenario. Those with an increase in Australian effort to 28 million hooks, with effort creep, and scenario 8 (doubling in Australian and foreign effort, with effort creep), all yielded probabilities greater than 14%, while scenario 1-4, 7 and 12 indicate a less than 5% probability of the spawning biomass declining to less than 30% of its initial value. For the 15% depletion regime, only scenario 11 (increase to 28 million domestic hooks over 5 years, doubling of foreign effort, effort creep) had a greater than 2% probability of the spawning biomass declining to less than 30% of its initial value.

For the 50% depletion regime, the probability that the spawning biomass dropped below 50% of its initial values was insensitive to the assumed future effort scenario. This was due to the fact that the level of depletion was already at 50% at the start of the projection period, after which time it dropped below this value and did not recover. For the lower assumed depletion regimes, the probability that the spawning biomass dropped below 50% of its initial values was more sensitive to the future effort scenarios. For the 30% depletion regime, the spawning biomass dropped below 50% of its initial value in at least 20% of all time steps in all scenarios except the status quo, while for those scenarios where Australian effort was at least doubled, the spawning biomass dropped below 50% in over 25% of time steps (with the exception of when Australian effort was increased to 28 million hooks over 15 years with no effort creep). For the 15% depletion regime, the proportion of time steps in which the spawning biomass dropped below 50% of its initial value ranged from zero for the status quo to around 16% for scenario 11 (increase to 28 million domestic hooks in 5 years, foreign effort doubled, effort creep). Within the 15% depletion regime, there was a higher probability of spawning biomass dropping below 50% of its initial value for scenarios when foreign effort doubled while Australian effort increased, with no effort creep (scenarios 4, 7 and 10), than for the scenarios with corresponding levels of increase in Australian effort, with effort creep, but with foreign effort held at status quo (scenarios 3, 6 and 9). The converse was true for the 30% depletion regime, which implies that a doubling in foreign effort had a higher relative impact in those situations were past fishing has had the least impact on the stock.

6.3.3 Performance Measures and Management Trade-Offs

The results listed in Tables 6.2 and 6.3 report the values of a selection of performance indicator under each of the 12 future effort scenarios. As mentioned in section 4.4, performance indicators convey information about some aspect of the system under study (eg.

the size of the catch, the level of depletion of the swordfish population). However, in order to interpret the success or otherwise of a management strategy, it is often useful to consider the related performance measures. Again, performance measures were defined in section 4.4 as conveying information about how well the system is performing relative to some management objective (eg. it compares the performance indicator with some reference value or benchmark, say 30%B_o). The reference values or benchmarks could be target values that identify desirable conditions at which management should aim (target reference points) and / or threshold or limit values that identify critical levels which if exceeded could result in potentially adverse fishery situations (limit reference points).

Both target and limit reference points should be set by the managers of the fishery in consultation with the industry and other stakeholders *a priori* so the management process is transparent and future actions are explicitly defined and agreed. While rigorous reference limits have yet to be determined for the ETBF, the approach of developing a set of performance measures, based on the results presented above, is outlined here.

We focus initially on the biological performance measures. Conservation of the spawning biomass above an agreed reference value is a management objective for many fisheries. For example, the Commission for the Conservation of Southern Bluefin Tuna has adopted a management objective of rebuilding the SBT spawning stock to 1980 levels. However, what levels of spawning biomass should serve as target and limit reference points has been the subject of much debate over the past decade (Polacheck *et al*, 1999). Nevertheless, for the purpose of explaining the approach we use the results of the recent stock assessments undertaken for yellowfin and bigeye tunas in the WCPO (Hampton and Kleiber 2003; Hampton et al 2003). As part of these assessments, the values for a range of performance indicators were determined, including SB_{MSY}/SB_o, the ratio of the predicted spawning biomass at MSY and the initial spawning biomass. For both yellowfin and bigeye tuna, SB_{MSY}/SB_o was estimated to be around 0.28-0.29. As MSY is now commonly seen as a limit reference point, and although the value may be different (possibly higher) for a longer lived species like swordfish, we adopt $SB_{MSY}/SB_o = 0.30$ as the limit reference point for swordfish in the SWPO. The corresponding performance measure then becomes the measure of how well each of the future effort scenarios perform against this objective. For example, if the spawning biomass falls below this limit over a period of time we may say that the strategy has performed poorly. In a similar manner, one may adopt $SB_{MSY}/SB_o = 0.50$ as a target reference point.

Table 6.4 Indicative reference levels used to qualitatively assess each economic and biological performance measure listed in Table 6.3.

Management Objectives							
Economic					Conservation		
Total Australian Catch	Annual Change in Catch	Fish Weights in Area 2	Proportion of Large Fish	Economic Value ($m)	Final Spawning Biomass	Time (%) Biomass < 30% Bo	Time (%) Biomass < 50% Bo
>=2.0 Excellent				>=2.0 Excellent	>60% Excellent		
<2.0 Very Good	<1.0 Very Good	>1.0 Very Good	>1.0 Very Good	<2.0 Very Good	>50% Very Good		
<1.5 Good	<1.1 Good	>0.90 Good	>0.90 Good	<1.5 Good	>40% Good	3% Good	<25% Good
<1.0 Moderate	<1.2 Moderate	>0.80 Moderate	>0.80 Moderate	<1.0 Moderate	>30% Moderate	<10% Moderate	<50% Moderate
	>=1.2 Poor	>0.7 Poor	>0.7 Poor		>20% Poor	<20% Poor	<75% Poor
		<=0.7 Very Poor	<=0.7 Very Poor		<=20% Very Poor	>=20% Very Poor	>=75% Very Poor

Table 6.5 Example of a qualitative assessment of the value of each economic and biological performance measures for each fixed effort scenario, grouped by the assumed depletion level.

Scenario		Management Objectives							
		Economic					Conservation		
B(2001) = 85% Bo		Total Australian Catch	Annual Change in Catch	Fish Weights in Area 2	Proportion of Large Fish	Economic Value ($m)	Final Spawning Biomass	Time (%) Biomass < 30% Bo	Time (%) Biomass < 50% Bo
1	D=11.2m, F=sq	Good	Good	Good	Good	Good	Excellent	Good	Good
2	D=11.2m+ec, F=double+ec	Good	Good	Good	Good	Good	Very Good	Good	Good
3	D=16.8m+ec, F=sq	Very Good	Good	Good	Good	Very Good	Very Good	Good	Good
4	D=16.8m, F=double	Good	Good	Good	Good	Good	Very Good	Good	Good
5	D=16.8m+ec, F=double+ec	Very Good	Good	Good	Good	Good	Good	Good	Good
6	D=22.4m+ec, F=sq	Very Good	Good	Good	Good	Very Good	Very Good	Good	Good
7	D=22.4m, F=double	Very Good	Good	Good	Good	Very Good	Good	Good	Good
8	D=22.4m+ec, F=double+ec	Very Good	Good	Good	Good	Very Good	Good	Good	Moderate
9	D=28.0m+ec, F=sq	Excellent	Moderate	Good	Good	Excellent	Good	Good	Moderate
10	D=28.0m, F=double	Very Good	Moderate	Good	Moderate	Very Good	Good	Good	Moderate
11	D=28.0m+ec, F=double+ec	Excellent	Moderate	Good	Moderate	Excellent	Moderate	Moderate	Moderate
12	D=28.0m(15yrs), F=double	Very Good	Good	Good	Good	Very Good	Good	Good	Good

Scenario		Management Objectives							
		Economic					Conservation		
B(2001) = 70% Bo		Total Australian Catch	Annual Change in Catch	Fish Weights in Area 2	Proportion of Large Fish	Economic Value ($m)	Final Spawning Biomass	Time (%) Biomass < 30% Bo	Time (%) Biomass < 50% Bo
1	D=11.2m, F=sq	Good	Good	Good	Good	Good	Very Good	Good	Good
2	D=11.2m+ec, F=double+ec	Good	Good	Good	Good	Good	Moderate	Moderate	Poor
3	D=16.8m+ec, F=sq	Very Good	Good	Good	Good	Good	Moderate	Moderate	Poor
4	D=16.8m, F=double	Good	Good	Good	Good	Good	Good	Good	Poor
5	D=16.8m+ec, F=double+ec	Good	Good	Good	Moderate	Good	Poor	Very Poor	Poor
6	D=22.4m+ec, F=sq	Very Good	Good	Good	Moderate	Very Good	Poor	Poor	Poor
7	D=22.4m, F=double	Very Good	Good	Good	Good	Very Good	Moderate	Moderate	Poor
8	D=22.4m+ec, F=double+ec	Very Good	Good	Moderate	Moderate	Very Good	Poor	Very Poor	Poor
9	D=28.0m+ec, F=sq	Excellent	Moderate	Moderate	Moderate	Very Good	Poor	Very Poor	Poor
10	D=28.0m, F=double	Very Good	Moderate	Good	Moderate	Very Good	Poor	Very Poor	Poor
11	D=28.0m+ec, F=double+ec	Very Good	Moderate	Moderate	Poor	Very Good	Very Poor	Very Poor	Very Poor
12	D=28.0m(15yrs), F=double	Very Good	Good	Good	Good	Very Good	Moderate	Moderate	Poor

Scenario		Management Objectives							
		Economic					Conservation		
B(2001) = 50% Bo		Total Australian Catch	Annual Change in Catch	Fish Weights in Area 2	Proportion of Large Fish	Economic Value ($m)	Final Spawning Biomass	Time (%) Biomass < 30% Bo	Time (%) Biomass < 50% Bo
1	D=11.2m, F=sq	Good	Good	Good	Good	Good	Poor	Very Poor	Very Poor
2	D=11.2m+ec, F=double+ec	Moderate	Good	Good	Moderate	Moderate	Very Poor	Very Poor	Very Poor
3	D=16.8m+ec, F=sq	Good	Good	Good	Moderate	Good	Very Poor	Very Poor	Very Poor
4	D=16.8m, F=double	Good	Good	Moderate	Moderate	Good	Very Poor	Very Poor	Very Poor
5	D=16.8m+ec, F=double+ec	Good	Good	Moderate	Poor	Good	Very Poor	Very Poor	Very Poor
6	D=22.4m+ec, F=sq	Very Good	Good	Moderate	Poor	Good	Very Poor	Very Poor	Very Poor
7	D=22.4m, F=double	Good	Moderate	Moderate	Poor	Good	Very Poor	Very Poor	Very Poor
8	D=22.4m+ec, F=double+ec	Good	Moderate	Moderate	Very Poor	Good	Very Poor	Very Poor	Very Poor
9	D=28.0m+ec, F=sq	Very Good	Moderate	Moderate	Poor	Very Good	Very Poor	Very Poor	Very Poor
10	D=28.0m, F=double	Good	Moderate	Moderate	Very Poor	Good	Very Poor	Very Poor	Very Poor
11	D=28.0m+ec, F=double+ec	Good	Moderate	Moderate	Very Poor	Good	Very Poor	Very Poor	Very Poor
12	D=28.0m(15yrs), F=double	Good	Good	Moderate	Poor	Good	Very Poor	Very Poor	Very Poor

Based on this example, for each of the indicators listed in Table 6.3 we have created a qualitative scale of performance measures. These are listed in Table 6.4. This set of performance measures was then used to qualitatively assess the performance of each indicator under each of the effort scenarios. The results are given in Table 6.5. While these results should be taken as being indicative only, they allow a qualitative assessment to be made regarding the success or otherwise of each of the alternative fixed effort harvest strategies. Furthermore, this manner of presenting the results makes explicit the trade-offs between achievement of, the often conflicting, economic and conservation objectives.

For the 15% depletion regime, all performance measures are rated at moderate or above. Hence, all effort strategies can be viewed as being at least moderately successful in achieving both sets of the management objectives. More important from an industry point of view, increases in future effort may be possible while still achieving agreed conservation targets. On the other hand, under the 30% depletion regime, the relative achievement of the objectives is much more mixed. Successful achievement of the three conservation objectives can only be rated as good or above for the status quo scenario, while achievement of the first two conservation objectives is rated as being moderate or above for scenarios 1-4, 7 and 12 only (essentially those scenarios where effort is limited to being twice the present levels and there are no increases in fishing efficiency). For all other scenarios, achievement of the conservation objectives is either poor or very poor. Under this depletion regime, it is interesting to note that the higher effort scenarios do not always lead to greater success of all economic objectives. For example, whilst scenario 11 is rated very high from the point of view of achieving a higher catch, achievement of a high proportion of large fish in the catch is rated as poor. Hence, we are not only beginning to see a trade-off between effort levels and the success of both the economic and conservation objectives, but also between effort levels and the success of individual economic objectives.

Finally, for the 50% depletion regime, the achievement of the conservation objectives is poor to very poor under all alternative effort strategies. This is despite the successful achievement of some of the economic objectives, though again some are only unsuccessful under the higher effort scenarios. For this depletion regime there does not appear to be much scope for trade-offs between the relative success of the main economic and conservation objectives.

6.4 Discussion

It should be reiterated that all results presented here are based on an operating model that assumes the reference biological scenario. As illustrated by the previous chapter, the outcomes are sensitive to assumptions made about the natural mortality, recruitment and extent of movement within the population. However, the results from that chapter indicated that the model outputs were equally or more sensitive to the assumed level of depletion at the end of the historical period, and for this reason the results above have been presented for three alternative depletion regimes.

Clearly, the results for the various fixed effort strategies are highly sensitive to the assumed depletion regime. This is to be expected, as a higher assumed level of depletion corresponds to the assumption that the swordfish population has been less robust to the historical levels of fishing effort. Thus, as future effort is increased, the stock performs more poorly if depletion levels are higher. When the assumed depletion is set at 50%, future increases in actual or effective effort are likely to be at a high risk to the population, with spawning biomass being depleted to less than 16% of its initial value. If 30% depletion is assumed, then 2.5-fold increases in Australian effort are also likely to be a high risk (spawning biomass reduced to less than 29% of its initial level), especially if effective effort also increases and foreign effort doubles. For the 30% depletion regime, only for scenarios 1-4, 7 and 12 is the final spawning biomass predicted to remain, on average, above 30% of its initial level.

Increasing effort by 2.5 times to 28 million hooks over a longer time period (15 years as opposed to 5 years) yielded a more favourable outcome for the population, but the final predicted biomass level was likely to be less than the target reference point and very close to what many may see as a limit reference point. Also, having such a long period over which effort is continuously increased is likely to be inappropriate from a management viewpoint. It would not be possible to guarantee an end result of 25 million hooks that far into the future, as ongoing monitoring, assessment and research would most likely result in revisions and updating of the management strategy during that time.

Under an assumed depletion level of only 15%, all future effort scenarios had more favourable outcomes, in terms of both economic and conservation performance indicators, with only scenario 11 (increase to 28 million domestic hooks in 5 years, effort creep, foreign effort doubled) resulting in greater than 60% decline in the final spawning biomass relative to its initial level. However, there may be a higher level of risk associated with the assumption that the depletion level in 2001 is only 15% (against, say, 30%) given the size of the historical catches.

The important question therefore remains - which is the most realistic depletion assumption? The only data available to address this is the New Zealand length-frequency and the weight-frequency data from Australian observers on Japanese vessels. The goodness of fit of the model to this data may give some indication as to the most appropriate level of depletion. The weight-frequency data is available by quarter for Areas 1-3, while the length frequency data is available for quarters 2 and 3 within Area 5. The total residual sums of squares across these 14 distributions was 1.803×10^{-2} for the 30% depletion regime, 1.842×10^{-2} for the 15% depletion regime, and 1.828×10^{-2} for the 50% depletion regime. While the differences are relatively small (the value for the 30% depletion regime is 2.1% lower than that for the 15% depletion regime, and 1.4% lower than that for the 50% depletion regime), these results suggest that the true depletion level may be closer to 30% than to the other two assumed levels. In the absence of any additional evidence to support the 30% depletion assumption, it is probably the most sensible one on which to base management decisions, given that it can be argued that 15% is probably not precautionary while the 50% level is likely to be too extreme, thus invoking unnecessary or premature limitations on recommended future effort levels.

An alternative to trying to identify which of the alternative depletion regimes may be most likely is to achieve a synthesis of the results by taking a weighted average across each depletion regime. The weight assigned to each regime should be some measure of the probability of each state of nature (i.e. depletion) at the end of the conditioning period. Guided by the fit between the historically observed and model predicted catch-at-size size data for the Australian and Japanese fleets and by the relative size of the historical catches in relation to swordfish fisheries elsewhere, the low, medium and high depletion regimes were assigned probabilities of 30, 60 and 10 percent respectively, and the corresponding weighted average of each performance indicator for each effort strategy was then calculated. The result is given in Table 6.6. Only two effort strategies (# 1 and 4) are seen to achieve a qualitative performance of moderate or better for all eight performance measures. While several other strategies achieved a ranking of moderate for at least one of the conservation-based performance measures (# 2, 3, 5, 6, 7, 10 and 12), these strategies all had a poor outcome based on the probability that the spawning biomass fell below 30 percent of its initial value (which was estimated to be vary 10 and 22 percent). The trade-off between higher catches and lower spawning biomass is more extreme for the other strategies. Apart from consideration of the conservation objectives, the results again indicate an economic trade-off between higher catches and a reduction in the proportion of large fish in the catch. This is most clearly seen for scenario 11 where the proportion of large fish in the catch is rated as poor. As large fish generally return a higher price, a decrease in the proportion of large fish in the catch would result in a lower unit return across the total catch.

Table 6.6 (a) Weighted mean across the three assumed levels of depletion in 2001 of mean values for the main economic and biological performance indicators for each fixed effort scenario under the reference biological scenario. Values for the economic indicators are expressed relative to those obtained for the status quo effort scenario. **(b)** Qualitative assessment of the performance of each performance measure show in (a). (Note: D gives the annual level of Australian effort in million of hooks, while F gives the level of foreign effort relative to the status quo (sq), and ec denotes the application of a 2% annual increase in effective effort due to effort creep.)

(a)

		Management Objectives							
Scenario		Economic					Conservation		
B(2001) = Weighted Mean		Total Catch	Annual Change	Fish Weights	Proportion Large	Economic Value	Final Spawning Biomass	Time (%) Biomass < 30% Bo	Time (%) Biomass < 50% Bo
		Relative to Status Quo							
1	D=11.2m, F=sq	1.00	1.00	1.00	1.00	1.00	54.3	2.8	22.0
2	D=11.2m+ec, F=double+ec	1.06	1.01	0.95	0.92	1.04	37.9	12.7	50.3
3	D=16.8m+ec, F=sq	1.55	1.04	0.96	0.93	1.52	39.6	10.1	47.4
4	D=16.8m, F=double	1.27	1.04	0.96	0.93	1.25	42.1	7.9	45.6
5	D=16.8m+ec, F=double+ec	1.39	1.05	0.92	0.87	1.35	31.4	22.1	58.1
6	D=22.4m+ec, F=sq	1.84	1.09	0.93	0.89	1.79	32.7	18.5	56.0
7	D=22.4m, F=double	1.53	1.08	0.93	0.90	1.50	36.4	12.9	56.2
8	D=22.4m+ec, F=double+ec	1.66	1.09	0.90	0.83	1.60	26.3	33.3	63.7
9	D=28.0m+ec, F=sq	2.08	1.12	0.90	0.85	2.01	27.4	30.3	62.0
10	D=28.0m, F=double	1.75	1.11	0.91	0.86	1.70	31.6	21.0	62.2
11	D=28.0m+ec, F=double+ec	1.88	1.13	0.87	0.80	1.80	22.3	41.6	68.4
12	D=28.0m(15yrs), F=double	1.53	1.04	0.94	0.91	1.49	33.4	13.1	49.9

(b)

		Management Objectives							
Scenario		Economic					Conservation		
B(2001) = Weighted Mean		Total Australian Catch	Annual Change in Catch	Fish Weights in Area 2	Proportion of Large Fish	Economic Value ($m)	Final Spawning Biomass	Time (%) Biomass < 30% Bo	Time (%) Biomass < 50% Bo
1	D=11.2m, F=sq	Good	Good	Good	Good	Good	Very Good	Good	Good
2	D=11.2m+ec, F=double+ec	Good	Good	Good	Good	Good	Moderate	Poor	Poor
3	D=16.8m+ec, F=sq	Very Good	Good	Good	Good	Very Good	Moderate	Poor	Moderate
4	D=16.8m, F=double	Good	Good	Good	Good	Good	Good	Moderate	Moderate
5	D=16.8m+ec, F=double+ec	Good	Good	Good	Moderate	Good	Moderate	Very Poor	Poor
6	D=22.4m+ec, F=sq	Very Good	Good	Good	Moderate	Very Good	Moderate	Poor	Poor
7	D=22.4m, F=double	Very Good	Good	Good	Moderate	Good	Moderate	Poor	Poor
8	D=22.4m+ec, F=double+ec	Very Good	Good	Moderate	Moderate	Very Good	Poor	Very Poor	Poor
9	D=28.0m+ec, F=sq	Excellent	Moderate	Good	Moderate	Excellent	Poor	Very Poor	Poor
10	D=28.0m, F=double	Very Good	Moderate	Good	Moderate	Very Good	Moderate	Very Poor	Poor
11	D=28.0m+ec, F=double+ec	Very Good	Moderate	Moderate	Poor	Very Good	Poor	Very Poor	Poor
12	D=28.0m(15yrs), F=double	Very Good	Good	Good	Good	Good	Moderate	Poor	Moderate

In conclusion, the results presented in this chapter indicate that considerable fishing pressure would be placed on the swordfish population under several of the future effort scenarios considered. If one adopts 30%B_o as a limit reference point then all scenarios where the Australian effort is increased above 16.8 million hooks were found to place the stock at high risk of being over-fished, while even an increase to 16.8 million hooks resulted in a moderate level of risk. The results also indicate that the impact of any set level of domestic effort depends on the changes in effort of the foreign fleets, and on their efficiency. For example, when foreign effort was held at status quo, as opposed to being doubled, the same level of Australian effort had a reduced probability of driving the spawning biomass to below 30% of its initial value, and Australia achieved higher catches for identical or lower levels of effort. If one were to adopt a precautionary approach then one should assume future increases in foreign effort and efficiency, and then re-evaluate the situation once the extent of change in foreign effort becomes apparent.

Chapter 7: Harvest Strategies Involving Decision Rules

7.1 Implementing a Decision Rule

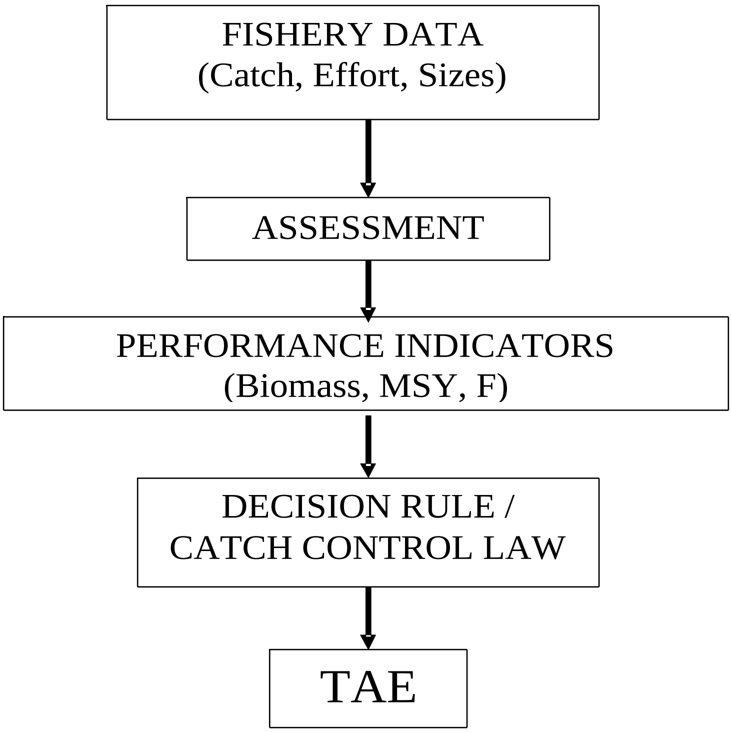
The previous chapter examined the response of the broadbill swordfish stock to alternative future fixed effort harvest strategies. For all of these strategies, the effort time series was pre-specified, with fixed rates of increase over time. While this was instructive in terms of exploratory analysis of stock behaviour under given levels of exploitation, and in terms of making an informed decision about an initial *TAE* for the Australian fleet, in practice it is unrealistic to expect that future effort levels can be implemented at pre-determined levels 20 years into the future without some ongoing assessment of the performance of the fishery. Some of the effort strategies examined in the previous chapter resulted in the depletion of the stock under ongoing exploitation such that limit reference points were triggered. This is not only undesirable, but ideally it would be hoped that ongoing monitoring and assessments would be capable of detecting declines in stock biomass and revise effort levels accordingly before such levels are reached.

This chapter considers the response of the stock and the impact on the effort and catch levels for the Australian fleet when decision rules or management feedback loops are incorporated in the domestic fishery. To achieve this, simple empirical and a model-based assessment are used to evaluate the status of the stock at pre-determined time intervals. Using the results of the assessment, a decision rule is applied to set the level of domestic effort. In developing a decision rule (or set of rules) for updating the *TAE*, the management objectives for the fishery need to be set *a priori*, as the decision rules adopted by the mangers will be used to achieve these objectives. Thus trigger points used to invoke the decision rule are pre-specified, giving a harvest strategy that is transparent to all stakeholders. A great advantage of this approach is that it allows management of the fishery to become pro-active instead of only reactive to changes in the performance of the fishery.

The components of a decision-ruled based harvest strategy are outlined in Figure 7.1. Within the MSE evaluation framework, the operating model is used to generate the fishery data that is fed into the assessment. Based on the results of the assessment, the values of various performance indicators (eg. the ratio of the present biomass to its initial value) are obtained, and these feed into the decision-rules used to determine catch or effort levels in the fishery. This procedure is repeated for the duration of the evaluation or projection period, after which time the success or otherwise of the harvest strategy can be evaluated. There is a choice as to how often an assessment is carried out, and consequently how often the *TAC* or *TAE* will be adjusted (if needed). Again, success in achieving the stated management objectives of the fishery should be the criteria used to evaluate the performance of the harvest strategy.

As a harvest strategy is comprised of several components (data collection, assessment, choice of performance indicators, application of decision rule, implementation of management decisions), the performance of the harvest strategy will be dependent on the performance of each component. While under-performance of any one component may result in the failure of the overall harvest strategy, identification of such problems may not be obvious. The MSE approach can, however, also be used to evaluate the performance of the assessment used in the harvest strategy. The fishery data generated by the operating model, and used in the assessment, should reflect the types of data collected from the fishery. That is, it should contain the same types of sampling errors and biases that may exist in the real data. Combined with uncertainties in the population dynamics of the stock, the results of the assessment would therefore likely contain biases and be uncertain about the true state of the stock. However, the *MSE* approach allows the performance of the assessment to be evaluated, as the

Figure 7.1 Components of a decision rule based harvest strategy.



assessment-based estimates of stock status can be compared with true state of the stock "known" by the operating model. For example, the assessment output may indicate a stable stock and make no adjustment to the effort level, but the true state of the stock in the operating model may be declining.

In evaluating the performance of the decision-rule based harvest strategies for the ETBF, a suite of alternative harvest strategies were examined. These considered the influence of the quality of the input effort data, the types of assessment and decision rules, the frequency with which assessments were undertaken, and the magnitude of the management response to the assessment results. The choice of harvest strategies was also influenced by the following issues:

- The lack of catch-by-age data, difficulties in determining effective effort, and the relatively short time-series of large catches have, to date, precluded the development of a sophisticated model-based stock assessment for swordfish in the SW Pacific. Thus the model-based assessment in this chapter is limited to a simple (multiple fleet) production model. However, the framework of the management strategy evaluation approach is such that more comprehensive stock assessments would readily be able to be incorporated as they become available.
- When implementing decision rules based on stock assessments, it must be borne in mind that Australia has no jurisdiction over foreign fleets. Although the results of stock assessments are shared at international forums such as the Standing Committee for Tunas and Billfish, each fishing nation is currently responsible for its fishing practices within its EEZ and on the high seas. The imminent formation of the Western Pacific Tuna Commission will result in a more unified management approach for broadbill swordfish, but meanwhile it is inappropriate to apply harvest strategies to foreign fleets. Instead, both the scenarios where foreign effort remains at 2001 levels, and where foreign effort doubles, with effort creep, were considered. Effort creep in the domestic fleet is also considered.

7.2 MSE Trials

For the first year of model projection, an initial, arbitrary *TAE* of 15 million hooks for the Australian domestic fleet was allocated according to the proportion of annual effort occurring in each quarter from the previous year. Once an initial *TAE* was set for the fishery, a decision rule was used to update the *TAE* in light of the information forthcoming from the assessments. Details of the assessments and decision rules are given below. Note, several trials were run where a 2% effort creep was applied to the domestic effort over the projections years.

For the non–domestic fleets (Japan and New Zealand), we assumed no control over management regimes and as such no management strategies or decision rules were incorporated in the model framework for these fleets. For the majority of trials, the foreign effort was set to the 2001 level (status quo), but trials were also run where the foreign effort was doubled over 5 years, with an effort creep of 2% per annum over that time.

The effort levels set for each fleet at the start of each year, and adjusted via the decision rules described below, relate to the nominal effort. However, changes in nominal effort often do not reflect changes in effective effort, which is required for assessment purposes. The relationship between nominal effort, E_{nom}, and fishing mortality, F, for each fleet at time t is given by either equation 4.15 or 4.16 (cf. section 4.3), both of which have the general form:

$$F(t) = Q(t)E_{nom}(t)e^{\varepsilon_t - \sigma^2/2}$$

where Q is the catchability and ε_t is a factor to account for random variation in catchability ($\varepsilon_t \sim N(0;\sigma^2)$). By re-parameterising $Q(t)$ to be composed of a time-independent component, q_o, and a time-varying component, Q_t, such that $Q(t) = q_oQ_t$, we can rewrite the above equation in terms of the effective effort, E_{eff}:

$$F(t) = q_o Q_t E_{nom}(t)e^{\varepsilon_t - \sigma^2/2} = q_o E_{eff}(t)e^{\varepsilon_t - \sigma^2/2} \qquad (7.1a)$$

$$\text{where} \qquad E_{eff} = Q_t E_{nom} \qquad (7.1b)$$

For the Australian and New Zealand fleets, q_o gives the value of the catchability which was assumed to be constant before 1995, while for the Japanese fleet q_o is the value of the catchability at the start of the historical time series (1971). The time-varying component, Q_t,, for all fleets then gives the temporal change in the catchability relative to the time-independent component, ie for the Australian fleet, Q_t =1 and $E_{eff} = E_{nom}$ before 1995.

The above relation was used to calculate the effective effort at each time step, and it is the effective effort which is used in both the empirical and model-based assessments described below. This is akin to using a “standardized” effort in a real assessment. However, it should be realized that in practice the calculated standardized effort is unlikely to be as accurate as the effective effort used here, as equation 7.1a contains no bias between the effective effort and fishing mortality. In reality, it is likely that the standardization procedure will not be able to account for all sources of changes in catchability over time and so a temporal bias between effective effort and fishing mortality will remain. While a bias could have been added to the above relation, this was not done. Nevertheless, we compared the effectiveness of one of the harvest strategies against the alternative situation where the amount of stochastic variation in the above equation, as determined by the parameter _, was arbitrarily fixed at a higher level (0.5) than that determined from the conditioning process (where _ = 0.2 - 0.4 across fleets and quarters).

7.2.1 Empirical assessments

The general principle underlying the empirical (ie. non-model based) approach to updating a *TAE* is to identify some measurable statistic and then change the *TAE* in response to changes in that statistic (Punt *et al*, 2001). In principle the statistic chosen should be some measure of the (exploitable) biomass or of fishing mortality. In this study, the following statistics were used.

1) Catch rate
2) The upper 95th percentile of the average mass of fish in the catch. Note: In the preliminary work done for this study, Punt *et al*. (2001) found that the 95th mass percentile was a performance indicator that reflected changes in abundance more closely than catch, effort or mean length.

For updating the *TAE*, the following empirical approach was considered (Magnusson and Stefansson 1989). This involved changing the *TAE* using the formula:

$$TAE_{t+1} = TAE_t (1 + \beta_{emp} S_{emp,t}) \qquad (7.1)$$

where β_{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 $t\text{-}y_{emp}+1$ to t.

If set too high, the level of feedback gain can lead to instability in catch limits (Magusson 1992).

As an example of this procedure, consider the hypothetical fishery with the time series of annual catch rates given in Table 7.1. An initial *TAC* = 100 units is set for the fishery. The first update of the *TAC* is carried out after the 5th year and these updates are undertaken annually after this time. This sequence is also shown in Table 7.1.

Table 7.1 Time-series of annual catch rates in a hypothetical fishery.

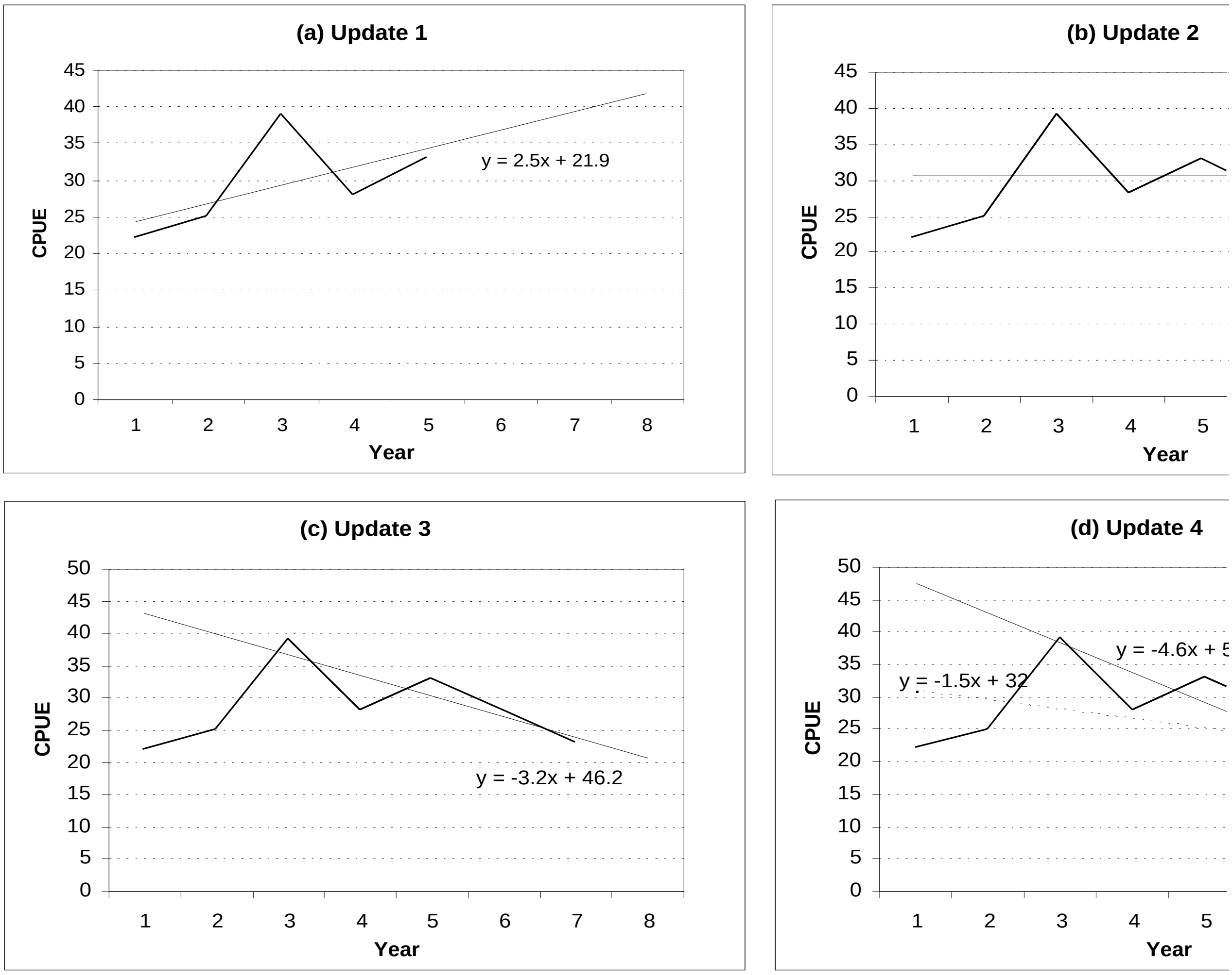
Year	**1**	**2**	**3**	**4**	**5**		**6**		**7**		**8**	
CPUE	22	25	39	28	33		28		23		10	
Update						**1**		**2**		**3**		**4**

During each update, the linear regression over the catch rates during the past five years (ie. y_{emp}=5) is used in the decision rule to change the *TAC*. The time-series of catch rates when the first update is undertaken, together with the linear regression line, is shown in Figure 7.2a. The slope of this regression line is $S_{emp,t}$ = 2.5, so if we set the control parameter, β_{emp} = 0.1, then the updated *TAC*, based on equation (9.1) above, can be calculated as follows:

$$TAC(6) = TAC(5)*(1+ \beta_{emp}\ S_{emp,t}) = 100*(1+0.1*2.5)=125 \text{ units.}$$

The time-series of catch rates after the 6th year, together with the trend line used in the updating process, is shown in Figure 7.2b. At this time, the slope of the trend line is zero and so the *TAC* remains unchanged. However, at the time of the next update after the 7th year, the trend line (shown in Figure 7.2c) has a negative slope with a value of -3.2. Hence, using equation (1) again, the new *TAC* becomes 125*(1+0.1*(-3.2)) = 85 units. With a continued

Figure 7.1. Time-series of catch rates in a hypothetical fishery, with the trend line associated with the decision rule to update the TAC/TAE.



decline in catch rates, at the time of the final update the trend line (cf. Figure 7.2d) is found to have a slope of -4.6 giving a new *TAC* of 46 units.

There are obvious variations to the above procedure. For example, also shown in Figure 7.2 is the trend line based on taking the regression over the last six years (ie. setting y_{emp}=6), instead of the last five used in the procedure above. In this instance, the slope is smaller, having a value of -1.5. Using this value in equation (1), the *TAC* would only decrease to 85 units. One could also use different values of the control parameter. Alternatively, instead of updating the *TAC* annually, one may do this, say, after every third year. This may be preferable in a fishery with large inter-annual variations in catch rates (such as the ETBF) and also introduces a degree of stability to the annual *TAE*s.

In this chapter, alternative feedback gain factors (_$_{emp}$) of 0.1 and 0.3 were trialled. Regressions were performed on the past 5 and past 7 years (y_{emp}) of data, and the decision rule was applied either every year, or every 4 years.

7.2.2 Model-based assessments

Unlike empirical based methods described above, model-based methods make use of formal stock dynamics models to integrate information about the fishery and provide estimates of the trends in biomass and fishing mortality. As stated above, the present study uses production (or biomass dynamics) models that describe changes in biomass in terms of an intrinsic growth rate parameter. Production models are often used in those situations where age-/size-composition data are not available, but have been criticised for lack of biological realism (Punt 1995).

For each year of the projection period, an annual stock assessment estimates the status of the population (which is known through the operating model) and generates fishery performance indicators for use in management. The stock assessments use both the historical data from the real fishery, together with the simulated future data from the operating model. For feedback harvest strategies, the value of the performance indicators (as estimated by the assessment) is used to determine annual adjustments to the management of the fishery. Due to a lack of age- or length-specific catch data, the assessment in the MSE framework is undertaken using a production model.

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. Production models can either be discrete (e.g. Butterworth and Andrew, 1984) or continuous (Prager, 1994), although for relatively long-lived species, such as broadbill swordfish, there is little difference between the two types of production model. In this study, the continuous model is used.

The continuous production model has the following general form (Prager, 1994):

$$\frac{dB_t}{dt} = \alpha_t B_t - \beta \quad B_t^2$$

where $\alpha_t = r - F_t$ and $\beta = r / K$,

and F_t is the fishing mortality at time t,

B_t is the stock biomass at time t,

r and K are model parameters.

For the period beginning at $t = h$ and ending at time $t = h + \delta$, during which the instantaneous fishing mortality rate is F_h, the solution to the above equation is

$$B_{h+\delta} = \frac{\alpha_h B_h e^{\alpha_h \delta}}{\alpha_h + \beta \quad B_h (e^{\alpha_h \delta} - 1)} \qquad \text{when } \alpha_h \neq 0 \text{, or}$$

$$B_{h+\delta} = \frac{B_h}{1 + \beta\delta B_h} \qquad \text{when } \alpha_h = 0.$$

Recorded yield in each time step is used to estimate the fishing effort for each fleet by integrating:

$$Y_h = \int_{t=h}^{h+\delta} F_h B_t dt$$

where	B_t,	is the biomass at instant t, as defined as above
	F_h	is the (constant) instantaneous rate of fishing mortality during the time period, and
	Y_h	is the yield taken during the period,

and solving for total fishing mortality rate, one obtains:

$$F_t = \frac{\beta \quad Y_t}{\ln\left[\frac{\beta \quad B_t (e^{\alpha_t} - 1)}{\alpha_t} + 1\right]} \qquad \text{when } \alpha_t \neq 0 \text{, or}$$

$$F_t = \frac{\beta \quad Y_t}{\ln[1 + \beta \quad B_t]} \qquad \text{when } \alpha_t = 0,$$

Finally, dividing by the catchability, q, one obtains the estimated effort.

A useful feature of the above model is that it is easily extended to allow for multiple fleets. The total instantaneous fishing mortality in period t is:

$$F_t = \sum_{j=1}^{Nfleets} q_j E_{t,j}$$

where the fleet specific efforts in each period, $E_{t,j}$, are estimated by assigning the estimated total fishing mortality among fleets according to their relative catches:

$$E_{t,f} = \left(Y_{t,f} / Y_t\right) \left(F_t / q_f\right)$$

More details of how the above extensions are implemented are given in Prager (1994).

When implementing the results of the assessment, the corresponding decision-rule first determined whether or not the assessment returned a biologically plausible result by examining the value of the r-parameter (the intrinsic population growth rate). If the value of r was excessively small or large, the model reverted to the empirical *TAE* setting approach. Otherwise the assessment parameters were used to determine F_{msy} (= r/2) and *MSY* (=r**K/4*).

The decision rule for setting the overall fishing mortality was based on the “40/10 rule”, whereby the estimates of current biomass, B_{cur}, from the stock assessment was used to set the future fishing mortality, according to whether it was within or outside the range of 10-40% of the estimated carrying capacity, K. This is illustrated in Figure 7.3, and the rule for adjusting the fishing mortality was as follows:

Figure 7.3 Representation of the “40/10” rule used for adjusting fishing mortality.

$$F = \begin{cases} 0 & : B_{cur} \leq 0.1 * K \\ F_{targ} * F_{msy} * 10 * (B_{cur} / K - 0.1) / 3 & : 0.1 * K < B_{cur} < 0.4 * K \\ F_{targ} * F_{msy} & : B_{cur} < 0.4 * K \end{cases}$$

where F_{targ} is a target fishing mortality as a fraction of the *MSY* rate (set to 0.9). That is, when current biomass is between 0.1 and 0.4 of the carrying capacity, *F* follows a straight line relationship between 0 and F_{targ}. A revised E_{msy} (i.e. *TAE*) is then determined by dividing *F*, as calculated by the above decision rule, by the average catchability across all three fleets, and a revised *MSY* is determined by multiplying *F* by the current biomass from the assessment.

Using these results, two options for adjusting the previous year’s *TAE* were then trialled:

(1) calculate the fraction that the E_{msy} based on the above 40/10 rule is of the previous year’s effort (across all fleets) and apply that to the Australian effort,

(2) calculate an Australian *TAC* as the product of the revised *MSY* and the Australian fraction of the previous year’s annual effort, then determine the adjusted Australian effort by dividing by the average Australian catch rate.

Finally, as abrupt inter-annual changes in effort may not be acceptable or economically optimal, for some trials a maximum adjustment of 30% was specified and applied if the change in effort from the assessment was larger. Additionally, a trial was run where a production model assessment was conducted only every four years instead of annually.

7.2.3 Performance indicators

Under any future effort scenario, the operational model allows predictions to be made of the corresponding annual catches for each fleet and the response of the swordfish population to these catches. As with the previous chapters, for each scenario, the model was run 100 times, over a 20 year projection period and the model predictions were summarised as previously described (cf. section 4.3). The values of various performance indicators were also calculated for each future effort scenario as previously described (cf. section 4.4). However, additional indicators were also considered using specific output from the production model. These were:

- Maximum sustainable yield, *MSY*.
- The ratio of the biomass at the start of year y_{curr} to the biomass at which *MSY* is achieved, B_{MSY} (abbreviation B_{curr}/B_{MSY})

As compared to the previous chapters, where the future effort level for the Australian fleet in any year was pre-specified or fixed, the use of decision rules results in regular adjustments to these effort levels. As such, it was important to consider the impact of these adjustments on temporal effort trends in conjunction with the above performance indictors. Abrupt inter-annual changes may not be acceptable or economically optimal, and as such it must be confirmed that desirable outcomes in a conservation and long-term economic context are not achieved at the cost of a stock assessment that invokes large inter-annual fluxes in effort. This is controlled to some extent by the choice of values for the feedback control parameter in the empirical assessment and for the maximum adjustment placed on the outcome of the production model-based assessment.

7.2.4 Listing of Alternative Harvest Strategies

A summary listing of the alternative harvest strategies evaluated is given in Table 7.2. In order to help assess the performance of those harvest strategies involving a decision rule, two reference future effort scenarios were run where no decision rule was used, ie. the effort assigned to each fleet was kept constant for all projection years. These two reference scenarios were as follows:

Reference Effort Scenario 1:

- Annual total domestic effort set equal to 15 million hooks, distributed by area and quarter the same as in 2001.
- Foreign effort within each quarter/region strata remains at the average level of effort in that strata over the last 3 years 1999-2001.

Reference Effort Scenario 2:

- Nominal domestic effort stays as for scenario 1, but effective effort increases at 2% p.a. for all projection years,
- Nominal foreign effort stays as for scenario 1, with effective effect increasing at 2% p.a. for the first five years, i.e. after the fifth year, both nominal and effective foreign effort remain constant.

In total, seven harvest strategies using the empirical decision rule, and five harvest strategies using the model-based decision rule were evaluated.

Table 7.2 Listing of alternative harvest strategies evaluated.

Strategy	Assess. Timeframe	Effort Error _	Empirical Based Assessment			Model Based Assessment	
			Indicator	$\_{emp}$	y_{emp}	*Method*	*Max. Adj*
1	Reference Effort Scenario 1: Australia (15 million), Foreign (Status Quo)						
2	Annual	Calc	CPUE	0.1	5	E_{msy}	30%
3	Annual	Calc	CPUE	0.3	5	MSY	30%
4	Annual	Calc	95th Mass	0.1	5		
5	Annual	Calc	CPUE	0.1	7	MSY	None
6	4 Years	Calc	CPUE	0.3	4	MSY	None
7	Annual	0.5	CPUE	0.3	5		
8	Reference Effort Scenario 2: Scenario 1 + Annual Effort Creep						
9	Annual	Calc	CPUE	0.3	5	MSY	30%

Finally, the evaluations were conducted under two different biological scenarios, as the performance of the harvest strategies may be dependent on the level of "information" (or contrast) about the response of the stock in the time series of catch and effort data. The two biological scenarios chosen were the reference case scenario described in Chapter 5, where the steepness parameter in the stock-recruitment relationship was set to 0.9 and the depletion level at the end of the historical time period was assumed to the 30%, and the "worse-case' scenario where steepness was set to 0.4 and the depletion level to 50%. The results of these comparisons are, however, only reported for the use of the empirical decision rule.

7.3 Results

The average values for the performance indicators over the 100 simulations are presented for each harvest strategy in Figures 7.4 and 7.5. The former figure presents the three economic related performance indicators, while the latter presents the three conservation related performance indicators.

7.3.1 Empirical based results

The empirical assessments were undertaken for both the reference biological scenario and for the biological scenario where depletion at the start of the projection period was assumed to be 50% and the stock-recruitment steepness parameter was 0.4. However, as the results became unstable when applying two of the harvest strategies under the reference biological scenario (namely, #6, the CPUE regression with $\_{emp}$=0.3 and y_{emp}=7 years, and #7, that with the effort error _ = 0.5), no results are given for these two combinations. For the remaining empirical-based harvest strategies, however, the results are generally consistent in the sense that the relative difference between each strategy is similar across the two biological scenarios. As such, generally only the results based on the biological scenario with steepness 0.4 and 50% depletion will be discussed in detail below, as these can then be compared with the corresponding results for the model-based harvest strategies.

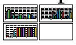
Of the three economic related performance indicators, the greatest relative change due to the application of the different harvest strategies was seen in the average of the predicted annual Australian catch (Figure 7.4). Generally, there was an inverse relationship between the average size of the catch and the size of fish caught, with smaller catches resulting in the catch of larger fish. Of the three conservation related performance indicators, the greatest relative change was seen in the probability that the spawning biomass drops below 30% of its initial value (Figure 7.5). While there were also large relative changes in the other conservation related indicators, the changes in the probability that the spawning biomass drops below 50% of its initial value showed little change under the biological scenario which assumed a 50% depletion. This indicates that once the spawning biomass drops below this level (it is assumed under this biological scenarios to reach this level at the end of the historical period) that, in most instances, it stays below this level for the entire projection period.

Relative to the corresponding performance indicators for the two reference fixed effort strategies, the averages of the predicted annual Australian catch and the predicted probability of spawning biomass dropping below 50%B_0 were reduced for all (but one) of the alternative decision-rule based harvest strategies, while the average predictions for the final relative spawning biomass were all increased. The only exception to this result was for the harvest strategy where the effort update was conducted every fourth year instead of annually. This suggests that the empirical assessments were effective in controlling declines in spawning biomass (though not without some economic cost).

The harvest strategy that was most successful in terms of reducing the probability that the

Figure 7.4 Pictorial comparison of the values of economic based performance indicators for each set of empirical and model-based harvest strategies. Note that the empirical-based harvest strategies were evaluated using both the reference biological scenario and that assuming a depletion of 0.5 and a steepness of 0.4. The bar colours have different interpretations for the empirical and model-based strategies as indicated in the legend.

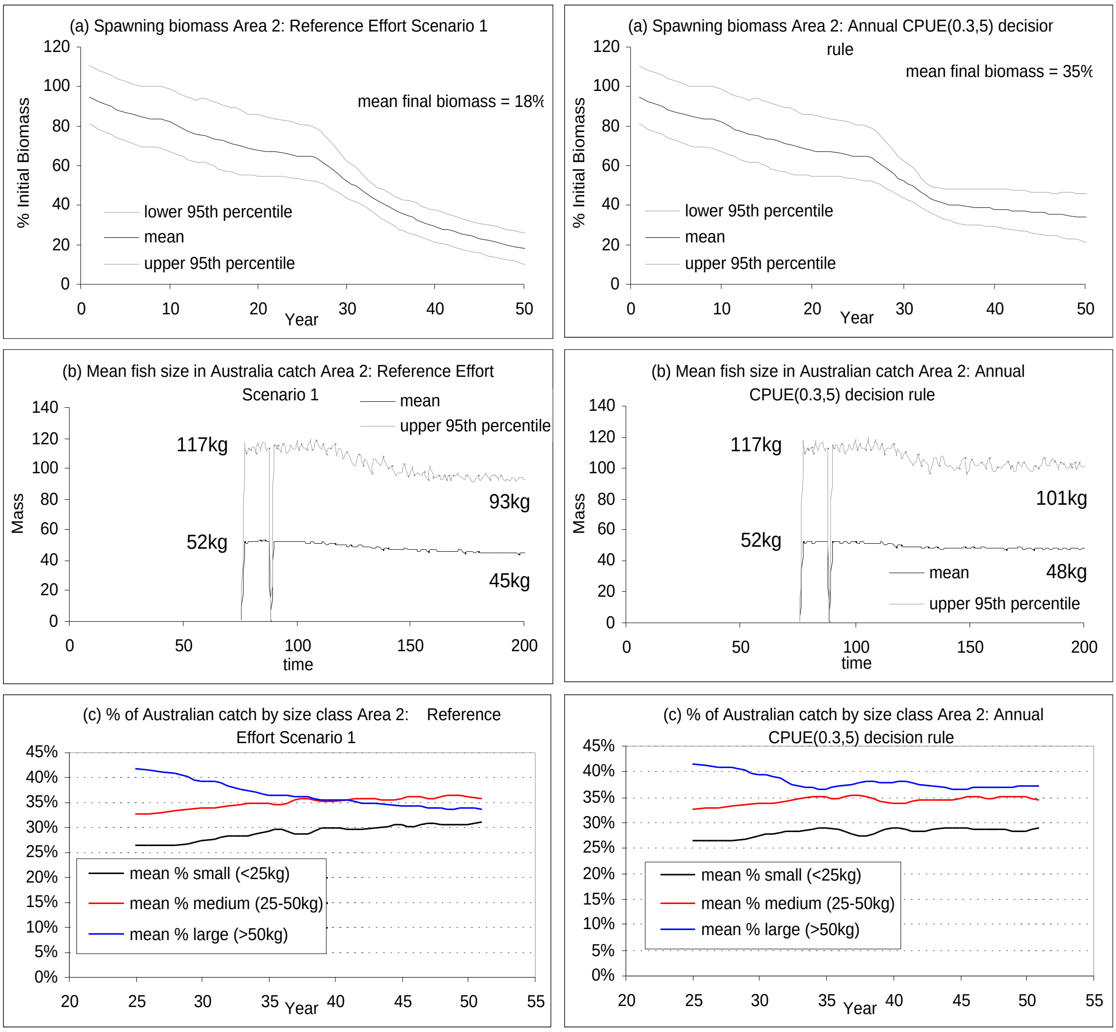
Figure 7.5 Pictorial comparison of the values of the conservation based performance indicators for each set of empirical and model-based harvest strategies. Note that the empirical-based harvest strategies were evaluated using both the reference biological scenario and that assuming a depletion of 0.5 and a steepness of 0.4. The bar colours have different interpretations for the empirical and model-based strategies as indicated in the legend.



spawning biomass fell below 30%B_o (which may be seen as a limit reference point) was that where assessments were undertaken annually using the decision rule based on CPUE regressions where $_{emp}$ = 0.3 and y_{emp}= 5 years. This reduced the associated probability from around 53% for the reference harvest strategy to 6% for this harvest strategy. There is a corresponding increase in the estimated value of the final spawning biomass at the end of the projection period from 18% to 35%. However, associated with the increased performance of the conservation objectives, the average predicted annual Australian catch is reduced from 2024t under the reference strategy to 954t.

The time series of the size of the spawning biomass within Area 2 for this strategy is compared to the reference harvest strategy in Figure 7.6a. This shows that decline in biomass continued for the first 2-4 years of the projection period before it was arrested by the application of the decision rule. This was partially due to the initial Australian *TAE* being set at 15 million hooks, which represented a substantial increase from the 2001 effort levels. However, the spawning biomass remained at a relatively stable level once the decision rule had become effective.

Figure 7.6 Time series of (a) the mean and 95th confidence limits of the spawning biomass in Area 2 (expressed as a percentage of the original biomass), (b) the mean and upper 95th percentile weight of fish caught by the Australian fleet in Area 2, and (c) the expected proportion of the Australian catch in Area 2 within various size classes. Trajectories are given for i) the reference fixed effort harvest strategy (left panel), and ii) the empirical decision rule-based (CPUE regressions where $_{emp}$ = 0.3 and y_{emp}= 5 years) harvest strategy.



Applying the same harvest strategy in the situation where the error on the effective effort time series was assumed to be greater (scenario 7) gave a similar result (*cf*. Figure 7.5). However, while the mean value remained relatively unaffected, the individual realizations showed a greater spread.

Comparison of the performance indicators based on the size of fish in the Australian catch in Area 2 (cf. Figure 7.2) indicates that mean mass and proportion of large fish in the catch were not strongly influenced by the differences in the harvest strategies. The greatest increase in final mass relative to the reference strategy was around 3kg, again achieved under the same strategy as before (where assessments were undertaken annually using the decision rule based on CPUE regressions where $\_{emp}$ = 0.3 and y_{emp}= 5 years). A comparison of the time-series trend in the mean size and proportion of large fish under both strategies is shown in Figures 7.6b&c. The maintenance of large sized fish as the dominant component of the catch is a direct benefit of this harvest strategy, and this would help to maintain a higher economic value of the catch despite the prediction of lower total catches.

Consistent with the results from previous chapters, the average upper 95th mass percentiles were more sensitive to differences between the harvest strategies. This result is also seen in a comparison of the performance of harvest strategy 2, which used catch rate as the performance statistic in the decision rule, and strategy 4, which used the upper 95th mass percentile. (Note, unlike the strategy described above, both these strategies use $\_{emp}$ = 0.1). The latter maintained a slightly higher proportion of large fish in the catch and performed better on the conservation related performance criteria. Again, these benefits came at the cost of a lower catch.

Overall, decision-rules using a feedback control factor $\_{emp}$ = 0.1 were less effective with respect to the conservation related objectives than those which used $\_{emp}$ = 0.3 (Figure 7.2). A higher value of the feedback control parameter implied greater sensitivity to changes in CPUE and thus a greater reduction in mean catch and increase in spawning biomass. However, when using a control factor of 0.1, a stronger conservation outcome was achieved when the regression was undertaken on 7 rather than on 5 years of data. A comparison of the harvest strategy which adjusted effort every 4 years, with the corresponding strategy which adjusted effort annually, (both using $\_{emp}$ = 0.3 and $y_{em\ p}$= 5 years) indicates that the former gave a significantly poorer result. Although $\_{emp}$ was set at 0.3, the results were also poorer than those where regressions were performed annually (on 5 years of data) with the $\_{emp}$ set to 0.1. Indeed, the results for this strategy were not much different than those obtained under the reference harvest strategy where no adjustment of the annual effort was undertaken.

Finally, when effort creep and foreign effort increases were allowed, the relative response to the harvest strategy based on CPUE regression with $\_{emp}$ = 0.3 was greater than when this strategy was applied to the former effort strategy with no effort creep or foreign increases (ie. strategies 3 and 9 Figure 7.2). However, although the average annual Australian catch was reduced below that obtained under this former scenario, the final spawning biomass was still reduced to a lower level (being similar to that obtained under the reference effort scenario 1).

7.3.2 Model-based results

As mentioned previously, the model-based harvest strategies were only applied under the worst-case biological scenario (ie. 50% depletion, steepness 0.4), and only four alternative harvest strategies involving a use of a decision rule were evaluated. Again, all strategies were effective in controlling declines in spawning biomass (though again not without a corresponding reduction in catch). The strategy having the strongest effect on all performance indicators was that with an annual assessment with the effort adjustment calculated using the ratio of modelled E_{msy} to current effort (Method 1) and a maximum effort adjustment of 30%. For this strategy, the average annual Australian catch was reduced from 2024t under the status quo scenario to 740t (Figure 7.4), while the relative final spawning biomass increased to 39% from 18% (Figure 7.5). In comparison with the most effective empirical-based harvest strategy, the predicted catch was lower while the final spawning biomass was higher. Comparison of the outcomes of this strategy with that where the *MSY* based decision rule was used (both allowing for a maximum adjustment of 30%), indicates the latter achieves slightly lower conservation outcomes and a corresponding higher catch.

All harvest strategies involving an annual application of the associated decision rule achieved significant reductions in the probability of the spawning biomass dropping below 30%B_o. Indeed, all these strategies achieved conservation outcomes similar to that achieved under the most effective empirical strategy. Again, the harvest strategy which involves application of the decision rule every 4 years was found to be significantly less effective than those involving application of the decision rule annually. Finally, comparison of strategies 3 and 5 (with and without the use of a maximum allowable adjustment) indicated only a minor difference between the results, although a maximum adjustment may still be preferable in order to avoid undesirably large inter-annual fluctuations in effort.

7.3.4 Evaluation of Assessments

<u>Empirical Assessments</u>

The success of the empirical-based decision rules rests upon finding an empirical-based indicator that has a linear relationship with the underlying component of the fishery one is interested in managing (such as spawning biomass). For the empirical-based decision rules investigated here, we have assumed that the slope of either the annual Australian CPUE or 95th mass percentile of the Australian catch in Area 2 has such a relationship with the underlying trend in the total spawning biomass within that area.

Figure 7.6 Scatterplots (for a single simulation) of (a) annual Australian CPUE and total spawning biomass, (b) the annual 95th mass percentile of fish in the Australian catch and spawning biomass, and (c) the annual trend in both the Australian CPUE and spawning biomass calculated at the time of each annual assessment. Finally, (d) is the same as (c) but for another simulation. Regression lines have been fitted to each scatterplot.

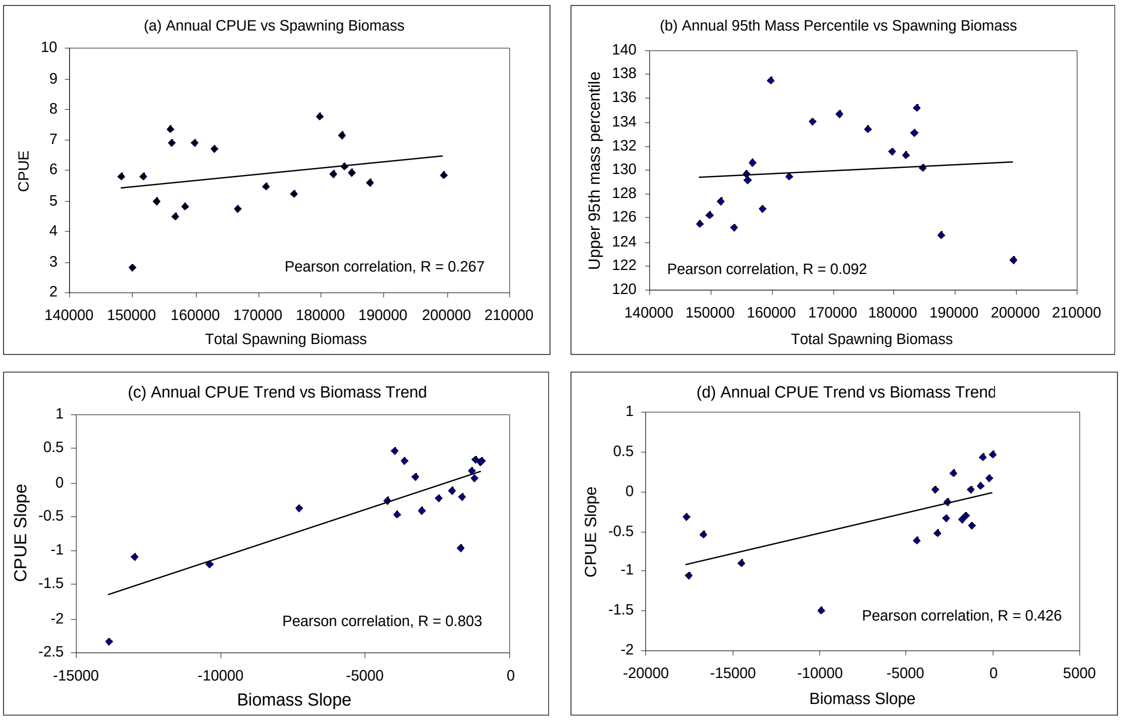
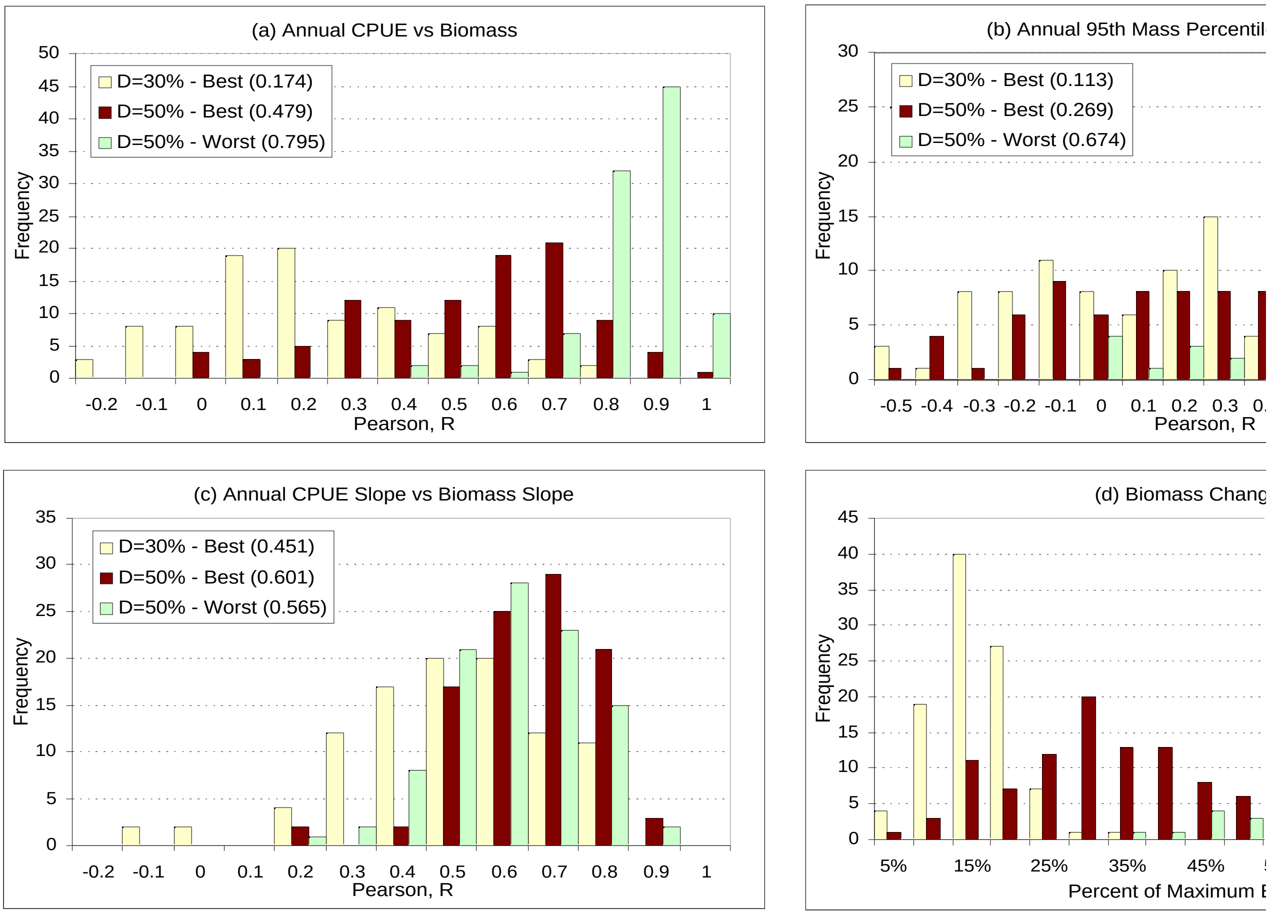


Figure 7.7 Histograms (across 100 simulations) of Pearson's R between (a) the annual Australian CPUE and spawning biomass, and (b) the annual 95th mass percentile of fish in the Australian catch and spawning biomass, and (c) the annual trends in both the Australian CPUE and spawning biomass, across all annual assessments during the projection period. Also shown is (d) the histogram of the maximum change in the spawning biomass over the projection period. (Note: D refers to assumed depletion level at the start of the projection period, and the number in parentheses is the mean value across all simulations.)



In order to investigate the nature of these relationships, we used the annual values of each indicator variable (the annual Australian CPUE and the upper 95th mass percentile) used in each annual assessment undertaken during the 20 year projection period and the corresponding spawning biomass values obtained from the operating model. Examples of these relationships for a single simulation are shown in Figure 7.6a&b. Each plot displays a scatter around the linear relationship shown by the regression line. The value of Pearson's correlation coefficient R is also shown and each case was found to be not significant, (R_{crit}(0.01)=0.561 and R_{crit}(0.05)=0.444) indicting that changes in either indicator variable are only weakly correlated with changes in the underlying biomass. Adjusting annual effort levels based on the annual change in either of these indicator variables would, therefore, not be considered optimal. The relationship between the trends in the Australian CPUE and the trend in the spawning biomass is shown in Figure 7.6c, where for each variable the trend is based on the regression of each variable over the previous 5 years (including the year of the assessment). The correlation (R=0.803) is significant at the 1% level, suggesting a stronger relationship between these two variables than between the variables used in the previous relationships. However, the correlation for the CPUE and biomass trends is not significant in the second example shown in Figure 7.6, indicating the nature of this relationship varied across each of the simulations.

To examine the nature of these relationships more fully, the value of Pearson's correlation coefficient R was calculated in a similar manner as above for all 100 simulations for the following harvest strategies and biological scenarios:

A) Decision Rule: Annual, CPUE regression with $\_{emp}$=0.3, y_{emp}=5, ("Best")

Biology - Depletion in 2001 = 30%, steepness = 0.9

B) Decision Rule: Annual, CPUE regression with $\_{emp}$=0.3, y_{emp}=5, ("Best")

Biology - Depletion in 2001 = 50%, steepness = 0.4

C) Decision Rule: Every 4th year, CPUE regression with $\_{emp}$=0.3, y_{emp}=5, ("Worst")

Biology - Depletion in 2001 = 50%, steepness = 0.4

where the qualifiers "Best" and "Worst" refer to the conservation outcomes across all harvest strategies listed in Table 7.2. Histograms of R for each harvest strategy are shown in Figure 7.7. A number of features are apparent:

- The relationship between the annual CPUE and spawning biomass is strongest for scenario C and weakest for scenario A (*cf.* Figure 7.7a). The strength of this relationship is believed to be based on the range of the biomass values over which the relationship is calculated, as when the biomass change is large there is a larger contrast in the data. For example, the largest range of biomass values occurred under the third harvest strategy while the smallest range occurred under harvest strategy (*cf.* Figure 7.7d).
- On average, the relationship between the annual values of the 95th mass percentile and the spawning biomass is weaker than that between the annual CPUE and spawning biomass. The strength of this relationship is again dependent on the contrast in the biomass over which the relationship is calculated.
- Except for scenario C, the relationship between the trends in the annual CPUE and spawning biomass is significantly stronger than either of the other relationships. The reason for the poorer result for the scenario C is due to the fact that the decision rule was applied only every 4th year so there is greater variability in the calculated slopes.

These results indicate that it is generally preferable to use a decision rule based on the trend in an indicator variable rather than the annual value of the indicator variable. In this manner we negate some of the stochastic features of the indicator variable which may not be related to the underlying feature of the fishery in which we are interested (eg. biomass). However, even for the best performing harvest strategy, the relationship between the indicator (the slope of the CPUE over 5 years) and the underlying biomass was not strong (having mean R^2 of 0.38 across the 100 simulations). Furthermore, the range in R values (between 0.16 and 0.83) also indicates that there were realizations where the correlation was quite weak, and for these realizations the performance of the decision rule may be quite poor. However, while the empirical assessments evaluated here performed well in terms of arresting declines in spawning biomass, it appears that this may have been more reflective of the use of conservative or appropriate decision rules rather than the choice of a quality indicator that directly reflects the underlying biomass trend.

<u>Production Model</u>

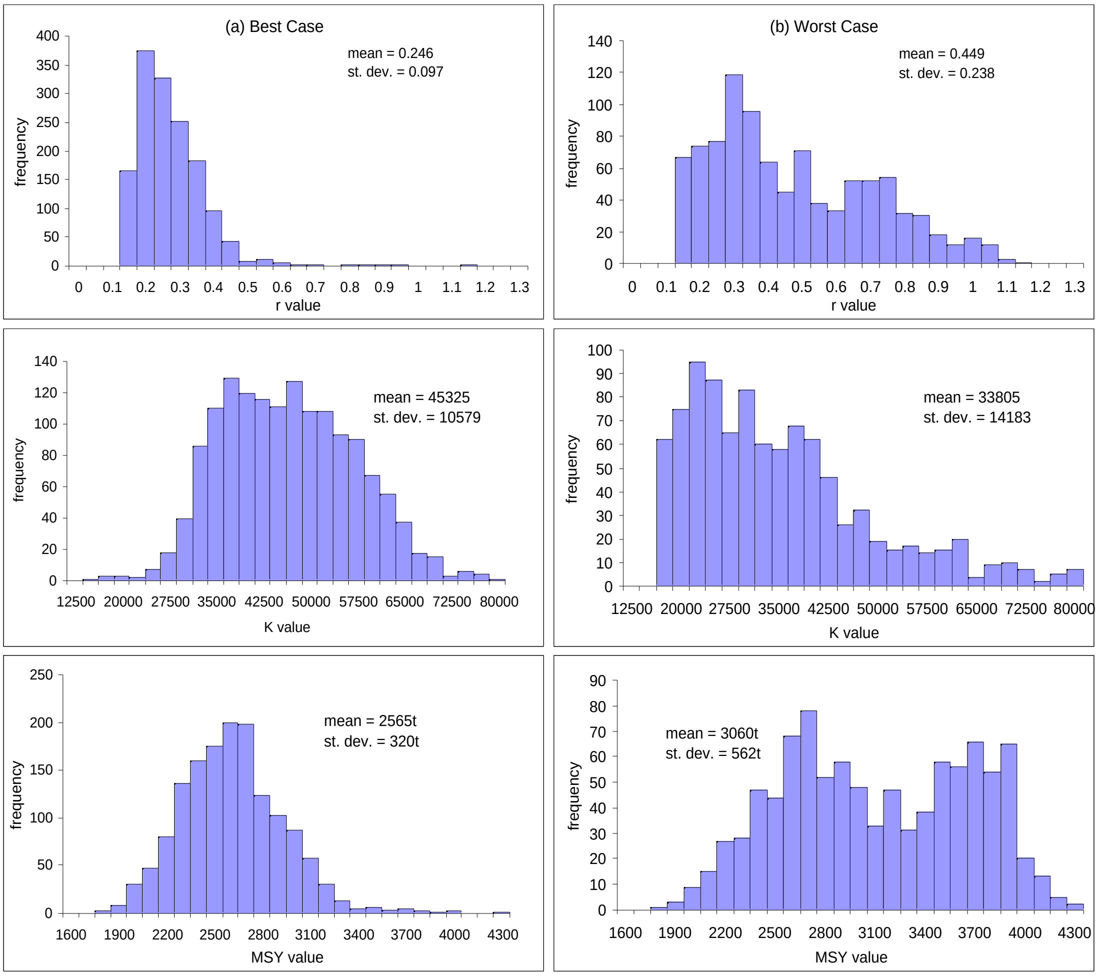
We can compare the results of the production model based assessments for the two alternative scenarios where the corresponding harvest strategy performed the best and the worst, ie:

A) "Best" Case Strategy
Reference Effort Scenario 1
Decision rule: Annual, based on E_{msy} with maximum adjustment of 30%

B) "Worst" Case Strategy
Reference Effort Scenario 2 (ie. includes effort creep)
Decision rule: Annual, based on *MSY* with no maximum adjustment

As described previously, the harvest strategy included the decision rule to not use the results of the production model if the estimated value of the intrinsic growth parameter, *r*, was less

Figure 7.8 Histograms of the values of *r*, *K* and the calculated MSY for the (a) Best and (b) Worst case Prager assessments described in the text.



than 0.05. Of the 1900 assessments conducted across the 100 simulations for each harvest strategy, the results of the production model were used 78% and 51% of the time for the "Best" and "Worst" case strategies respectively. Histograms of the values of *r*, *K* and the calculated MSY for each of these assessments are shown in Figure 7.8, together with the mean and standard deviations of these values. For each variable, the corresponding histogram shows less spread for harvest strategy A, as can be seen by the smaller standard deviations. The poorer results under harvest strategy B were most likely due to the fact that there was a bias in the effort data used in the assessments, as the effort for each fleet was not adjusted for the underlying creep in effective effort.

For harvest strategy A, the intrinsic population growth rate *r* generally ranged between 0.1 and 0.5, with a mean value of 0.246, while the carrying capacity parameter *K* generally ranged between 27,500 t and 70,000 t, with a mean value of 45,325 t. For strategy B, the intrinsic population growth rate was generally larger, having a mean value of 0.449, while the carrying capacity parameter *K* was generally smaller, having a mean value of 33,805 t.

Comparison of the biomass trajectories predicted by the production models with the known fishable biomass trajectories obtained from the operating model (Figure 7.9) shows that the production model consistently underestimated the operating model biomass by about 35-40%. This indicates that the value of *K* was, on average, underestimated by the production model assessments. This was likely due to the low contrast in the fishery data (ie, the one way trip problem) and the strong confounding between the model parameters *r* and *K* (cf. Figure 7.10). Nevertheless, the assessment biomass trajectory tracked the trend in the operating model biomass fairly well, which may explain why the assessment performed well in spite of its underestimating the biomass in an absolute sense. The exception was for those assessments where effort creep was included. As would be expected, the higher relative decline in the operating model biomass over the projection years under the additional effort load was not reflected by the assessment predictions of biomass (Figure 7.9).

The *MSY* values from harvest strategy A assessments range between 1,900 t and 3,400 t, with a mean of 2,565 t, while the corresponding range for harvest strategy B assessments were generally larger, with a larger mean of 3,060 t. These estimates of *MSY* can be compared with the estimated catches in the SW Pacific of round 4,600-5,000 t in recent years, of which the Australian catch has been between 2,500 and 3,000 t (around 62% of the total). Under each harvest strategy, the fact that the estimated *MSY* values were significantly less than the catches taken at the start of the projection period resulted in the decision rule greatly reducing the effort in future years. However, given that these results were based on the biological scenario that assumed a low steepness of 0.4 (implying significant declines in recruitment at

Figure 7.9 Mean time series (over the projection years) of modelled selected biomass from the operating model, and the biomass estimated by the production model assessments, for each of the "Best" and "Worst" case harvest strategies described in the text.

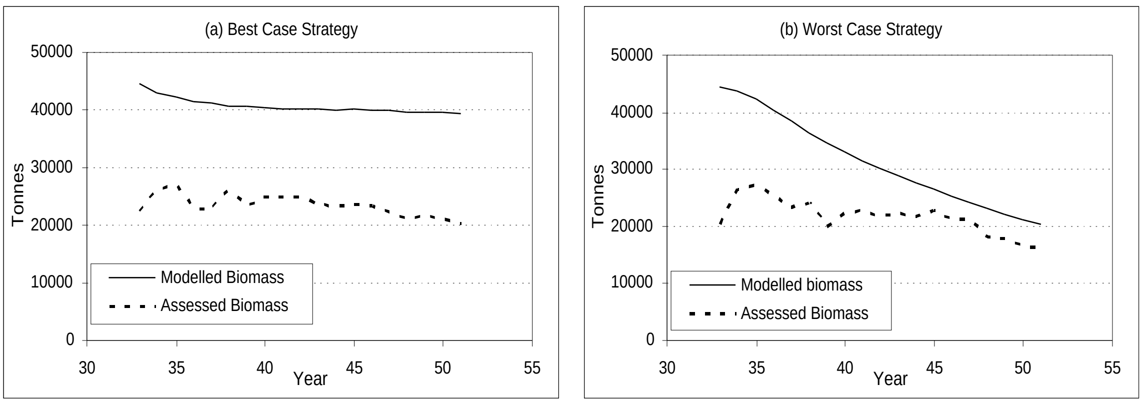
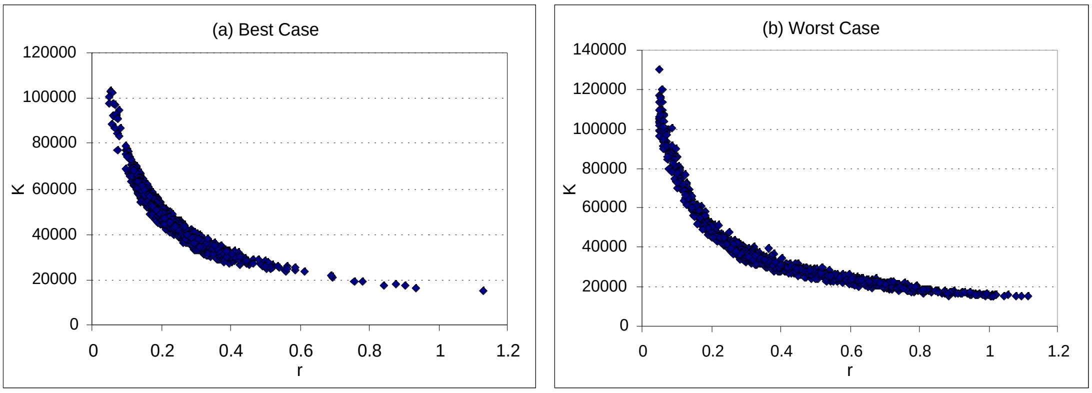


Figure 7.10 Scatterplot of the values of r and K estimated from the production models.



low biomass levels) and that the depletion at the start of this period was 50% (implying that historical catches had significantly depleted the resource), it was not surprising that the effort levels at the start of the projection period were above those corresponding to the *MSY*. Furthermore, given that it had also been assumed that there were no effort reductions for the foreign fleets, large reductions in domestic effort were required in order to arrest the declines in biomass. On the other hand, the under-estimation oft the fishable biomass was likely to imply that the estimated *MSY* values were also underestimated; with the result that the imposed effort reductions may have been too great.

For the model-based assessments, having no maximum adjustment on the decision rule could be problematic, as large inter-annual fluctuations in effort were prone to occur. For example, effort levels for a harvest strategy where there was no maximum adjustment level set indicated that approximately 80% reduction in effort occurred in the second projection year. Additionally, large inter-annual fluctuations in effort levels (resulting in a doubling or halving of effort levels) were also found to occur in subsequent years.

7.4 Discussion

Of the alternative forms of both the empirical and model-based assessments evaluated in this chapter, the results indicate that most performed reasonably well in achieving the objective of arresting the decline in the spawning biomass that would otherwise have occurred under a continuation of the effort levels set of the start of the projection period. Across both types of assessments, the results also indicate that it is more desirable to undertake assessments annually rather than every few years.

As with the fixed effort projections from the previous chapter, the results indicate a trade-off between the achievement of the conservation and economic objectives. While the assessments and decision rules were successful in conserving the stock, most did so by driving the domestic effort down over the projection time series, resulting in low catches that may not be economically viable across the entire fleet. Additionally, some of the production model assessments resulted large inter-annual fluctuations in effort. However, it must be recalled that the assumption of 50% depletion and 0.4 steepness implies a low-productivity stock that is not resilient to high levels of fishing effort. Hence it is not unexpected that large reductions in effort would be required to control the decline in biomass in such situations. The empirical assessments undertaken assuming the reference biology also resulted in large declines in average Australian catch (Figure 7.3).

While the results indicate that simple empirical and model based decision rules can be used to halt continued declines in biomass, the apparent success of these strategies may have been influenced by the measure of effective effort used in each of the assessments. In particular, the effort used in these assessments was that calculated using the fishing mortality and catchability curves determined by the operating model under a given biology. In practice, however, it is likely that both the biology and changes in the effectiveness of fishing effort will remain somewhat uncertain with the consequence that the effort would probably not be able to be standardised to the same level as was achieved here. Furthermore, as the above results indicate, unless trends in effective effort can be adequately accounted for, a temporal bias is likely to enter into the assessment results. Further work may be warranted to more fully assess the consequences of imperfect effort data on the performance of each of the above decision rules.

The results presented here provide a preliminary evaluation of possible feedback harvest strategies which could be utilized in the ETBF. As such, they form the basis for future consideration of appropriate assessment models, performance indicators and decision rules which should be considered for adjusting the annual TAE. In the absence of a single and reliable stock assessment model, a combination of a suite of empirical indicators together with consideration of an age-structured production model is recommended. As a more formal stock assessment model is developed for broadbill swordfish, it may readily be incorporated into the current model framework.

Chapter 8: Estimating Equilibrium Yields for Yellowfin and Bigeye Tuna within Regions of the Pacific Ocean

8.1 Introduction

As explained in Chapter 1, due to the relatively small size of the bigeye catch in the ETBF and the likelihood of a single Pacific-wide stock for this species, the MSE approach was not seen as appropriate for the evaluation of harvest strategies for bigeye tuna in the ETBF. This is because there are unlikely to be any harvest strategies that are robust to the uncertainties in stock structure. Nevertheless, the catch of bigeye tuna remains an important component of the ETBF and sustainable catch limits for this species (along with others) needs to be taken into consideration in determining the overall management strategy to be adopted in the ETBF. A workshop was held in December 2002 for the purpose of making recommendations to the AFMA Board on a suite of risk weighted options for an initial *TAE* for the longline sector of the ETBF. These recommendations took into account a variety of issues, including current stock status, by-catch issues and the potential for further industry development of the ETBF (including the high seas). Crucial to this process, however, was the need to estimate potential sustainable yields in the region fished by the ETBF. While some estimates of stock-wide equilibrium yields were available based on recent stock assessments, no such estimates existed for individual sub-regions across the Pacific Ocean. This chapter outlines an approach for estimation of equilibrium yields within different regions of the Pacific Ocean under the assumption that the current selectivity patterns in the fishery remain unchanged.

8.2 Outline of Methodology

1. Catch-per-unit-effort (CPUE) in any region is often assumed to give an index of available biomass density in that region. In the approach described here, the distribution of Japanese longline CPUE for a given species within each 5x5-degree square of latitude and longitude is assumed to reflect the spatial distribution of the biomass density of that species available to longliners across the Pacific Ocean. The 5x5-degree squares fished by Japanese longliners between 1962-2000 are shown in Figure 8.1, while the distribution of mean annual Japanese longline effort within each square for this period is shown in Figure 8.2. (Note: squares where less than 10,000 hooks were deployed in any year were excluded from the analysis). In total, information was available for 508 5x5-degree squares. The corresponding distributions of nominal CPUE for yellowfin tuna and bigeye tuna are shown in Figures 8.3 and 8.4. Again, these distributions are based on the mean of the annual CPUE for Japanese longline vessels within each square for the years 1962-2000.

2. For a given species, the sum of the mean CPUE within each 5x5-degree square across the entire Pacific Ocean is taken as an index of the total biomass of that species.

$$\textit{Biomass Index(Pacific Ocean)} = B_{PO} = \sum_{i=1}^{N_{tot}} CPUE_i \qquad (8.1a)$$

   where $CPUE_i$ is the mean annual catch rate within the *i-th* 5x5-square (based on the data described above) and N_{tot} is the total number of squares fished by the Japanese longline fleet within the Pacific Ocean.

3. In equation 8.1a, CPUE in each square is interpreted as an index of density (biomass per unit area), so a simple summation over all squares assumes that each 5x5-degree square has the same size (as the biomass density in each square contributes equally to the total). Two corrections were made to this assumption:

Figure 8.1 Spatial distribution of regions (5x5-degree squares of latitude and longitude) fished by Japanese longliners between 1962-2000.

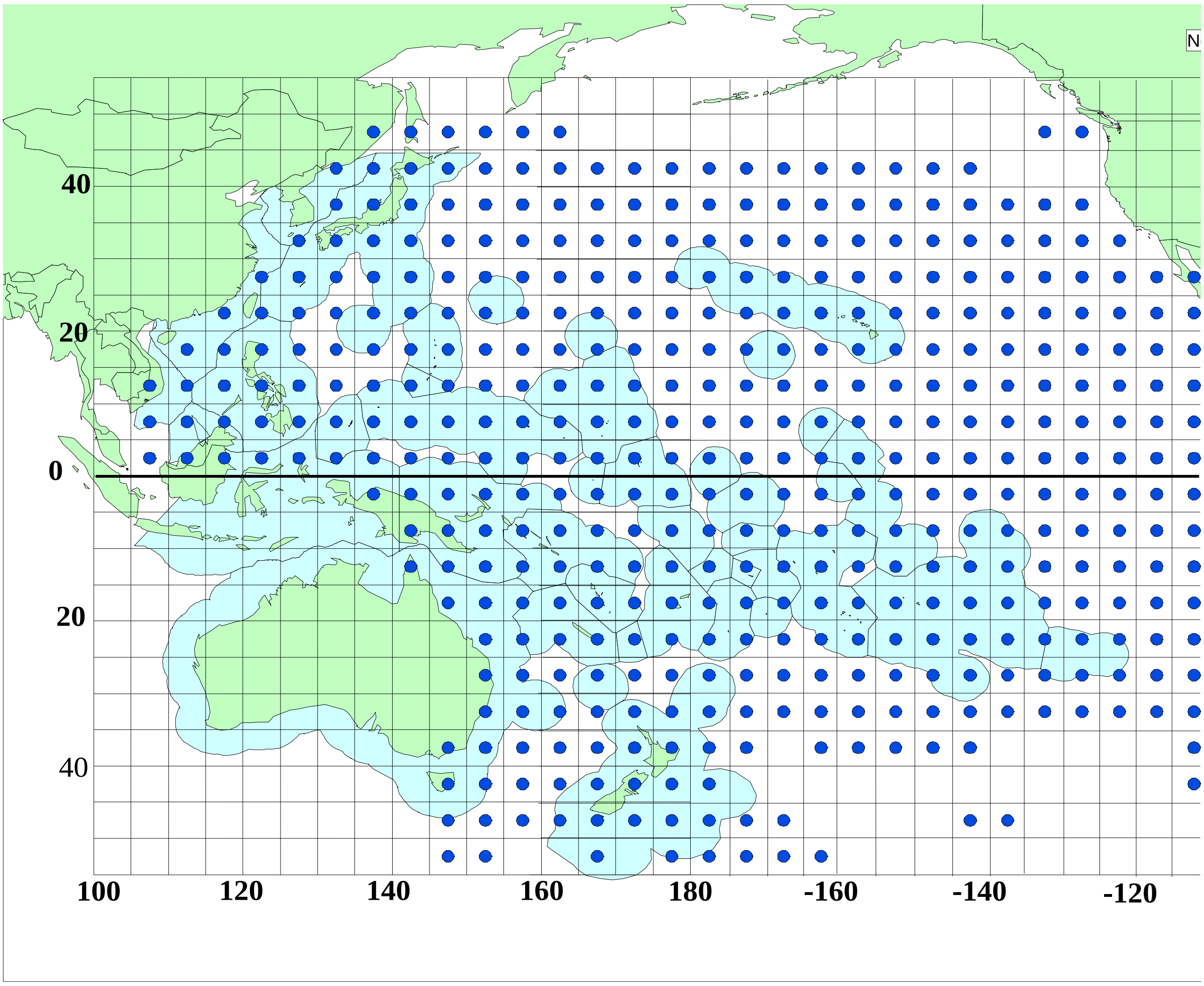


Figure 8.2 Mean distribution of annual Japanese longline effort (number of hooks) within each 5x5-degree square of latitude and longitude for the years 1962-2000.

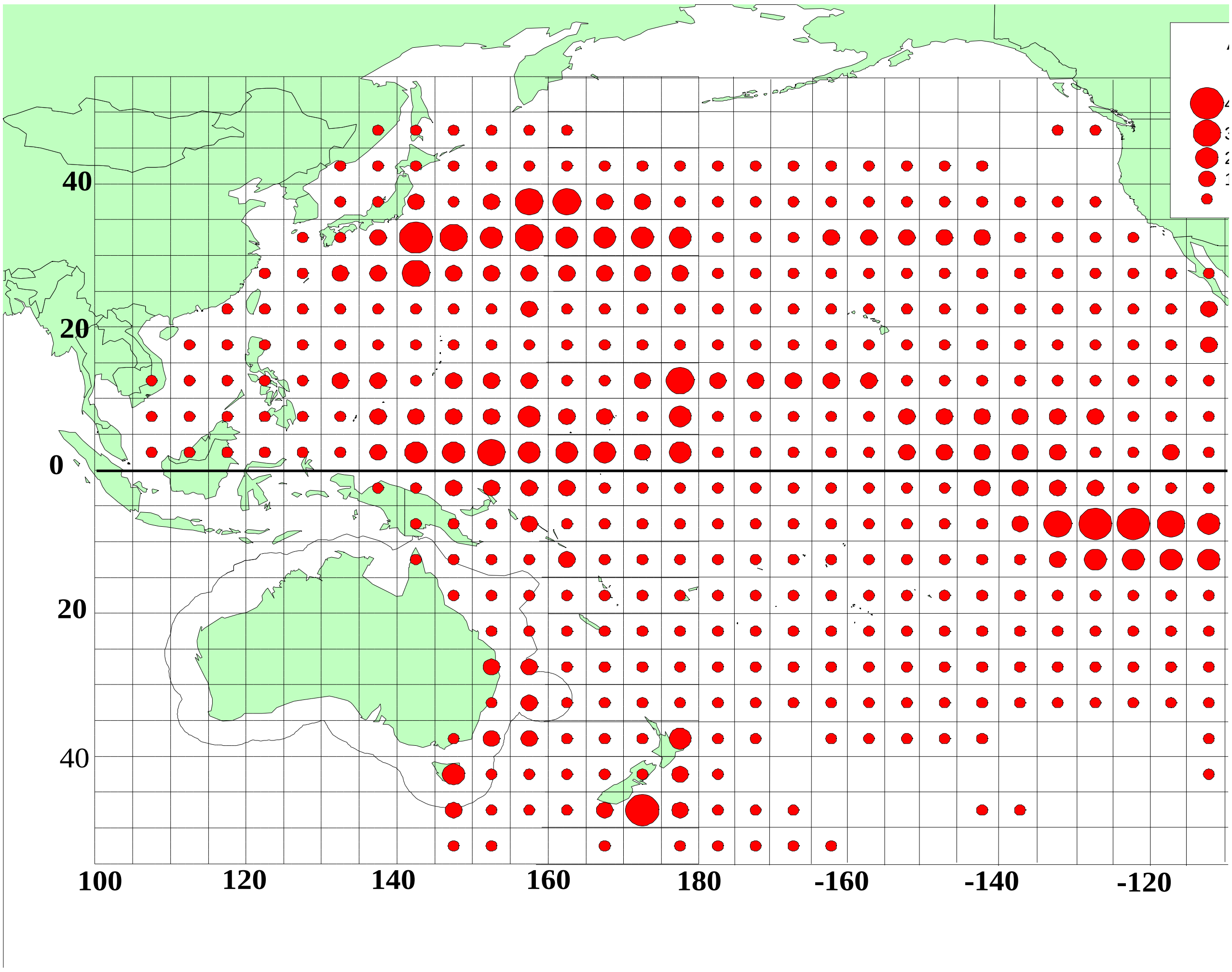


Figure 8.3 Mean distribution of annual nominal yellowfin CPUE within each 5x5-degree square of latitude and longitude for Japanese longliners for the years 1962-2000.

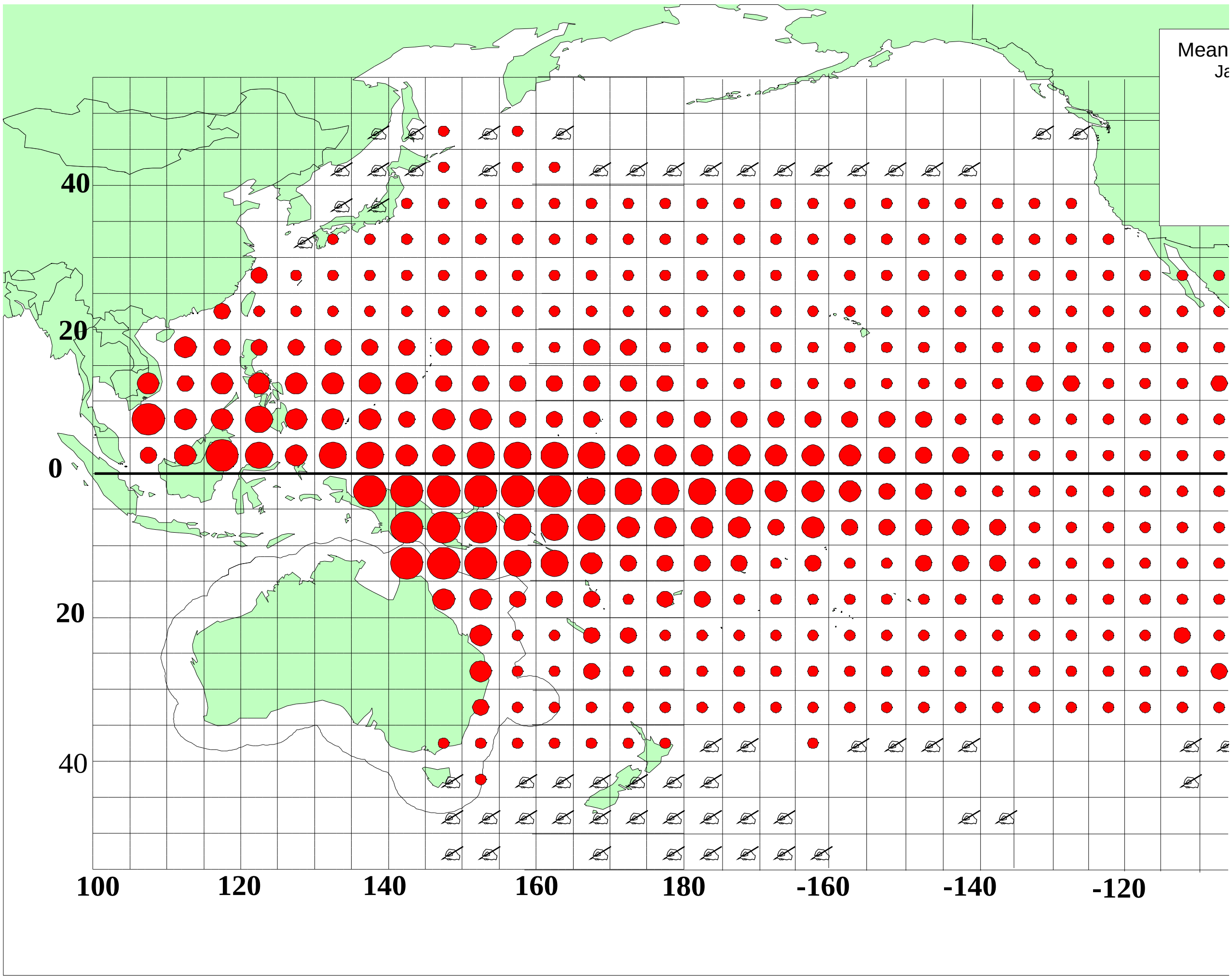


Figure 8.4 Mean distribution of annual nominal bigeye CPUE within each 5x5-degree square of latitude and longitude for Japanese longliners for the years 1962-2000.

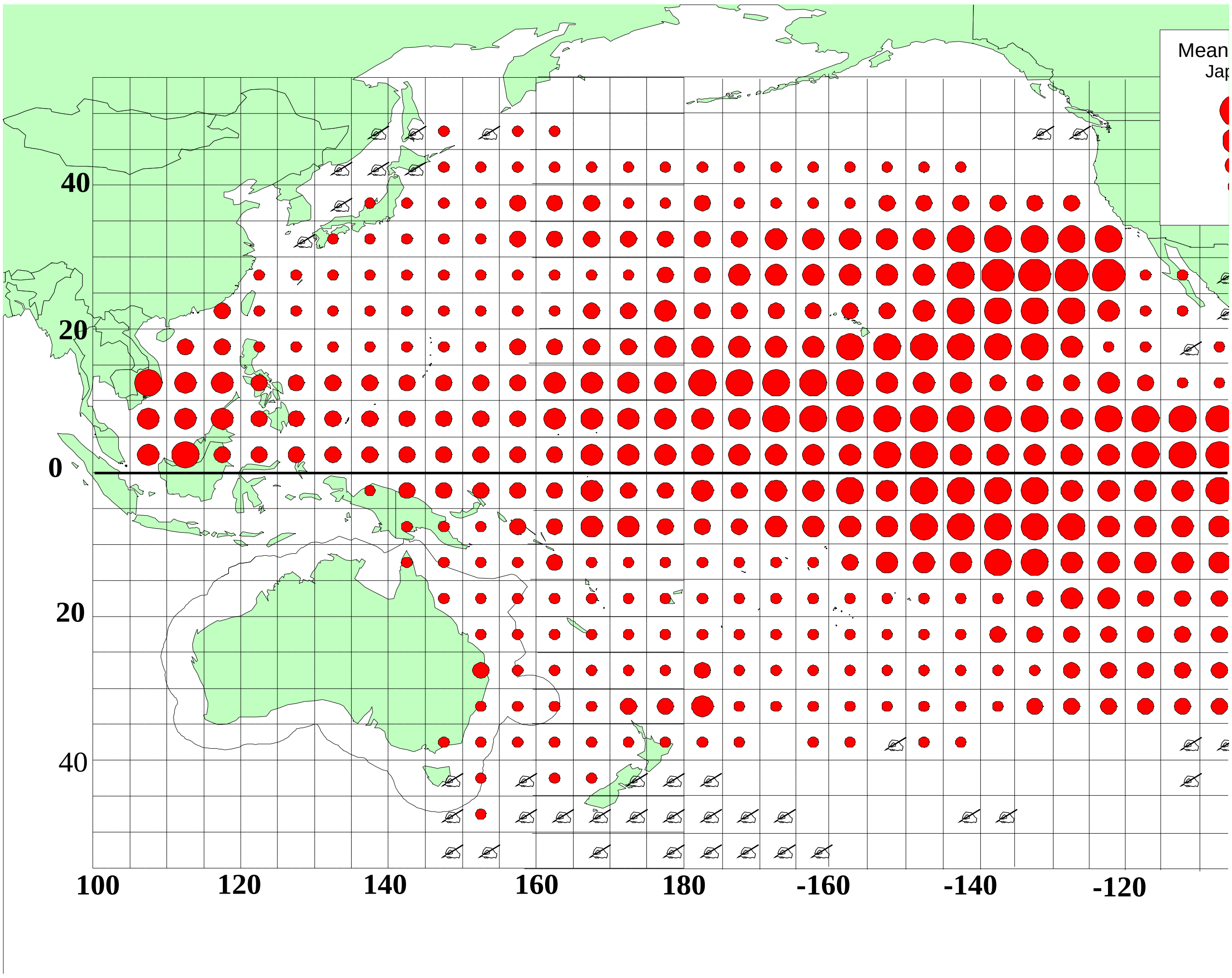
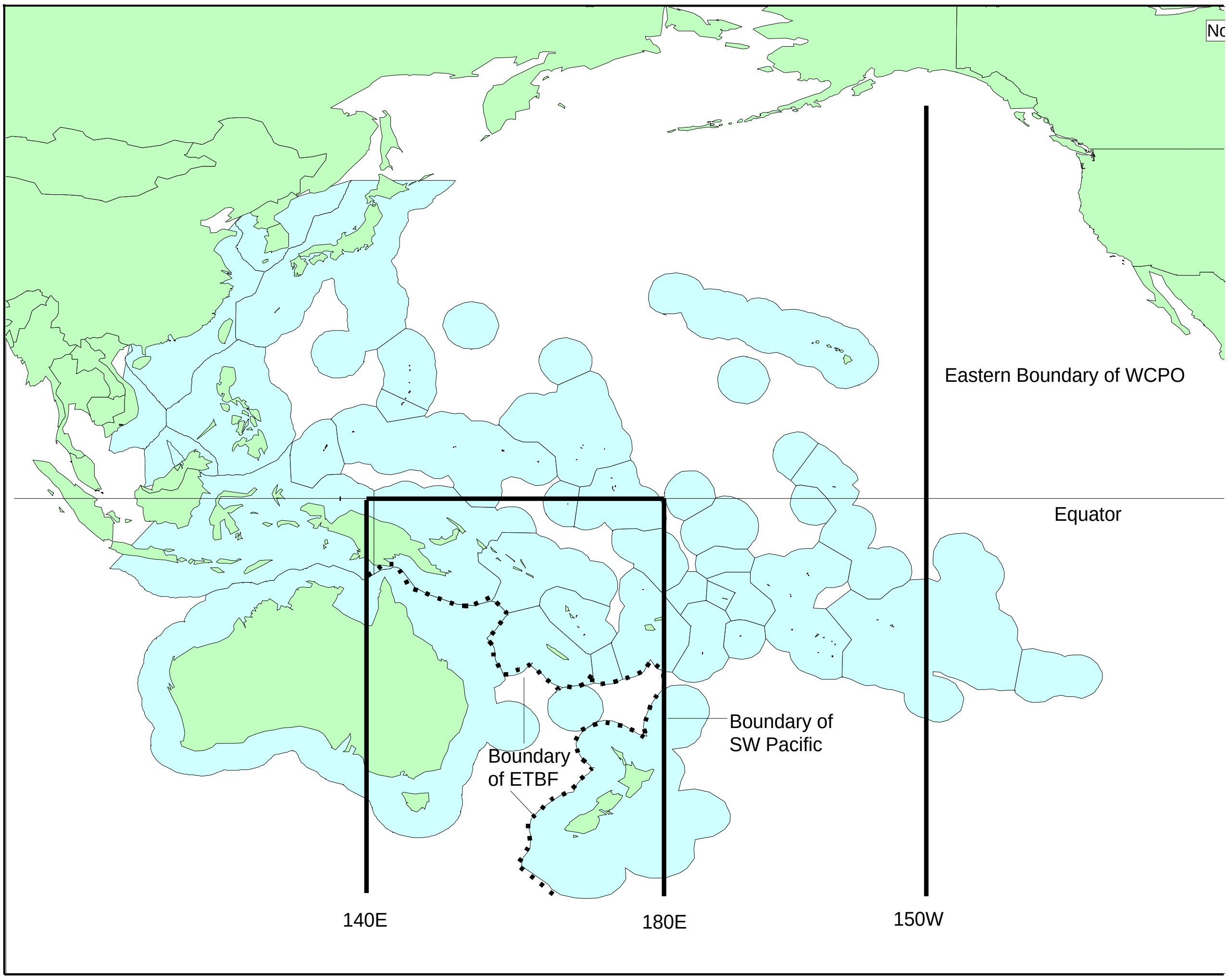


Figure 8.5 Boundaries of the various regions of the Pacific Ocean used in the analyses.



- Correction for land content. From the grid of 5x5-degree squares shown in the accompanying maps, it can be seen that many squares where data are indicated also include land. In order to account for the land content, each square was given an index, F_{land}, indicating the fraction of that square which was land. (Note, the land content of each square was estimated visually).
- Correction for curvature of earth. Due the curvature of the earth, the distance subtended by each degree of longitude decreases as one moves from the equator to the poles. For example, at the equator one minute of longitude subtends a length of 1 nautical mile but this length decreases to zero at the poles. Due to this change, the size of each 5x5-degree square at a given latitude relative to a 5x5-degree square at the equator is given by *cos(latitude)*. Hence, in order to account for the different size of 5x5-degree squares, each square was assigned an index, $Area_i$, equal to the cosine of the average latitude. This factor is important in the current context due to the large latitudinal range of the fishery.

With these additions, the equation used to calculate the biomass index across the Pacific Ocean is given by the following:

$$\textit{Biomass Index(Pacific Ocean)} = B_{PO} = \sum_{i=1}^{N_{tot}} Area_i (1 - F_{land\,i}) CPUE_i \tag{8.1b}$$

4. In order to obtain an index of biomass for any specific region of the Pacific Ocean, the sum of the mean CPUEs within each 5x5-degree square across this region is calculated as before.

$$\textit{Biomass Index(Specific Region)} = B_{Region} = \sum_{i=1}^{N_{Region}} Area_i (1 - F_{land\,i}) CPUE_i \tag{8.2a}$$

where N_{Region} is the number of squares fished by the Japanese longline fleet in the specified region. The proportion of the total biomass in the Pacific Ocean which, on average, occurs within the specified region is then calculated:

$$\textit{Proportion(Specified Region)} = P_{Region} = \frac{B_{Region}}{B_{PO}} \tag{8.2b}$$

5. Finally, in order to obtain an index of biomass in the eastern AFZ and the adjacent international waters off eastern Australia, the sum of the mean CPUEs within each 5x5-degree square across this region (known hence forth as the *ETBF*) was also calculated.

$$\textit{Biomass Index(ETBF)} = B_{ETBF} = \sum_{i=1}^{N_{ETBF}} Area_i F_{ETBF\,i} CPUE_i \tag{8.3a}$$

where N_{ETBF} is the number of squares fished by the Japanese longline fleet in this region and F_{ETBF} indicates the fraction of each square which lies within this region. The proportion of the total biomass in the Pacific Ocean which, on average, occurs within the *ETBF* can then be calculated:

$$Proportion(ETBF) = P_{ETBF} = \frac{B_{ETBF}}{B_{PO}} \tag{8.3b}$$

6. Given a total (sustainable) catch for the Pacific Ocean, C_{PO}, an estimate of the (sustainable) catch (or total yield) for each of the two regions mentioned above can be estimated as follows:

$$Total\_Yield(Specified\ Region) = C_{PO}P_{Region} = C_{PO}\frac{B_{Region}}{B_{PO}} \tag{8.4a}$$

$$Total\_Yield(ETBF) = C_{PO}P_{ETBF} = C_{PO}\frac{B_{ETBF}}{B_{PO}} \tag{8.4b}$$

7. As all the above calculations are based on longline CPUE, which reflect that component of the resource available to longline gear, the resulting biomass indices and estimates of total yield relate only to the longline component of the total catch only.

8.3 Selected Regions

Several regions of the Pacific Ocean were selected for the following analyses. These regions were the following:

1. The whole Pacific Ocean - defined as that region covered by the 508 five-degree squares shown in Figure 8.1.
2. The western and central Pacific Ocean (WCPO) - defined as the region of the Pacific Ocean west of 150°W.
3. The south west Pacific Ocean - defined as the region of the Pacific Ocean south of the equator and west of 180°E.
4. The eastern AFZ and the international waters off eastern Australia with the southern boundary at 48°S (known as the ETBF).

The boundaries of these various regions are shown in Figure 8.5.

8.4 Illustrative Results for Yellowfin Tuna

For the purposes of illustrating the above approach, some results are presented here for yellowfin tuna in the Pacific Ocean.

The distribution of mean annual Japanese yellowfin CPUE across the Pacific Ocean for the years 1962-2000 is shown in Figure 8.3. Based on these average CPUE values, the total biomass index of yellowfin tuna available to longline gears across the Pacific Ocean (as described by equation 8.1a) is found to be 2,035 units. The respective biomass indices for each of the other three regions (*cf.* equations 8.2a and 8.3b) of the Pacific Ocean are given in Table 8.1. The proportion of the biomass of yellowfin tuna in each region, as represented by the biomass index, is also indicated. These results indicate that around 74 percent of the yellowfin tuna available to longline gears across the Pacific are found in the WCPO, with around 24 percent occurring in the SW Pacific and just under 5 percent in the ETBF zone. Of the resource in the SW Pacific alone, around 19 percent occurs within the ETBF.

Table 8.1 Biomass indices of yellowfin tuna available to longline gears, and proportions, within various regions of the Pacific Ocean.

Region	Longline Biomass Index	Proportion of Pacific Ocean	Proportion of WCPO	Proportion of SW Pacific
Pacific Ocean	2,035.0	100.0%		
WCPO	1505.9	74.0%	100.0%	
SW Pacific	4,90.3	24.1%	32.6%	100.0%
ETBF	91.1	4.5%	6.0%	18.6%

The sustainable catch levels across any of these regions presently remain unknown. However, the most recent stock assessment for yellowfin tuna in the WCPO indicate that the maximum equilibrium yield (equivalent to MSY) for yellowfin tuna may be around 370,000 tonnes (Hampton, 2002a). For the Eastern Pacific Ocean (EPO), the most recent assessments indicate a maximum equilibrium yield of around 276,000 tonnes (Maunder, 2002). These yield estimates are premised on the age-specific selectivities and related fishing mortalities remaining similar to those observed in recent years and on the recruitment levels remaining similar to those observed over the assessment period. In order to satisfy the first of these conditions, in the following analyses we assume that the proportion of the total catch taken by the various gears will remain similar to that in recent years. These proportions are shown in Table 8.2. Hence, if one assumes a total Pacific-wide equilibrium yield of 646,000 tonnes, the corresponding longline component will be around 67,184 tonnes. Alternatively, for a total equilibrium yield of 370,000 tonnes in the WCPO, the corresponding catch component for longline gears will be around 54,390 t.

Table 8.2 Mean annual total catch of yellowfin tuna (1998-2001) in the Pacific Ocean and WCPO and the proportion of that catch taken by the main fishing gears.

Region	Catch	Longline	Pole-Line	Purse Seine	Other
WCPO	464,371	14.6%	3.5%	49.1%	32.7%
EPO	321,222	4.2%	1.0%	94.6%	0.2%
Pacific Ocean	785,592	10.4%	2.5%	67.7%	19.4%

Given these yield estimates, and assuming distributions of yellowfin tuna biomass available to longline gear as given in Table 8.1, one can use equations 8.4a and 8.4b to estimate yields in the various regions of the Pacific Ocean. The results are given in Table 8.3. Finally, we can compare these regional longline yield estimates with the catches taken by longline gears in each region in recent years (Campbell 2002). For this purpose the average annual longline catch in each region was calculated over the years 1998-2001. These average catch levels are also shown in Table 8.3, together with the difference between the estimated yield and current catch in each region.

Table 8.3 Equilibrium yield estimates for longline caught yellowfin tuna across various regions of the Pacific Ocean. Also shown are the mean annual longline catches of yellowfin tuna in each of the regions (averaged over the years 1998-2001) together with the estimated surplus yield (= estimated yield - current annual catch).

Fished Region	Annual Catch (98-01)	Pacific Ocean Stock		WCPO Stock	
		Est. Yield	Surplus	Est. Yield	Surplus
Pacific Ocean	81,708	67,184	-14,524		
WCPO	68,125	49,716	-18,409	54,390	-13,735
SW Pacific	9,815	16,186	6,371	17,708	7,893
ETBF	2,905	3,007	102	3,290	385

For the scenario of a single stock across the entire Pacific Ocean, these results indicate that recent catches (of around 81,500 t) have been above the equilibrium yield estimate of around 67,200 t. Similarly, recent catches in the WCPO sub-region (~68,000 t) have also been above the equilibrium yield estimated for this region (~50,000 t). However, catches in the SW Pacific sub-region (9,815 t) have been about 40 percent below the estimated equilibrium yield (16,186 t) while recent catches in the ETBF sub-region are about 4 percent below the estimated equilibrium yield.

These results, and the inferences drawn from them, are, however, based on the assumption of a single stock of yellowfin tuna across the entire Pacific Ocean, necessitating a single yield estimate. However, tagging and genetic based studies have indicated the possibility that the yellowfin tuna found in the eastern Pacific Ocean and the WCPO are separate stocks. As such, it may be probably more realistic to consider the yield estimates for the stock in the WCPO alone. In this case, recent catches in the WCPO are again above the equilibrium yield estimate, but recent catches in the SW Pacific and ETBF are significantly below the estimated equilibrium yield levels for these regions (by 45 percent and 12 percent respectively).

The above results indicate the possibility for further increases in the catch of yellowfin tuna by longline gears in the SW Pacific and ETBF regions, though the increase in catch in the ETBF is estimated to be relatively small (between 100 and 400 tonnes). However, if a single stock of yellowfin tuna exists throughout the WCPO, then increasing the catches in these regions should be done in a manner which is commensurate with the total catch in the WCPO not exceeding the maximum equilibrium yield for the entire stock. As such, increases in the SW Pacific region need to coincide with decreased catch levels outside this region.

8.5 Alternative Estimates

A number of assumptions underlie the above calculations. Violation of these assumptions in reality, together with uncertainties in the catch data used, will create corresponding uncertainties in the yield estimates in each of the regions as calculated above. Central to the assumptions used are those pertaining to the distribution of the available yellowfin tuna biomass across the Pacific Ocean and the assumed equilibrium yields in the two regions corresponding to the two stock assumptions used (ie. Pacific wide and WCPO). In this section we provide some alternatives to both and discuss their implications.

A. Stock distribution

The stock distribution used in the previous section was based on the distribution of Japanese longline CPUE for the years 1962-2000. This long period was used as it was assumed that it would give a meaningful average distribution over all years. However, in any fishery the resultant catch rates of any particular species are usually dependent of the targeting practices and gear settings used. The calculation of the distribution of yellowfin tuna CPUE used above therefore assumes that there were not significant changes in either targeting or gear setting practices by Japanese longline vessels over the entire period. However, we know this not to be true. Up until the mid-1970s, Japanese vessels generally deployed longline gears with around 5 hooks-between-buoys (known as shallow longlining) and generally targeted yellowfin tuna. After the mid-1970s, many Japanese vessels started deploying deeper longline gear (having 10 or more hooks-between-buoys) in an effort to increase to the targeting of bigeye tuna. These changes are likely to have an influence on the catch rates of yellowfin tuna obtained and the resulting distribution of these catch rates. In order to understand the impact of these changes on the results of the previous section, the calculation of potential yields in each region were repeated using the inferred yellowfin distributions based on data the following two periods: i) 1962-1975 and ii) 1986-2000. The results of these calculations are given in Table 8.4 and illustrated for some cases in Figures 8.6a and 8.6b. Note: due the different data set used in each period, the spatial coverage of 5x5-degree squares across the Pacific Ocean was found to be different for each period. The spatial coverage for each of the periods 1962-1975 and 1986-2000 was 487 and 426 squares respectively and are shown in Figures 8.7 and 8.8. These can be compared with the coverage shown in Figure 8.1 for the entire period 1962-2000.

B. Uncertainties in Equilibrium Yield Estimates

The stock assessments for yellowfin tuna in the WCPO and the EPO, and the equilibrium yield estimates inferred from these assessments, both contain a number of assumptions. These assumptions are outlined in Hampton (2002a) and Maunder (2002) and will not be repeated here. However, the estimates of equilibrium yield were found by both authors to be sensitive

Table 8.4. Results of yield analyses for yellowfin tuna across several regions of the Pacific Ocean.

		Lower Yield Estimate				Yield Estimate			
	Assumed Stock Area	***Pacific***	***WCPO***	***SWP***	***ETBF***	***Pacific***	***WCPO***	***SWP***	***E***
	Estimated Total Equilibrium Yield	586,000	310,000			646,000	370,000		
	% Longline catch (98-01)	10.4%	14.7%			10.4%	14.7%		
	Estimated LL Equilibrium Yield	60,944	45,570	15,107	3,123	67,184	54,390	17,351	
	Mean Australian LL catch (98-01)	2,233	2,233	2,233	2,233	2,233	2,233	2,233	
	Mean non-Australian LL catch (98-01)	79,475	65,892	7,582	672	79,475	65,892	7,582	
	Mean Total LL Catch (98-01)	81,708	68,125	9,815	2,905	81,708	68,125	9,815	
Data: 1962 - 2000	Est. Equilibrium LL Yield : Pacific	60,944				67,184			
	Est. Equilibrium LL Yield : WCPO	45,098	45,570			49,716	54,390		
	Est. Equilibrium LL Yield : SW Pacific	14,683	14,836	14,759		16,186	17,708	16,947	
	Est. Equilibrium LL Yield : ETBF	2,728	2,756	2,742	3,123	3,007	3,290	3,148	
	Est. Yield - Current Catch: Pacific	-20,764				-14,524			
	Est. Yield - Current Catch: WCPO	-23,027	-22,555			-18,409	-13,735		
	Est. Yield - Current Catch: SW Pacific	4,868	5,021	4,944		6,371	7,893	7,132	
	Est. Yield - Current Catch: ETBF Area	-177	-149	-163	218	102	385	243	
Data: 1962 - 1975	Est. Equilibrium LL Yield : Pacific	60,944				67,184			
	Est. Equilibrium LL Yield : WCPO	42,654	45,570			47,021	54,390		
	Est. Equilibrium LL Yield : SW Pacific	13,354	14,267	13,811		14,722	17,029	15,875	
	Est. Equilibrium LL Yield : ETBF	2,340	2,500	2,420	3,123	2,579	2,983	2,781	
	Est. Yield - Current Catch: Pacific	-20,764				-14,524			
	Est. Yield - Current Catch: WCPO	-25,471	-22,555			-21,104	-13,735		
	Est. Yield - Current Catch: SW Pacific	3,539	4,452	3,996		4,907	7,214	6,060	
	Est. Yield - Current Catch: ETBF Area	-565	-405	-485	218	-326	78	-124	
Data: 1986 - 2000	Est. Equilibrium LL Yield : Pacific	60,944				67,184			
	Est. Equilibrium LL Yield : WCPO	45,058	45,570			49,671	54,390		
	Est. Equilibrium LL Yield : SW Pacific	16,655	16,844	16,749		18,360	20,104	19,232	
	Est. Equilibrium LL Yield : ETBF	4,183	4,231	4,207	3,123	4,612	5,050	4,831	
	Est. Yield - Current Catch: Pacific	-20,764				-14,524			
	Est. Yield - Current Catch: WCPO	-23,067	-22,555			-18,454	-13,735		
	Est. Yield - Current Catch: SW Pacific	6,840	7,029	6,934		8,545	10,289	9,417	
	Est. Yield - Current Catch: ETBF Area	1,278	1,326	1,302	218	1,707	2,145	1,926	

Figure 8.6a. Surplus yield estimates (ie. MEY - current catches) for longline caught yellowfin tuna based on a WCPO stock scenario.

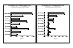


Figure 8.6b Surplus yield estimates (ie. MEY - current catches) for longline caught yellowfin tuna based on a Pacific-wide stock scenario.

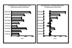


Figure 8.7 Spatial distribution of regions (5x5-degree squares of latitude and longitude) fished by Japanese longliners between 1962-1975.

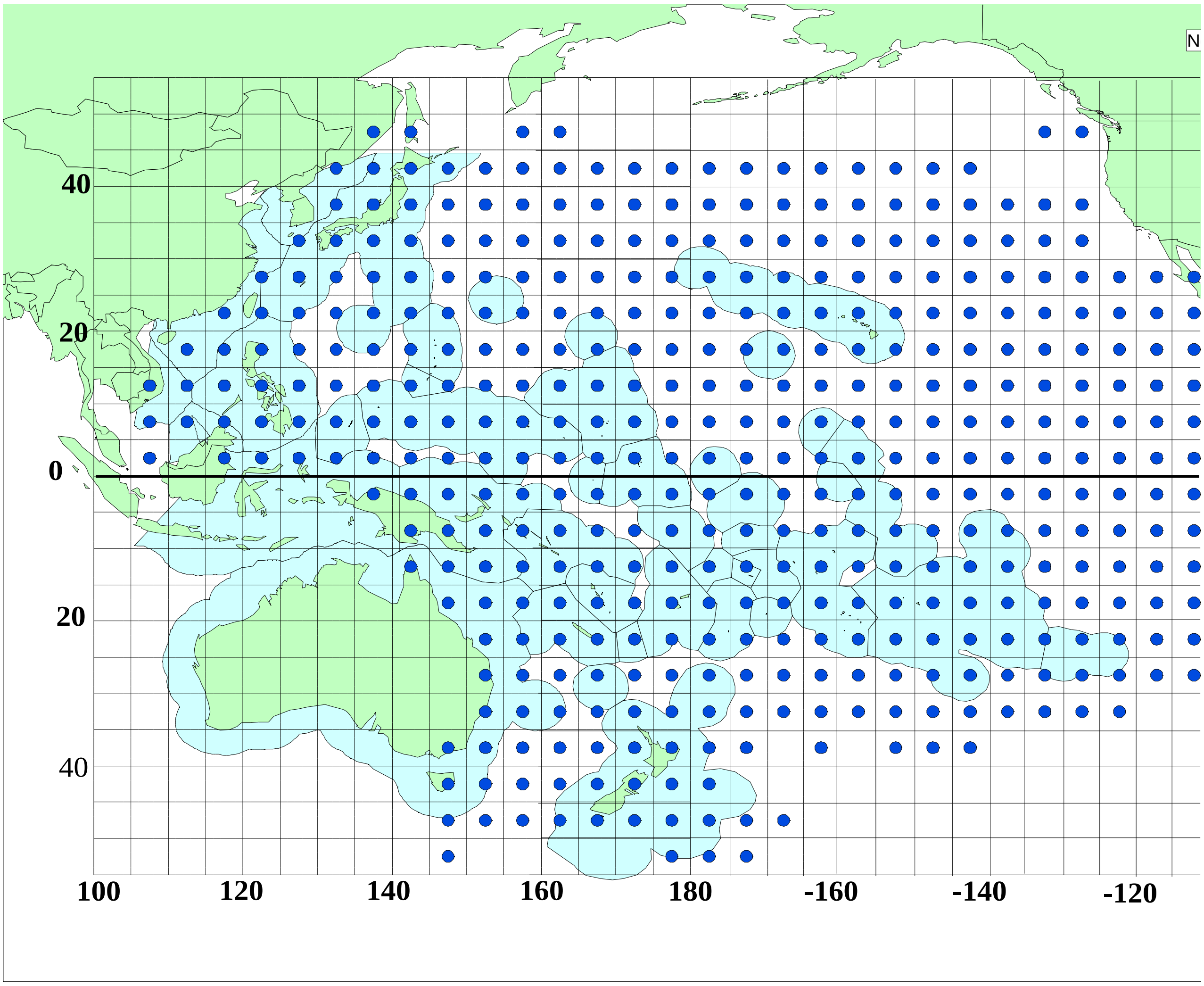
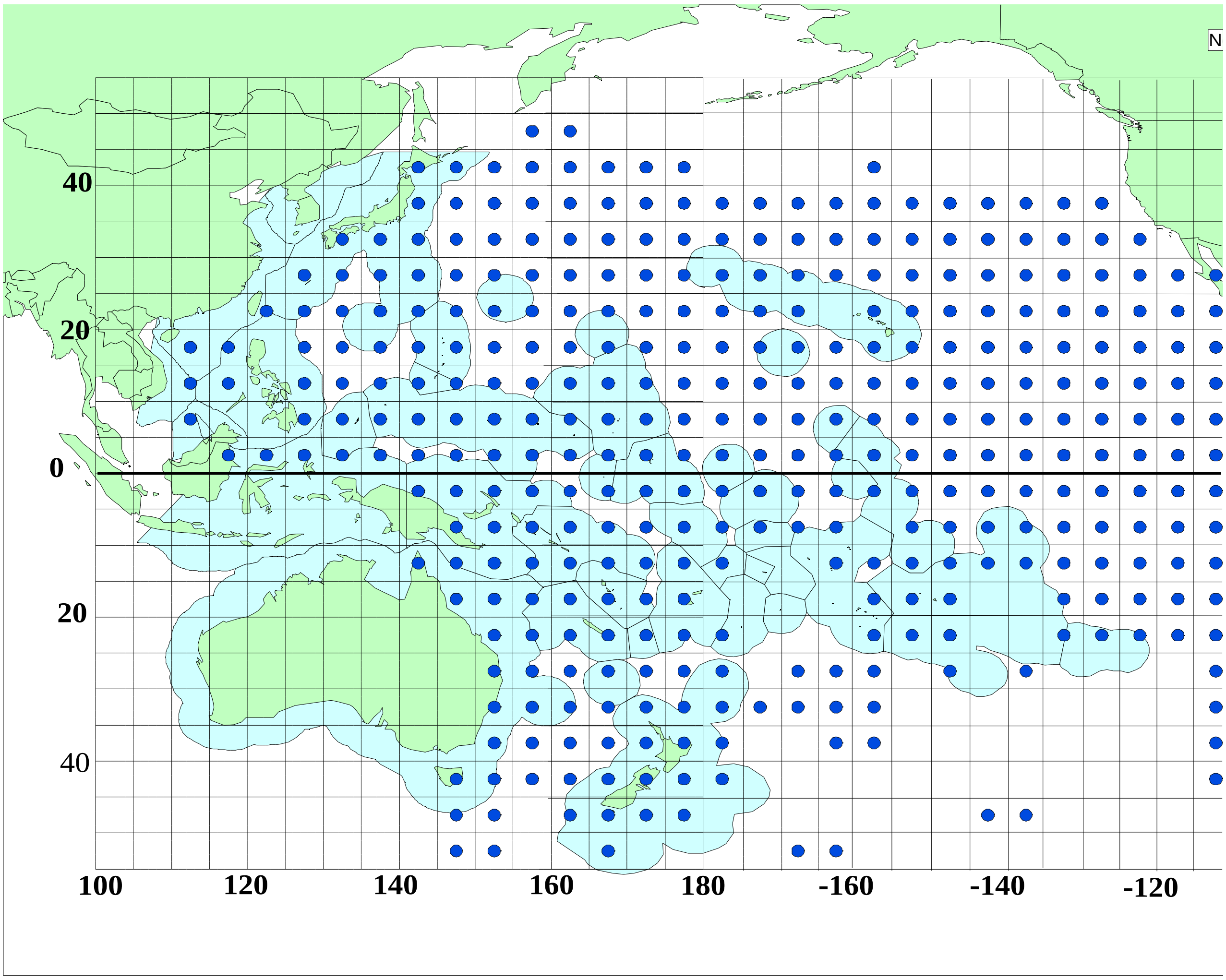


Figure 8.8 Spatial distribution of regions (5x5-degree squares of latitude and longitude) fished by Japanese longliners between 1986-2000.



to the assumed stock recruitment relation. In particular, due to the potential impact of a regime shift in the Pacific on the productivity of the yellowfin tuna stock in the WCPO, alternative yield estimates for this region were calculated. These analyses used the estimated average recruitment during the period 1962-1980 (low-recruitment period) and the period 1981-2001 (high-recruitment period) instead of using a single stock recruitment relation over the whole period. The resulting equilibrium yield estimates were found to be 310,000 t and 515,000 t respectively. The resulting variations in the yield estimates in each of the sub-regions used previously are again shown in Table 8.4 and in Figures 8.6a and 8.6b. Note, for these calculations the estimated equilibrium yield in the EPO was held constant at 276,000 t.

Note: In Table 8.4, two additional stock regions have been added - SW Pacific and the ETBF. For the SW Pacific stock scenario, and for each data period, the estimated equilibrium yield in the SW Pacific is just the average of the estimates for this region based on the Pacific-wide and WCPO stock assumptions. On the other hand, the estimated equilibrium yield in the ETBF is based on the proportion of this yield that is in the ETBF (cf. Table 8.1). For the ETBF stock scenario, the estimated equilibrium yield is seen to the same for each data period. This estimate is based on the average of the estimated yield for this region under the SW Pacific stock scenario across the three data periods.

Under the high productivity scenario, the results indicate that there may be considerable scope for increasing the catch of yellowfin tuna in the ETBF. However, these estimates are dependent on the assumed stock hypothesis and the data period considered. Under the single stock hypothesis, the increased catches are estimated to be between 250 and 2,700 tonnes, while under the WCPO stock hypothesis the increases may be slightly larger (between 1,250 and 4,100 tonnes). On the other hand, under the low productivity scenario, it remains possible that present catches already exceed the sustainable yield estimates for this region, with an increase in catch only deemed possible under if the data for the latter period is more appropriate.

8.6 Results for Bigeye Tuna

A similar suite of calculations were undertaken for bigeye tuna in the Pacific Ocean. The distribution of mean annual bigeye CPUE (based on data for Japanese longline vessels for the period 1962-2000) is shown in Figure 8.4 while the results of these calculations are given in Table 8.5 and illustrated for some cases in Figures 8.9a and 8.9b. Note: the estimates of equilibrium yields in the WCPO and the EPO are taken from Hampton (2002b) and Maunder and Harley (2002). Also, unlike the calculations for yellowfin tuna, the lower and upper yield estimates for the WCPO are based on the lower and upper 95th confidence limits for the mean equilibrium yield of 87,000 t (Hampton, 2002b).

Unlike the results for yellowfin tuna, the results for bigeye tuna indicate that there is little, if any, surplus production still available in either the SW Pacific or the ETBF. All productivity and stock hypotheses indicate that the present catches taken in the ETBF region exceed the estimated sustainable yield by around 700 tonnes. However, the analyses presented here are premised on a number of assumptions (see the next section) so consequently all results remain uncertain and need to be treated with some caution. Nevertheless, it perhaps could be argued that the above results indicate that there is little, if any. scope for increasing catches of bigeye tuna in the ETBF, or elsewhere in the Pacific Ocean, above their present levels. This result is consistent with the current assessment of bigeye tuna in the WCPO which indicates that over-fishing of the bigeye stock in the WCPO is occurring (Hampton *et al*, 2003).

Table 8.5 Results of yield analyses for bigeye tuna across several regions of the Pacific Ocean.

		Lower Yield Estimate				Yield Estimate			
	Assumed Stock Area	***Pacific***	***WCPO***	***SWP***	***ETBF***	***Pacific***	***WCPO***	***SWP***	***ETI***
	Estimated Total Equilibrium Yield	142,000	72,000			157,000	87,000		
	% Longline catch (98-01)	51.5%	59.5%			51.5%	59.5%		
	Estimated LL Equilibrium Yield	73,130	42,840	4,968	1,059	80,855	51,765	5,778	1
	Mean Australian LL catch (98-01)	1,084	1,084	1,084	1,084	1,084	1,084	1,084	1
	Mean non-Australian LL catch (98-01)	97,589	65,639	6,729	821	97,589	65,639	6,729	
	Mean Total LL Catch (98-01)	98,673	66,723	7,813	1,905	98,673	66,723	7,813	1
Data: 1962 - 2000	Est. Equilibrium LL Yield : Pacific	73,130				80,855			
	Est. Equilibrium LL Yield : WCPO	35,050	42,840			38,752	51,765		
	Est. Equilibrium LL Yield : SW Pacific	4,527	5,534	5,031		5,006	6,687	5,846	
	Est. Equilibrium LL Yield : ETBF	937	1,145	1,041	1,059	1,036	1,384	1,210	1
	Est. Yield - Current Catch: Pacific	-25,543				-17,818			
	Est. Yield - Current Catch: WCPO	-31,673	-23,883			-27,971	-14,958		
	Est. Yield - Current Catch: SW Pacific	-3,286	-2,279	-2,782		-2,807	-1,126	-1,967	
	Est. Yield - Current Catch: ETBF Area	-968	-760	-864	-846	-869	-521	-695	
Data: 1962 - 1975	Est. Equilibrium LL Yield : Pacific	73,130				80,855			
	Est. Equilibrium LL Yield : WCPO	30,706	42,840			33,949	51,765		
	Est. Equilibrium LL Yield : SW Pacific	3,356	4,682	4,019		3,711	5,658	4,684	
	Est. Equilibrium LL Yield : ETBF	951	1,326	1,139	1,059	1,051	1,603	1,327	1
	Est. Yield - Current Catch: Pacific	-25,543				-17,818			
	Est. Yield - Current Catch: WCPO	-36,017	-23,883			-32,774	-14,958		
	Est. Yield - Current Catch: SW Pacific	-4,457	-3,131	-3,794		-4,102	-2,155	-3,129	
	Est. Yield - Current Catch: ETBF Area	-954	-579	-766	-846	-854	-302	-578	
Data: 1986 - 2000	Est. Equilibrium LL Yield : Pacific	73,130				80,855			
	Est. Equilibrium LL Yield : WCPO	34,500	42,840			38,144	51,765		
	Est. Equilibrium LL Yield : SW Pacific	5,222	6,484	5,853		5,774	7,835	6,804	
	Est. Equilibrium LL Yield : ETBF	891	1,106	998	1,059	985	1,336	1,161	1
	Est. Yield - Current Catch: Pacific	-25,543				-17,818			
	Est. Yield - Current Catch: WCPO	-32,223	-23,883			-28,579	-14,958		
	Est. Yield - Current Catch: SW Pacific	-2,591	-1,329	-1,960		-2,039	22	-1,009	
	Est. Yield - Current Catch: ETBF Area	-1,014	-799	-907	-846	-920	-569	-744	

Figure 8.9a. Surplus yield estimates (ie. MEY - current catches) for longline caught bigeye tuna based on a WCPO stock scenario.

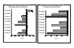
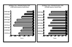


Figure 8.9b. Surplus yield estimates (ie. MEY - current catches) for longline caught bigeye tuna based on a Pacific-wide stock scenario.



8.7 Discussion

Several points needs to be made in interpreting the above results and there are a number of other issues which need to be considered when determining appropriate species specific sustainable yields for different regions of the Pacific Ocean. These include:

- The above results have elements of uncertainty because of the assumptions used in the methodology and incomplete biological and fisheries information available for the calculations. Consequently, the results should be treated with some degree of caution and it is recommended that they be used only as a guide in regards to possible maximum equilibrium (or sustainable) yields in each of the regions.
- The estimates of maximum equilibrium yield for yellowfin and bigeye tuna in the WCPO and the EPO used in the above calculations are based on a number of assumptions. Uncertainties about stock structure and the population dynamics of the fish resources need to be acknowledged, and the consequences of possible changes in the recruitment dynamics of a resource on yield estimates have already been highlighted. The yield estimates are also based on the current age-specific patterns of selectivity observed in the fisheries in recent years. If there were to be major changes in the fleet composition of the fishery (eg. a higher portion of purse seining or longlining) then the yield estimates would need to be re-calculated. Depending on the change, the revised maximum equilibrium yield estimates may be lower or higher than those used here. Whilst the estimation of equilibrium yields under different selectivity assumptions has not been undertaken to date in the WCPO, an illustrative re-examination of how the estimated yield might change if effort is reallocated among the various component of the fisheries has been undertaken for the EPO (Maunder 2002). This result indicated that yield is greatest for the longline fisheries and lowest for the bait-boat and floating object based purse-seine fisheries. However, the maximum yield would undoubtedly be achieved under some optimum mix of fleets. What this optimum mix is, and whether the fleet structures in the present fisheries are near optimal, remains unknown.
- As a follow-up to the previous point, and as described in the text, the yield estimates provided in this paper are for the longline component of the total catch only. Furthermore, these estimates are based on the assumption that the proportion of the total catch taken by each of the main fishing gears in the Pacific Ocean will remain relatively unchanged over the next few years. Again, if there were a restructuring of the fleets in future years, there would be a corresponding influence on the longline component of the estimated sustainable yield. Based on the results mentioned previously, it is likely that if the current catch taken by the purse seine component were reduced, an increase in the yield (but not necessarily in the same proportion) from the longline fleet would be possible.
- The above calculations assume that the productivity of the sub-populations in each region is similar. This follows from a simple production model analysis, where given an initial biomass, B_o, and productivity, r, in any region, the estimated MSY is given by the expression $rB_o/4$. As the analysis presented in this paper assumes that the ratio of MSY in any region to the MSY for the entire stock is equivalent to the ratio of the corresponding biomasses (*cf.* equations 8.4a, 8.4b), it follows that the productivity, r, in each region is assumed to be similar. In reality, it is likely that there is some spatial heterogeneity with respect to productivity, with regions with lower productivity having a corresponding lower MSY and vice versa. For tropical tunas it is likely that the warmer equatorial waters (where spawning is year round) have a higher productivity than the cooler temperate waters off eastern Australia (where spawning is more seasonal).
- While not explicit to the above calculations, the movement and migration patterns of the tuna and billfish resources in the WCPO will need to be taken into consideration in any long term management plan for the fisheries in this region. If there is fast and broad-scale mixing of the resources across this region, then the regional distribution of fishing effort is less important than just limiting the catch to sustainable levels. For example, if there is

instantaneous mixing of the resource, then theoretically all the effort could be concentrated at one place (think of a straw sucking water out of a large bowl - the water level remains the same everywhere). On the other hand, if the stock is characterised by slow movement and mixing between adjacent regions, then effort and catch levels that exceed regional MSY limits may result in temporal depletion of the sub-populations in these regions. At present the movement dynamics of the tropical tunas and billfish remains uncertain, though there is some evidence that lifetime displacements of these fish may be measured more on the scale of localised regions than on the basin scale (Sibert and Hampton 2002).

- Finally, it is now recognised in many international agreements (e.g. FAO Code of Conduct, UN agreement on Straddling fish stocks and highly migratory fish stocks) that MSY should be regarded as a limiting condition (or limit reference point) that should not be exceeded, and not as a target reference point.

Chapter 9: Conclusions and Further Work

9.1 Summary and Conclusions

In this report we have evaluated, using two distinct methodologies, a range of harvest strategies for the catch of the three principal target species in the ETBF. Due to the belief that swordfish has a more localised stock-structure than either bigeye or yellowfin tuna, a Management Strategy Evaluation approach was adopted for this species. Using a detailed operational model, this allowed the evaluation of a range of alternative input effort strategies and the examination of the trade-offs in achieving a range of management objectives. On the other hand, estimates of sustainable catches of yellowfin and bigeye tuna in the ETBF were obtained based on preliminary estimates of stock-wide MSY values and an inferred knowledge of the distribution of these resources throughout the Pacific Ocean.

The operating model for swordfish was an age-, length- and area-structured population dynamics model which assumed a single stock of swordfish within the south-west Pacific. It also explicitly considered the dynamics of three principal fleets catching swordfish in this region - Australia, New Zealand and Japan - with the catch of swordfish taken by other fleets incorporated into the latter. A reference, or baseline, biology for the population dynamics of the swordfish population in the south-west Pacific was adopted for the evaluation of most harvest strategies. This biology was based on published research undertaken on swordfish both within the south-west Pacific and elsewhere. However, due to the lack of a stock assessment for swordfish in the south-west Pacific, the condition of the stock at the end of 2001 remains unknown. Hence, for scenario testing, a range of assumed levels of depletion (*ie*. the reduction in the initial biomass level due to removals up until the year 2001) was considered which included upper and lower extremes as well as a “baseline” value of 30%. Sensitivity of the results to alternative biological scenarios and assumed depletions were then considered. Each scenario, or alternative operating model, was also conditioned on the available historical data.

The development of the operational model was undertaken in consultation with the Fisheries Assessment Group for the ETBF. This allowed a range of models to the identified which incorporate a range of views on a number of aspects about the fishery and helped identify a number of input parameter values (eg. predation loss and retention practices). The identification of the various economic and conservation-based performance measures and future effort scenarios was also undertaken in consultation with the FAG. In particular, consideration of a range of fixed future effort harvest scenarios for the Australian longline fleet allowed a range of candidate initial *TAE* levels to be evaluated for the fishery. For this purpose, annual effort levels for the Australian longline fleet were allowed to range between 11 million and 28 million hooks. These harvest strategies were also evaluated against a range of alternative scenarios concerning both the future effort deployed by non-Australian vessels in the south-west Pacific, increased gains in effective effort due to effort creep, and the population dynamics of the swordfish resource.

Each harvest strategy was evaluated by assessing the performance of each performance indicator over a 20 year projection period. As would be expected, the annual size of the Australian catch over the projection years was found to generally increase with greater effort. However, with increased effort and catches there was a general decrease in the average size of fish caught, and an increased probability that the biomass would be fished down to levels below 30% and 50% of its initial level. As large fish generally return a higher price, a decrease in the proportion of large fish in the catch would result in a lower unit return across the total catch. Furthermore, the fishing down of the stock to lower levels may move the stock into an over-fished state. If one adopts 30%B_o as a limit reference point, (ie. a level below which one does not want the stock to drop below) then all scenarios where the Australian effort is increased above 16.8 million hooks are likely to place the stock at high risk of being over-fished, while even an increase to 16.8 million hooks will result in a moderate level of risk. The results indicate that large increases in effort and catches will generally result in a poor conservation outcome, and illustrated the trade-offs between the achievement of both the economic and conservation objectives for the fishery.

The results also highlight the fact that the achievement of management objectives for any individual fleet will be dependent on the future effort levels of the other fleets. For example, when foreign effort remains at the status quo, as opposed to being doubled, the same level of Australian effort had a reduced probability of driving the spawning biomass to below 30%B_o, and Australia achieved higher catches for identical or lower levels of effort. Alternatively, when there are significant increases in both Australian and foreign effort, the likelihood of a poor conservation outcome is significantly increased. As such, the impact of a set level of Australian effort also depends largely on the changes in effort of the foreign fleets, and on their efficiency. If one were to adopt a precautionary approach then one should assume future increases in foreign effort and efficiency, and then re- evaluate the situation once the extent of change in foreign effort becomes apparent. Furthermore, this result reinforces the need for multi-lateral management arrangements for widely distributed and highly migratory stocks such as swordfish.

The results displayed a range of sensitivities to the uncertainties concerning both the biology and assumed 2001 depletion level. All of the economic indicators were found to be relatively insensitive to changes in the stock-recruitment steepness parameter. However, sensitivity to this parameter increased with increases in future effort, especially for the proportion of large fish in the Australian catch in Area 2 (which decreased with increasing effort). On the other hand, all economic indicators were quite sensitive to the assumption of an increased natural mortality, though there was little interaction with the level of future effort. Conversely, the conservation indicators were more sensitive to changes in the nature of stock-recruitment relation and less to natural mortality, though there was a reasonable level of interaction associated with each of these biological parameters.

The reference biological scenario assumed reasonable levels of movement between different regions in the south-west Pacific, and the performance of the fishery was found to be relatively independent of the precise nature of this assumed movement. However, under the assumption of no regional movement, the resource levels in areas with relatively high levels of effort, such as that off central eastern Australia, readily became depleted, as they were not replenished by fish moving in to them from other regions. A similar sensitivity is likely to also occur in situations where movement is limited. While swordfish are usually referred to as a "highly migratory" species, recent patterns of a sequential spatial and temporal declines in catch rates of swordfish observed within the Australian fishery (Campbell and Hobday 2003) do pose specific questions regarding the nature of this movement and the susceptibility of the swordfish resource to localized depletions. Further research is recommended to ascertain the exact nature of the movement of swordfish in and around the south-west Pacific.

The performance of individual harvest strategies was found to be most sensitive to the assumed level of historical depletion. Examination of various fixed effort scenarios showed that as future effort was increased, the conservation objectives performed increasingly more poorly, particularly at higher assumed depletion levels. Under the 50% depletion scenario, continuation of present effort levels is likely to place the stock at high risk of being over-fished. On the other hand, assuming a depletion of only 15% gave more favourable economic and conservation outcomes than under the reference scenario discussed previously. While the 50% depletion scenario may be considered extreme, there may also be a high level of risk associated with the assumption that the depletion in 2001 was only 15% (ie. this assumption may not be seen as being precautionary), given both the size of the historical catches and the fact that the conditioning process indicated a better fit to the 30% depletion scenario.

The evaluation of the range fixed-effort scenarios provided guidance on identifying an appropriate initial *TAE* level for the longline fleet in the ETBF. However, ideally, harvest strategies should incorporate feedback decision rules whereby the status of the fishery is regularly assessed, and harvest strategies are updated and applied depending on the results. Without management feedback loops, high levels of combined effort may continue to drive down the biomass. Alternatively, if effort levels can be adjusted in an appropriate manner, the risk of not achieving either the conservation and/or economic objectives should be diminished. Two sets of harvest strategies that incorporated either a simple empirical-based decision rule or a model-based decision rule for adjusting annual effort for the Australian fleet during the 20 year projection period were evaluated. The empirical-based decision rules considered changes in the annual trends of either catch rates or the upper 95th percentile of individual fish weights in the catch, while the model-based decision rules used the results of a production model assessment. Both were found to be successful in arresting the declines in spawning biomass that would otherwise have occurred in the absence of the feedback decision rule, but most did so by decreasing domestic effort until stability was attained in the monitored indicator variable used in the decision rule. However, empirical approaches may be poor if the stock is already highly depleted, while the production model assessments were found to significantly underestimate true biomass levels, possibly because of a lack of contrast in the data and a confounding between the fitted parameters. Ultimately, more comprehensive data and a more sophisticated stock assessment are required if one is to better estimate sustainable yields.

Unlike the MSE approach adopted for swordfish, which assessed the performance of the ETBF based on input effort strategies, for bigeye and yellowfin tuna direct estimates of the sustainable catch of each species in the ETBF region were obtained. These were based on estimates of stock-wide MSY values and the distribution of each resource across the Pacific based on the distribution of catch rates for Japanese longliners. As with the MSE approach, several different estimates were obtained based on a range of alternative stock and productivity scenarios. Under the high productivity scenario, the results indicated that there may be considerable scope for increasing the catch of yellowfin tuna in the ETBF, while under the low productivity scenario, it remains possible that present catches may already exceed the sustainable yield for this region. On the other hand, the results for bigeye tuna under all scenarios indicated that there is little, if any, scope for increasing catches of bigeye tuna above their present levels either in the ETBF or elsewhere in the Pacific Ocean. This result is consistent with the current assessment of bigeye tuna in the WCPO which indicates that over-fishing of the bigeye stock in the WCPO is presently occurring.

In conclusion, the MSE framework has been found to be a valuable tool for ongoing analysis of alternative harvest strategies, and the results presented in this report are but a small subset of the management strategies that may potentially be evaluated using this technique. The results have allowed a quantitative and comparative evaluation to be made regarding the economic and conservation-based impacts of a range of alternative effort harvest strategies for the longline sector of the ETBF, and have assisted AFMA identify an appropriate initial *TAE* for this fishery. Furthermore, the qualitative manner of presenting the results has helped to make explicit the trade-offs between achievement of, the often conflicting, economic and conservation objectives and has helped convey the outcomes of the project to a range of stakeholder groups in the fishery.

9.2 Planned Outcomes

This project provided the main source of quantitative assessment advice and evaluation of harvest strategies to AFMA to assist in the determination of the initial *TAE* which is required for implementation of the new management plan for the Eastern Tuna and Billfish Fishery in 2004. This advice was conveyed to AFMA through two ETBF Effort Setting workshops held in December 2002 and March 2003 to consider and discuss appropriate initial *TAE* levels for the ETBF. The results of this project were also conveyed to the AFMA Board via written reports of these workshops and personal presentations by the workshop chair, John Gunn, and were instrumental in guiding the Board's decision on an initial *TAE* for the ETBF. In a media release from AFMA, dated 2 June 2003, it was stated that "The AFMA Board has decided that on the basis of the latest risk-weighted scientific advice, a preliminary estimate of the *TAE* or maximum number of hooks that can be deployed in the fishery each year will be 13.5 million."

The additional work summarized in this report on the evaluation of harvest strategies which incorporate a feedback decision rule for adjusting the *TAE* in response to changes in the performance of the ETBF will also assist AFMA identify appropriate decision rules for this fishery. The identification of appropriate decision rules for adjusting effort levels will be an important goal for the successful management of the ETBF.

9.3 Benefits and Adoption of Project Results

The benefits of this project will flow to all stakeholders in the longline sector of the ETBF, as this project has, and will, continue to provide guidance to AFMA on the selection of appropriate harvest strategies to ensure the sustainable management of the fishery. These benefits results from an improved understanding of the possible impact of alternative harvest strategies on the pelagic resources available to the longline sector of the ETBF and the likely trade-offs in achievement of the economic and conservation-based management objectives for the fishery.

This project also have flow on benefits to the Southern and Western Tuna and Billfish Fishery (SWTBF). The methodology outlined in Chapter 8 of this report was used to estimate sustainable removals in the western part of the Australian Fishing Zone and parts of the eastern Indian Ocean and provided one of the main sources of information on this fishery to assist AFMA identify initial *TAC*s for this fishery. The SWTBF will also benefit from the development of the operational model and the results of Management Strategy Evaluations of harvest strategies undertaken for the ETBF. In particular, the operational model developed under the auspices of this project will provide the basis of the model to be used in the new FRDC funded project "Development of a robust suite of stock status indicators for the Southern and Western and the Eastern Tuna and Billfish Fisheries".

This project also has benefits to the management of pelagic fisheries which exist throughout the Western Central Pacific Ocean and the Indian Ocean. This is because the methodologies outlined in this report regarding the evaluation of harvest strategies are generic and, as such, will provide guidance to both the Western Pacific Tuna Commission (to be formed in 2004) and the Indian Ocean Tuna Commission on appropriate methodologies for identifying sustainable management strategies. Such work has already commenced in the Indian Ocean.

9.4 Further Developments

The analyses presented and described in this report, while comprehensive, raise a number of issues which should be addressed through future research. Attention to each of these issues will also allow continued improvements in the scientific advice to the managers of the ETBF on the sustainable harvest of the main target species taken in this fishery. Some of these issues are discussed here.

a) Historical depletion: The results in this report indicated that the future performance of the Australian fishery was sensitive to assumptions about the present level of stock depletion. While some evidence was presented which indicated that extreme (*ie* 50%) levels of depletion are unlikely, the uncertainty concerning the present status of the swordfish stock needs to be addressed as a matter of urgency. Towards this end the ETBF Fisheries Assessment Group is recommended to identify this as a high priority task.

b) Assessment based decision rules: A more formal stock assessment for broadbill swordfish needs to be developed and incorporated into the current model framework to improve the reliability of assessment-based decision rules. Furthermore, while the monitoring of temporal changes in catch rates and sizes within the catch (as described in this report) will be used in the first instance, a range of additional performance indicators and reference points need to be developed given the multi-species nature and large spatial range of the ETBF. This task will be greatly assisted by the three-year FRDC funded project “Development of a robust set of Stock Status Indicators for the Southern and Western, and the Eastern Tuna and Billfish Fisheries” being undertaken by CSIRO.

c) Movement patterns. The results in this report indicated that the performance of the Australian fishery was sensitive to assumptions about the spatial movement patterns of swordfish in the SW Pacific. Furthermore, spatial-temporal declines in swordfish catch rates observed within the domestic fishery in recent years suggest that the swordfish population may not mix rapidly across the entire SW Pacific, and that some degree of spatial residency or spatial sub-structuring of the stock may be possible. As such, the operating model should be extended to incorporate both migratory and resident components of the stock. Additionally, alternative spatial hypotheses (possibly with a finer spatial scale) for structuring the movement of the stock should also be considered.

d) Underlying biology: The operating model should be modified to incorporate new knowledge and/or understanding of the population dynamics of the swordfish population in the SW Pacific as it becomes available. For example, CSIRO is about to complete a two-year study on the age and growth of swordfish caught within the ETBF and the results of this study should replace the growth curves presently used in the model (which are based on studies undertaken on swordfish in the Atlantic). To help guide research on swordfish, those aspects of the population dynamics to which the harvest strategies display the greatest sensitivity should receive the highest priority.

e) The present operating model considers the dynamics of a single species only. However, the ETBF is a multi-species fishery for which there are a number of principal target and by-product species. There is no conceptual reason while the operating model could not be (and should not be) extended to incorporate the range of different fishing strategies adopted by the fishers in the ETBF and the resulting technical interactions among these different species. However, in practice a number of challenges need to be overcome. In particular, these relate to gaining an understanding of the suite of decision rules (practical, economic and social) used by fishers to switch target species. A greater understanding of the stock structure of the other principal target species, such as bigeye tuna, is also required, together with a concomitant understanding of their movement patterns in and out of the ETBF.

Finally, whilst this report has focused on the use of the MSE approach in the context of evaluating effort strategies to assist with establishing an initial *TAE,* and identifying decision rules for adjusting this *TAE*, for the Australian domestic fleet, the operating model may as readily, and indeed should, incorporate formal stock assessments for broadbill swordfish when they become available. Indeed, the definitive MULTIFAN-CL stock assessments that have been developed by the SPC for yellowfin, bigeye, skipjack and albacore in the WCPO could be incorporated into an MSE framework for these species in the WCPO. While this remains a challenging task, this would greatly assist the soon to be formed Western Pacific

Tuna Commission undertake a comprehensive evaluation of proposed harvest strategies within the "reality" described by the operating model(s).

Acknowledgements

Thanks are extended to Drs Andre Punt, Tony Smith, Tom Polacheck, Marinelle Basson and John Gunn for guidance and suggestions in the completion of this work. In particular, Andre Punt is thanked for his diligent assistance in the development of the operational model and his review of the project. Paavo Jumppanen and Dale Kolody are also thanked for assistance with the implementation of AD Model Builder. Thanks are also extended to Drs Talbot Murray, Naozumi Miyabe and Tim Lawson for supplying the catch and effort data used in the analyses. The members of the ETBF Fisheries Assessment Group are thanked for their input into the development of the operational model, the provision of information concerning aspects of fishing operations, and the selection of performance indicators and decision rules. The authors also gratefully acknowledge the financial support received from the Fisheries Research and Development Corporation and the Australian Fisheries Management Authority towards this project.

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Appendix A: Intellectual Property

No intellectual property has arisen from the project that is likely to lead to significant commercial benefits, patents, or licences. Nevertheless, the Fisheries Research and Development Corporation‘s share of any intellectual property associated with this project will be 33%.

Appendix B: Project Staff

Robert Campbell	Principal Investigator, CMR	50%
Natalie Dowling	Modeller, CMR	75%

Appendix C: Associated Working Papers

Campbell. R.A. and Taylor, N.A. (2000) *Data and biological parameter specifications for a spatially structured operating model for broadbill swordfish and bigeye tuna in the south-west Pacific*. Information document provided to the Eastern Tuna MAC Fisheries Assessment Group meeting. 43pp.

Campbell, R.A. (2001) *Procedures for the determination of TACs and Decision Rules for the Southern and Western Tuna and Billfish Fishery*. Background paper presented to the third meeting of Stock Assessment Group for the SWTBF, held 5 September 2001, Como, Perth.

Campbell. R.A. and Dowling, N.A. (2002) *Technical description of the operating model to be used for evaluation of harvest strategies for swordfish in the Eastern Tuna and Billfish Fishery*. Background document to the Fisheries Assessment Group meeting, held 5-6th March, Mooloolaba, 43pp.

Campbell, R.A. (2002) *Management strategies, the determination of a TAE, and the use of decision rules within the Eastern Tuna and Billfish Fishery*. Background document to the Fisheries Assessment Group meeting, held 5-6th March, Mooloolaba, 7pp.

Campbell, R.A. (2002) *Identification of performance measures and harvest strategies for swordfish in the Eastern Tuna and Billfish Fishery*. Background document to the Fisheries Assessment Group meeting, held 10-11th July, Hobart, 7pp

Campbell, R.A. (2003) *An Approach for Estimating Equilibrium Yields within Regions of the Indian Ocean*. Background paper to the 2nd TAC Setting Workshop for the Southern and Western Tuna and Billfish Fishery, held 11 February 2003, Fremantle, Perth.

Campbell, R. and Dowling. N. (2003) *A management strategy evaluation approach for broadbill swordfish, Xiphias gladius, in the south-west Pacific Ocean*. Working Paper BBRG-4 presented to the 16th meeting of the Standing Committee on Tunas and Billfish, held 9-17th July 2003, Mooloolaba, Queensland, Australia.

Appendix D: Revised estimates of annual catches in the Eastern Tuna and Billfish Fishery based on a comparison of logbook data and size monitoring data.

D.1. Introduction

The current AL05 logbook used by the domestic tuna longline fleets in both the Eastern Tuna and Billfish Fishery (ETBF)and the Southern and Western Tuna and Billfish Fishery requests that fishers record the processed weights of retained catch for each species. These weights are based on visual estimates as the weight of fish are not measured at sea. Since 1997, the processor measured weights of individual fish landed in the ETBF have been recorded as part of an ongoing size monitoring program. This paper compares the weights recorded by these two methods in order to ascertain the best estimate of total annual catch of swordfish in the ETBF.

D.2. Logbook recorded catches

Various logbooks have been used over the past fifteen years to record catch and effort in the Australian tuna longline fisheries. A summary of the years each logbook type has been used in the ETBF is given in Table D.1.

Table D.1 Years each logbook was used by tuna longliners in the ETBF.

Year	ALO2	AL03	AL04	AL05
1985				
1986				
1987				
1988				
1989				
1990				
1991				
1992				
1993				
1994				
1995				
1996				
1997				
1998				
1999				
2000				
2001				
2002				

With the changes in logbook type, there have also been changes in the manner in which the weights of the landed catch have been recorded. These changes are summaries as follows:

1. AL02 - Four options: A = Estimated whole, B = Estimated processed, C = Actual whole and D = Actual processed
2. AL03 - Estimated Total Weight to be recorded for each set. Verified total weights to the recorded for each trip - together with form code (W = whole, G = gilled and gutted, T = trunked, F = Filleted, H = Headed)
3. AL04 - same as AL03
4. AL05 - Estimated Processed weight to be recorded for each set, together with associated form code. No verified weights required.

The reason for the change from the AL02 to the AL03 logbook is not known. However, the change from Total Weight (used in the AL03 and AL04) logbooks to Processed Weight (used on the current AL05 logbook) was instigated after the author pointed out that it remained unclear whether Total Weight referred to Total *Whole* Weight of the retained catch or Total *Processed* Weight of the retained catch. Indeed, on being informed of this uncertainty, the AFMA logbook officer (Hein Sturmann) phoned around the ETBF longline fleet in order to ascertain which weights individual skippers had been recording. Based on this small survey, it appeared that some skippers had been recording whole weights while others had been recording processed weights - this also depended to some extent on the species. This was obviously not a desirable situation.

CSIRO maintains a version of the logbook data collected by AFMA. Like the data recorded in logbooks, this data also records the retained catches for each longline set. The catches are recorded as either whole weights or dressed weights. Also, a Form Code is used to indicate the type of processing or the manner in which the total weights are obtained. For the purposes of illustration, the manner in which the swordfish catch in the ETBF has been recorded is shown in Table D.2.

Table D.2 Summary of swordfish catch data held in the CSIRO Pelagic database in Hobart pertaining to longline operations in the ETBF.

Logbook	Longline Sets	Number of Fish	Whole Weight (kg)		Dressed Weight (kg)	
			Form code*	Weight	Form Code#	Weight
AL02	242		M	9,871		
	204		E	8,959		
	1,173					80,973
	5,484	6,104				128,213
AL03	2,784	15,004				747,746
AL04	23,021	123,183		6,006,604		
AL05	122	257	E	4,367		
	261	1,322			HG	62,769
	10	35			G	1,366
	8	25			H	116
	1	2			F	5
	6	19			T	1,035
	158	618			GG	29,457
	8,279	38,353			TR	1,670,876

* M=Measured, E=Estimated

\# HG = Headed and gutted, G = Gutted, H=Headed, F=Filleted, TR=T=Trunked, GG=Gilled and Gutted

As the AL02 logbook provided an option for either whole or processed weight to be recorded, both types of data appear in the database. On the other hand, for the AL03 and AL04 logbooks only a single weight type is indicated - as only Total Weight was required to be recorded in these logbooks. However, for the AL03 logbook this has been recorded as processed weight whilst for the AL04 logbook this has been recorded as whole weight. The reason for this difference, despite similar requirements on the two logbooks, remains unknown. Finally, the weights for the AL05 logbook are mainly recorded as processed weights as this is the type requested in the logbook. The reason for the estimated whole weights being recorded for 122 sets remains unknown.

From Table D.2 it is also seen that only weight data was recorded for much of the AL02 data, i.e. the corresponding number of fish was also not recorded. A closer inspection of the data indicates a number of other data records where only one type of catch (weight or number but not both) have been recorded. Being cognizant of these missing data, the following protocol was adopted in order to obtain total catch estimate (number of fish and whole weights) for each set:

1. Where weight data was provided, the total whole weight for that set was calculated as:

$$Total\ Whole\ Weight = \frac{Recorded\ Dressed\ Weight}{Dressed\ Weight\ Factor}\ and/or\ Recorded\ Whole\ Weight$$

   where the *Dressed Weight Factor* gives the fraction of whole weight represented by each dressed weight form code.
2. For each year, the average whole weight of an individual swordfish was calculated as:

$$Average\ Individual\ Weight = \frac{\sum_{Sets} Total\ Whole\ Weight}{\sum_{Sets} Number\ of\ Fish}$$

   Note: only those sets where both weight and number of fish were recorded were used.
3. Where weight data was recorded, but no corresponding fish number, the latter was estimated by dividing the Total Whole Weight for that set (from 1) by the estimated individual weight of a fish caught in the corresponding year (from 2).
4. Where the number of fish was recorded, but not the weight, the latter was estimated by multiplying the number of fish for that set by the estimated individual weight of a fish caught in the corresponding year (from 2).
5. The total number and whole weight of swordfish caught was then totaled for each year. The results, for the years 1997-2001 are given in Table D.3.

An interesting feature of the above catch data is the apparent discrepancy between the 23% decline in the number of swordfish retained between 1999 and 2001 and the apparent 4% increase in the total whole weight of these fish over this same period. From this we would infer that the average weight of a retained swordfish has increased from 47.5 kg to 64.3 kg.

Table D.3 Total annual catch (number and estimated whole weight, WWT) of swordfish based on logbook data recorded by the longline sector of the ETBF between 1997-2001.

Year	AL03		AL04		AL05		Total	
	Number	WWT	Number	WWT	Number	WWT	Number	WWT
1997*	6,036	442,340	21,317	1,108,428			27,431	1,556,603
1998	22	1,894	34,934	1,773,508			34,956	1,775,402
1999	54	3,866	39,704	1,885,809			39,758	1,889,675
2000			27,489	1,239,740	10,057	698,792	37,546	1,938,532
2001			20	711	30,558	1,965,861	30,578	1,966,572

* 78 swordfish (5835kg) were also reported on the AL02 logbook this year and are included in the Total.

D.3 Comparison with Size Monitoring Data

Since mid-1997, processed weights pertaining to individual yellowfin tuna, bigeye tuna and broadbill swordfish caught and landed in the ETBF have been collected as part of an ongoing size monitoring program. The data, collected by WW Fisheries, is passed onto CSIRO Marine Research where it is stored in an Oracle database. At present, weight data for 328,737 fish (consisting of 139,416 yellowfin, 78,997 bigeye and 110,324 swordfish) are stored in this database. A full description of the data is provided in Campbell et al (2002).

The number of swordfish for which individual processed weight are available each year, together with the average weight of these fish, for the years 1998-2001 are given in Table D.4. The corresponding number and total whole weight of swordfish retained for each year, as estimated from the logbook data, are also shown. (Note: for 1997 the size-monitoring data are only available for the last six months this year so the logbook data only covers this period.

Similarly, for 2001 the size-monitoring data are only available for the first six months of this year so the logbook data only covers this period.) Using the estimates of the number of fish retained and the average processed weights, an estimate can be obtained of the total processed weight of all fish retained in each year. These estimates are also shown in Table D.4. Finally, these estimates can

Table D.4 Summary of swordfish size data collected via the ETBF size monitoring program, together with the corresponding logbook data and several inferred results (see text for details).

Year	Size Monitoring Data			Logbook Data		Inferred Results	
	Number of Fish Sampled	Sampling Fraction	Average Processed Weight	Number of fish Retained	Estimated Total Whole Weight	Estimated Total Processed Weight	Whole-to-Dressed Weight Ratio
1997*	14,555	89.37%	59.895	16,287	873,031	975,510	0.895
1998	26,187	74.91%	52.958	34,956	1,775,402	1,851,200	0.959
1999	31,211	78.50%	51.588	39,758	1,889675	2,051,036	0.921
2000	29,221	77.83%	51.996	37,546	1,938,532	1,952,242	0.993
2001#	8,518	61.54%	47.317	13,841	830,055	654,915	1.267

* July-December only, # January-June only

Figure D.1 Monthly ratio of estimated total whole weight (based on logbook data) and estimated total processed weight (based on size-monitoring data).

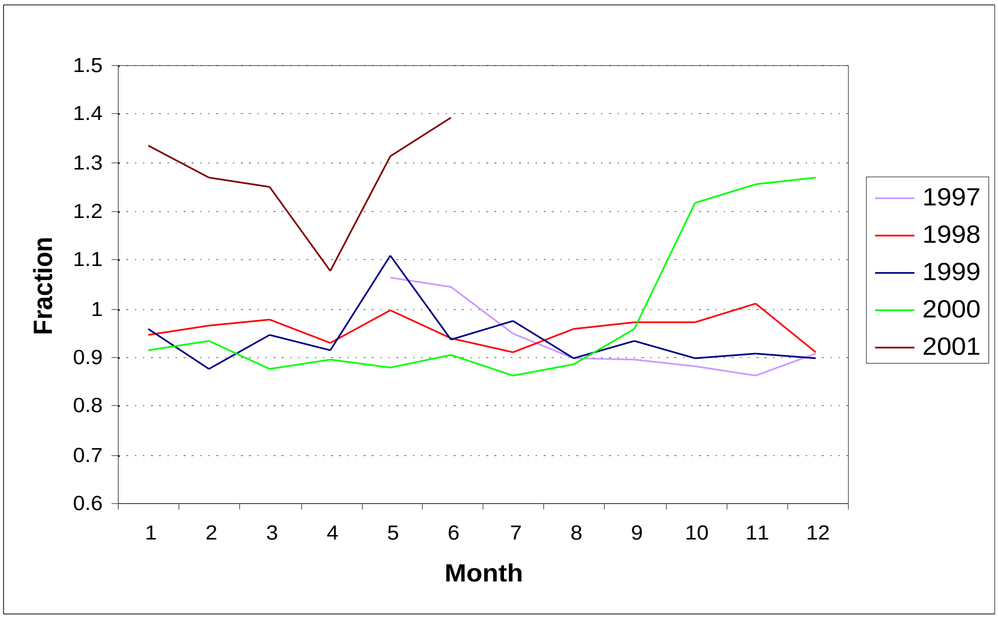
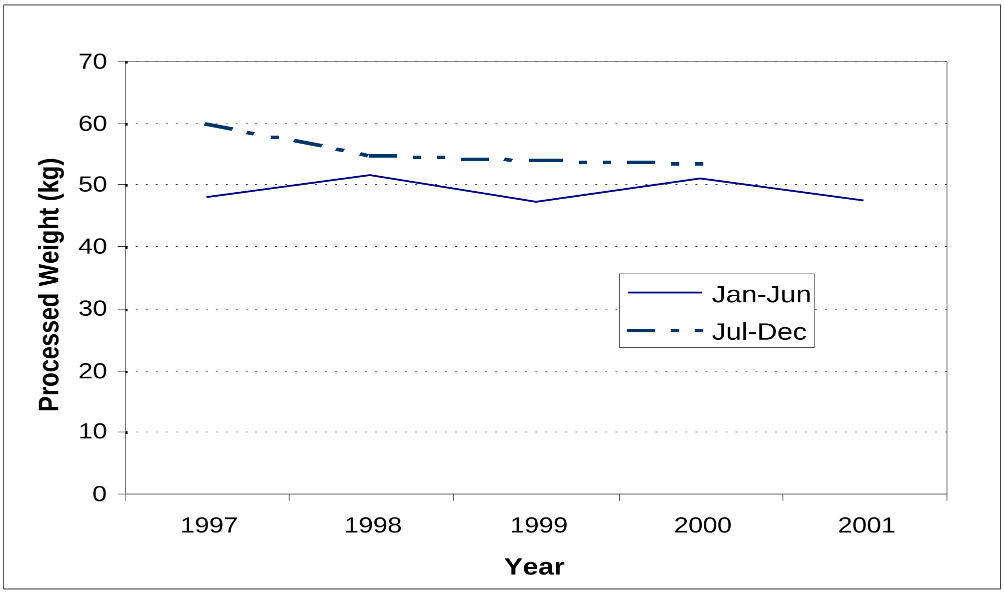


Figure D.2 Average processed weights of swordfish landed in the ETBF.



be compared with the annual estimates of the total whole weight of retained fish (as calculated from the logbook data). For this purpose, the ratios of the whole-to-processed weights were calculated and are also shown in Table D.4. (Note, this calculation was also undertaken for each month and the results are shown in Figure D.1.) If the true ratio of whole-to-dressed weights is around 1.5 then one would expect the calculated ratios to have a similar value.

Several points can be noted in the above results:

1. For the years 1997 to mid-2000 the whole-to-dressed weight ratio is less than 1, indicating that the estimate of total whole weight of retained fish is less than the estimate of the total processed weight. There is a sharp increase in this ratio during 2000, coinciding with the increasing use of the AL05 logbook.
2. If the fish sampled in the size-monitoring program can be considered a relatively random sample of all fish retained (and the high sampling fraction would appear to indicate this may be the situation), then this result would indicate that the weights recorded in the logbooks are, on average, quite poor estimates of true whole weight.
3. The above results also indicate a decrease in the average weight of landed swordfish over the five year period. However, the largest changes occur at the start and end of this time series and may be due a sampling bias as the data for 1997 and 2001 relate, respectively, only to fish landed in the second half and first half of the year only. In order to overcome this problem, the average weight of fish landed in the first six months and the last six months of the year were calculated separately and the results are displayed in Figure 2. The results indicate that larger fish are landed during the second half of the year. Furthermore, apart from the decrease in size in the second half of the year between 1997 and 1998, the average size of fish has remained relatively constant over the period shown. This is in contrast to the significant increase in average size inferred from the logbook data alone.
4. If we believe that the numbers of retained swordfish being recorded in the logbooks are correct, that the true ratio of whole-to-processed weight for swordfish is 1.5, and that the estimates of total annual processed weight given above (i.e. from the size monitoring program) provide accurate estimates of the true weights of the catch, then the bias between the true whole weight (1.5*Processed weight) and the estimated whole weights being recorded in the logbooks can be calculated as follows:

$$Bias = \frac{\left(Logbook\ Estimated\ Whole\ Weight - 1.5 * Estimated\ Process\ Weight)\right)}{1.5 * Estimated\ Process\ Weight} * 100\%$$

The corresponding factor by which the logbook weights need to be raised in order to reach agreement with the processor determined weights can also be calculated:

$$Logbook\ Raising\ Factor = \frac{1.5 * Estimated\ Processed\ Weight}{Logbook\ Estimated\ Whole\ Weight}$$

The corresponding values for each year are shown in Table D.5.

Table D.5 Estimated bias in logbook estimates of whole weight and associated raising factors required to match estimates based on size-monitoring data. Also shown is the ratio of the logbook based-to-process based estimates of annual total weight achieved when estimating the fraction of weights entered in the AL04 logbook as processed weights (see text below).

Year	Logbook Bias	Logbook Raising Factor	Logbook/Size Monitoring Based Estimates
1997	-40.34%	1.68	0.971
1998	-36.06%	1.56	1.043
1999	-38.58%	1.63	1.002
2000	-33.80%	1.51	0.973
2001	-15.51%	1.18	0.999

The reason for the fluctuation in the bias and raising factors between years remains somewhat unknown but the change over the last two years is most likely related to the change from the AL04 to the AL05 logbook. The catch in the former logbook was entered in the database as whole weight while the catch in the current logbook is entered as dressed weight (cf. Table D.2). As already mentioned, there was uncertainty associated with the AL04 logbook as to which catch type (whole or dressed) needed to be entered by the skippers.

The above results can also be used to estimate the raising factor associated with any particular logbook. For example, practically all the catch data during 2001 was entered into the AL05 logbook (cf. Table D.3). As such, the raising factor of 1.18 for this year can be associated with this logbook. On the other hand, practically all the catch data recorded during 1998 and 1999 pertains to the AL04 logbook, indicating that the raising factor for this logbook is between 1.56 and 1.63. A check on these estimates can be made by multiplying the estimated whole weights associated with each logbook during 2000 by each of the above raising factor to see if the result agrees with the processor estimated total weight for that year. The best result (raised logbook based weight = 97.3% processor based weight) is obtained using a raising factor of 1.63 for the AL04 logbook. (Note, total agreement (ie. raised logbook based weight = 100% processor based weight) is obtained if one uses a raising factor of 1.69 for the AL04 logbook and 1.18 for the AL05 logbook.) Repeating this exercise for the 1997 data, and assuming the same raising factor for the AL03 logbook as for the AL05 logbook (as both are based on dressed weights), agreement between the two weight estimates is obtained using a raising factor for AL04 of 1.68. This result is similar to that obtained previously.

Finally, the above results can also be used to estimate the fraction of the catch weight entered in the AL04 logbook as processed weight. As mentioned earlier, it was uncertain as to whether processed or whole weights should have been entered in this logbook and a small survey undertaken by the AFMA logbook officer had ascertained a wide degree of difference between skippers. In order to estimate this value, we assume that a fraction x of the catch weight was entered as processed weight. This percentage needs to be raised by 1.5 in order to bring it up to whole weight. We then assume that the total whole weight estimated from all logbooks needs to be raised by a factor *y* to account for the general under-estimation of weights, ie.

$$Annual\ Whole\ Weight\ Estimate = y * [WWT(AL03) + (x * 1.5 + (1 - x)) * WWT(AL04) + WWT(AL05)]$$

We then minimise the sum across all years of the difference between the logbook-based estimate of annual whole weight and the corresponding size-monitoring based estimate. This gives the result of x=76.15%. and y=1.182. It is reassuring to note that the factor y is very close to that estimated above for the AL05 logbook alone, indicating that this factor may have remained relatively constant over the last few years. The annual ratio of the logbook based-to-process based estimates of annual total weight achieved with this result are listed in Table D.5.

D.4 Conclusions

In summary then, the above comparison of the catch weights recorded in the logbooks and the weights of individual swordfish measured at processors indicates:

· There is a general under-estimation of dressed weights of retained fish recorded in all logbooks of 18%. Note: this result concurs with comments passed on the AFMA logbook officer of a general under-estimation of catch weights on logbooks - fishers liked to be 'surprised' when they land their fish and obtain a receipt of the correct weight of the catch which is larger than previously thought (Hein Sturmann, pers. comm.)
· The fraction of weights reported in the AL04 logbook as processed weight is estimated to be around 77%, though this fraction may have varied from year-to-year. This is a significant deviation from the assumption that it was all whole weight. Again, this result concurs with comments from fishers as to what was generally reported in logbooks - it is processed weight that determines the price paid and dollars received! (Hein Sturmann, pers. comm.)

Based on the above results, revised estimates for the annual whole weight of swordfish landed in the ETBF each year can be obtained. These are based on multiplying the average processed weight of fish measured by processors by the number of fish recorded in logbooks and then converting to whole weight (using the conversion factor of 1.5). The results, together with the previous estimates based on the logbook data are given in Table D.6. Unlike the logbook catch estimates, which indicate an increasing trend in the catch of swordfish over the five-year period, the revised catch estimates indicate that the catch of swordfish peaked in 1999 at around 3000 mt and has declined significantly since that time to around 2300 mt.

Table D.6. Revised estimates of swordfish catches in the ETBF.

Year	Number of Fish	Weight (kg) Logbook Estimate	Weight (kg) Revised Estimate	Difference
1997	27,431	1,556,603	2,336,087	50.1%
1998	34,956	1,775,402	2,776,785	56.4%
1999	39,758	1,889675	3,076,552	62.8%
2000	37,546	1,938,532	2,928,370	51.1%
2001	30,578	1,966,572	2,327,788	18.4%

These results are based on a number of assumptions:

1. The processed-to-whole weight ratio for swordfish is 1:1.5. Note: the processed-to-whole weight ratio for swordfish used in the present analysis is based on data recorded by observers on Japanese longliners, but this measure needs to be verified independently for the domestic fishery. This can be undertaken as part of an observer program. The ratio

used in New Zealand, where a domestic based observer program does exist, is 1:1.4 (Talbot Murray, pers. comm.).

2. The numbers of swordfish recorded in the logbooks are an accurate record of the numbers of fish retained. As reported in Campbell (2001) this assumption, on an annual basis, appears to be correct to within about 4 percent.
3. The estimate of total weight of swordfish, based on pro-rating the sum of all individual swordfish weights collected via the size-monitoring program, is an accurate measure of the total landed weight in the fishery. Given the large sampling of the landed catch by the size monitoring program (c.f. Table D.4) this should be a reasonable assumption to accept.

The above analysis have been repeated for the two other main target species (yellowfin and bigeye tuna) for which size-monitoring data exists, and the results are given in Tables D1 and D2 of the Annex. Again, the revised catches for both species are significantly higher than the nominal logbook based catch estimates. However, due to the smaller difference between whole and processed weights for yellowfin and bigeye tuna (a factor of 1.15 was used for both species), the difference between the two catch estimates is not as large as for swordfish. The fraction of the AL04 logbook weights entered as processed weights (x) was estimated to be 71% for yellowfin and 75% for bigeye tuna, and are similar to the estimate of 76% found for swordfish. The overall bias (y), or under-estimation of catch weight, across all logbooks was also found to be similar for both species, being 12% for yellowfin tuna and 8% for bigeye tuna, but smaller than the bias of 18% found for swordfish. This difference may be due to swordfish catch weights being more prone to under-estimation due to the fact that swordfish are on the average larger and the difference between whole and processed weights is also larger. However, despite these slight differences, the estimates of x and y across the three species are relatively consistent.

Finally, revised annual catch estimates for each species since 1985 are provided in Table D3 of the Annex. The revised catch estimates for the years 1997-2001 are the same as those in Tables D.6, D1 and D2. Before 1997, the logbook estimates of retained catch weights have been multiplied to the factor y, estimated for each species above, and which represents a general under-estimation of retained weights across all logbooks. For swordfish y was set to 1.18 (as estimated above) while for yellowfin and bigeye tuna y was set to 1.10 (being fish of a similar size, the average of the values estimated above for these two species was used).

These results should be taken into consideration during the current process of determining *TAE*s and *TAC*s in the Australian longline fisheries. Furthermore, the general under-estimation of catch on the logbooks indicates the need for an independent catch monitoring process in those fisheries where management will be based on use of a *TAC*.

References:

Campbell (2001) Campbell, R.A. (2001) *Comparison of number of fish measured at processors with number recorded in logbooks*. Information document provided to Eastern Tuna MAC, May, 22pp.

Campbell, R.A., K. Williams and D. Williams (2002) *Eastern Tuna & Billfish Fishery: Size Data Summary*. Background document to the ETBF Fisheries Assessment Group meeting, held in Mooloolaba, 5-6 March, 44pp.

Annex D1: Revised estimates of annual catches of yellowfin and bigeye tuna

Annex Table D.1 Revised estimates of yellowfin tuna catches in the ETBF (x=0.7114, y=1.123)

Year	Number of Fish	Weight (kg) Logbook Estimate	Weight (kg) Revised Estimate	Difference
1997	53,006	1,531,955	1,834,621	19.8%
1998	63,822	1,851,448	2,261,182	22.1%
1999	45,351	1,578,218	2,060,426	30.6%
2000	52,989	1,562,141	1,890,424	21.0%
2001	65,816	2,420,839	2,719,473	12.3%

Annex Table D.2 Revised estimates of bigeye tuna catches in the ETBF (x=0.7499, y=1.082).

Year	Number of Fish	Weight (kg) Logbook Estimate	Weight (kg) Revised Estimate	Difference
1997	26533	901,590	1,062,760	17.9%
1998	28882	1,032,002	1,262,367	22.3%
1999	21420	791,722	973,253	22.9%
2000	20800	689,233	793,857	15.2%
2001	32726	1,207,622	1,307,212	8.2%

Annex Table D.3 Revised estimates of annual yellowfin tuna, bigeye tuna and swordfish catches (rounded to nearest tonne) in the ETBF since 1985.

Year	Yellowfin	Bigeye	Swordfish
1985	4	0	0
1986	10	1	0
1987	849	40	19
1988	669	34	17
1989	691	15	18
1990	744	24	30
1991	766	30	76
1992	970	37	61
1993	689	23	41
1994	1,075	119	48
1995	1,379	196	87
1996	1,814	338	817
1997	1,835	1,063	2,336
1998	2,261	1,262	2,777
1999	2,060	973	3,077
2000	1,890	794	2,928
2001	2,719	1,307	2,328

Appendix E: Data Tables for Swordfish Operational Model

Table E.1: Catch and effort data by year, quarter and region for the Japanese longline fleet in the Western Pacific Ocean

		Area 1		Area 2		Area 3		Area 4		Area 5	
Year	Qtr	Hooks	Catch	Hooks	Catch	Hooks	Catch	Hooks	Catch	Hooks	Catch
1971	1	990,800	88	699,300	407	228,000	96	476,500	30	3,698,000	1,462
1971	2	1,236,300	175	2,240,500	2,748	1,329,100	1,119	276,300	45	6,100,300	3,611
1971	3	2,536,900	1,591	3,882,500	8,878	2,216,800	1,964	802,700	40	2,972,900	2,611
1971	4	4,028,100	368	1,420,400	2,450	815,900	314	1,005,400	340	1,059,600	341
1972	1	445,800	62	1,403,000	994	695,900	351	924,200	84	2,232,900	846
1972	2	1,522,000	222	1,288,700	2,712	602,500	627	372,100	56	6,553,800	3,799
1972	3	1,755,900	190	1,498,800	5,425	4,507,900	6,997	1,739,400	413	4,568,900	4,043
1972	4	1,300,200	84	1,291,200	1,496	523,600	254	1,881,000	389	126,000	11
1973	1	2,319,200	1,139	684,300	497	1,020,700	693	363,300	28	864,200	310
1973	2	2,276,700	169	1,054,200	1,868	2,335,100	3,788	170,100	16	3,883,600	2,251
1973	3	3,654,500	281	1,876,600	3,723	3,606,900	5,061	1,052,600	78	1,500,400	1,058
1973	4	1,901,700	199	2,733,700	1,763	414,100	225	836,300	95	2,500	0
1974	1	492,900	46	1,770,400	984	988,500	407	169,100	3	2,007,200	881
1974	2	1,216,100	174	1,921,700	2,436	1,642,800	1,627	303,300	21	3,711,200	2,329
1974	3	1,159,500	132	3,043,500	7,802	3,599,700	4,567	926,000	111	2,425,000	1,444
1974	4	2,043,300	351	2,488,100	4,452	178,400	120	636,300	64	361,600	98
1975	1	66,100	18	1,265,000	559	227,800	175	136,000	3	1,457,200	698
1975	2	291,300	28	968,100	2,133	848,000	1,043	79,500	3	2,473,200	1,689
1975	3	1,015,700	110	1,235,700	4,124	1,022,000	1,449	549,000	31	1,255,200	555
1975	4	3,033,000	346	972,900	648	5,200	0	2,848,800	290	17,800	25
1976	1	2,532,800	324	981,000	684	273,900	135	249,400	19	2,979,100	818
1976	2	543,100	63	798,000	1,233	675,300	705	87,600	19	8,693,600	3,135
1976	3	1,266,200	195	3,171,200	13,502	197,400	161	1,626,600	315	3,113,600	1,739
1976	4	1,595,800	253	669,400	2,351	27,900	5	1,484,200	222	0	0
1977	1	2,705,500	251	217,900	107	45,500	11	204,300	7	1,026,100	521
1977	2	1,657,400	199	239,000	219	652,200	1,034	382,300	45	3,071,500	1,914
1977	3	1,286,800	235	67,600	77	1,171,100	1,191	1,731,400	284	255,800	114
1977	4	2,813,100	429	478,800	336	2,600	0	1,339,400	153	131,800	53
1978	1	2,107,000	184	692,000	426	6,900	1	339,700	24	672,300	175
1978	2	1,291,300	254	433,600	503	1,714,900	2,271	674,400	90	7,300	2
1978	3	2,314,700	319	922,400	1,651	1,864,400	2,346	1,352,300	133	0	0
1978	4	2,892,800	541	1,056,600	1,002	32,600	9	1,386,400	123	9,100	4
1979	1	1,573,900	130	682,300	612	6,900	2	321,100	39	110,000	8
1979	2	1,825,300	190	998,900	1,318	1,355,100	1,716	538,000	32	4,024,200	2,675
1979	3	2,316,700	243	2,489,800	3,402	2,121,700	1,305	1,312,800	183	3,019,900	3,484
1979	4	3,046,200	514	2,244,500	2,548	34,300	12	1,581,100	274	129,900	78
1980	1	4,225,200	372	488,200	425	2,100	0	373,300	20	503,600	190
1980	2	4,930,300	617	843,300	1,475	1,197,400	1,727	1,109,500	109	6,674,300	2,096
1980	3	5,913,100	970	1,689,700	4,235	2,327,100	2,040	3,802,400	618	4,785,200	2,669
1980	4	7,381,600	1,704	1,930,000	3,722	23,800	2	2,738,900	337	435,900	258
1981	1	6,636,900	630	549,400	1,431	22,800	14	719,100	41	1,699,700	1,075
1981	2	7,915,500	1,556	1,903,200	1,988	846,900	402	1,107,700	1,377	7,648,100	5,698
1981	3	8,952,600	973	4,198,000	5,219	2,817,800	1,962	884,600	68	5,057,200	2,907
1981	4	10,590,500	1,793	2,920,600	2,974	25,000	7	2,635,400	231	153,100	92
1982	1	9,671,400	627	2,150,500	1,304	189,900	79	2,391,500	94	2,676,200	1,697
1982	2	6,931,100	428	2,688,800	2,984	1,108,600	811	3,983,400	1,271	7,522,000	5,355
1982	3	5,325,100	861	4,501,300	8,202	2,381,200	1,097	4,201,000	619	5,514,100	2,871
1982	4	4,740,500	1,200	3,316,300	3,801	0	0	1,694,800	413	106,100	223
1983	1	4,288,300	493	1,418,600	899	183,000	50	1,763,500	86	1,496,100	906
1983	2	3,841,300	500	1,879,300	3,054	1,063,200	824	584,800	72	6,084,300	2,645
1983	3	4,097,100	548	3,499,600	5,764	2,756,700	904	1,404,100	194	3,419,300	2,379
1983	4	4,777,700	530	1,237,300	633	17,700	1	3,419,800	334	36,300	3
1984	1	2,790,000	220	517,700	213	10,100	3	599,900	33	736,500	474
1984	2	3,840,300	266	2,208,100	2,450	908,800	498	1,229,500	119	3,335,600	2,793
1984	3	1,424,500	348	4,403,400	7,269	1,022,400	808	3,376,100	322	3,560,200	2,149
1984	4	3,836,700	2,035	1,044,600	2,185	0	0	2,024,900	312	61,400	222
1985	1	3,503,700	326	642,100	360	35,500	8	674,100	136	285,700	203
1985	2	3,982,500	560	2,391,400	3,056	487,900	1,186	1,922,300	222	1,963,000	1,726
1985	3	3,150,300	877	5,681,500	11,847	480,100	675	4,569,700	643	3,340,300	2,089
1985	4	4,219,900	941	899,700	1,119	0	0	6,309,700	953	0	0
1986	1	4,221,000	318	534,000	194	0	0	2,260,800	232	657,000	1,481
1986	2	3,326,000	796	1,900,600	4,238	622,200	594	1,562,900	254	3,619,700	5,773
1986	3	1,834,600	321	4,828,600	8,304	1,095,600	838	2,232,100	312	3,076,100	3,164
1986	4	2,276,300	453	771,500	648	0	0	184,300	23	271,500	247

Table E.1 (cont'd) Catch and effort data by year, quarter and region for the Japanese longline fleet in the Western Pacific Ocean

		Area 1		Area 2		Area 3		Area 4		Area 5	
Year	Qtr	Hooks	Catch	Hooks	Catch	Hooks	Catch	Hooks	Catch	Hooks	Catch
1987	1	947,100	141	313,700	152	66,300	25	120,900	26	1,149,500	1,818
1987	2	1,900	0	2,071,800	4,624	843,800	676	166,100	71	3,692,700	4,708
1987	3	277,700	32	4,935,800	7,972	645,200	291	1,605,400	242	4,652,900	3,140
1987	4	638,600	653	813,100	1,629	0	0	1,577,700	161	0	0
1988	1	2,636,500	432	1,195,700	440	26,500	5	2,573,000	166	178,300	195
1988	2	1,021,300	42	3,640,900	9,952	768,600	544	2,368,400	277	4,768,800	9,470
1988	3	3,016,800	668	7,727,300	8,523	1,037,200	606	2,577,900	1,276	3,709,400	2,289
1988	4	2,540,700	935	395,400	173	0	0	876,400	65	79,600	34
1989	1	1,380,300	272	1,151,400	836	0	0	1,824,400	211	138,300	230
1989	2	1,315,500	106	2,500,700	3,590	3,629,800	2,440	1,813,200	245	2,763,200	3,326
1989	3	2,179,300	485	8,640,000	9,208	1,576,600	726	3,481,600	410	1,901,000	1,543
1989	4	1,366,100	274	1,521,300	935	0	0	2,797,300	366	117,700	62
1990	1	2,122,200	281	608,300	222	0	0	754,100	98	199,200	227
1990	2	654,100	32	901,600	704	4,627,700	1,741	2,381,000	258	1,617,400	922
1990	3	731,800	372	8,300,400	8,111	941,600	411	2,936,200	262	4,561,600	5,469
1990	4	1,317,940	346	1,589,300	2,465	0	0	2,290,100	183	203,600	392
1991	1	1,189,500	46	402,200	90	0	0	1,274,300	145	233,300	128
1991	2	1,686,400	46	707,700	2,140	2,444,000	1,403	2,291,500	103	3,467,700	3,622
1991	3	977,800	75	5,342,600	9,983	1,451,400	700	1,264,600	190	3,325,400	2,030
1991	4	2,095,100	77	719,100	253	0	0	991,400	84	69,200	25
1992	1	186,100	28	537,300	158	24,700	9	740,700	67	115,300	206
1992	2	168,990	6	1,290,900	6,808	1,914,200	1,216	341,000	16	3,876,300	7,130
1992	3	1,274,400	87	5,727,000	7,848	2,671,700	1,462	1,733,600	281	2,412,400	996
1992	4	1,173,900	59	35,800	31	0	0	1,802,600	136	24,400	32
1993	1	650,614	87	669,200	543	164,700	93	1,068,000	59	397,200	464
1993	2	1,354,500	65	1,795,300	2,252	5,330,100	4,886	2,503,400	96	1,547,300	4,236
1993	3	4,226,720	1,153	5,930,200	4,971	104,700	43	5,978,800	358	591,500	315
1993	4	786,600	88	58,000	7	0	0	2,790,600	202	0	0
1994	1	1,213,858	102	646,700	573	214,200	110	1,463,400	88	329,400	256
1994	2	1,959,592	263	3,566,200	9,041	5,491,900	3,279	4,283,900	171	1,132,400	3,851
1994	3	4,331,352	999	4,712,500	4,826	125,600	39	7,681,900	617	268,200	140
1994	4	1,840,288	158	64,100	20	0	0	3,157,000	226	0	0
1995	1	2,669,115	240	848,528	537	183,416	78	2,464,113	324	381,013	1,081
1995	2	2,567,736	160	4,247,323	4,417	4,118,395	2,900	3,719,790	235	839,044	1,527
1995	3	2,905,452	215	5,083,805	3,729	147,149	125	4,461,761	346	1,117,330	1,147
1995	4	1,430,220	79	276,332	78	0	0	3,005,339	216	0	0
1996	1	317,566	15	1,436,594	1,716	190,550	139	1,173,251	59	328,485	454
1996	2	329,934	12	3,119,800	4,242	6,381,795	3,248	2,686,921	65	3,129,905	3,191
1996	3	673,908	692	4,495,062	4,700	332,389	75	2,270,894	89	1,788,896	2,415
1996	4	0	0	59,300	9	0	0	506,063	22	0	0
1997	1	0	0	514,702	480	142,489	74	357,705	20	533,274	408
1997	2	7,066	7	1,217,519	2,339	9,954,571	4,833	31,919	1	2,325,936	6,694
1997	3	1,301,678	582	5,960,445	5,631	712,848	300	1,756,822	64	480,468	433
1997	4	26,730	0	4,323	6	0	0	3,381,049	166	30,260	22
1998	1	0	0	1,385,249	705	55,920	15	1,318,222	77	379,554	159
1998	2	6,340	0	1,530,601	633	10,261,190	3,757	236,055	5	1,770,311	1,790
1998	3	589,815	49	2,599,424	2,534	1,847,197	723	3,150,997	353	2,736,380	3,392
1998	4	197,100	22	379,100	233	0	0	800,336	57	42,100	17
1999	1	0	0	610,850	327	55,000	26	21,437	1	283,950	80
1999	2	14,000	0	1,049,856	774	10,381,020	3,247	178,722	23	813,995	980
1999	3	44,590	6	1,214,400	1,257	2,382,273	1,289	1,269,259	201	1,972,936	995
1999	4	0	0	47,603	17	0	0	134,460	16	0	0
2000	1	56,585	3	491,840	126	9,750	6	290,550	16	207,990	194
2000	2	20,430	4	1,141,350	641	6,926,263	2,393	730,600	52	1,100,976	1,852
2000	3	3,276	2	76,798	27	1,396,604	549	6,908,266	869	466,366	127
2000	4	0	0	0	0	0	0	451,386	49	11,360	0
2001	1	12,000	1	171,240	31	0	0	126,890	19	154,720	34
2001	2	0	0	201,490	48	9,865,185	1,776	655,227	62	777,402	1,158
2001	3	2,800	0	1,501,900	606	1,516,211	441	3,837,155	409	1,680,590	817
2001	4	184,840	2	391,970	75	10,000	0	1,615,424	187	104,950	20

Table E.2 Quarterly effort (number of hooks) and swordfish catch (number of fish) within each spatial area of the operational model for the Australian and New Zealand longline fleets.

		Australia						New Zealand	
		Area 1		Area 2		Area 3		Area 5	
YEAR	QTR	Hooks	Catch	Hooks	Catch	Hooks	Catch	Hooks	Catch
1990	1	0	0	8,490	4	116,527	18		
1990	2	0	0	35,930	14	232,588	168		
1990	3	109,142	8	212,214	60	40,160	44		
1990	4	96,270	12	249,540	70	46,610	0		
1991	1	10,776	0	42,760	11	136,993	61	32,633	0
1991	2	13,808	0	28,941	47	567,973	460	28	0
1991	3	23,150	4	169,677	88	319,748	233	33,201	0
1991	4	34,610	0	230,687	66	105,736	11	1,638,332	454
1992	1	45,750	0	71,412	35	201,690	66	226,255	148
1992	2	48,950	3	22,518	11	485,639	295	275,798	196
1992	3	42,200	9	332,388	142	272,558	133	86,943	57
1992	4	28,350	0	272,515	123	271,280	18	35,912	0
1993	1	44,010	2	15,496	0	133,145	38	350,769	254
1993	2	54,660	55	19,545	1	373,344	240	917,268	741
1993	3	72,560	22	214,993	107	238,641	110	194,066	75
1993	4	80,270	0	173,950	23	243,592	11	265,894	191
1994	1	122,160	5	131,700	84	376,984	153	568,324	459
1994	2	134,680	18	97,822	124	493,735	364	654,091	606
1994	3	168,455	7	225,311	135	269,101	129	82,527	168
1994	4	189,455	5	194,080	91	335,060	23	209,027	75
1995	1	217,380	20	239,530	148	403,820	126	1,219,770	826
1995	2	227,533	26	256,122	131	640,533	264	343,707	295
1995	3	224,225	33	654,269	441	228,501	43	71,542	65
1995	4	200,220	20	286,496	138	189,738	5	503,444	150
1996	1	347,968	28	191,462	321	310,502	74	992,309	1,410
1996	2	284,074	173	260,905	665	800,681	648	607,607	590
1996	3	228,945	411	604,822	2,922	238,197	237	74,986	119
1996	4	147,210	55	592,682	3,507	482,743	24	362,156	102
1997	1	147,729	58	655,877	5,513	302,542	145	1,547,387	1,681
1997	2	199,925	104	802,131	4,494	886,069	830	1,215,905	1,545
1997	3	170,970	247	1,060,875	7,506	401,411	348	267,031	238
1997	4	206,125	91	1,082,508	8,039	260,512	56	887,496	125
1998	1	185,555	82	1,393,247	8,131	363,380	199	1,397,664	2,444
1998	2	269,850	319	1,337,475	6,725	966,914	1,212	1,298,923	3,052
1998	3	267,725	772	1,519,326	6,983	879,532	920	944,468	996
1998	4	198,388	140	1,790,322	9,331	484,970	142	1,233,749	637
1999	1	230,463	138	1,585,649	8,101	368,950	133	2,348,556	3,629
1999	2	309,250	944	1,464,732	5,491	898,396	721	2,064,940	4,680
1999	3	189,154	391	2,340,945	11,614	346,930	551	1,840,513	2,475
1999	4	168,170	546	2,025,031	10,986	274,190	142	2,304,289	1,241
2000	1	200,168	326	1,900,284	10,638	276,790	137	2,710,517	5,103
2000	2	221,526	467	1,556,225	7,179	491,500	826	2,030,238	4,614
2000	3	204,120	446	2,143,428	8,459	97,690	150	2,467,070	1,990
2000	4	245,386	362	1,961,146	8,469	206,895	87	2,301,913	1,266
2001	1	267,330	190	1,831,966	6,444	322,300	184	2,480,029	5,307
2001	2	333,140	594	2,113,213	5,870	364,708	559	1,949,011	4,931
2001	3	294,530	403	2,612,664	8,608	103,650	162	3,491,068	4,008
2001	4	311,389	467	2,516,386	9,233	147,820	68	2,209,093	1,544

Table E.3 Swordfish weight-frequency histograms (by percent) for the Australian fleet in Areas 1-3 by quarter.

	Area 1				Area 2					
Weight (kg)	quarter 1	quarter2	quarter 3	quarter 4	quarter 1	quarter2	quarter 3	quarter 4	quarter 1	qu
5	5.10	7.56	5.75	3.96	6.49	4.31	3.20	3.35	17.65	
15	13.73	18.81	18.18	17.29	14.35	15.23	13.31	11.61	19.31	
25	14.46	15.72	16.35	16.52	12.27	14.30	12.43	10.66	16.89	
35	13.85	12.41	13.06	12.22	10.99	12.14	12.21	10.49	12.97	
45	10.94	13.51	12.75	12.56	10.73	11.80	11.45	10.97	9.20	
55	11.42	10.20	9.67	10.46	9.90	11.35	10.55	10.37	5.13	
65	11.54	8.77	7.68	10.02	9.01	8.93	9.18	9.35	4.52	
75	6.08	4.80	5.90	6.50	7.60	7.12	7.65	8.21	5.13	
85	3.89	2.87	4.08	4.41	5.76	4.72	6.23	6.70	2.87	
95	4.62	1.43	2.46	2.64	3.99	3.22	4.29	5.11	2.87	
105	1.46	1.43	1.25	1.32	2.59	2.06	2.93	3.55	1.06	
115	0.73	0.72	1.20	0.88	1.82	1.38	1.80	2.62	0.75	
125	0.73	0.66	0.37	0.22	1.31	0.98	1.39	1.87	0.30	
135	0.61	0.61	0.42	0.33	0.93	0.54	0.86	1.25	0.45	
145	0.36	0.22	0.31	0.11	0.65	0.52	0.63	0.98	0.30	
155	0.12	0.17	0.05	0.00	0.57	0.44	0.55	0.76	0.30	
165	0.12	0.06	0.21	0.33	0.34	0.24	0.36	0.61	0.30	
175	0.00	0.06	0.16	0.00	0.23	0.17	0.28	0.41	0.00	
185	0.12	0.00	0.05	0.11	0.17	0.16	0.15	0.32	0.00	
195	0.00	0.00	0.05	0.11	0.13	0.13	0.18	0.29	0.00	
205	0.00	0.00	0.00	0.00	0.07	0.04	0.11	0.15	0.00	
215	0.00	0.00	0.00	0.00	0.03	0.04	0.07	0.11	0.00	
225	0.00	0.00	0.00	0.00	0.01	0.03	0.08	0.09	0.00	
235	0.00	0.00	0.00	0.00	0.02	0.04	0.05	0.06	0.00	
245	0.00	0.00	0.00	0.00	0.02	0.03	0.03	0.04	0.00	
255	0.00	0.00	0.00	0.00	0.01	0.03	0.02	0.03	0.00	
265	0.12	0.00	0.05	0.00	0.00	0.01	0.01	0.01	0.00	
275	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	
285	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	
295	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	
305	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
315	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	
Sample	823	1,813	1,914	908	24,706	17,829	24,736	28,360	663	

Table E.4 Swordfish length-frequency histograms (by percent) for Japanese and New Zealand fleets in region 5 by quarter.

	Japan		NZ	
Length	quarter 2	quarter 3	quarter 1	quarter 2
10	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00
30	0.00	0.00	0.00	0.00
40	0.07	0.00	0.00	0.00
50	0.00	0.00	0.00	0.00
60	0.00	0.00	0.00	0.00
70	0.14	0.00	0.00	0.00
80	0.21	0.17	0.61	0.61
90	0.43	0.44	1.84	1.23
100	1.42	1.57	4.60	3.07
110	2.98	3.59	7.67	5.52
120	3.55	7.35	8.28	4.91
130	7.10	7.00	7.98	7.98
140	5.68	6.82	7.06	3.68
150	6.10	8.22	7.98	8.59
160	7.59	10.41	7.98	7.98
170	8.59	11.81	10.43	9.20
180	8.59	9.97	7.36	8.59
190	8.45	10.94	8.28	9.20
200	6.67	6.30	5.52	9.20
210	7.45	5.95	6.75	7.98
220	7.74	3.94	3.07	6.75
230	6.74	2.27	2.15	2.45
240	4.47	1.75	1.53	1.23
250	3.34	0.87	0.31	1.23
260	1.99	0.26	0.31	0.00
270	0.21	0.26	0.00	0.61
280	0.28	0.09	0.31	0.00
290	0.21	0.00	0.00	0.00
300	0.00	0.00	0.00	0.00
Sample	1409	1143	326	163

Figure E.1 Annual time-series of effort used in the operational model. For Australian and New Zealand fleets nominal number of hooks is used, for the Japanese fleet effort has been standardized and adjusted to account for the catch by other fleets in the SW Pacific.

Figure E.1 (cont'd) Annual time-series of effort used in the operational model. For Australian and New Zealand fleets nominal number of hooks is used, for the Japanese fleet effort has been standardized and adjusted to account for the catch by other fleets in the SW Pacific.

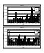


Figure E.2 Annual time-series of swordfish catch (number of fish) used in the operational model. The Japanese catch has been adjusted to account for the catch by other fleets in the SW Pacific.

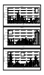
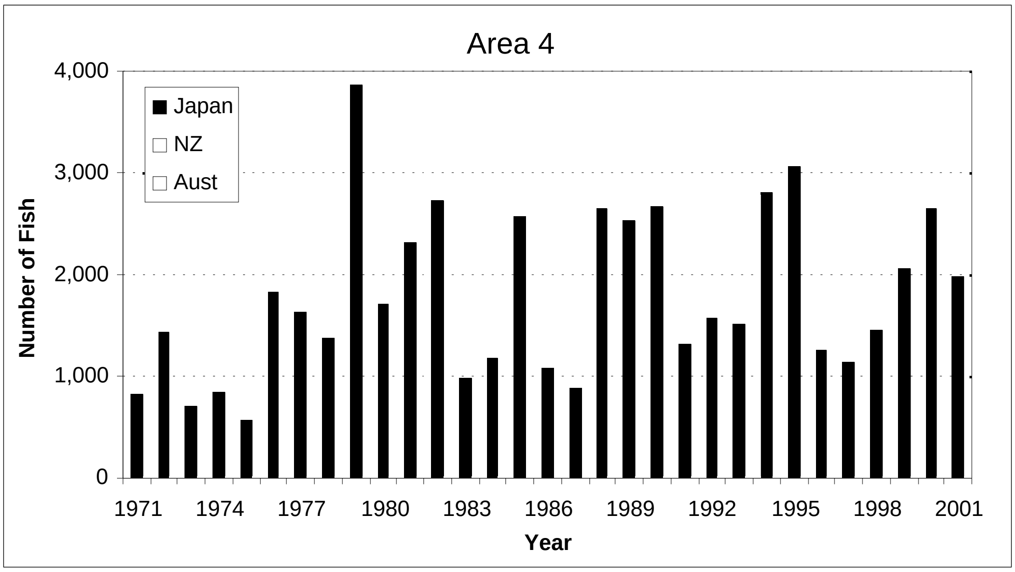
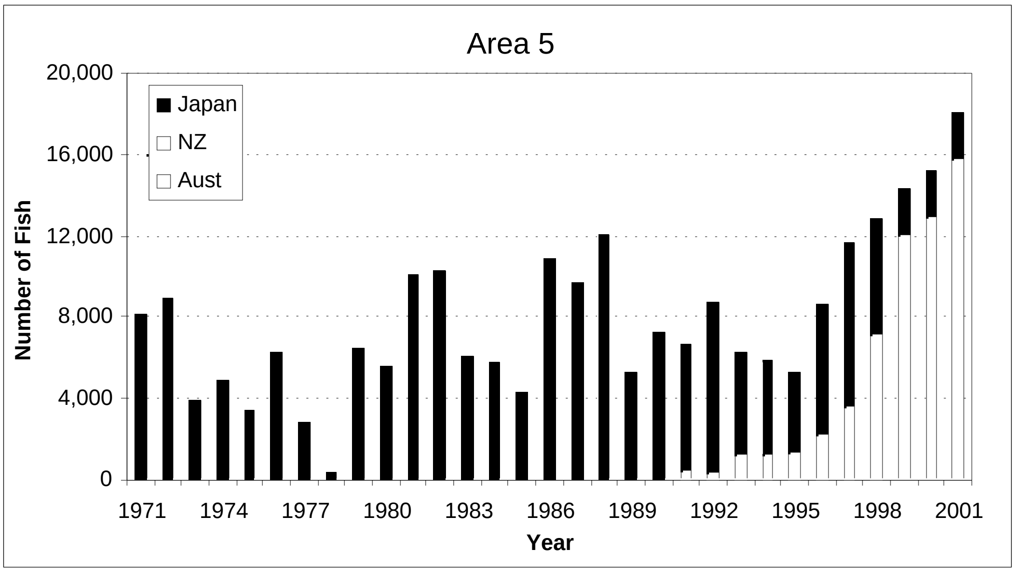


Figure E.2 (cont'd) Annual time-series of swordfish catch (number of fish) used in the operational model. The Japanese catch has been adjusted to account for the catch by other fleets in the SW Pacific.





Appendix F: Stanadardisation of Japanese Effort

The data used were the catch and effort data for the Japanese longline fleet aggregated by month, 1-degree square and stratified by the number of hooks-per-basket (hooks-between-buoys). The time series was for the years 1971-2000 and the spatial range was 140-180^{o}E, 0-45^{o}S. (Dr Naozumi Miyabe of the NRIFSF in Shimizu, Japan is thanked for providing this data.) A General Linear Model (GLM) was used to standardise the data. Briefly, the data for each quarter was standardised separately, with the model used for each quarter is as follows:

$$\log(CPUE+k) = Year*Five + Region*HPBcat + Region*SOIcat \qquad (F.1)$$

where CPUE = number of swordfish/10,000 hooks
k = 10% of the mean cpue for the entire fitted data set.
Five = 5x5-degree square of latitude and longitude
Region = one of six large regions shown in Figure F.1.
HPBcat = Hook-per-Basket category (see Table F.1)
SOIcat = Southern-oscillation-index category (see Table F.1)

Table F.1 Categorisations used in GLM model

Category	HPB	SOI
1	5	<-15
2	6	-15 to -5
3	7	-5 to +5
4	8-11	+5 to +15
5	>11	> +15

Using the GLM results for each quarter q, a biomass index for each year was calculated as follows:

1) For each region and year, a biomass index $B_q(year, region)$ is calculated by summing the standardised CPUE for that year across all the five-degree squares fished in that region, ie.

$$B_q(year, region) = \sum_{i=1}^{N5_{obs}(i)} \exp(Year * Five(i)) - k \qquad (F.2)$$

where $N5_{obs}(i)$ is the number of five-degree areas in region i fished during that year.

2) In order to account for the fact that not all five-degree squares in a region are fished each year, the index $B_q(year, region)$ is pro-rated to the maximum number of fives fished in any single year. In this manner, the index relates to the same spatial area each year:

$$B_q(year, region) = \frac{N5_{\max}(i)}{N5_{obs}(i)} \sum_{1=1}^{N5_{obs}(i)} \exp(Year * Five(i)) - k \qquad (F.3)$$

3) For each year, a total biomass index $B_{q,SWP}(year)$ for the entire SW-Pacific is calculated by summing the regional indices:

$$B_{q,SWP}(year) = \sum_{j=1}^{Nregions} B_q(year, region(j)) \tag{F.4}$$

4) There may be regions which are not fished in a given year and for which the calculation of $B_q(year, region)$ is not possible based on the above model. When this occurs, a proxy index for that region is calculated as follows: for each year, the maximum biomass index $B_{q,max}(year)$ across all fished regions is found, and the ratio of the index in each region relative to this maximum is calculated. The average of these ratios, $R_{avg}(region)$, is then calculated across all years for each region. Finally, when a region is not fished in any year, a proxy index for that region is estimated by

$$B_{q,proxy}(year, region) = B_{q,max}(year) * R_{avg}(region) \tag{F.5}$$

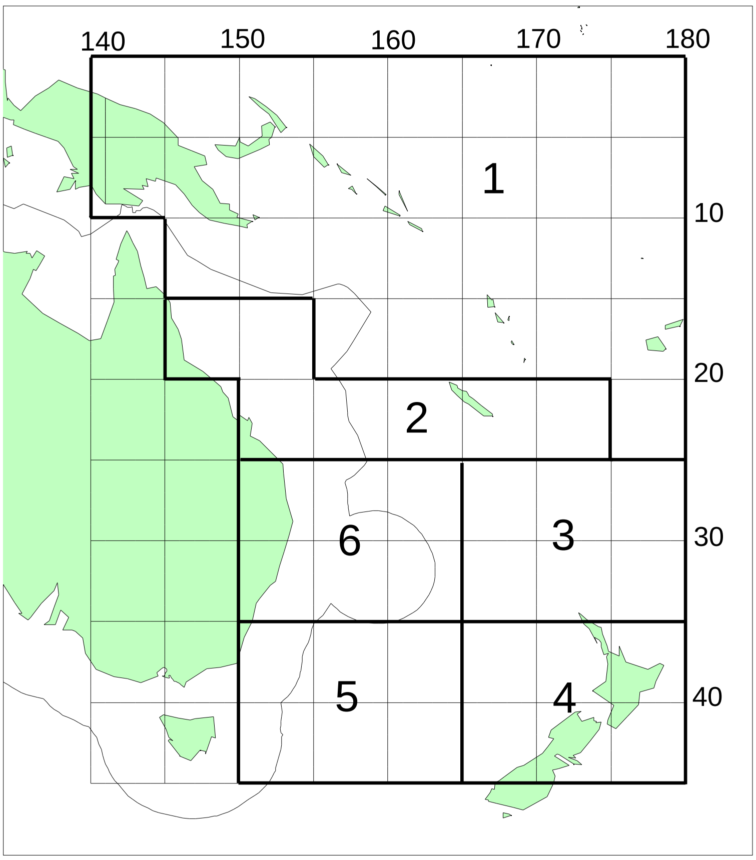


Figure F.1 Map of the SW-Pacific indicating the six regions used in the GLM model.

5) Finally, a total annual biomass index for the SW Pacific is calculated by taking the geometric mean of the quarterly indices for each year.

$$B_{SWP}(year) = \sqrt[4]{\prod_{k=1}^{4} \left(B_{k,SWP}(year)\right)} \tag{F.6}$$

Two problems arise in the above procedure. First, the goodness of the estimate of *B(year, region)* will be dependent on the number and spatial coverage of observations in that region in a given year. If the number of observations is small, or the spatial coverage limited, then the likelihood of the index being biased is increased. Second, the goodness of the estimate $B_{proxy}(year,\ region)$ will be dependent on the region having the maximum biomass being fished in that year. If this does not happen, then the index B_{proxy} will likely under-estimate the biomass in that region.

The data used in the GLM models was aggregated by 5-degree and month. The GLM-model was fitted to the data for each quarter of the year after which an annual biomass index for each quarter was calculated. A relative biomass index for each year, $B_{rel}(year)$, was calculated by dividing the index for each year by the average index for the entire time-series (this makes the average of $B_{rel} = 1$). A single index for each year was then obtained by taking the geometric mean of the four quarter-based indices. The nominal and standardized indices are shown in Figure F.2.

Figure F.2 Relative indices of swordfish biomass in the SW-Pacific based on the standardisation of Japanese longline catch rates.