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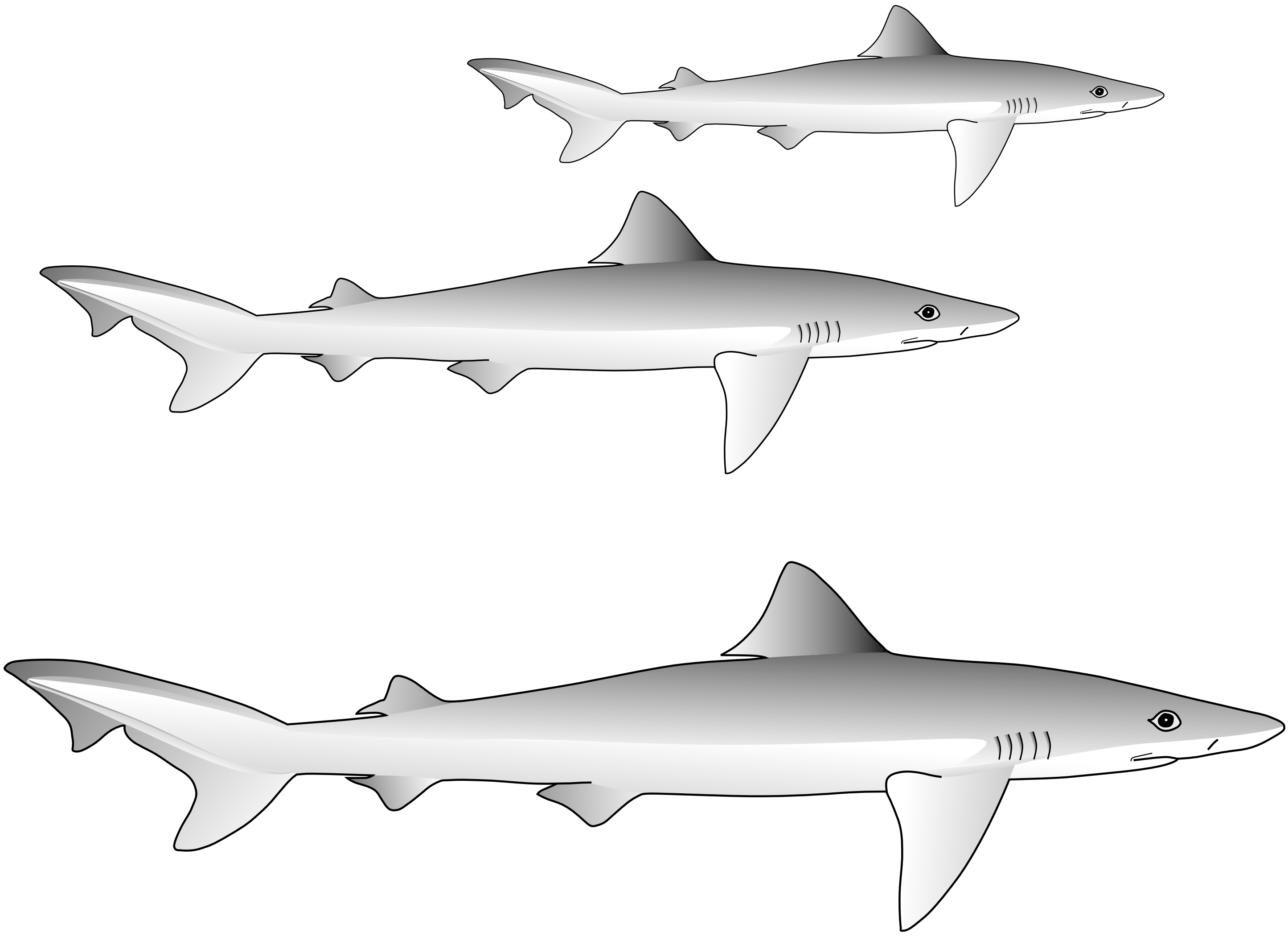

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2001

POPULATION MODELLING AND HARVEST STRATEGY EVALUATION FOR SCHOOL AND GUMMY SHARK

André E. Punt[1], *Fred Pribac*[1], *Terence I. Walker*[2], *Bruce L. Taylor*[2]

1- **CSIRO Marine Research, GPO Box 1538, Hobart, Tas 7001,Australia**
2- **Marine and Freshwater Research Institute, PO Box 114, Queenscliff, Vic 3225, Australia**

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Population Modelling and Harvest Strategy Evaluation for School and Gummy Shark

Punt, A.E, Pribac, F., Walker, T.I. and B.L. Taylor.

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PRINCIPAL INVESTIGATOR: Dr André E. Punt
ADDRESS: CSIRO Marine Research
GPO Box 1538
Hobart, TAS 7001
Australia
Telephone 03 6232-5492 Fax 03 6232-5000

OBJECTIVES:

1. To provide the information necessary for the development of an operational definition of ESD for gummy and school shark, in collaboration with SharkFAG, SharkMAC and AFMA.
2. To complete a spatially-structured stock assessment of gummy shark for use as the biological basis for an evaluation of harvest strategies for this species.
3. To provide SharkMAC and AFMA with an evaluation of the trade-offs associated with a range of harvest strategies for gummy and school shark.

NON-TECHNICAL SUMMARY:

OUTCOMES ACHIEVED

The Total Allowable Catch (*TAC*) for the gummy shark, *Mustelus antarcticus,* resource off southern Australia was set by the Board of the Australian Fisheries Management Authority (AFMA) based on the conclusion from the assessment that the populations of gummy shark in Bass Strait and off South Australia are currently above conventional target and limit levels. The Southern Shark Fishery Management Advisory Committee (SharkMAC) has actively discussed making the management objectives for the Southern Shark Fishery operational. The results of the harvest strategy evaluation calculations have focused discussions at SharkMAC and by the Southern Shark Fishery Assessment Group (SharkFAG) on the implications of trying to recover the school shark resource while simultaneously not reducing *TAC*s for gummy shark.

The populations of gummy shark in Bass Strait and off South Australia are assessed using a variant of the Integrated Analysis method of fisheries stock assessment. The assessment model is age- and sex-structured, takes account of the selectivity patterns of the gear types employed in the fishery and explicitly considers the peculiarities of the pupping process. The assessment made use of catch, catch-rate, length-frequency, age-composition and tagging data within a maximum-likelihood estimation framework. This assessment considered the period 1927–99 and is the first attempt to fit the length-frequency and age-composition distributions. The results confirm the value of including the length-frequency data in assessments of gummy shark as these data provide a basis for estimating year-class strength. There is therefore value in continuing to collect this type of data. Catch rate is found not to be related linearly to abundance as gear-competition is estimated to be substantial in Bass Strait and there is evidence that not all fish are equally available to the fishery.

Broadly, the results of the gummy shark assessment are consistent with those of earlier assessments as they indicate that the gummy shark populations are in a relatively healthy state with current pup production estimated to be in excess of conventional target and limit levels. Nevertheless, recruitment to the fishable stock (which comprises only a fraction of the total biomass) in Bass Strait is estimated to have been poor though recovering, while recruitment to the fishable stock off South Australia remains relatively poor at present. Even though none of the assessment scenarios considered suggest the resource to be biologically over-exploited, the quantitative results are nevertheless sensitive to values assumed for some of the parameters and the choice of data included in the analysis.

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

The Management Strategy Evaluation (MSE) approach is used to compare the performances of a variety of harvest strategies for gummy and school shark. The key steps in the MSE approach are to develop (operating) models that are used to represent the reality in the calculations, to develop measures to quantify performance relative to the management objectives for the fishery, and to select appropriate candidate harvest strategies.

The biological scenarios that underlie this evaluation of harvest strategies are based on the most recent assessments of gummy and school shark. However, these scenarios encompass a wider range of uncertainties than would normally be considered for an assessment, in order to identify harvest strategies that are robust to uncertainty. A key aspect of the evaluation is that TAC-related discarding is included in the analysis. This type of discarding will occur if the *TAC*s for school and gummy shark are mismatched, as might occur if attempts are made to rebuild the school shark resource while maintaining (or increasing) catches of gummy shark. A range of assumptions regarding future fishing practices that impact the extent of TAC-related discarding is considered. The extremes of this range are that fishers can modify their fishing practices to avoid any TAC-related discarding and fishing practices will remain essentially unchanged compared with the last five years. SharkMAC provided guidance regarding performance measures and also desirable properties of harvest strategies (frequency of *TAC* updates, and minimum and maximum *TAC*s). The actual harvest strategies considered in the project were based on production models, age-structured models and rates of change in survey results.

The harvest strategies that performed best were based on age-structured population dynamics models that included the selectivity patterns of the gears employed in the fishery, the peculiarities of the pupping process, and used all the available data (except future catch rate data) when estimating the parameters of the model. This is the approach currently used to conduct stock assessments for Southern Shark Fishery species. Nevertheless, none of the harvest strategies considered in this report perform well at allowing the school shark resource to recover in the short term. This is partly because of the poor status of the resource and the relatively low productivity of school shark, but it is also because of the interaction between gummy and school shark. Therefore, if fishers are unable (or unwilling) to modify their targeting practices to avoid TAC-related discarding of school shark, it may be necessary to reduce the catches of gummy shark to lower levels than would be appropriate if gummy shark was the target of a single species fishery.

This study identified several areas where further development work is necessary. The most important of these relates to the need for additional research on initial tag-loss / tagging mortality, the discard practices of fishers under ITQ management, and the productivity of school shark.

KEYWORDS: gummy shark, harvest strategy, Monte Carlo simulation, school shark, Southern Shark Fishery

1. INTRODUCTION

1.1 Background

In Australia, school and gummy shark are the main target species of the Southern Shark Fishery (SSF). Sharks are taken predominantly by demersal gillnets and longlines although some are also taken by other means such as trawl. Landings by the Southern Shark Fishery have varied between 2234 and 4226 (carcass weight) during the period from 1970 to 2000. However, the species composition of these landings has changed markedly over the past 10 years. In 1987, gummy and school sharks constituted 40 and 46%, respectively, of the total shark catch by the SSF, whereas, in 2000, these percentages were 69 and 11%, respectively.

The biology and basic demographics of gummy and school sharks have been studied since the 1940s (school shark) and 1970s (gummy shark) and are considered to be relatively well understood. Nevertheless, this understanding is far from complete as has been demonstrated by the considerable interest that the results of the recent archival tagging programme have generated by scientists and industry alike. Quantitative assessments for school shark stocks have been conducted since the 1950s and those for gummy shark stocks since the 1970s. The results of these assessments have often been controversial. For example, the 1991 assessment of gummy shark where a single stock was assumed suggested that this species was overexploited: a conclusion in conflict with industry observations. However, a re-analysis of the data for gummy shark by Dr Jeremy Prince where he assumed a series of spatially separate stocks (Prince, 1992) indicated that this species has been relatively stable for many years. The lack of agreement between the results of scientific assessments and industry perceptions for both gummy and school shark has meant that management decisions have not always been based on the most recent stock assessments.

Most of the stock assessment work in recent years has been directed towards conducting assessments of and providing management advice for school shark. This led, in April 1996, to a revised assessment of school shark by SharkFAG (Southern Shark Fishery Assessment Group). The results of this assessment, along with information on the likely implications of different future levels of fishing effort, were considered by the Southern Shark Fishery Management Advisory Committee (SharkMAC), which selected a harvest strategy for school shark. A harvest strategy is a set of rules that are used to determine management measures and is selected to achieve a desired trade-off among the management objectives using agreed sets of data. Following a review of the stock assessment of school shark by Dr Richard Deriso (Deriso, 1996), this harvest strategy was revised to allow a phase-in of the necessary reductions in catch. SharkMAC subsequently agreed that management of gummy and school shark stocks in the Southern Shark Fishery should be based on output controls.

The review of the April 1996 assessment by Dr Richard Deriso supported the view of SharkFAG that an assessment of school shark should ideally be based on a spatially-structured population dynamics model. Since 1996, therefore, SharkFAG developed a variety of aspects of a spatially-structured stock assessment for school shark. This work was completed in 1999 (Punt *et al*., 2000a).

1.2 Need

The harvest strategy for school shark recommended by SharkMAC after consideration of the November 1996 assessment needed to be revised. This is because the spatially-structured assessment of school shark represented a major change to the understanding of the dynamics of school shark stocks. The current harvest strategy was based on the results of an assessment (Punt and Walker, 1998) that accounted for spatial-structure in only an approximate manner. Other reasons for the need to re-evaluate the harvest strategy for school shark are that it was not selected with direct reference to AFMA's legislative objectives and that it does not explicitly define how additional information (e.g. additional catch rate data) would be utilised in the calculation of future Total Allowable Catches (*TAC*s).

No harvest strategy currently exists for gummy shark. This is one of the reasons that SharkMAC had some difficulties in recommending a *TAC* for 1998/1999 for this species. At its March 1998 meeting, SharkMAC requested that SharkFAG develop a harvest strategy for gummy shark.

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

1.3 Objectives

1. To provide the information necessary for the development of an operational definition of ESD for gummy and school shark, in collaboration with SharkFAG, SharkMAC and AFMA.
2. To complete a spatially-structured stock assessment of gummy shark for use as the biological basis for an evaluation of harvest strategies for this species.
3. To provide SharkMAC and AFMA with an evaluation of the trade-offs associated with a range of harvest strategies for gummy and school shark.

2. SPATIALLY-STRUCTURED ASSESSMENTS OF GUMMY SHARK

2.1 Introduction

Assessments of the populations of gummy shark (*Mustelus antarcticus*) in Bass Strait and off South Australia and Tasmania are needed to determine the current status of this resource relative to agreed target and limit reference points and as the basis for the evaluation of alternative harvest strategies. Assessments are conducted separately for each of these three regions for various reasons. For instance, tagging data suggest low rates of movement across the South Australia / Victoria border (Walker *et al*., 2000), there are differences in habitat among regions, and there appear to be differences in the proportion of gummy shark breeding in Bass Strait and South Australia (Walker *et al*., 1989). Other reasons for treating the populations of gummy shark in the two regions differently are not biological. For example, the existence of political boundaries and hence past management jurisdictions, differences in targeting practices over time (gummy shark have been targeted extensively using gill-nets in Bass Strait since the early 1970s whereas gummy shark have only recently become the prime target species in South Australia). Also, the difference in the types, amount and quality of data available for the different regions (negligible data available for Tasmania until very recently, whereas the data set for Bass Strait is extensive)

Assessments of gummy shark have been conducted historically using a wide variety of stock assessment methods, ranging from simple yield-per-recruit approaches (Walker, 1986) to applications of an age-structured production model approach that allows for density-dependence in the rate of natural mortality (Walker 1992, 1994a, b). These last assessments were based on age- and sex-structured population dynamics models that incorporate the selectivity patterns for the gears used in the fishery and peculiarities of the pupping process.

The previous age-structured assessments assumed that the natural mortality rate was density-dependent, ignored inter-annual fluctuations in pup survival, and used only a sub-set of the available information (catch rates and information on the mean weight (or length) of the catch) to estimate the parameters of the model. In contrast, in addition to estimating the values for the virgin biomass, B_0, and the magnitude of density dependence, the current assessments estimate the relative strengths of each of the year-classes during 1927–95 (the last year-class that has recruited to the fishery). In addition to using catch rate data, the assessments also make use of length-frequency, age-composition and tagging data. The assessment is therefore based on the 'Integrated Analysis' approach to fisheries stock assessment. This approach has been used in several assessments off southern Australia (e.g. Smith and Punt 1998; Punt *et al*. 2001a) because it is able to take a wide variety of data types into account and can provide the basis for conducting risk analyses.

The following sections outline the data available for assessment purposes, the population dynamics model, the estimation framework, and the results of the assessment. Assessments are presented in this Chapter for the populations of gummy shark in Bass Strait and off South Australia only. There are insufficient data to carry out an assessment for Tasmania. However, account is taken of the size and dynamics of the population off Tasmania (the area south of 41^0S) when evaluating harvest strategies (see Chapter 3). The methods and results presented below relate to the assessment of gummy shark presented to the Southern Shark Fishery Management

Advisory Committee (SharkMAC) in June 2000. Some of the specifications of the assessment were modified for the subsequent evaluation of harvest strategies for school and gummy shark (see Chapter 3).

2.2 The data for gummy shark.

The data available for assessment purposes include catches by gear-type (1927–98), catch-rates (1976–98), length-frequency data (1970–98), age-composition data (1986–87, 1990–93) and tagging data (1943–98). Each of these data sources is described in turn below.

The data are presented for ten ‘sub-regions’ off southern Australia: i) western Australia (WA), ii) western South Australia (WSA), iii) central South Australia (CSA), iv) eastern South Australia (SAV-W), v) far western Bass Strait (SAV-E), vi) western Bass Strait (WBas), vii) eastern Bass Strait (EBas), viii) western Tasmania (WTas), ix) eastern Tasmania (ETas), and x) New South Wales (NSW). These regions (Figure 2.1) were selected by the Shark Fishery Assessment Group (SharkFAG) on the basis of their physiography, the history of the fishery, movement patterns of gummy sharks inferred from tag release-recapture data, and the spatial distribution of the various age-classes inferred from available length-at-age and length-frequency data. The region Bass Strait comprises sub-regions SAV-E, EBas and WBas; the region South Australia comprises sub-regions WSA, CSA and SAV-W; and the region Tasmania comprises sub-regions WTas and ETas. Data are presented for sub-regions WA and NSW for information only – the data for these sub-regions are ignored when conducting assessments and evaluating harvest strategies.

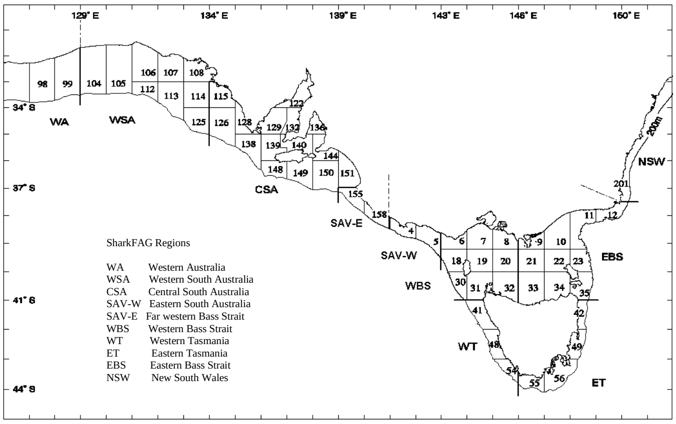

Figure 2.1 : Sub-regions of the Southern Shark Fishery.

2.2.1 Catch data

Catches of gummy shark are taken by several sectors and an assessment of gummy shark needs to be based on time-series of catches for each sector that takes a ‘substantial’ catch of gummy shark. The main commercial fishing sectors are the southern shark fishery (Commonwealth), the State fisheries for shark off Tasmania and South Australia, the South East Non-trawl fishery, the South East Trawl fishery, and the Great Australian Bight Trawl Fishery. Small quantities of gummy shark are taken within Victorian Territorial waters by fishing methods other than shark monofilament gillnets and shark longlines (Walker *et al.*, in press).

2.2.1.1 The directed shark fisheries (State and Commonwealth) and the Commonwealth non-trawl fishery

The catches of gummy shark by these fisheries by longline and mesh (6-inch, 6.5-inch, 7-inch and 8-inch) gears for 1927–72 and 1973–98 are listed in Tables 2.1 and 2.2, respectively. Taylor *et al*. (1996) describe the methods used to estimate the catches using longline and mesh gears for the years 1973–98. The data for the years 1973–98 are stored in the Southern Shark Fishery Monitoring Database (SSFMBD). The SSFMDB provides for data validation, checking and correcting for multiple reporting from fishers, for standardization of landed catch weights, and for reporting of data summaries for management, licensing, monitoring and research purposes. Landed catch weights of sharks are adjusted to ‘untrimmed carcass weight’ (i.e. beheaded and gutted shark with all fins attached); this is necessary because the fins are removed from the carcasses in some regions of the fishery.

The methods used to estimate catches for the years 1927–72 (Table 2.1) differ from those used to estimate catches for 1973 onwards (Table 2.2) because the early data were not recorded in a particularly systematic manner. The catches for three periods were assembled from different sources: 1927–56 from Olsen (1959), 1957–64 from annual summaries in *Fisheries Newsletter*, and 1965–72 from computer summaries prepared by the Australian Bureau of Statistics. The mean ratio of gummy shark to school shark (i.e. 3:7) from Victorian catch and effort data available for the period 1952–64 was adopted to split the combined school and gummy shark catch presented by Olsen (1959) for the years before 1952.

2.2.1.2 South East / Great Australian Bight Trawl fisheries

Table 2.3 lists the reported catches (kg) of gummy shark for the South East and Great Australia Bight trawl fisheries by year and sub-region. The catches by the SEF for 1991 to 1996 include estimated components of catches determined from the pro rata of catches reported as school and gummy shark combined. If some catches by species are available for years / sub-regions for which combined catches are also available, the split to species for the year / sub-region concerned is used to split the combined catch. If this is not the case, the split (by sub-region) of the total gummy to school catch over all years is used.

2.2.1.3 Catch series used in the assessments

There are at least three reasons why the historical catches of gummy shark may be in error (the deliberate mis-reporting during the ‘mercury ban’ in Victoria during 1973–85, general under-reporting, and reporting of ‘paper fish’ in anticipation of possible management actions). Therefore, in addition to a catch series based on the ‘best estimates’ of the historical catches, analyses are also conducted for an alternative series of historical catches. This series involves increasing the catches (all regions) by 15% (1927–79), 10% (1980–89) and 5% (1990–96) to reflect the last two sources of error. Industry advice at the May 2000 meeting of SharkFAG was that attempts to circumvent the ‘mercury ban’ in Victoria would not have led to mis-reporting of school as gummy shark in any substantial numbers.

2.2.2 Catch rate indices

2.2.2.1 Standardized catch and effort data

Figure 2.2 shows the sub-regions and statistical cells used for the analysis of the catch and effort data for the southern shark fishery. Catch rate indices are developed for

Bass Strait (sub-regions WBas, EBas and SAV-E) and South Australia (sub-regions WSA, CSA and SAV-W) only because of paucity of usable catch and effort data for the remaining sub-regions.

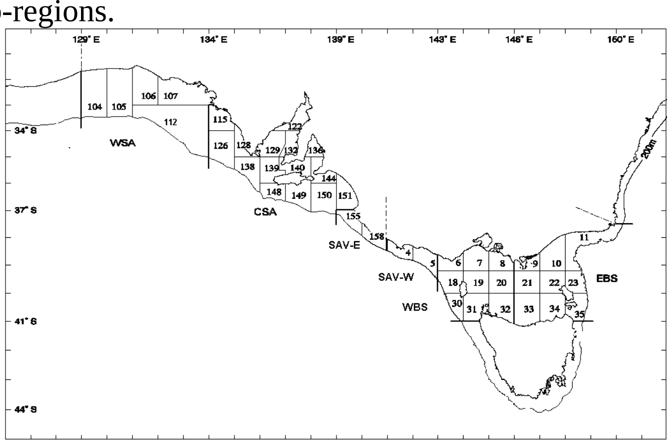

Figure 2.2 : Map of southern Australia showing the sub-regions and 42 statistical cells used when standardizing the catch and effort data.

2.2.2.2 Data utilised

The data were sourced from the SSFMDB for the period 1976–98. The information provided for each shot (or group of shots recorded as daily or monthly information) recorded in the database includes:

i) Unique vessel identification code
ii) Year
iii) Month
iv) Gear-type ('unknown', longline, 6-inch mesh, 6.5-inch mesh, 7-inch mesh, 8-inch mesh and 'unknown mesh')
v) Sub-region
vi) Catch
vii) Effort (gill-net metre lifts for mesh gear and number of hook lifts for longlines)
viii) Statistical cell (see Figure 2.2)
ix) Depth (divided into four depth-strata: 0-19m, 20-39m, 40-79m, ≥80m)
x) Catch rate of school shark.

All records for the same month, vessel code, statistical cell and depth stratum are combined into a single record. One reason for combining information from different shots in this way is the past practice by some skippers to total all their catches from several shots into the first entry in their log-book and record only fishing effort for subsequent entries. Another reason for combining data into monthly records is because in Bass Strait fishermen have provided daily records (prior to June 1978) and shot-by-shot records (after and inclusive of June 1978), whereas South Australian fishermen have provided daily or monthly records. Therefore, when reference is made to 'record', this refers to a monthly record (irrespective of the original resolution of the data).

Some of the records have to be rejected because either information about effort is not recorded, statistical cell is missing, or because the gear-type is 'unknown' or 'unknown mesh'. Table 2.4 gives the number of catch-effort records and the corresponding catch of gummy shark for each year for South Australia, Bass Strait and

Tasmania. The percentages of the annual catch of gummy shark unavailable for inclusion for each of the three reasons listed above are also given. Note that a record may be rejected for more than one reason. The column ‘Percentage accepted’ in Table 2.4 provides the percentage of the catch of gummy shark not subject to any of the three problems.

The percentage of the catch available for inclusion in the catch and effort standardization for South Australia drops from 96% in 1973 to only 4% in 1982, primarily because of lack of information on gear. Except for 1985 and 1997, the percentage of the gummy shark catch in South Australia available for use in the catch and effort standardization exercise exceeds 90% from 1984. The percentage of the catch that can be used for Bass Strait is less variable, ranging from 52% (1989) to more than 99% (1996). As is the case for South Australia, the percentage of useable catch-effort records for Bass Strait is less for 1997 than for 1996 or 1998. Except for the most recent four years (since the introduction of the new Tasmanian and subsequently the GN01 logbook), very little of the gummy shark catch from Tasmania can be included in a catch-effort standardization. It should be noted, however, that the Tasmanian catch has always been a relatively small (<20%) component of the overall catch of gummy shark and this has also been the situation for South Australia until 1996.

2.2.2.3 Selection of ‘indicative’ vessels

The SSFMDB contains records for over 2,700 vessels for the period 1976–98. However, the bulk of these vessels took catches of gummy shark only infrequently and consequently over 80% of the catch of gummy shark over this period was taken by only 170 vessels (Figure 2.3). For 1998, 389 vessels reported catches of gummy shark and of the total catch 80 and 95% respectively was taken by 53 and 100 vessels. The model used for the standardization exercise includes separate factors for each vessel. Including all of the vessels would lead to an unnecessarily over-parameterized model. It was decided therefore to base the catch-effort standardization on a subset of ‘indicative’ vessels. Four criteria were identified on which to select vessels for this purpose: i) the number of years in which the vessel recorded a catch ($Year_{crit}$), ii) the median annual catch of gummy and school shark combined ($Catchc_{crit}$), iii) the median annual catch of gummy shark ($Catchg_{crit}$), and iv) the fraction of the total catch of gummy and school shark that consists of gummy shark ($Ratio_{crit}$). Criteria i) and ii) restrict the analyses to vessels that have fished consistently for shark over several years while criteria iii) and iv) attempt to eliminate vessels that are primarily targeting school shark.

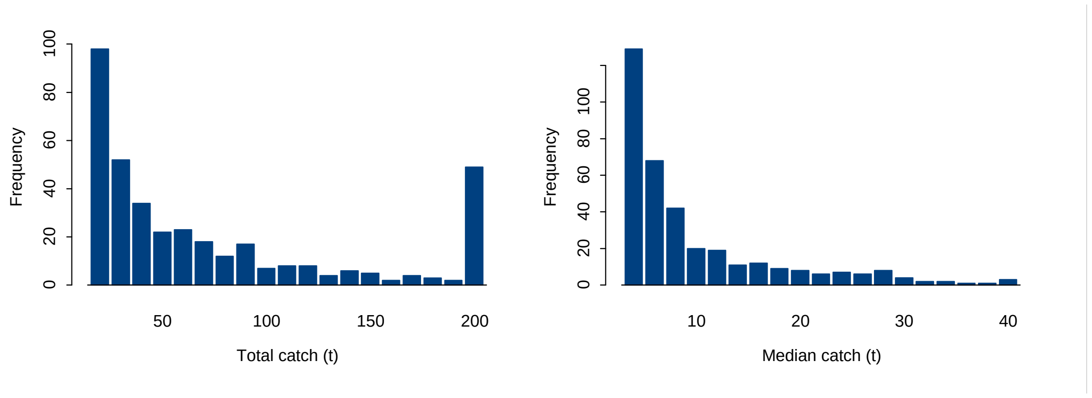

Figure 2.3 : Distribution of catches of gummy shark among vessels. The left panel shows the distribution of the total catches during 1976–98 and the right panel shows the distribution of the median catch over this period. The bars for total catch < 10*t* (2,332 vessels) and median catch < 2*t* (2,348 vessels) have been omitted to improve clarity.

The first three criteria are applied to the median catch over a time period rather than the annual catches to avoid problems caused by changes in density. In years when density (or availability) is low, even ‘indicative’ shark vessels will take small amounts of gummy shark, and may therefore be eliminated from consideration for those years. Examining the median catch over several years does not eliminate this problem completely, but should reduce it. The vessels included in the analyses are restricted further by imposing a minimum number of records (20 for the base-case analyses) and a maximum percentage of shots in South Australia in which the catch of gummy shark equals that of school shark (25%). This last constraint is imposed to eliminate fishers who do not attempt to divide their catch into species, noting that 50 : 50 splits of the catch are possible in some sub-regions (particularly EBas and WBas).

The analyses are constrained further to data obtained using 6-inch, 6.5-inch and 7-inch mesh gill-nets only. Data for longlines and other mesh sizes are not included in the analyses because of paucity of data for these gear-types. The data for the 6-inch, 6.5-inch and 7-inch gears are combined because 6-inch mesh gill-nets have not been used much in CSA and WSA while 7-inch mesh gill-nets have not been used much in the more eastern areas in recent years. The data for the WTas and ETas regions are ignored because they are known to be poor as there was no facility to record fishing effort data on returns received in Tasmania during 1979–87 (Table 2.4c).

The data are analysed separately for the South Australian region (sub-regions WSA, CSA, and SAV-W) and the Bass Strait region (sub-regions EBas, WBas, and SAV-E). This is because i) few vessels fish in both regions, ii) the mesh sizes used in the two regions differ, iii) useable data are only available from 1984 for the South Australian region, iv) the two regions may contain separate stocks, and v) targeting practices differ between the two regions.

The base-case analyses are based on data for 1976–98 because the data for 1973–75 may have been impacted by mis-reporting during the early part of the ‘mercury ban’ years. The base-case choices for the thresholds $\text{Year}_{\text{crit}}$, $\text{Catchc}_{\text{crit}}$, $\text{Catchg}_{\text{crit}}$, and $\text{Ratio}_{\text{crit}}$ were chosen to be 5, 10*t*, 5*t* and 0.6 respectively based on advice from SharkFAG. The $\text{Catchc}_{\text{crit}}$ and $\text{Catchg}_{\text{crit}}$ criteria are ignored for the South Australian Gulfs (cells 112, 129, 132 and 136) to increase the number of data points for this area. Instead, vessels that fish the Gulfs are included in the analysis if their median annual catch of gummy shark exceeds 2*t* and over half their historical catch of gummy shark came from the Gulfs.

Table 2.5 provides statistics that summarise the vessels selected using the base-case thresholds as well as seven alternative sets of choices. Statistics are also shown for analyses that increase the minimum number of records from 20 to 30 (Min_{rec}=30), base the standardization on data for 6-inch / 7-inch mesh gear only, include the data for 1973–75, and apply the 0.6 constraint on an annual basis (Annual 0.6 const). The base-case selection criteria lead to 61 vessels being selected. This corresponds to 18,295 records (or 12,455*t* of gummy shark – 34% of the total catch of gummy shark over the period 1976–98). For the South Australian region, 29% of the gummy shark catch during 1984–98 is included in the analysis, whereas for the Bass Strait region, 43% of the gummy shark catch during 1976–98 is included. The lower figure for the South Australian region is not surprising because the fishery in this region has been targetted primarily at school shark so much of gummy shark caught in WSA and CSA has been caught while vessels are targeting for school shark. The average number of years in the fishery for the 61 vessels is 14.0 years and their average median annual catch of gummy shark is 18.1*t*. The distribution of catches among the selected vessels is skewed with only 15 vessels recording median annual catches of 30*t* or larger (Figure 2.4). In contrast, the distribution of the number of years in the fishery is more symmetric. There are data for most of the statistical cell / year combinations for Bass Strait. However, the base-case values for the thresholds lead to insufficient data for South Australia to conduct a catch-effort standardization.

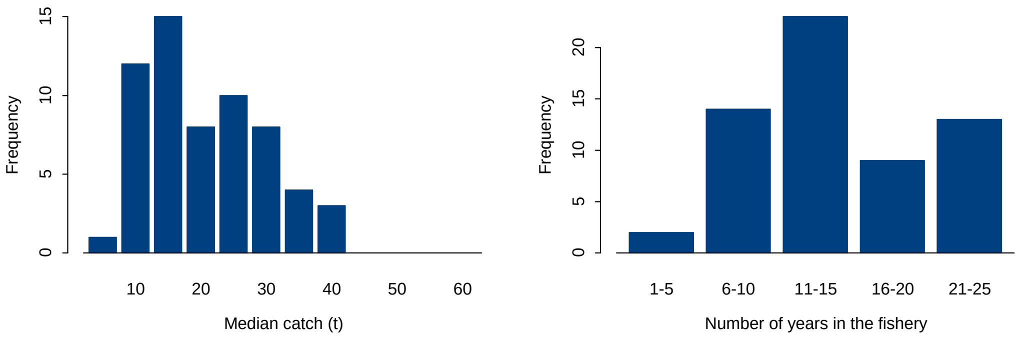

Figure 2.4 : Distribution of the median annual catch of gummy shark and the number of years in the fishery for the 61 vessels included in the base-case analysis.

Increasing $\text{Year}_{\text{crit}}$ from 5 to 10 eliminates 13 vessels but increases the average median annual catch of gummy shark from 18.1 to 18.7*t*. Increasing $\text{Catch}g_{\text{crit}}$ from 5*t* to 10*t* and then to 15*t* decreases the number of vessels from 61 to 50 and then to 35. However, changing $\text{Catchg}_{\text{crit}}$ from 5*t* to 15*t* leads to only a 17% drop in the total catch included in the analysis. Applying the 60% constraint on an annual basis leads to an increase in the number of vessels but to a decrease in the total number of records and the average median catch of gummy shark. Most of the catch of gummy shark has been taken using 6-inch mesh gear so the summary statistics in Table 2.5 for a 6-inch mesh gear only selection are almost the same as those for the base-case analysis. In contrast, restricting the analysis to 7-inch mesh gear only reduces the number of vessels markedly. Dropping the $\text{Ratio}_{\text{crit}}$ criterion (‘No 0.6 constraint’ in Table 2.5) increases the number of vessels from 61 to 86 and the catch of gummy shark by 25%. Unlike the base-case choices, this selection does lead to sufficient data for South Australia to justify the application of GLM techniques. For this reason all of the analyses for South Australia are based on the specification $\text{Ratio}_{\text{crit}}$=0, irrespective of how the data are selected for Bass Strait.

*2.2.2.4 Estimating year * statistical cell interactions*

The purpose of the catch-effort standardization is to obtain indices of relative abundance for each combination of year and statistical cell. This is achieved by fitting a model of the form:

$$\frac{C_{y,v,m,b}}{E_{y,v,m,b}} = e^{\mu+\alpha_{y,b}+....} \qquad \text{or} \qquad C_{y,v,m,b} = e^{\mu+\alpha_{y,b}+....}\, E_{y,v,m,b} \tag{2.1}$$

where $C_{y,v,m,b}$ is the catch of gummy shark by vessel v in statistical cell b during month m of year y,

$E_{y,v,m,b}$ is the effort expended by vessel v in statistical cell b during month m of year y,

μ is the global mean catch rate,

$\alpha_{y,b}$ is the factor for statistical cell b and year y, and

$\ldots$ represents other factors that influence the catch.

The factors that are included in the models are chosen from: a) year, b) month, c) vessel, d) statistical cell, e) depth, f) catch rate of school shark, g) the square of the catch rate of school shark, and h) year x statistical cell interaction. Analyses (not shown here) confirm that other interactions are insubstantial. A month factor is considered because some months lead to higher catch rates than others do. A year x statistical cell interaction is needed to capture the effect of catch rates in different parts of the fishery changing at different rates over the history of the fishery. A factor for each vessel is included in the model rather than attempting to characterise vessels by means of other variables (horsepower, tonnage, etc.) as was undertaken in several previous studies (e.g. Vignaux, 1994, 1996). This is because the efficiency of a vessel in this fishery at catching gummy shark depends more on the fishing master’s targeting practices, skill level and annual time commitment to the fishery than on the attributes of the vessel. The two school shark catch rate covariates are included to capture the dependence of the catch of gummy shark on the catch rate of school shark. The square term is included in order to examine whether the catch of gummy shark is related in a non-linear way to the catch rate of school shark.

The question of whether a catch rate is zero or not, and the size of a non-zero catch rate are treated separately (Punt *et al*., 2000b). For the purposes of this investigation, the non-zero catch rates are modelled using the Poisson, log-gamma and negative binomial error-models while whether the catch rate is zero or non-zero is modelled as a Bernoulli random variable (i.e. a binomial error-model is assumed when fitting to the data). Fitting to the data on whether the catch rate is zero or not, therefore involves specifying a model of the form:

$$g() = \mu + \alpha_{y,b} + ...$$

where g is the logit link function.

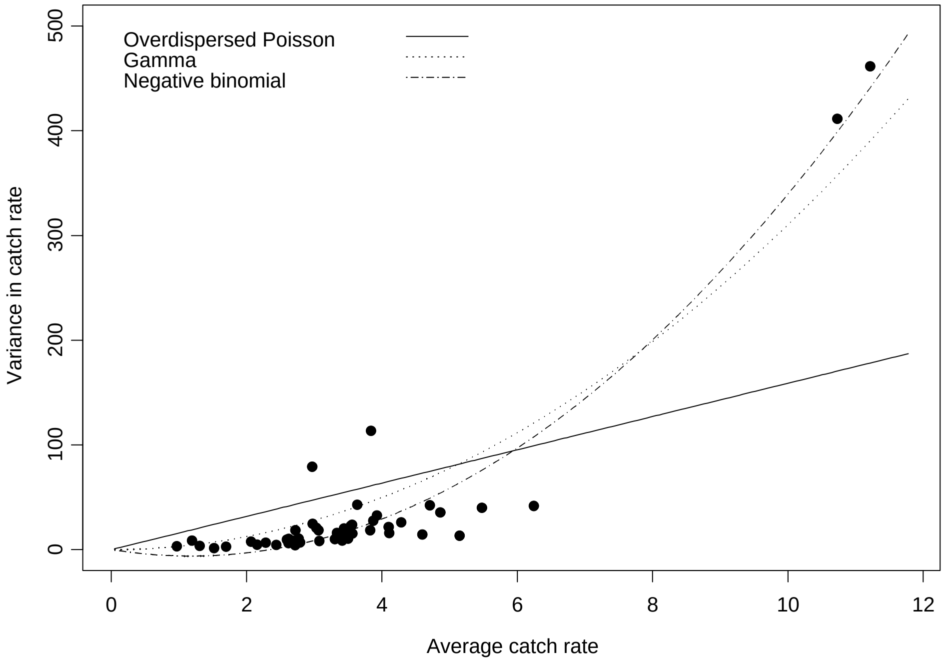

Figure 2.5 : Plots of the variance in catch rate against the average catch rate for Bass Strait. The solid line corresponds to the (over-dispersed) Poisson distribution, the dash-dotted line to the negative binomial distribution, and the dotted line to the log-gamma distribution.

The average catch rate and the variance of that catch rate for each vessel are shown for the Bass Strait region in Figure 2.5. A choice can be made among the Poisson, log-gamma and negative binomial error-models using the results in Figure 2.5 (Dong and Restrepo, 1996). If the (over-dispersed) Poisson error-model mimics the structure of the data, the variance in catch rate would fall along a straight line whereas if the log-gamma error-model fitted the data well, the variance in catch rate would be proportional to the square of the average catch rate. The negative binomial error-model assumes that the variance of catch rate is a function of both the average catch rate and the square of the average catch rate. The data are well approximated by the assumption underlying the negative binomial distribution. Therefore, the bulk of the analyses are based on this distribution.

2.2.2.5 Estimating regional indices of abundance

It is commonly assumed that the catch rate for a year and statistical cell is proportional to the fish density in that cell during that year. Therefore, if it is assumed that catchability is invariant across statistical cells (within separate regions) and time, a relative abundance index can be determined using the formula:

$$I_y = \sum_b A_b I_{y,b} \tag{2.2}$$

where I_y is the relative abundance index for year y,

$I_{y,b}$ is relative abundance index for year *y* and statistical cell *b*, and
A_b is the size of the available area of statistical cell *b*.

By definition, A_b is the area in which gummy shark could potentially be found. For this study, A_b is taken to be the area of each cell between 20 and 80 m. The sensitivity of the results to defining A_b as the area of each cell shallower than 200 m is considered in one of the tests of sensitivity. It is plausible that the size of the available area in some cells may have changed over time due to fishing-induced habitat modification but this cannot be accounted for quantitatively without a much better understanding of the habitat requirements and distribution patterns of gummy shark.

The value for $I_{y,b}$ is computed by multiplying the probability of a non-zero catch by the expected catch rate given that the catch is non-zero. This is achieved using the equation

$$I_{y,b} = V_{y,b} e^{\hat{\alpha}_{y,b}} \tag{2.3}$$

where $\hat{\alpha}_{y,b}$ is the estimate of $\alpha_{y,b}$ (see Equation 2,1),
$V_{y,b}$ is the probability of a non-zero catch in statistical cell *b* during year *y*, and is computed using the equation:

$$V_{y,b} = \frac{e^{\phi_1+\phi_{2,y}+\phi_{3,b}+\phi_{4,v}+\phi_{5,m}}}{1+e^{\phi_1+\phi_{2,y}+\phi_{3,b}+\phi_{4,v}+\phi_{5,m}}} \tag{2.4}$$

ϕ_1 is the intercept of the binomial regression,
$\phi_{2,y}$ is the binomial factor for year *y*,
$\phi_{3,b}$ is the binomial factor for statistical cell *b*,
$\phi_{4,v}$ is the binomial factor for vessel *v*, and
$\phi_{5,m}$ is the binomial factor for month *m*.

The reference vessel used for the calculations is the one with the most records. The reference month *m* is taken to be October.

Application of Equation (2.3) is not completely straightforward because values for $\hat{\alpha}_{y,b}$ and hence $I_{y,b}$ are not available for all statistical cells and years. For those combinations of statistical cell and year for which estimates of $\alpha_{y,b}$ are not available, $I_{y,b}$ is obtained by applying the following algorithm:

a) The rule used to specify $I_{y,b}$ if GLM estimates are not available for statistical cell *b* for any year prior to year *y* is:

$$I_{y,b} = \frac{\sum_{highest 3} I_{y_*,b}(y_* - y)^{-2}}{\sum_{highest 3} (y_* - y)^{-2}} \tag{2.5}$$

where $\sum_{highest\,3}$ indicates summation over the three highest catch rates.

b) If GLM estimates are available for statistical cell *b* for at least one year prior to year *y* but not thereafter, $I_{y,b}$ is set equal to the arithmetic average catch rate for the last three years for which GLM estimates are available.

c) If neither rule a) nor b) is applicable then GLM estimates are available for earlier and later years than year *y*. The value for $I_{y,b}$ is then set from the results of a linear regression of the GLM estimates for the two years before and after year *y* (one if two estimates are not available) on year.

The model fitted to the data on whether the catch of gummy shark is zero or not includes only the main effects (year, month, vessel and statistical cell). It explains 17% of the deviance for the Bass Strait region and 24% for the South Australian region. Figure 2.6 plots the observed versus expected fraction of records with non-zero catches (constructed by sorting all of the observed and predicted values on the predicted value, grouping the data into bins based on the predicted value, and computing the average observed values). This figure suggests that the model fits the data fairly well. This is, however, somewhat misleading because there is substantial variation about the fit (the model explains only a relatively small fraction of the overall deviation). Including depth when standardising the non-zero catch rates for Bass Strait improves the percentage of the deviance explained by 0.3% while including the catch rate of school shark and its square leads to almost no improvement in the fit of the model to the data.

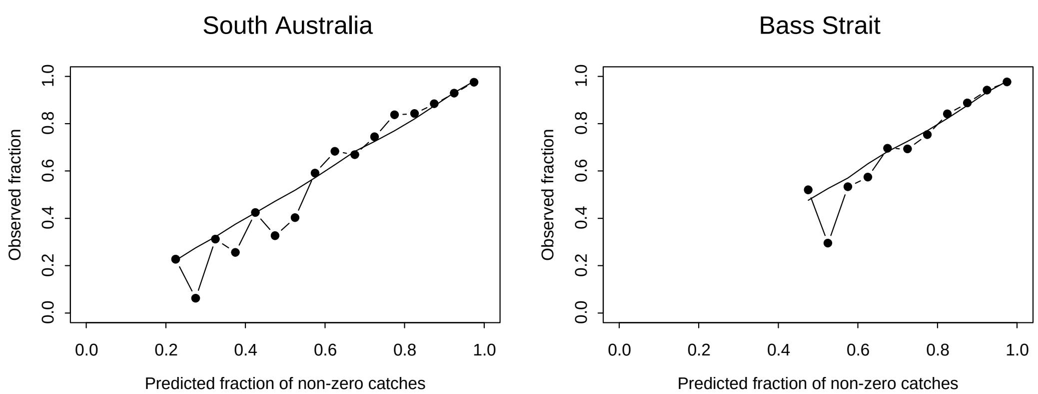

Figure 2.6 : Observed fraction of records with non-zero catches of gummy shark *v.* model predicted values. Results are shown separately for the Bass Strait and South Australian regions. Results based on less than 20 data points have been omitted from this figure.

Figure 2.7 shows trends in standardized catch rate for the WSA, CSA, SAV-W, SAV-E, WBas and EBas sub-regions as well as for South Australia (WSA, CSA and SAV-W combined) and Bass Strait (WBas, EBas and SAV-E combined). The results in Figure 2.7 are based on assuming that the errors are distributed according to the negative binomial model, as discussed above. It was not necessary to apply rule b) in Bass Strait. However, catch rates are not available for South Australia for 1998 for cells 122 and 136 (Table 2.6). For South Australia, rule c) was applied 14 times and rule a) 16 times (implying that catch rates are available for 90% of the cell-year combinations for South Australia). For the Bass Strait region, rule c) was applied 16 times and rule a) seven times (i.e. catch rates are available for 95% of the cell-year combinations for Bass Strait). A large fraction of the missing catch rates are for the SAV-W and SAV-E sub-regions (16 of the 57) and the South Australian gulfs (23 of the 57).

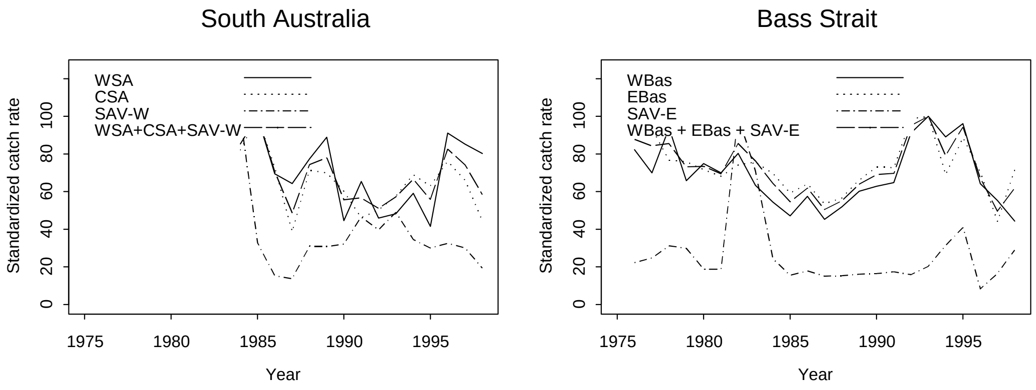

Figure 2.7 : Base-case time-trajectories of standardized catch rate for Bass Strait and South Australia. The results in this figure are based on the negative binomial error model.

The standardized catch rates for the WBas and EBas sub-regions exhibit similar trends. The catch rates for these sub-regions drop below the 1976–83 average from 1984–90 and then increase to above this average during 1991–94 (Figure 2.7). The 1997 catch rate is the lowest in the time-series for the EBas sub-region while the 1998 catch rate for the WBas sub-region is the lowest encountered to date. The catch rates for the SAV-E sub-region were highest in 1982 and 1983 but have generally been stable. The catch-rate for the WSA and CSA sub-regions drops during 1984–86 levels to a minimum in 1991–93 and increases somewhat thereafter (Figure 2.7). Catch rates in all three South Australian sub-regions drop during 1996–98.

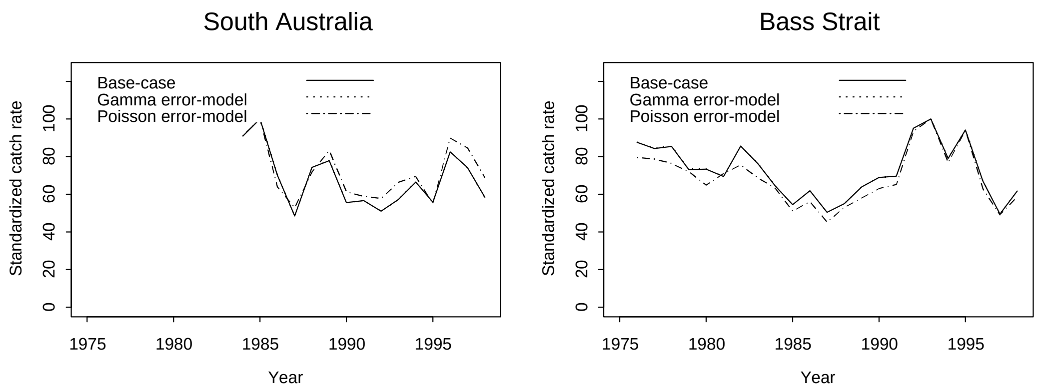

Figure 2.8 : Sensitivity of the annual indices of abundance for gummy shark to changing the error model assumed when applying the General Linear Model.

The catch rate indices for Bass Strait and South Australia (Table 2.7) are insensitive to changing the error model from the negative binomial to the gamma or the Poisson models (Figure 2.8). In addition, a variety of sensitivity tests to the results in Figure 2.7 were conducted, and the results for some of these are reported in Figure 2.9. There is, however, very little sensitivity evident in Figure 2.9 suggesting that the values for the thresholds, and the method used to define area (i.e. A_b in Equation 2.2) do not impact the results noticeably. The trends in standardized catch-rate over the years 1976–98 for Bass Strait for the sensitivity test that includes the 1973–75 data are almost identical to those for the base-case analysis.

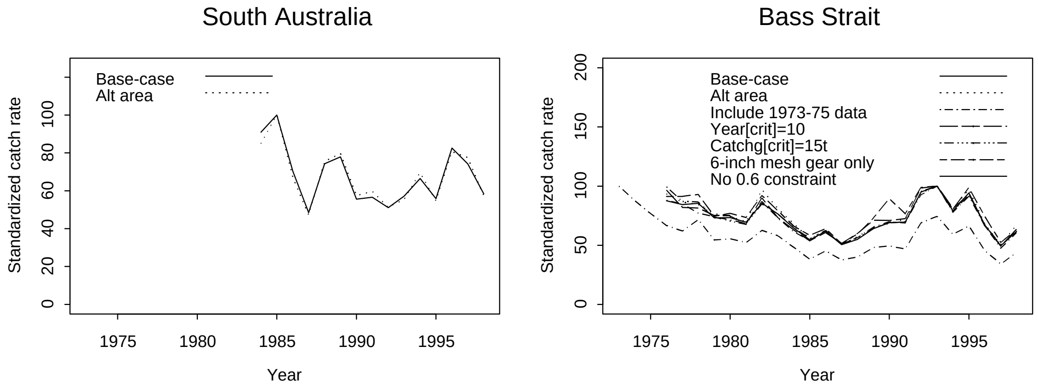

Figure 2.9 : Sensitivity of the annual indices of abundance for gummy shark to changing the thresholds used to select the data.

2.2.3 Tagging data

Sharks were tagged and released in the Southern Shark Fishery during 1947–56, 1973–76 and 1990–99[1]. Most were school and gummy sharks but small numbers of 26 other species of sharks, rays and a chimaera were also tagged. The available tag release-recapture data have been consolidated in the Southern Shark Tag Database developed in Microsoft ACCESS as part of two recent FRDC projects (Walker *et al.*, 1997; Brown *et al.*, 2000; Walker *et al.*, 2000). The database is routinely updated with tag recaptures.

Of the gummy sharks tagged and released during 1947–56, 363 were double tagged with an external Petersen disc tag and an internal tag while 223 were tagged only with an internal tag. Of these, 60 (10%) have been recaptured and reported by fishers. The last one was during 1969 after 14.7 years at liberty. During 1973–76, 1525 gummy sharks were tagged with internal tags of which 380 (25%) had been recaptured by the end of 1999. The last one was in 1987 after 12.6 years at liberty. During 1990–99, gummy sharks were tagged with roto-, jumbo, dart and other tags. Of the releases, 12% were double tagged for estimating tag-shedding rates and 29% were injected with the vertebra-marking tissue-dye oxytetracycline for validating ageing methods.

It is necessary to specify a tag-shedding rate for each tag-type and tag-reporting rates for each combination of year, tag-type and sub-region / region of recapture to include the tagging data in the assessment.

2.2.3.1 Tag-shedding rate

Rototags and jumbo tags attached to the anterior lower portion of the first dorsal fin of sharks during 1990–99 were highly successful with low shedding rates. Similarly, internal tags inserted into the coelomic cavity of sharks during 1947–56 and 1973–76 were successful in that they were not shed. However, they were not always seen by

[1] The tagging data for 1999 are commented on in this section but not included in the assessments, the terminal year for which is 1998.

fishers when the sharks were caught. Peterson disc fin tags attached to the first dorsal fins during 1947–56 and nylon-headed dart tags inserted into dorsal muscle tissue had very high shedding rates. Inserting nylon-headed dart tags into the cartilage at the base of the first dorsal fin during 1990–99 rather than in the dorsal musculature reduced the shedding rate.

Tag shedding rates were addressed through double-tag experiments as part of the tag projects. Table 2.8 lists the various tag-types represented in the tagging database. Xiao *et al*. (1999) describe a general approach for estimating the rate of tag-shedding from the results of a double-tagging experiment. Table 2.9 lists the tag-shedding rates for the tag-types for which the methods outlined by Xiao *et al.* (1999) allow reliable estimation. The results in this table are based on data up to the end of June 1998. Results are shown in Table 2.9 for separate analyses based on the assumption that the tag-shedding rate is sex-specific and on the assumption that it is the same for males and females. The negative log-likelihoods in Table 2.9 suggest that the tag-shedding rates for males and females can be assumed to be the same.

2.2.3.2 Tag-reporting rate

Two methods: (a) the ‘tag reporting rate from catch method’ (TRRC Method) and (b) the ‘tag reporting rate from tags per unit catch method’ (TRRT Method) have been applied to data for gummy and school shark combined (Brown and Walker, 1999). Application to the combined data set is based on the assumption that the tag-reporting rate should be independent of species (but dependent on sub-region and time). Table 2.10 lists the estimates of tag-reporting rates for the five sub-regions for which sufficient data are available (the results for SAV-E and SAV-W have been pooled). Results are shown for 1973–78 and 1994–96 for the WBas and EBas sub-regions and 1994–96 for the remaining sub-regions.

2.2.4 Length- and age-composition data

Length-frequency and sex composition data for commercial gummy shark landings have been collected routinely by a team of part-time fish measurers operating in several fishing ports and regional fish processing plants in Victoria during 1970–98 and South Australia during 1973–76 and 1986–98. Total length was measured for each shark sampled at sea and the partial length from the fifth gill-slit to the base of the tail was measured for each shark sampled from commercial landings. A small proportion of the data have been collected at sea. Data from samples of 40–150 sharks (less in the case of very small catches) are stored in the Southern Shark Fishery Monitoring Database. Within this database, the samples can be matched by vessel distinguishing mark and date of landing with fishers’ catch and effort data to assign samples to sub-region, fishing gear and, for some samples, fishing depth-range.

The numbers of sharks measured annually by gear-type, sex, and sub-region are listed in Table 2.11. The sample sizes for longlines and 8-inch gill-nets are small (generally less than 100 fish per annum). Therefore, the assessment is based solely on the data for 6- and 7-inch mesh (Bass Strait) and 6.5- and 7-inch mesh (South Australia). Length-frequency data are available for each sub-region separately. Therefore to construct length-frequencies by region, the data by sub-region were combined after weighting by the corresponding catch (Table 2.12). For Bass Strait, the 6-inch mesh length-frequency data for 1984, 1985, and the years prior to 1974 and the 7-inch mesh length-frequency data for the years after 1974 are not included in Table 2.12 and the assessment. This is because the length-frequency data for 1984 and 1985 are known to be unreliable and the sample sizes for the other years are small.

Length-at-age data are available for gummy sharks sampled from Bass Strait (1973–75, 1986–87, and 1990–93), South Australia (1986–87 and 1990–93), and Tasmania (1990–93). The numbers of sharks for which age estimates are available by year, gear-type, sex and region are listed in Table 2.13. The sample sizes for 1973–75 are very small and the data for these years are consequently not included in the assessment. Table 2.14 lists the age-composition data actually included in the assessment.

2.3 Method of assessment

2.3.1 The population dynamics model

The population dynamics model upon which the assessments are based is a variant of that applied by Punt and Walker (1998) to assess the school shark (*Galeorhinus galeus*) resource off southern Australia. The differences between the models relate to the form of the relationship that determines the number of pups per pregnant female, relaxation of the assumption that all animals are equally available to the fishery, allowance for more flexible density-dependence relationships, and the fact that account is taken of variation in length-at-age.

2.3.1.1 Basic Dynamics

The population dynamics of gummy shark are assumed to be governed by the equation:

$$N_{g,t+1,a} = \begin{cases} N_{g,t+1,0} & a = 0 \\ (N_{g,t,a-1}e^{-M_{t,a-1}/2} - C_{g,t,a-1})e^{-M_{t,a-1}/2} & 1 \le a < x \\ N_{g,t,x-1}e^{-M_{t,x-1}} - C_{g,t,x-1}e^{-M_{t,x-1}/2} + N_{g,t,x}e^{-M_{t,x}} + C_{g,t,x}e^{-M_{t,x}/2} & a = x \end{cases} \quad (2.6)$$

where $N_{g,t,a}$ is the number of fish of age a and sex g (g=1 for females; g=2 for males) at the start of year t,

$M_{t,a}$ is the instantaneous rate of natural mortality on fish of age a during year t,

$C_{g,t,a}$ is the catch (in number) during year t of fish of age a and sex g:

$$C_{g,t,a} = \sum_j C_{g,t,a,j} \quad (2.7)$$

$C_{g,t,a,j}$ is the catch (in number) during year t by gear-type j of fish of age a and sex g, and

x is the maximum age considered (treated as a plus group) - taken to be 30.

2.3.1.2 Pup production

The expected number of pups in a given year depends on the number of mature females, the frequency of pregnancy, and the number of pups (taken here to be the same as the number of embryos) per pregnant female. The latter two quantities are taken to be functions of age. The total number of pups of sex g at the start of year t+1 is given by:

$$N_{g,t+1,0} = \Phi_g \, Q_{t+1} \, \Gamma_{t+1} \, e^{\varepsilon_{t+1} - \sigma_r^2/2} \tag{2.8}$$

where Φ_g is the fraction of pups that are of sex g (taken here to be 0.5),

Q_t is the density-dependent factor that multiplies the number of births during year t,

$$Q_t = 1 + \max\{(Q_0 - 1)[1 - D_t / D_0], 0\} \tag{2.9}$$

Q_0 is the parameter that determines the magnitude of density dependence,

D_t is the size of the component of the population on which density-dependence acts at the start of year t, either the number of pups produced during year t, Γ_t:

$$\Gamma_t = \sum_{a=1}^{x} P_a^{'} \, P_a^{''} \, N_{1,t,a} \tag{2.10}$$

or the total (1+) biomass at the start of year t, B_t^{1+}:

$$B_t^{1+} = \sum_{a=1}^{x} \sum_{L} \sum_{g} w_{g,L} \, \Phi(g, a+1/2, L) \, N_{g,t,a} \tag{2.11}$$

ε_t is the logarithm of the ratio of the expected and actual number of pups,

$$\varepsilon_t \sim N(0; \sigma_r^2)$$

σ_r is the standard deviation of ε_t (assumed to be 0.4),

$P_a^{'}$ is the number of pups per pregnant female of age a,

$P_a^{''}$ is the proportion of females of age a that become pregnant each year,

$w_{g,L}$ is the mass of a fish of sex g in length-class L, and

$\Phi(g, a, L)$ is the fraction of animals of age a and sex g that are in length-class L.

The subscript 0 in Equation (2.9) indicates an evaluation of D at the pre-exploitation equilibrium level. Equations (2.9) and (2.10) assume that all of the density dependence occurs on the mortality between birth and age one, in which case Q_0 is the expected ratio of the pup survival rate in the limit of zero population size to that at unexploited equilibrium. The ε_t term allows for ‘process error’ in the dynamics of the population by permitting the actual number of pups to differ from the value predicted from the deterministic component of Equation (2.9). A reason for incorporating process error is inter-annual variation in pup survival. The magnitude of process error is determined by the value assumed for σ_r. The choice for σ_r of 0.4 is largely arbitrary and was chosen to be lower than the values for this parameter typically assumed for teleost fish (e.g. Beddington and Cooke, 1983) but greater than that assumed for school shark by Punt and Walker (1998).

The number of pups (actually embryos) per pregnant female of age *a* (total length $\lambda_{1,a}$) is given by:

$$P_a^{'} = \begin{cases} 0 & \lambda_{1,a} < 995\text{mm} \\ e^{a'+b'\lambda_{1,a}} & \text{otherwise} \end{cases} \tag{2.12}$$

where *a'* and *b'* are the parameters that govern the relationship between total length and number of pups per pregnant female.

The proportion of female sharks of age *a* (total length $\lambda_{1,a}$) that are pregnant each year is given by:

$$P_a^{''} = P_{\max}^{''}\left(1+\exp(-\lambda n(19)\frac{\lambda_{1,a}-\lambda_{50}^{''}}{\lambda_{95}^{''}-\lambda_{50}^{''}})\right)^{-1} \tag{2.13}$$

where $P_{\max}^{''}$ is the proportion of very large ($\lambda_{1,a} \rightarrow L_{\infty,1}$) females that are pregnant each year,
$\lambda_{50}^{''}$ is the length at which half of the maximum proportion of females are pregnant each year, and
$\lambda_{95}^{''}$ is the length at which 95% of the maximum proportion of females are pregnant each year.

Table 2.15 lists the values assumed for the parameters of Equations (2.12) and (2.13).

2.3.1.3 Catches

The annual catches are assumed to be taken in a pulse in the middle of the year (after 50% of the natural mortality) and the fisheries are assumed to be sequential (gauntlet). The catch (in number) during year *t* by gear-type *j* of fish of age *a* and sex *g* is calculated from the total catch (in mass) during year *t* by gear-type *j*, $\tilde{C}_{t,j}$:

$$C_{g,t,a,j} = F_{t,j}\sum_L A_{g,L}\, S_{g,j,L}\, \Phi(g,a+1/2,L)\ \left(N_{g,t,a}e^{-M_{t,a}/2} - \sum_{i=1}^{j-1} C_{g,t,a,i}\right) \tag{2.14}$$

where $S_{g,j,L}$ is the selectivity of gear-type *j* on fish of sex *g* in length-class *L*,
$A_{g,L}$ is the availability of a fish of sex *g* in length-class *L*, and
$F_{t,j}$ is the fully-selected exploitation rate by gear-type *j* during year *t*:

$$F_{t,j} = \tilde{C}_{t,j} / \left(\sum_g \sum_{a=1}^{x} \sum_L w_{g,L}\quad A_{g,L}\, S_{g,j,L}\, \Phi(g,a+1/2,L)\left(N_{g,t,a}e^{-M_{t,a}/2} - \sum_{i=1}^{j-1} C_{g,t,a,i}\right)\right) \tag{2.15}$$

2.3.1.4 Length and mass

The total length of a fish of age *a* and sex *g* at the start of the year, $\lambda_{g,a}$, is described by the von Bertalanffy growth equation:

$$\lambda_{g,a} = L_{\infty,g}(1-e^{-\kappa_g(a-t_{0,g})}) \tag{2.16}$$

and the live mass by the allometric equation:

$$w_{g,L} = a_g (\bar{L}_L)^{b_g} \tag{2.17}$$

where $\bar{L}_L$ is the mid-point of length-class L.

The values assumed for the parameters of Equations (2.16) and (2.17) are listed in Table 2.15.

The probability that a fish of age a and sex g lies in length-class L (length-class L is defined to be $[L-\Delta L, L+\Delta L]$) is given by:

$$\Phi(g,a,L) = \int_{L-\Delta L}^{L+\Delta L} \frac{1}{\sqrt{2\pi}\,\sigma_{g,a} l} e^{-\frac{(\lambda n l - \lambda n \lambda_{g,a})^2}{2\sigma_{g,a}^2}} dl \tag{2.18}$$

where ΔL is half the width of a length-class (25 cm), and
$\sigma_{g,a}$ is (approximately) the coefficient of variation of the length of an animal of age a and sex g.

2.3.1.5 Gear selectivity

Different selectivity patterns are assumed for the two major gear-types (hooks and gill-nets). The catch by hooks is assumed to be taken uniformly from the 2+ component of the population (Walker, 1983), i.e.:

$$S_{g,j,L} = \begin{cases} 0 & \bar{L}_L < l_{g,2} \\ 1 & \text{otherwise} \end{cases} \tag{2.19}$$

The selectivity pattern for gill-nets is assumed to follow a gamma function (Kirkwood and Walker, 1986):

$$S_{g,j,L} = \left(\frac{\bar{L}_L}{\alpha_{g,j}\,\beta_{g,j}} \right)^{\alpha_{g,j}} e^{\alpha_{g,j} - \frac{\bar{L}_L}{\beta_{g,j}}} \tag{2.20}$$

where α, β are the parameters of the selectivity pattern.

2.3.1.6 Availability

Availability as a function of length is either assumed be independent of length or governed by a double-logistic equation:

$$A_{g,L} = A'_L / \max_{L'}(A'_{L'}) \tag{2.21}$$

$$A'_L = (1+e^{-\ln 19(\bar{L}_L - L_{50}^{A,1})/(L_{95}^{A,1} - L_{50}^{A,1})})^{-1}(1+e^{-\ln 19(\bar{L}_L - L_{50}^{A,2})/(L_{95}^{A,2} - L_{50}^{A,2})})^{-1} \tag{2.22}$$

where $L_{50}^{A,1}, L_{50}^{A,2}, L_{95}^{A,1}, L_{95}^{A,2}$ are the parameters of the availability function.

2.3.1.7 Initial conditions

The population is assumed to have been at pre-exploitation equilibrium at the start of 1927 (the assumed start of harvesting) because there are no data to estimate the age-structure of the population at that time:

$$N_{g,y_1,a} = \begin{cases} \Phi_g\, R_0\, e^{-\sum_{a'=0}^{a-1} M_{y_1,a'}} & 0 \le a \le x-1 \\ \Phi_g\, R_0\, e^{-\sum_{a'=0}^{x-1} M_{y_1,a'}} / (1-e^{-M_{y_1,x}}) & a = x \end{cases} \tag{2.23}$$

where R_0 is the number of pups at the (deterministic) equilibrium that corresponds to an absence of fishing, and

y_1 is the first year considered (1927).

The value for R_0 is calculated from the value assumed for the virgin total (1+) biomass at the start of the year, B_0:

$$R_0 = B_0 \Big/ \sum_g \Phi_g \left(\sum_{a=1}^{x-1} w_{g,a} e^{-\sum_{a'=0}^{a-1} M_{y_1,a'}} + w_{g,x} \frac{e^{-\sum_{a'=0}^{x-1} M_{y_1,a'}}}{1-e^{-M_{y_1,x}}} \right) \tag{2.24}$$

$$w_{g,a} = \sum_L w_{g,L}\, \Phi(g, a+1/2, L) \tag{2.25}$$

2.3.1.8 Natural Mortality

Natural mortality-at-age is assumed to be governed by the equation:

$$M_{t,a} = \begin{cases} M_a (1 - Q_1 (1 - D_t / D_0)) & 0 \le a \le a_d \\ M_a & \text{otherwise} \end{cases} \tag{2.26}$$

where M_a is the rate of natural mortality on fish of age a at pre-exploitation equilibrium:

$$M_a = \begin{cases} M_0\, e^{-\ln(M_2/M_0) a/2} & 0 \le a \le 2 \\ M_2\, e^{\ln(M_x/M_2)(a-2)/(x-2)} & 2 < a \le x \end{cases} \tag{2.27}$$

Q_1 is the parameter that determines the extent of density-dependence in natural mortality,

a_d is the oldest age at which density-dependent natural mortality applies,

M_x is the rate of natural mortality on animals of age x and older,

M_2 is the rate of natural mortality on two-year-olds, and

M_0 is the rate of natural mortality on pups.

This formalism implies that natural mortality decreases exponentially between age 0 and age 2, and increases exponentially thereafter The values for M_2 and M_x / M_2 are either estimated or pre-specified while the value for M_0 is calculated so that, in the absence of harvesting, the population satisfies the balance equation:

$$\frac{1}{\Phi_1} = \sum_{a=1}^{x-1} P_a^{'} P_a^{"} e^{-\sum_{a'=0}^{a-1} M_{a'}} + P_x^{'} P_x^{"} \frac{e^{-\sum_{a'=0}^{x-1} M_{a'}}}{1-e^{-M_x}} \qquad (2.28)$$

2.3.2 Parameter and variance estimation

The values for all of the parameters of this model, except those related to the virgin biomass, B_0, the magnitude of density-dependence (determined through *MSYR*), the extent of variation in length-at-age (see Equation 2.18), natural mortality (M_2 and M_x/M_2), and the recruitment residuals (ε_t - see Equation 2.8) are fixed using ancillary information. The model allows for density-dependence on pup survival or more generally on the rate of natural mortality over several age-classes (Equations 2.9 and 2.26). The bounds imposed on M_{adult} and *MSYR* are [0.1, 0.3yr^{-1}] and [0.1, 0.3] respectively, while a constraint reflecting the assumed level of variation in the recruitment residuals is also imposed. The data for South Australia are not very informative. Therefore, the values for *MSYR*, M_2 and the parameters that define availability as a function of length are set equal to the estimates from the base-case assessment for the population in Bass Strait.

The variances for the estimates of the model parameters and for the other quantities of interest are determined using an 'asymptotic approach'. This involves finding the asymptotic variances for the parameters by inverting a numerical approximation to the Hessian matrix[2], generating 500 sets of parameter estimates from the estimated variance-covariance matrix and calculating the values for each interest quantity for each of the 500 sets. This approach is referred to as the 'numerical delta' method by Patterson *et al*. (2001).

The following sections outline the contribution of each of the four sources of data to the likelihood function.

2.3.2.1 Catch rate data

The contribution of the catch rate data to the likelihood function is based on the assumption that effective effort for gear-type *j* is lognormally distributed about the fishing mortality rate:

$$F_{t,j} = q_j \; f(\tilde{C}_{t,j} / I_{t,j}) e^{\phi_{j,t}} \qquad \phi_{j,t} \sim N(0;\sigma_j^2) \qquad (2.29)$$

where $f(E)$ is relative fishing mortality as a function of actual fishing effort, modelled by one of three alternatives:

$$f(E) = E \qquad (2.30a)$$

$$f(E) = E^{\gamma} \qquad (2.30b)$$

$$f(E) = E/(1+\gamma_1 E) \qquad (2.30c)$$

[2] The Hessian matrix is the matrix of second partial derivatives of the negative log-likelihood with respect to the model parameters,

q_j is the catchability coefficient for gear-type *j*,

γ, γ_1 are control parameters (constrained to be positive), and

$I_{j,t}$ is the catch rate index for gear-type *j* and year *t*.

Equation (2.30a) reflects the assumption that effort is linearly proportional to exploitation rate whereas Equations (2.30b) and (2.30c) allow for 'gear competition' effects. 'Gear competition' has been postulated for the fishery for gummy shark off southern Australia based on the observation that catches have been relatively insensitive to large changes in fishing effort.

The negative of log-likelihood function (ignoring constant terms) is

$$-\ln L_j = \sum_{t(j)} \left(\ln \sigma_j + \frac{1}{2\sigma_j^2} \left(\ln(q\, f(\tilde{C}_{t,j} / I_{j,t})) - \ln(F_{t,j}) \right)^2 \right) \tag{2.31}$$

where σ_j is the (assumed) residual standard deviation and the summation over *t* is taken over all years for which catch rates are available for gear-type *j*.

2.3.2.2 Length-frequency data

The contribution of the length-frequency data (by gear-type) to the negative of logarithm of the likelihood function is based on the assumption that the observed proportion of the catch by gear-type *j* in length-class *L* is multinomially distributed about the model prediction:

$$-\ln L = -N_j^{\text{len}} \sum_g \sum_t \frac{N_{g,t,j}^{\text{len}}}{\overline{N}_{g,j}^{\text{len}}} \sum_L \rho_{g,t,L,j} \ln(\hat{\rho}_{g,t,L,j} / \rho_{g,t,L,j}) \tag{2.32}$$

where $\rho_{g,t,L,j}$ is the observed fraction of the catch of animals of sex *g* during year *t* by gear-type *j* that lies in length-class *L*,

$N_{g,t,j}^{\text{len}}$ is the number of animals of sex *g* caught by gear-type *j* measured during year *t* (Table 2.11),

$\overline{N}_{g,j}^{\text{len}}$ is mean of the $N_{g,t,j}^{\text{len}}$ s,

N_j^{len} is the weight assigned to the length-frequency data for gear-type *j* (the average annual effective sample size), and

$\hat{\rho}_{g,t,L,j}$ is the model-estimate of the fraction of the catch of animals of sex *g* during year *t* by gear-type *j* that lies in length-class *L*:

$$\hat{\rho}_{g,t,L,j} = F_{t,j}\, A_{g,L}\, S_{g,j,L} \sum_a \Phi(g, a+1/2, L) \left(N_{g,t,a}\, e^{-M_a/2} - \sum_{i=1}^{j-1} C_{g,t,a,i} \right) / \sum_{a'} C_{g,t,a',j} \tag{2.33}$$

2.3.2.3 Age-composition data

The contribution of the age-composition data (by gear-type) to the negative of logarithm of the likelihood function is based on the assumption that the observed proportion of the catch by gear-type *j* that is assigned to be age *a* is multinomially distributed about the model prediction:

$$-\ln L = -N_j^{\rm age} \sum_g \sum_t \frac{N_{g,t,j}^{age}}{\overline{N}_{g,j}^{age}} \sum_a \rho_{g,t,a,j} \ln(\hat{\rho}_{g,t,a,j} / \rho_{g,t,a,j}) \qquad (2.34)$$

where $\rho_{g,t,a,j}$ is the observed fraction of the catch of animals of sex *g* during year *t* by gear-type *j* that is of age *a*,

$N_{g,t,j}^{\rm age}$ is the number of animals of sex *g* caught by gear-type *j* aged during year *t* (Table 2.13),

$\overline{N}_{g,j}^{\rm age}$ is mean of the $N_{g,t,j}^{\rm age}$ s,

$N_j^{\rm age}$ is the weight assigned to the age-composition data for gear-type *j* (the average annual effective sample size), and

$\hat{\rho}_{g,t,a,j}$ is the model-estimate of the fraction of the catch of animals of sex *g* during year *t* by gear-type *j* that is of age *a*:

$$\hat{\rho}_{g,t,a,j} = C_{g,t,a,j} / \sum_{a'} C_{g,t,a',j} \qquad (2.35)$$

2.3.2.4 Tagging data

The information for each release includes year-of-release, age-at-release (calculated from the growth curve and the length-at-release) and tag-type. The information for each recapture includes year- and age-at-recapture. The latter is calculated by adding the time-at-liberty to the age-at-release. Any releases for which complete information is not available are discarded (irrespective of whether they were recaptured or not). Ignoring constants, the contribution of the tagging data to the negative of the log-likelihood function is (Hilborn, 1990; Xiao, 1996):

$$-\ln L = \sum_t \sum_g (\hat{R}_{g,t} - R_{g,t} \ln \hat{R}_{g,t}) \qquad (2.36)$$

where $R_{g,t}$ is the actual number of recaptures of animals of sex *g* during year *t*, and

$\hat{R}_{g,t}$ is the expected number of recaptures of animals of sex *g* during year *t*.

The equation that governs the dynamics of tags is defined analogously to that which governs the dynamics of the population itself, except that ‘births’ to the tagged population occur when a tag is released, and account needs to be taken of tag loss and ‘early’ recaptures[3]:

$$T_{t+1,a+1}^z = (T_{t,a}^z \, e^{-(M_{t,a}+\lambda^z)} + (I_{t,a}^z - \tfrac{1}{\theta_t^z} E_{t,a}^z) \, e^{-(M_{t,a}+\lambda^z)/2}) \prod_j \left(1 - F_{t,j} \, S_{g,j,a}\right) \qquad (2.37)$$

where $T_{t,a}^z$ is the number of fish of age *a* with tag-type *z* at the start of year *t*,

$I_{t,a}^z$ is the number of fish of age *a* which were released with tag-type *z* during year *t*,

[3] An ‘early recapture’ is defined as a recapture that occurs before it is reasonable to assume that the tagged animal has been at liberty sufficiently long for it to have ‘fully mixed’ into the population.

$E_{t,a}^{z}$ is the number of fish of age a that were recaptured with tag-type z 'early' during year t,

θ_t^z is the tag recapture reporting rate (defined as the product of a year- and tag-type-specific factor),

$S_{g,j,a}$ is the selectivity of gear-type j on fish of sex g and age a:

$$S_{g,j,a} = \sum_L A_{g,L}\, S_{g,j,L}\, \Phi(g, a+1/2, L) \tag{2.38}$$

λ^z is the instantaneous (long-term) rate of tag loss for tag-type z.

The tagging data included in the assessment are restricted to tag-types for which estimates of tag loss rate are available (Table 2.16). The expected number of fish of sex g and age a recaptured during year t is given by:

$$\hat{R}_{g,t} = \sum_z \theta_t^z \sum_a \left(1 - \prod_j \left(1 - F_{t,j}\, S_{g,j,a}\right)\right) \left(T_{t,a}^z\, e^{-(M_{t,a}+\lambda^z)/2} + I_{t,a}^z - \tfrac{1}{\theta_t^z} E_{t,a}^z\right) \tag{2.39}$$

2.3.3 The base-case assessment

The base-case assessment reflects the 'most likely' set of assumptions, and sensitivity tests examine sensitivity to changing these assumptions. The following are the base-case assumptions (assumptions indicated with asterisks are examined further in sensitivity tests):

a) Density-dependence impacts the instantaneous rate of natural mortality (a_d=∞), and is functionally related to the total (1+) biomass - these assumptions are made to avoid (unrealistic) oscillatory trajectories of population size*.
b) The variance in length-at-age increases linearly with expected length, $\sigma_{g,a} = \sigma_g \sqrt{\lambda_{g,a} / \lambda_{\infty,g}}$ - this assumption was selected after an initial analysis of the data.
c) The weights assigned to the catch rate, length-frequency and age-composition data are: $\sigma_j = 0.15$, N_j^{len} = 50 (Bass Strait) = 25 (South Australia), and $N_j^{\text{age}} = 25$ (see Equations 2.31, 2.32 and 2.34)*. The lower value for N_j^{len} for South Australia is a reflection of the lower sample sizes for this region (see Table 2.12)
d) The tag-reporting rate for internal tags is assumed to be 0.929 (Punt *et al*., 2000a).
e) The tag-reporting rates for the years 1950–54, 1973–77 and 1995–98 are assumed to be 0.7 while those for the remaining years are assumed to be 0.5 (Punt *et al*., 2000a).
f) Any recaptures within 60 days of release are treated as 'early recaptures' (see Equations 2.37 and 2.39)*.
g) Natural mortality is independent of age above age 2 ($M_x / M_2 = 1$)*.
h) Effort is related to fishing mortality according to Equation (2.30c)*.

2.4 Results and discussion

2.4.1 Fits to data

2.4.1.1 Bass Strait

The base-case model estimates that there is severe gear competition in Bass Strait so that essentially the same *expected* exploitation rate results for all levels of standardized fishing effort during 1976–98 (Figure 2.10). Gear competition is estimated to be substantial primarily because the effort data are negatively correlated with exploitation rate for some years. For example, the higher exploitation rates since 1990 and the lower exploitation rates during 1983–91 (dotted lines in Figure 2.10) correspond to periods when effort was low and high respectively. The estimated extent of gear competition is fairly robust irrespective of the weight placed on the effort data.

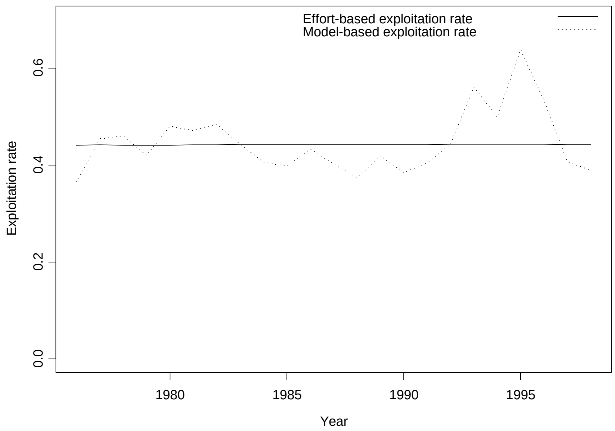

Figure 2.10 : Estimated exploitation rate time-trajectory for 6-inch mesh gear in Bass Strait (dotted line) and the values inferred from the effort information through Equation (2.30c) (solid line).

The fits to the length-frequency (Figures 2.11–2.13) and age-composition data (Figures 2.14 and 2.15) capture the general patterns. As expected, the fits to the data for the years for which sample size is large (and hence the value of W $= N_j^{\text{len}} \, N_{g,t,j}^{\text{len}} / \overline{N}_{g,j}^{\text{len}}$ is high) tend to be better than to the data for those years for which the sample size is low. However, there is a tendency to overestimate the mean length of the catch, particularly for 7-inch mesh (Figures 2.12 and 2.13). The fits to the age-composition data, although generally adequate, are remarkably poor for some years (1990 and 1991 for females and 1986 for males). The model is able to mimic the recent pattern in tag recaptures adequately (Figure 2.16). However, the model over-estimates the number of recaptures during the 1970s. Whether this is a consequence of poor choices for the tag-reporting rates or a structural problem with the underlying population dynamics model is, however, unclear.

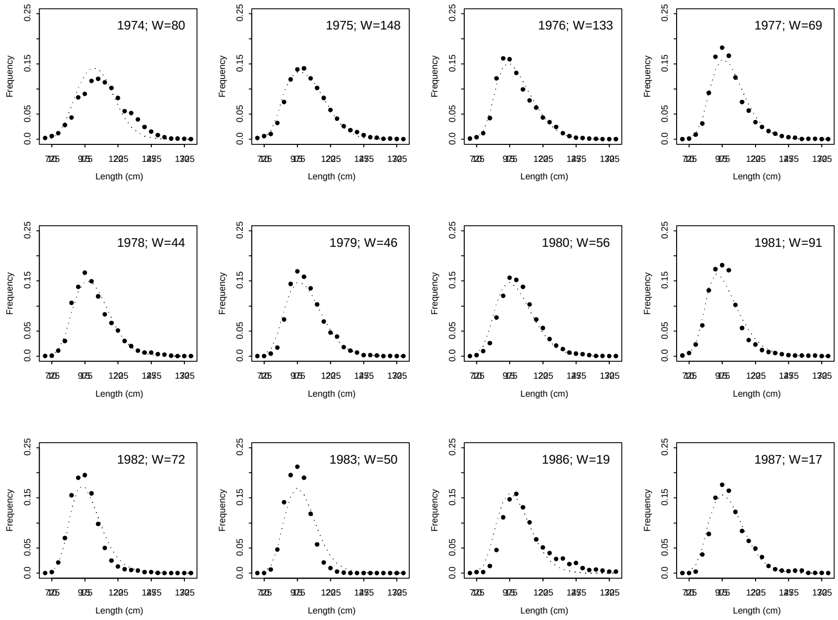

Figure 2.11 (a): Observed (solid dots) and model-predicted (dotted lines) female length-frequency data for 6-inch mesh catches in Bass Strait. The value of W indicates the relative weight assigned to the data for each year.

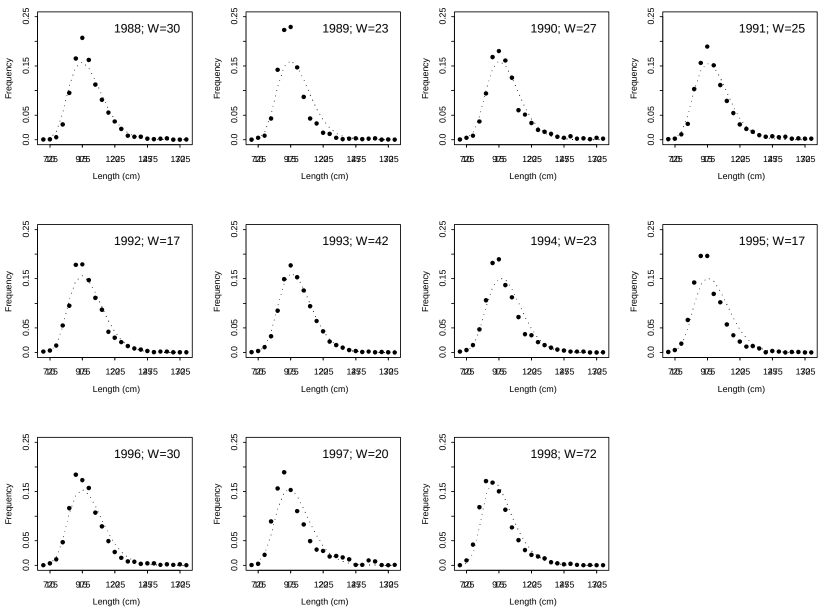

Figure 2.11(a) continued.

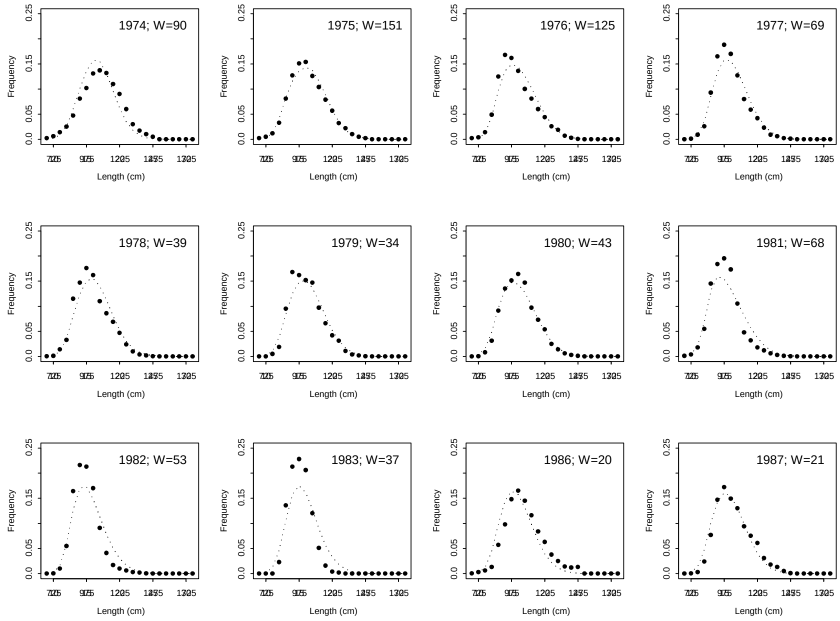

Figure 2.11 (b): Observed (solid dots) and model-predicted (dotted lines) male length-frequency data for 6-inch mesh catches in Bass Strait. The value of W indicates the relative weight assigned to the data for each year.

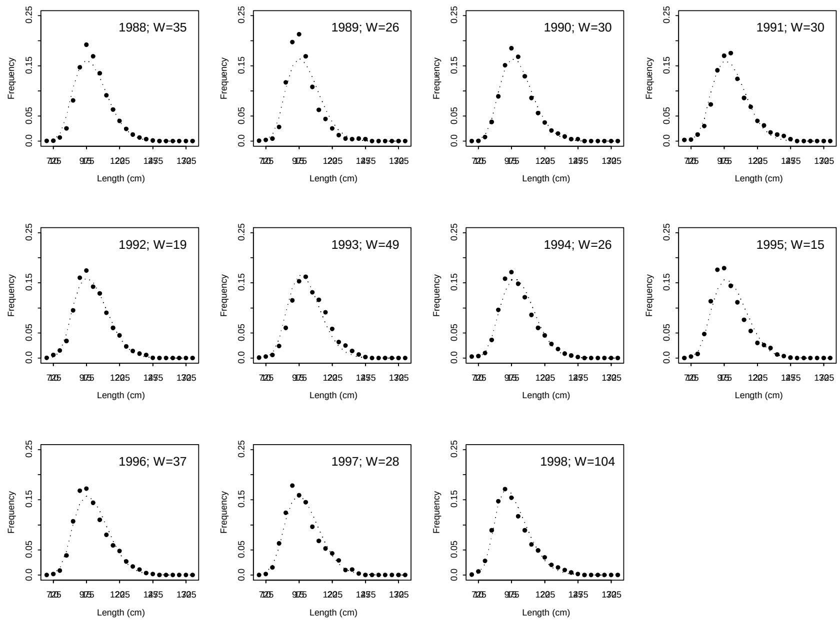

Figure 2.11(b) continued.

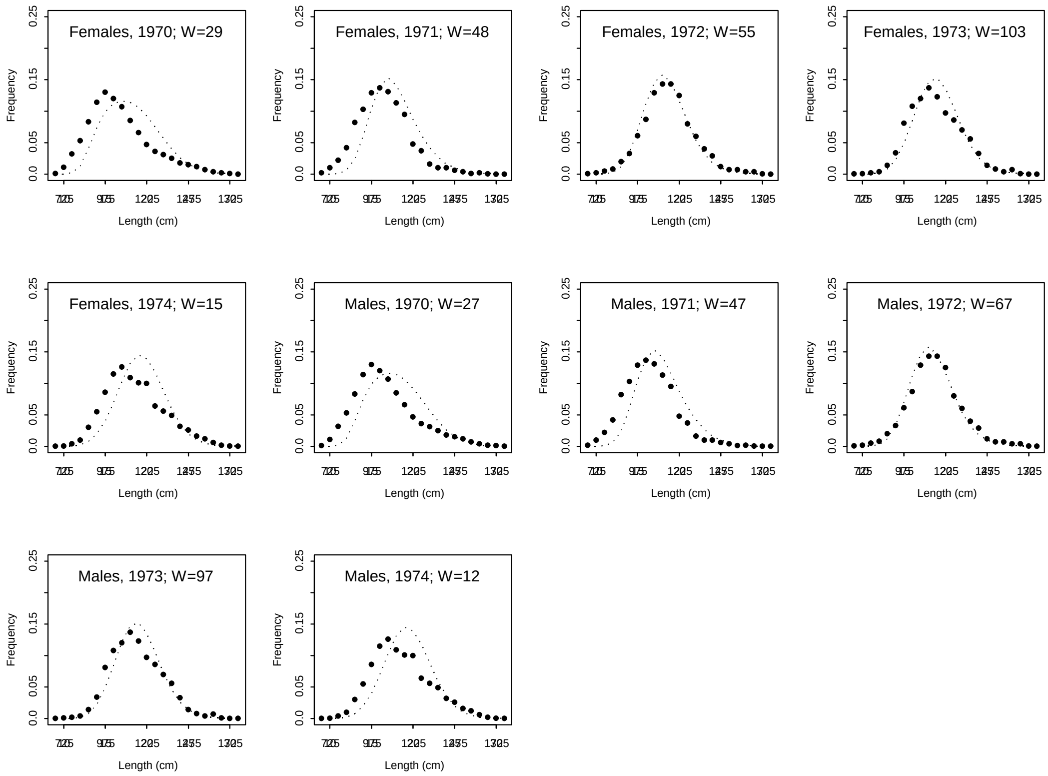

Figure 2.12 : Observed (solid dots) and model-predicted (dotted lines) length-frequency data for 7-inch mesh catches in Bass Strait. The value of W indicates the relative weight assigned to the data for each year.

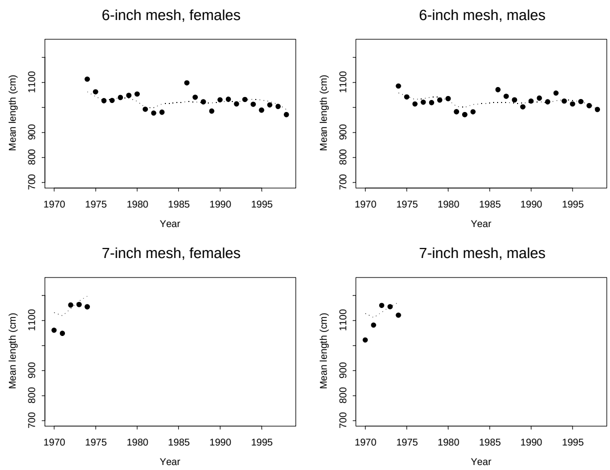

Figure 2.13 : Observed (solid dots) and model-predicted (dotted lines) mean length of the catch in Bass Strait. Results are shown in the upper panels for 6-inch mesh gear and in the lower panels for 7-inch mesh gear.

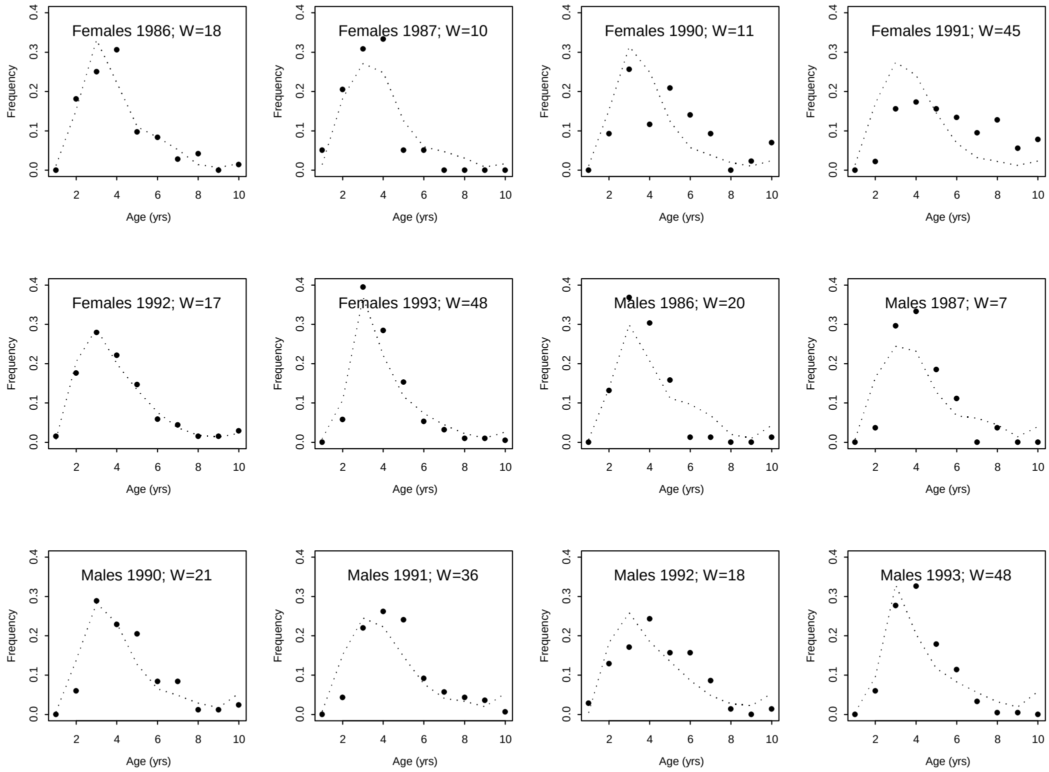

Figure 2.14: Observed (solid dots) and model-predicted (dotted lines) age-composition data (6-inch mesh catches) in Bass Strait. Results are shown separately for females and males. The value of W indicates the relative weight assigned to the data for each year.

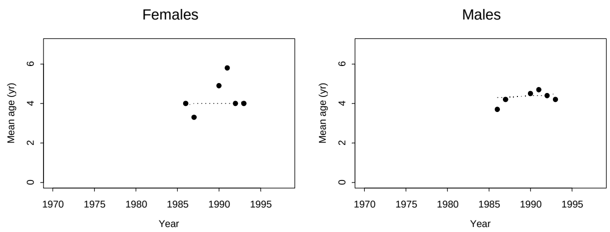

Figure 2.15 : Observed (solid dots) and model-predicted (dotted lines) mean age of the catch in Bass Strait using 6-inch mesh gillnets.

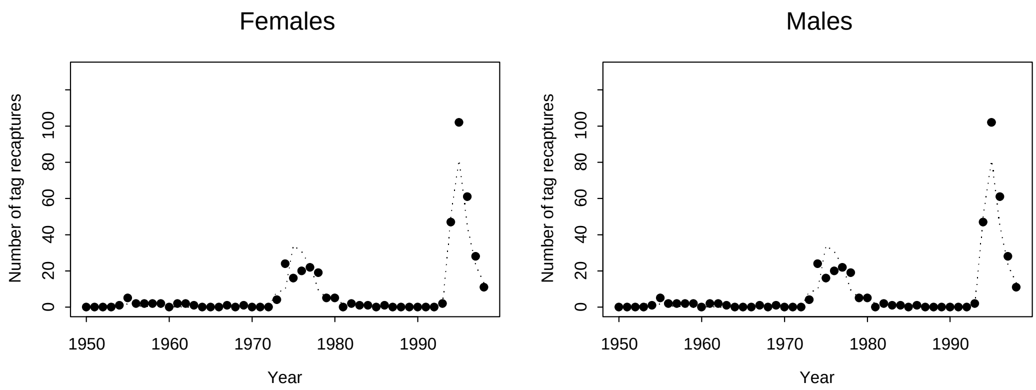

Figure 2.16 : Observed (solid dots) and model-predicted (dotted lines) number of tag recaptures in Bass Strait (by sex).

2.4.1.2 South Australia

The model mimics the trend in exploitation rate well (Figure 2.17). The fits to the length-frequency and age-composition data are, however, notably poorer for South Australia than was the case for Bass Strait (Figures 2.17 – 2.21). There are some cases in which the model fails to capture even the predominant lengths in the catch (e.g. 1997 for 6.5-inch mesh; 1990 for 7-inch mesh; Figure 2.14). The reasons for this are unclear but are probably related to the very small sample sizes for some years (see Table 2.12). The fit to the tag recapture information (Figure 2.22) is also not as good as was the case for Bass Strait although the model is able to capture the recent trend in tag recaptures.

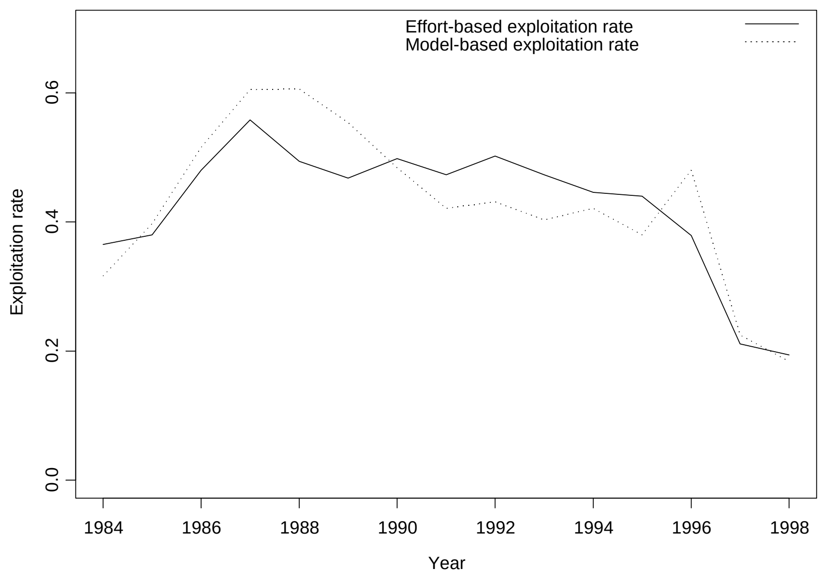

Figure 2.17 : Estimated exploitation rate time-trajectory for 7-inch mesh gill-nets off South Australia (dotted line) and the values inferred from the effort information through Equation (2.30c) (solid line).

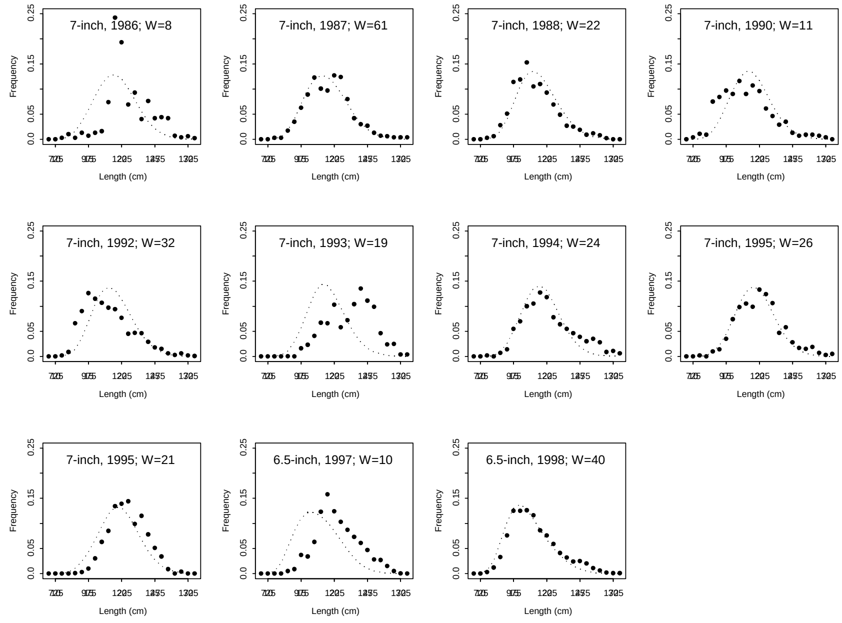

Figure 2.18 (a) : Observed (solid dots) and model-predicted (dotted lines) female length-frequency data for South Australia. The value of W indicates the relative weight assigned to the data for each year.

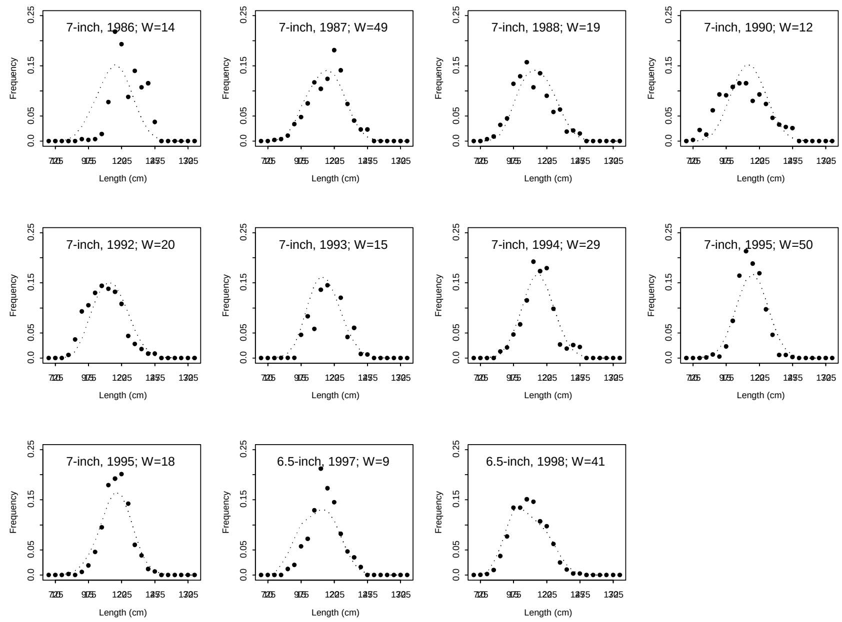

Figure 2.18 (b) : Observed (solid dots) and model-predicted (dotted lines) male length-frequency data for South Australia. The value of W indicates the relative weight assigned to the data for each year.

Figure 2.19 : Observed (solid dots) and model-predicted (dotted lines) mean length of the catch by 7-inch gill-nets off South Australia.

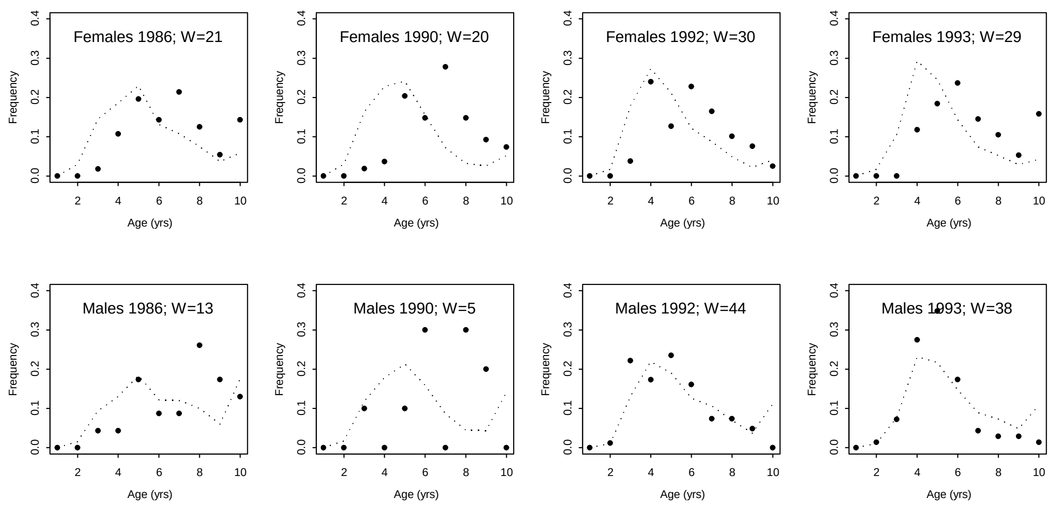

Figure 2.20 : Observed (solid dots) and model-predicted (dotted lines) age-composition data (7-inch mesh catches) for South Australia. Results are shown in the upper panels for females and in the lower panels for males. The value of W indicates the relative weight assigned to the data for each year.

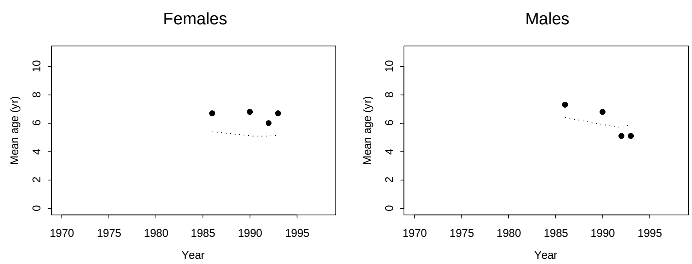

Figure 2.21 : Observed (solid dots) and model-predicted (dotted lines) mean age of the catch off South Australia using 7-inch mesh gillnets.

Figure 2.22 : Observed (solid dots) and model-predicted (dotted lines) number of tag recaptures off South Australia (by sex).

2.4.2 The base-case assessments

The results of the assessment are summarised by the values for 11 quantities of interest to management:

a) SB_0 the pup production in a virgin state,

b) M_2 the instantaneous rate of natural mortality for fish of age 2 (at pre-exploitation equilibrium when natural mortality is density-dependent),

c) *MSYR* the *MSY* rate (the ratio of *MSY* to the biomass at which *MSY* is achieved),

d) SB_{73} / SB_0 the ratio of the pup production in 1973 to that in a virgin state, expressed as a percentage,

e) SB_{99} / SB_0 the ratio of the pup production in 1999 to that in a virgin state, expressed as a percentage,

f) σ_{CPUE} the residual standard deviation about the fit of the model to the catch rate data,

g) $\sigma_{len,f}$ the residual standard deviation about the fit of the model to the female length-frequency data (based on a model that assumes that the proportion of the catch falling into a length-class is log-normally distributed with CV that is inversely proportional to the square root of the proportion itself – Smith and Punt (1998)),

h) $\sigma_{len,m}$ the residual standard deviation about the fit of the model to the male length-frequency data,

i) $\sigma_{age,f}$ the residual standard deviation about the fit of the model to the female age-composition data (based on a model that assumes that the proportion of the catch falling into an age-class is log-normally distributed with CV that is inversely proportional to the square root of the proportion itself),

j) $\sigma_{age,m}$ the residual standard deviation about the fit of the model to the male age-composition data, and

k) $-\ln L$ the negative of the logarithm of the likelihood function (ignoring constants independent of the model parameters).

2.4.2.1 Bass Strait

The estimates of the rate of natural mortality for 2+ animals (M_2) and the *MSY* rate (0.188 and 0.221 respectively) indicate a relatively short-lived but productive species (Table 2.17). The estimate of M_2 is slightly lower than would have been expected from previous studies (e.g. Walker, 1994a, b; Walker *et al*., 2000) although the present assessment is based on a larger data set than those used in previous assessments.

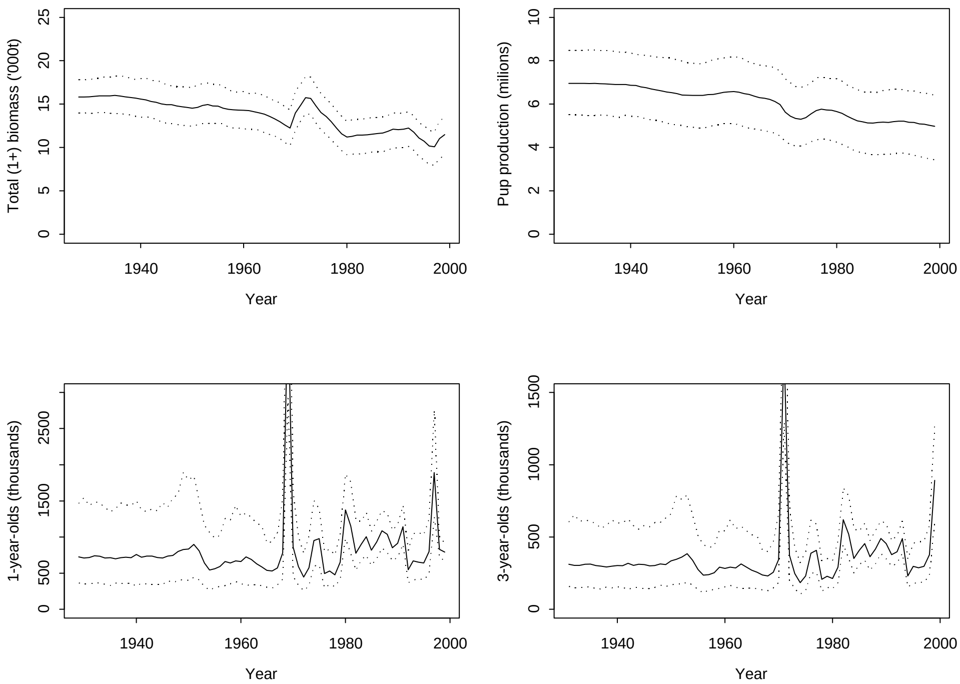

Figure 2.23 : Time-trajectories for Bass Strait (with 90% confidence intervals) for (a) 1+ biomass, (b) pup production, (c) number of 1-year-olds, and (d) number of 3-year-olds.

Figure 2.23 shows time-trajectories (with asymptotic 90% confidence intervals) for the total (1+) biomass, the pup production, the number of 1-year-olds, and the number of 3-year-olds. There is a gradual reduction in pup production over the period 1927–98. In contrast, the time-trajectory of (1+) biomass is more stable due to a large increase from 1970 to 1980. This increase is a consequence of a large 1968 year-class. Such a year-class is needed to fit the high mean catch lengths during the early 1970s (Table 2.12; Figures 2.12 and 2.13), as these can only be explained by a strong cohort passing through the population. The oscillations in total (1+) biomass are mirrored in the time-trajectories of age 1 and age 3 abundance (Figure 2.23). The combination of variation in pup survival (Figure 2.24) and density-dependence implies that recruitment to the fishery has been relatively constant (Figure 2.23 bottom right panel). A consequence of this is that exploitable biomass from 1976–98 has been more stable than total biomass or pup production (Figure 2.24). The marked increase in exploitable biomass from 1970 to 1973 is due to recruitment to the fishery of the strong 1968 cohort. The exploitable biomass is estimated to have declined from 1990 to 1996 but then to have recovered due to lower catches.

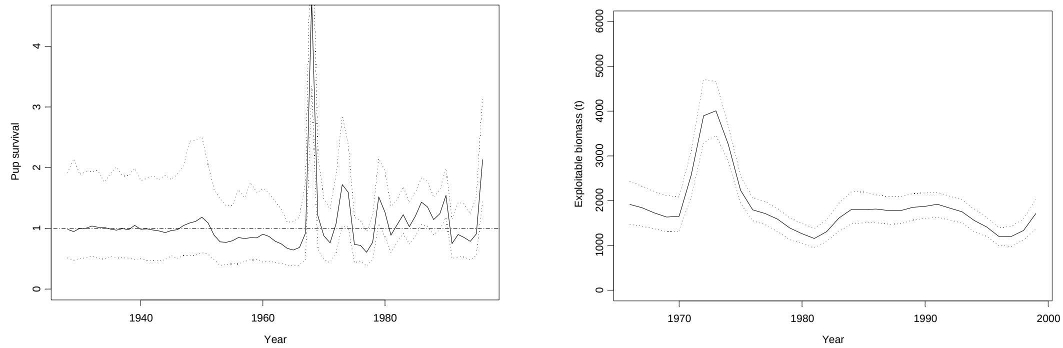

Figure 2.24 : Annual pup survival for Bass Strait expressed as fraction of that expected under the deterministic stock-recruitment relationship (with 90% confidence intervals) (left panel) and the time-trajectory for Bass Strait (with 90% confidence intervals) for the biomass available to 6-inch mesh gear (right panel).

The recruitment to the fishery in Bass Strait during 1999 is expected to be good owing to high (but nevertheless poorly determined) pup survival in 1996. The 90% confidence intervals for pup survival (Figure 2.24) are wide prior to about 1965 and narrower thereafter reflecting the lack of data that relate to the strengths of the year-classes pupped before 1965.

The result that the population is estimated to be currently more than 70% of its virgin size (Table 2.17) is a direct consequence of the estimated availability and selectivity patterns. These imply that only a relatively small fraction of the population is vulnerable to the fishery at any one time. The selectivity patterns are based on experimental results (e.g. Kirkwood and Walker, 1986) while the parameters that determine availability as a function of length are estimated as part of the model-fitting procedure. Independent analysis of survey data for gummy shark (Punt, 2000) also indicate that availability should not be assumed to be uniform.

2.4.2.2 South Australia

The assessments for the populations of gummy shark off South Australia are based on the values for M_2, *MSYR* and availability as a function of length derived from the base-case assessment for Bass Strait. The data for South Australia provide little information about the value of *MSYR* (although lower rather than higher values are preferred) (Table 2.18). The population is assessed to be between 74 and 78% of the virgin level (in terms of pup production). However, poor pup survival from 1990 has meant that recruitment during the mid-to-late 1990s has been weak (Figures 2.25 and 2.26). This has lead to a marked decline in total (1+) biomass (upper left panel of Figure 2.25) and in recruited biomass (Figure 2.26) in recent years. The impact of poor recruitment is evident from the length-frequency data – the mean length of the catch increased markedly from 1992. The estimates of pup survival and consequently of recruitment are, however, highly imprecise (essentially equal to the assumed default level of variation) until the late 1970s. This is due to a lack of length-frequency data prior to 1984.

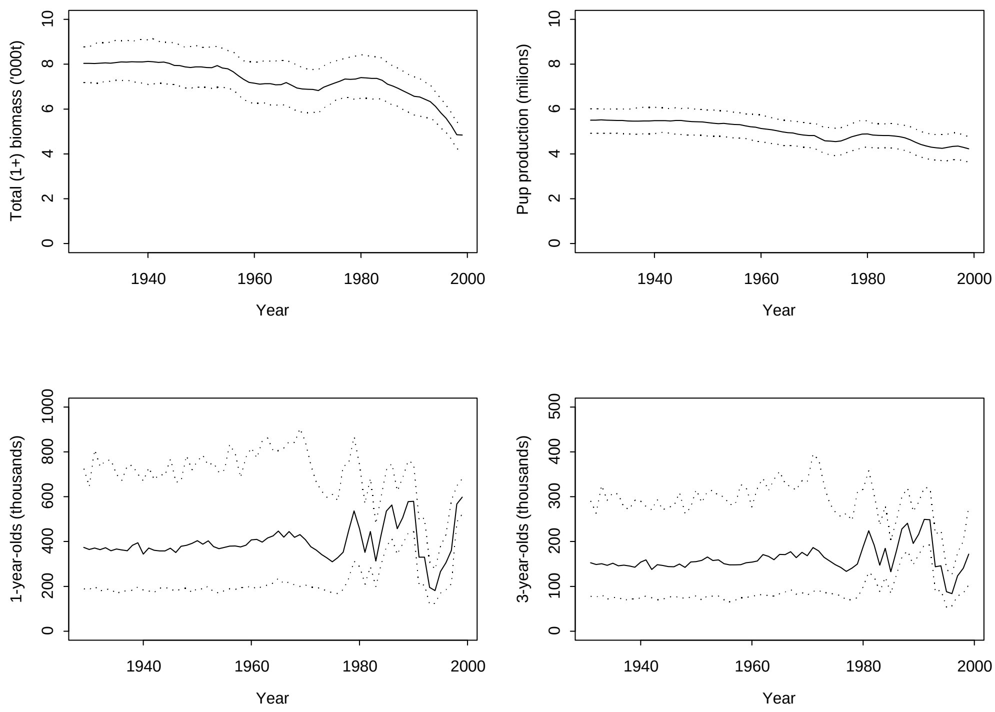

Figure 2.25 : Time-trajectories for South Australia (with 90% confidence intervals) for (a) 1+ biomass, (b) pup production, (c) number of 1-year-olds, and (d) number of 3-year-olds.

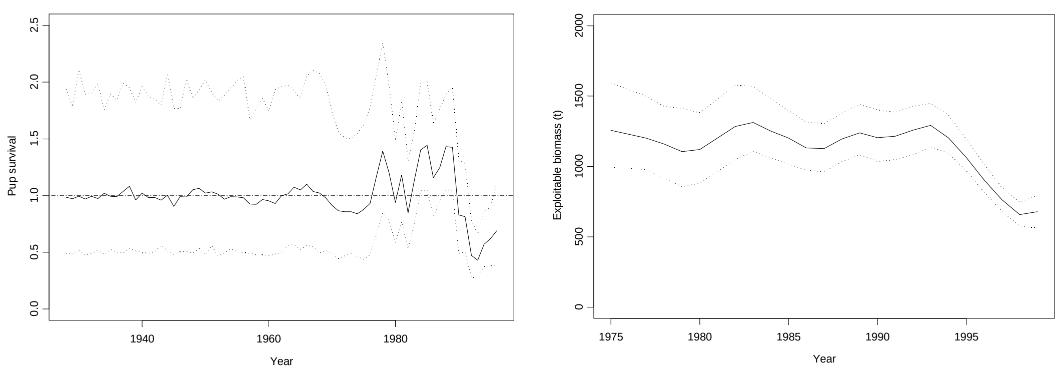

Figure 2.26 : Annual pup survival for South Australia expressed as fraction of that expected under the deterministic stock-recruitment relationship (with 90% confidence intervals) (left panel) and the time-trajectory for South Australia (with 90% confidence intervals) for the biomass available to 7-inch mesh gear (right panel).

2.4.3 Sensitivity tests

2.4.3.1 Bass Strait

Allowing natural mortality to increase with age (Equation 2.27) does not lead to a significant improvement in fit (Table 2.17, row '*M* age-dependent'). Making allowance for the possibility that the historical catches underestimate the true removals due to fishing (sensitivity test 'Higher catches') leads to a lower current depletion in 1973 (in terms of pup production) and a less productive stock. Furthermore, there is a slightly improved fit to the data (a decrease in the negative log-likelihood of 1.79 compared to the base-case assessment) if the historical catches are changed. Including the catch rates for 1973–75 in the assessment (sensitivity test 'With 73-75 CPUE data') leads to a less depleted and more productive resource. The results are largely insensitive to changing the approach used to incorporate the fishing effort data from Equation (2.30c) to Equation (2.30b) (sensitivity test 'Alter effort relationship'). This last result is not very surprising because the model estimates that the exploitation rate from 1976–98 has been virtually independent of fishing effort and both Equations (2.30b) and (2.30c) converge to this limit.

Two of the sensitivity tests examine the implications of changing how density-dependence is included in the assessment. The results are sensitive to this. For example, assuming that density-dependence acts on pup survival (Table 2.17, row 'Dens-dep pups') leads to the lowest value for the negative log-likelihood (a highly significant reduction from the base-case value of 10.9). This improvement is due to an improved fit to the length-frequency data (compare the values of $\sigma_{len,f}$ and $\sigma_{len,m}$ for the base-case assessment and the 'Dens-dep pups' sensitivity test in Table 2.17). However, this assumption also leads to somewhat unrealistic time-trajectories of population size (Figure 2.27) because assuming that density-dependence is functionally related to pup production increases the time-lags in the model and hence the possibility of (unrealistic) oscillatory behaviour. Unrealistic behaviour of models for long-lived animals based on the assumption that density-dependence impacts juvenile survival rate is well known (e.g. Givens *et al*., 1995). Assuming that density-dependence acts on natural mortality but only for ages 0-4 improves the model fit slightly.

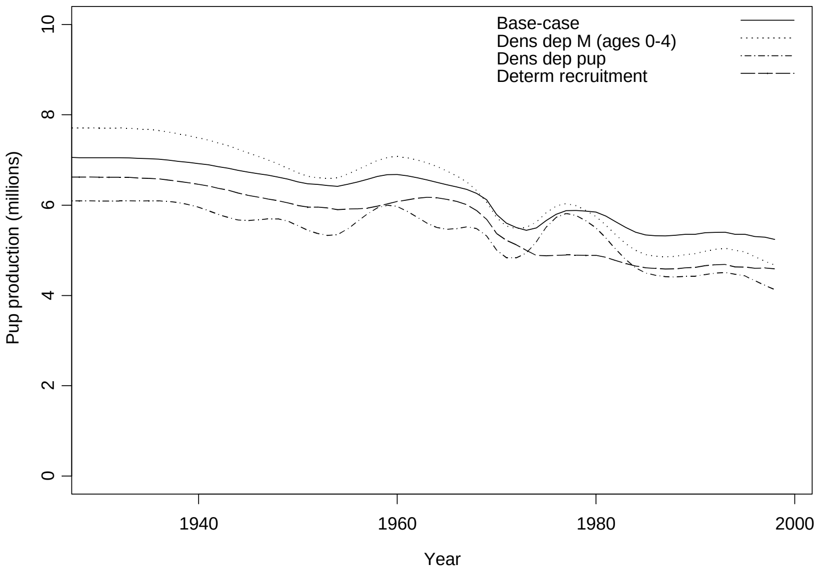

Figure 2.27 : Time-trajectories of pup production for Bass Strait for the base-case analysis, for two sensitivity tests that change how density-dependence is incorporated in the assessment, and for the sensitivity test that assumes that pup production is related deterministically to the number of pregnant females.

Ignoring the length-frequency and age-composition data (row 'No age / length data') leads to a lower estimate for *MSYR* and a higher estimate for M_2. It also leads to the conclusion that the pup production was depleted to 55% of the virgin level in 1999. The results are largely insensitive to ignoring the age-composition data but highly sensitive to omitting the length-frequency data for 7-inch mesh. This sensitivity test (row 'No 7-inch mesh') leads to a higher value for M_2 and lower values for *MSYR* and current depletion. It also leads to a lower value for strength of the 1968 year-class. Omitting the length-frequency data for 7-inch mesh gear is considered because these data relate to a period (1970–74) when fishers' practices may have been quite different from what they were later, so these data may not be representative.

Dropping the catch-rate data (row 'No CPUE data' in Table 2.17) has little impact on the results of the assessment. This is hardly surprising because the weight assigned to these data in the base-case analysis is low relative to the weight given to the other sources of data (see Section 2.3.3). Dropping the tagging data (row 'No tagging data' in Table 2.17) has a marked impact on the results. In particular, M_2 is estimated to be only 0.14yr^{-1} while *MSYR* is estimated to be equal to its upper bound of 0.3. This result indicates that the tagging and length frequency data are 'in conflict' to some extent. The tagging data suggest a higher value for natural mortality whereas the length frequency data suggest a lower value. This result is consistent with the relatively high estimate for the rate of natural mortality (0.28yr^{-1}) obtained by Walker *et al.* (2000) who used only tagging data in their analyses. Reducing the cut-off for 'early recaptures' (see Equations 2.37 and 2.39) from 60 to 30 days leads to a more depleted population; the opposite effect is evident if the cut-off is increased from 60 to 120 days.

Assuming that there is no process error and, instead, that the number of pups is related deterministically to the number of pregnant females (sensitivity test 'Deterministic recruitment') leads to a significantly poorer fit to the data. However, the time-trend in pup production is quite similar to that for the base-case analysis (Figure 2.27) suggesting that assessments based on deterministic recruitment may nevertheless provide relatively robust estimates of trends in pup production. This issue is explored further in Chapter 3.

Assuming that availability is uniform (Table 2.17, row 'Uniform availability') or that availability is never less than 10% of the maximum availability (Table 2.17, row 'Restricted availability') suggests much higher values for M_2 and *MSYR* and a more depleted population. The former result is not surprising –assuming that availability depends on length implies that numbers in the catch drop off quickly with length / age; under the assumption of uniform availability, this effect is mimicked by estimating a higher rate of natural mortality. The fits to the age-composition data by the 'Uniform availability' and 'Restricted availability' sensitivity tests are better than those achieved by the base-case analysis. However, this is more than offset by the much poorer fits to the length-frequency data. Consequently, the fits for these two sensitivity tests are highly significantly poorer than that of the base-case assessment.

It is possible to conduct separate assessments for western and eastern Bass Strait (although the amount of data for the former is considerably less than for the latter)[4]. The results for eastern Bass Strait are more optimistic than those for western Bass Strait and the fits for the former are also generally better (lower residual standard errors). Only the results for eastern Bass Strait suggest strong 1968 and 1996 year-classes and only the exploitable biomass in eastern Bass Strait is estimated to have increased markedly since a low in 1996. In contrast, the results for western Bass Strait indicate that, at best, some stabilization in exploitable biomass has occurred. However,

[4] Due to lack of data, the age-composition data for the whole of Bass Strait has been used for eastern and western Bass Strait.

the results for both these analyses need to be interpreted with caution because the estimates of *MSYR* are close to the bounds imposed (0.3 for eastern Bass Strait and 0.1 for western Bass Strait).

2.4.3.2 South Australia

As expected, the results for the lowest value for *MSYR* (0.19) are less optimistic than those for the other values (Table 2.18). However, the results are more sensitive to the choice of data included in the assessment that the pre-specified value of *MSYR*. In contrast to the situation for Bass Strait, assuming that density-dependence impacts natural mortality rather than pup survival leads to a lower negative log-likelihood. Dropping the age- and length-composition data (i.e. relying only on the catch rate and tagging data) leads to the conclusion of a resource closer to 50% of its virgin level. In contrast, ignoring the tagging data leads to the conclusion that the resource is above 80% of its virgin level. The results for the sensitivity test in which the age-composition data are ignored are again essentially identical to those for the base-case analysis, which is not surprising given the low weight assigned to these data. These results again suggest some ‘conflict’ between the tagging and length-frequency data.

The assessment based on the assumption of deterministic recruitment does not provide a significantly poorer fit to the data than the base-case analysis (at the 5% level).

2.4.4 General discussion

2.4.4.1 Stock status

The populations of gummy shark in Bass Strait and off South Australia are both estimated to be currently above the level at which *MSY* would be achieved, B_{MSY}, and recruitment to the fisheries in both areas is estimated to be stable. However, although this qualitative appraisal of the status of the populations is robust to the specifications of the assessment, this is not the case for the actual quantitative results. In particular, the results are very sensitive to assumptions about density-dependent processes and the extent to which gummy sharks are unavailable to the fishing gear. Furthermore, two of the key data sources included in the assessment (the tagging and length-frequency data) appear to be in conflict to some extent.

One consequence of a significant size-specific availability effect is that the fishery is more susceptible to periods of good and poor recruitment than would be a fishery that had access to all age- and length-classes. Furthermore, the apparent resilience of the population to (over)fishing can be attributed in no small part to this effect. If the fishery changes its behaviour so that non-traditional grounds become fished with increasing frequency, this resilience may be substantially reduced.

2.4.4.2 Assessment-related issues

The assessment confirms the value of attempting to make use of the length-frequency data. These data provide information about the relative strengths of different year-classes, which is of value in explaining past changes in abundance and of some considerable interest to fishers and managers. This is the first assessment of gummy shark that has made full use of these data (the assessments by Walker (1994a, 1998) were based on fitting to the data on the mean weight of individuals in the catch while that by Walker (1994b) was based on fitting to the data of the mean length of individuals in the catch). Monitoring of length-frequency data began during 1985/86, as part of a 3-year FRDC funded project, and has been operated by the Marine and Freshwater Resources Institute (MAFRI) since that time. The project was funded by the former Australian Fisheries Service and AFMA during the 7-year period 1988/89–1994/95, but since then (1995/96–2000/01) it has been funded by industry from industry levies. The collection of these data has been questioned in the past by members of SharkMAC. However, development of the current assessment has clearly established the scientific value of these data.

The assessment was conducted through the SharkFAG process and many of the assumptions / model scenarios considered arose during discussions at meetings of SharkFAG. The SharkFAG process also provided a forum within which the realism of some of the model assumptions and results could be discussed. Had the assessment been conducted without this input, it seems likely that the extent of uncertainty would have been under-estimated as some key model assumptions may not have been examined to the extent they were.

Table 2.1 : Estimates of catch (carcass weight, tonnes) by sub-region, year and gear-type for 1927–72 for the directed shark fisheries and the Commonwealth non-trawl fishery (estimates for the four gill-net mesh sizes used in the fishery have been pooled).

(a) Longline catches

Year	Sub-region								Total
	WSA	CSA	SAV-W	SAV-E	WBas	EBas	WTas	ETas	
1927				1		1			1
1928				1		1			1
1929				4		4			8
1930				2		2			3
1931				2		2			5
1932				3		3			6
1933				30		30			61
1934				17		17			34
1935				30		30			60
1936				57	5	35			97
1937		0	0	64	12	39			116
1938		1	1	54	15	59			129
1939		0	0	48	40	64			153
1940		1	1	71	40	57			171
1941		7	7	76	50	114			254
1942		9	9	58	77	94		15	260
1943		23	23	60	133	112		14	364
1944	8	39	37	46	126	120		31	407
1945	16	16	14	65	107	107		47	372
1946	42	12	8	67	79	144		55	406
1947	26	21	18	75	88	161		76	465
1948	27	13	12	63	128	189		63	495
1949	31	23	11	52	105	282		48	552
1950	22	45	29	53	123	216		24	511
1951	27	30	6	30	90	160		18	361
1952	29	11	4	40	129	182		41	436
1953	115	17	17	49	148	248		41	635
1954	110	12	12	26	96	129		31	415
1955	136	17	10	49	108	146		25	490
1956	181	60	41	60	112	119		13	586
1957	84	109	94	38	80	83	5	39	533
1958	70	91	79	41	69	83	3	26	462
1959	69	89	77	36	84	82	5	44	486
1960	63	82	71	42	147	111	12	97	623
1961	58	76	66	51	148	125	11	89	623
1962	75	98	85	80	120	158	5	37	658
1963	90	117	102	106	134	201	3	26	779
1964	78	101	88	117	138	217	3	20	762

(Table 2.1 Continued)

(a) Longline catches

Year	Sub-region								Total
	WSA	CSA	SAV-W	SAV-E	WBas	EBas	WTas	ETas	
1965	153	60	32	37	116	212	0	13	624
1966	223	88	47	82	135	151	4	13	743
1967	269	106	56	52	142	206	23	25	879
1968	227	89	47	55	145	163	15	41	782
1969	212	83	45	47	194	92	2	26	701
1970	13	24	20	24	193	149	7	23	453
1971	14	26	22	13	47	109	19	7	256
1972	8	14	12	3	34	49	13	6	138

(b) Mesh catches

Year	Sub-region								Total
	WSA	CSA	SAV-W	SAV-E	WBas	EBas	WTas	ETas	
1965					28	64			92
1966				0	31	79			111
1967				0	68	148			217
1968				3	84	290	0	24	400
1969				43	88	495	3	125	753
1970	161	107	28	48	41	151	3	20	558
1971	173	116	30	56	133	241	4	15	768
1972	94	62	16	90	396	526	11	15	1211

Table 2.2 : Estimates of catch (carcass weight, tonnes) by sub-region, year and gear-type for 1973–98 for the directed shark fisheries and the Commonwealth non-trawl fishery (estimates for the four gill-net mesh sizes used in the fishery have been pooled).

(a) Longline catches

Year	Sub-region								Total
	WSA	CSA	SAV-W	SAV-E	WBas	EBas	WTas	ETas	
1973	20	17	18	0	23	47	1	8	133
1974	15	18	2	1	81	36	7	53	213
1975	2	14	2	11	106	11	24	40	210
1976	0	3	2	13	52	15	0	24	109
1977	10	7	5	8	43	54	14	26	168
1978	12	11	0	4	40	54	2	9	133
1979	10	2	1	4	50	47	5	13	133
1980	8	9	1	3	59	64	8	13	164
1981	9	12	1	3	33	60	5	12	133
1982	3	7	0	2	31	23	2	17	85
1983	8	5	0	10	26	39	16	8	112
1984	2	28	3	9	25	66	17	41	191
1985	4	11	3	14	53	57	16	37	197
1986	4	10	6	7	34	56	15	28	160
1987	4	14	5	1	18	63	15	34	154
1988	8	16	5	7	15	49	25	37	162
1989	11	26	23	12	49	76	30	25	252
1990	12	25	2	4	31	40	25	46	185
1991	25	56	26	17	59	75	9	50	317
1992	21	67	32	19	81	88	81	23	412
1993	24	48	24	9	103	83	81	41	413
1994	15	57	6	2	50	27	33	33	224
1995	10	36	4	4	5	30	1	0	90
1996	10	23	3	8	16	27	2	4	93
1997	14	22	2	2	15	38	1	4	99
1998	17	24	2	1	20	25	1	9	100

(Table 2.2 Continued)

(b) Mesh catches

Year	Sub-region								Total
	WSA	CSA	SAV-W	SAV-E	WBas	EBas	WTas	ETas	
1973	30	135	21	106	350	942	15	67	1665
1974	44	72	33	93	206	748	10	84	1291
1975	23	86	22	108	190	559	0	12	1000
1976	7	68	27	102	178	550	3	54	990
1977	13	114	37	72	275	567	8	53	1140
1978	18	101	44	46	297	475	3	82	1065
1979	22	136	41	33	239	410	9	69	959
1980	46	213	28	25	283	436	17	100	1149
1981	36	196	41	36	318	509	9	84	1230
1982	49	196	22	51	464	549	15	51	1397
1983	48	168	18	26	334	696	21	39	1350
1984	62	313	15	17	261	663	31	106	1469
1985	47	302	50	20	221	666	72	110	1487
1986	24	363	55	21	276	701	41	83	1563
1987	58	398	51	30	333	551	49	83	1552
1988	46	477	43	32	280	548	21	116	1564
1989	58	464	60	29	290	687	14	105	1708
1990	58	416	81	25	324	568	22	82	1576
1991	79	278	75	59	368	520	20	74	1473
1992	79	297	39	38	376	605	23	89	1546
1993	50	305	77	39	436	776	38	126	1848
1994	66	299	73	49	383	557	37	118	1582
1995	49	313	43	86	514	585	25	114	1729
1996	100	377	48	45	292	548	15	129	1553
1997	117	469	65	66	265	415	24	81	1502
1998	100	357	28	52	174	616	15	83	1425

Table 2.3 : Reported catches (kg) by SEF and GAB trawlers of gummy shark by year and sub-region. Source: John Garvey (pers. commn)

(a) SEF

Year	Sub-region								Total
	CSA	SAV-W	SAV-E	WBas	EBas	WTas	ETas	NSW	
1985	0	131	154	214	2309	0	0	2023	4831
1986	0	2875	1649	310	9329	80	298	9829	24370
1987	0	215	15	0	3001	0	65	9798	13094
1988	0	60	0	0	2561	60	650	6924	10255
1989	0	241	0	90	6179	0	50	7077	13637
1990	0	240	635	30	4306	0	1012	6700	12923
1991	0	46	62	27	4741	190	275	8936	14278
1992	0	0	1349	1501	23921	35	5663	2619	35089
1993	0	1378	811	2283	19104	27	1941	5401	30944
1994	0	2660	1785	111	15942	23	1416	19901	41839
1995	13	1786	710	140	17578	50	1055	13559	34892
1996	42	3083	1950	362	15508	16	1751	11843	34555
1997	20	3383	1953	470	15379	107	1488	10891	33691
1998	0	2975	1838	307	21420	76	889	9813	37318

(b) GAB

Year	Sub-region								Total
	WA	WSA	CSA	SAV-W	SAV-E	WBas	EBas	WBas	
1987	0	0	205	0	0	0	0	0	205
1988	1255	0	1591	0	0	0	0	0	2846
1989	1472	1744	120	0	0	0	0	0	3336
1990	1510	6386	285	0	0	0	0	0	8181
1991	4864	12055	170	0	0	0	0	0	17089
1992	2365	5115	10	0	0	0	0	0	7490
1993	2546	2446	40	0	0	0	0	0	5032
1994	2351	2320	27	0	0	0	0	0	4698
1995	6460	8065	18	0	0	0	0	0	14543
1996	10267	7361	35	0	0	0	0	0	17663
1997	11401	8089	17	0	0	0	0	0	19507
1998	7167	6231	16	0	0	0	0	0	13414

Table 2.4 : Reported catches of gummy shark, total number of monthly catch-effort records, and the percentage of the reported catch of gummy shark rejected for use in the standardization of the catch and effort data for the three reasons listed in the text.

(a) South Australia

Year	Number of records	Catch (*t*)	Percentage rejected			Percentage accepted
			No Effort	No Cell	Gear	
1973	1600	139.2	2.18	0.00	3.66	96.34
1974	1754	116.0	1.47	0.16	12.23	87.61
1975	1381	115.4	0.23	0.15	1.79	98.06
1976	845	71.3	0.00	0.00	4.90	95.10
1977	899	162.6	20.52	0.00	68.16	31.81
1978	808	176.6	19.20	0.00	79.99	19.92
1979	557	207.0	11.27	0.00	92.86	7.14
1980	664	305.2	5.10	0.00	93.82	6.18
1981	694	293.6	7.99	0.00	92.80	7.20
1982	649	276.6	7.43	0.00	96.32	3.68
1983	698	246.3	15.42	0.03	53.77	37.16
1984	1001	417.7	8.72	0.00	0.10	91.17
1985	1131	415.9	22.04	0.00	0.06	77.90
1986	1523	462.2	7.68	0.00	0.04	92.29
1987	2153	520.8	4.13	0.00	0.00	95.87
1988	2131	584.1	3.06	0.00	0.00	96.94
1989	1947	640.8	2.54	0.00	0.05	97.45
1990	2279	554.9	6.00	0.00	1.24	92.81
1991	2406	482.3	6.98	0.00	0.89	92.94
1992	2364	432.2	7.34	0.00	0.42	92.49
1993	2117	433.3	1.81	0.00	0.27	97.92
1994	1937	452.2	2.70	0.00	0.14	97.16
1995	1955	403.3	1.55	0.00	1.55	98.45
1996	1840	531.0	0.81	1.30	0.81	97.89
1997	6924	669.8	6.20	0.00	14.20	80.65
1998	9944	506.6	3.90	0.00	1.04	96.02

(Table 2.4 Continued)

(b) Bass Strait

Year	Number of records	Catch (*t*)	Percentage rejected			Percentage accepted
			No Effort	No Cell	Gear	
1973	4218	1350.5	4.87	0.00	17.62	82.35
1974	3821	962.8	4.42	0.00	11.94	88.06
1975	4043	913.5	5.39	0.00	21.19	78.77
1976	3794	758.1	3.07	0.00	23.55	76.17
1977	4019	872.9	7.07	0.00	17.78	82.06
1978	4207	792.2	9.17	0.05	14.96	80.77
1979	4165	673.8	21.18	0.00	13.60	73.23
1980	4652	761.5	22.94	0.00	12.07	73.47
1981	4318	851.7	35.94	0.00	27.28	62.35
1982	5229	972.2	24.93	0.00	22.45	72.39
1983	5440	1014.5	37.60	0.68	31.93	62.37
1984	5241	973.1	42.96	0.00	35.26	57.03
1985	5769	942.6	46.72	0.00	38.12	52.55
1986	6144	1013.2	39.63	0.00	36.45	55.09
1987	6339	900.6	45.35	0.00	38.54	52.85
1988	7131	802.2	26.43	0.00	28.70	65.57
1989	6635	993.0	36.12	0.00	40.56	52.15
1990	5568	890.8	32.31	0.00	27.86	66.46
1991	7738	991.3	21.45	0.00	24.24	66.31
1992	7255	1112.2	16.28	0.00	13.12	76.88
1993	7084	1272.9	19.21	0.00	16.77	71.82
1994	6640	915.3	19.07	0.22	18.19	75.06
1995	7748	1128.2	1.82	0.13	0.00	98.05
1996	9747	879.2	0.55	0.00	0.55	99.45
1997	8875	785.1	4.44	0.00	2.50	94.43
1998	8494	879.7	2.50	0.00	2.31	97.50

(Table 2.4 Continued)

(c) Tasmania

Year	Number of records	Catch (t)	Percentage rejected			Percentage accepted
			No Effort	No Cell	Gear	
1973	396	68.6	17.97	0.00	24.98	75.02
1974	512	151.7	50.87	0.00	64.80	35.20
1975	219	75.5	25.97	0.00	28.82	71.18
1976	247	77.0	24.33	0.00	45.14	54.86
1977	443	99.3	20.20	0.00	39.25	60.75
1978	382	94.0	49.36	0.00	60.52	36.70
1979	512	93.9	97.49	0.00	78.75	2.51
1980	577	137.0	92.21	0.00	77.13	7.79
1981	298	109.7	93.10	0.00	77.45	6.90
1982	188	84.6	92.71	0.00	70.27	7.29
1983	176	83.0	97.53	0.00	69.52	2.47
1984	463	195.0	99.06	0.00	69.32	0.94
1985	983	230.4	97.92	0.00	74.68	2.05
1986	942	162.4	98.38	0.00	72.03	1.62
1987	1384	178.8	98.33	0.00	71.02	1.67
1988	1683	185.3	91.84	0.00	61.75	7.27
1989	1714	173.2	88.09	0.00	63.19	5.86
1990	2142	168.9	84.71	0.00	46.54	15.05
1991	903	147.1	80.22	0.00	52.72	17.40
1992	1168	210.7	76.57	0.00	38.39	21.55
1993	902	281.2	92.69	0.01	51.12	7.03
1994	650	218.1	96.03	0.00	66.60	3.82
1995	1707	138.5	0.19	15.69	0.19	84.12
1996	4915	149.8	1.62	0.00	1.62	98.38
1997	1606	109.6	6.30	0.00	6.88	93.12
1998	1923	108.5	7.28	0.00	6.77	92.72

Table 2.5 : Statistics related to alternative choices for the thresholds used to select vessels for inclusion in the catch and effort standardization.

Description	Number of records	Number of vessels	Total catch (t)	Average # of years in the fishery	Average median catch (gummy shark) (kg)
(a) Base-case	18295	61	12455	14.0	18115
(b) $Catchc_{crit} = 5t$	19586	72	13066	14.0	16353
(c) $Catchg_{crit} = 2.5t$	18346	62	12470	13.9	17901
(d) $Year_{crit} = 10$	16703	48	11476	16.0	18732
(e) $Year_{crit} = 3$	18478	64	12569	13.5	18005
(f) $Catchg_{crit} = 10t$	16484	50	11468	13.9	20273
(g) $Catchg_{crit} = 15t$	14596	35	10351	15.4	23783
(h) Annual 0.6 const	17349	77	12609	14.4	17402
(i) $Min_{rec} = 30$	18249	59	12409	14.1	18364
(j) 6-inch mesh only	16361	52	10353	14.5	17678
(k) 7-inch mesh only	711	9	1234	14.2	19661
(l) No 0.6 constraint	22643	86	15622	14.2	16539
(m) Include 73-75 data	19305	64	13629	14.5	18292

Table 2.6 : Summary of the application of the rules used to specify standardized catch rates for cells / years for which actual data are missing.

Bass Strait				South Australia			
Cell#	Rule a)	Rule b)	Rule c)	Cell#	Rule a)	Rule b)	Rule c)
4	0	0	12	101	3	0	1
5	0	0	3	102	5	0	0
6	1	0	0	103	0	0	0
7	0	0	0	107	0	0	0
8	0	0	0	112	0	0	0
9	0	0	0	115	0	0	0
10	0	0	0	122	5	1	5
11	0	0	0	126	0	0	0
18	0	0	0	128	0	0	0
19	0	0	0	129	0	0	0
20	0	0	0	132	0	0	3
21	0	0	0	136	2	3	4
22	0	0	0	138	0	0	0
23	0	0	0	139	0	0	0
30	2	0	0	140	0	0	0
31	0	0	0	144	0	0	0
32	0	0	0	148	0	0	1
33	4	0	1	149	0	0	0
34	0	0	0	150	0	0	0
35	0	0	0	151	0	0	0
				155	0	0	0
				158	1	0	0

Table 2.7 : The base-case catch rate indices for Bass Strait and South Australia.

Year	Bass Strait	South Australia
1976	87.7	
1977	84.4	
1978	85.5	
1979	73.2	
1980	73.5	
1981	69.5	
1982	85.7	
1983	76.4	
1984	64.5	91.0
1985	54.6	100.0
1986	61.9	70.4
1987	50.6	48.5
1988	55.0	74.4
1989	64.0	78.0
1990	69.0	55.6
1991	69.7	56.7
1992	95.2	51.1
1993	100.0	57.3
1994	79.2	66.6
1995	94.2	55.9
1996	67.2	82.6
1997	49.6	74.2
1998	61.8	58.4

Table 2.8 : The tag-types represented in the tagging database. The column ‘direct’ indicates whether the double-tagging experiments can be used to estimate tag-shedding rates for the tag-type concerned. The columns ‘#rel’ and ‘#rec’ contain the total number of gummy sharks released and recaptured respectively. Note that the total number of releases in this table exceeds the actual number (see row ‘total’) because some fish were double-tagged. An asterisk indicates a tag-type for which the tag-shedding rate is assumed to be 1.

Tag-type	Years	Details	#Rel	#Rec	Direct
Nesbit (S-tag)	1942-56	Internal — 35mm long, 10mm wide	98	5	Yes*
Nesbit (L-tag)	1942-56	Internal — 50mm long, 22mm wide	488	52	Yes*
W-tag	1942-56	External — white Peterson disc (16mm diameter, 1mm thick)	58	2	No
G-tag	1942-56	External — gray Peterson disc (16mm diameter, 1mm thick)	306	26	No
Roto	1987-96	External — 36 mm long, 9 mm wide	2750	682	Yes
Jumbo	1993-96	External — 45 mm long, 18 mm wide	1870	680	Yes
Mini	1995-96	External — 21 mm long, 5 mm wide	78	3	No
Dart – muscle	1991-96	External — 95 mm long, 2 mm diameter	2265	401	Yes
Dart – fin	1991-96	External — 95 mm long, 2 mm diameter	691	120	Yes
Steel	1993-96	External — 140 mm long, 2 mm diameter	78	7	No
T-Bar	1986-90		84	7	No
A-Int	1994-96	Dummy archival tag – internal	5	1	No
A-Block	1994-96	Dummy archival tag – block	1	1	No
A-Torp	1994-96	Dummy archival tag – torpedo	4	1	No
Nesbit (MAFRI)	1973-76	Internal – white (equivalent to S-tag)	89	7	Yes*
Nesbit (MAFRI)	1973-76	Internal – yellow (equivalent to J / L tags)	1436	373	Yes*
Total			9130	2053	

Table 2.9 : Tag-shedding rates for gummy shark (yr^{-1}) with asymptotic standard errors in parenthesis. Results are shown separately for males and females. The column ‘$-\ell nL$’ lists the negative of the logarithm of the likelihood function corresponding to the estimates provided.

	N	Jumbo / Roto / Dart (fin)	Dart (muscle)	$-\ell nL$
Males	129	0.152 (0.043)	0.677 (0.106)	115.74
Females	141	0.119 (0.046)	0.975 (0.133)	105.79
Both	270	0.139 (0.031)	0.823 (0.084)	223.50

Table 2.10 : The tag-reporting rates. Results are shown for the WBas and EBas sub-regions for analyses based on the years 1973–78 and for seven sub-regions for analyses based on the years 1994–96. Sensitivity is explored to the minimum level of catch used when applying the algorithms developed by Brown and Walker (1999).

(a) 1973–78

Annual	Sub-	Year						Annual	Year	
catch (t)	region	1973	1974	1975	1976	1977	1978	catch (t)	1973–75	1976–78
>5	WBas	0.21	0.35	0.50	0.56	0.62	0.46	>15	0.61	0.68
	EBas	0.53	0.54	0.59	0.39	0.30	0.20		0.87	0.50
	Both	0.45	0.49	0.56	0.44	0.42	0.31		0.75	0.57
>10	WBas	0.26	0.35	0.51	0.58	0.73	0.48	>30	0.59	0.67
	EBas	0.55	0.58	0.62	0.40	0.31	0.23		0.83	0.56
	Both	0.49	0.52	0.58	0.45	0.46	0.33		0.77	0.60
>15	WBas	0.30	0.34	0.55	0.66	0.74	0.48	>45	0.59	0.76
	EBas	0.58	0.63	0.68	0.41	0.32	0.26		0.86	0.62
	Both	0.52	0.55	0.64	0.48	0.46	0.35		0.79	0.67

(Table 2.10 Continued)

(b) 1994–96

Annual catch (t)	Sub-region	Year 1994	1995	1996	Annual Catch (t)	Year 1994–96
> 5	WSA	0.89	0.84	1.54	>15	0.88
	CSA	0.88	0.92	0.84		0.51
	SAV	1.35	1.96	2.70		0.88
	WBas	1.25	1.06	0.98		0.71
	EBas	0.96	1.03	1.02		0.90
	WTas	na	na	na		0.80
	ETas	na	na	na		0.79
	ALL	1.03	1.10	1.09		0.73
>10	WSA	0.99	0.95	0.83	>30	0.92
	CSA	0.89	0.81	0.79		0.41
	SAV	1.02	1.02	1.24		0.71
	WBas	1.00	0.96	0.88		0.79
	EBas	0.99	1.00	0.99		1.10
	WTas	1.83	1.22	1.22		0.80
	ETas	na	na	na		0.96
	ALL	0.89	0.97	0.95		0.73
>15	WSA	1.03	1.00	1.00	>45	0.75
	CSA	0.93	0.86	0.89		0.42
	SAV	0.85	0.65	0.60		na
	WBas	1.25	1.18	0.94		0.60
	EBas	0.97	1.03	1.01		0.90
	WTas	3.19	3.19	na		0.80
	Etas	0.94	0.81	1.17		0.96
	ALL	1.05	1.03	1.02		0.67

Table 2.11 : Length-frequency sample sizes for gummy shark (1970–98). The sample sizes for the sub-regions SAV-W and SAV-E have been combined.

(a) Females

Sub-region	Gear-type	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
WSA	Longline	0	0	0	81	163	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WSA	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	84	133
WSA	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	89	0	0	569	1201
WSA	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17	111	223	40	0	84	0	1129	736	694	815	520	0	0
WSA	8	0	0	0	392	1005	0	73	0	0	0	0	0	0	0	0	0	71	0	0	0	0	0	0	0	0	0	0	0	0
CSA	Longline	0	0	0	0	61	394	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0
CSA	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	593	637	64	206	56	285	172	406	0	0	0	211
CSA	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	154	0	0	321	415	752	0	649	3523
CSA	7	0	0	0	0	0	346	7	0	0	0	0	0	0	0	0	0	291	2742	1043	81	460	243	459	212	490	470	501	0	0
CSA	8	0	0	0	176	44	1123	596	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SAV	Longline	65	45	88	134	0	0	0	0	0	0	0	0	0	0	0	0	0	101	141	0	0	91	0	0	0	63	0	0	0
SAV	6	0	0	0	0	0	0	137	0	50	109	0	412	221	327	0	0	0	178	301	56	400	0	352	0	0	0	0	150	0
SAV	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	230	0	283	0	587	0	0	0	72
SAV	7	0	0	0	1115	0	0	0	0	0	0	0	0	0	0	0	0	78	986	469	80	141	0	0	0	0	93	0	89	0
SAV	8	0	0	0	448	0	0	0	0	0	0	0	0	0	0	0	0	0	0	178	0	0	0	0	0	136	0	0	0	0
WBas	Longline	22	134	72	44	93	315	369	0	0	0	86	26	0	19	0	5	24	0	15	0	25	0	16	115	76	45	0	0	0
WBas	6	0	0	0	0	1189	2391	3224	1975	1626	1911	1676	2328	3938	2138	105	481	431	577	801	473	579	558	264	867	970	401	579	267	1278
WBas	7	576	1014	1787	70	328	70	111	0	0	100	72	170	241	72	86	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EBas	Longline	301	963	543	1107	2052	698	521	0	53	66	18	0	0	0	0	55	52	19	43	46	0	66	135	311	423	0	0	44	0
EBas	6	0	0	0	512	6337	11493	9302	4552	2483	2422	3620	6247	2784	2565	72	1375	1326	1024	2025	1668	1912	1834	1379	3087	1227	948	2254	1630	5485
EBas	7	2679	4399	4500	11685	1423	54	0	0	0	50	25	301	41	59	0	81	0	0	0	23	0	0	0	0	0	0	0	0	0
WTas	Longline	0	0	0	92	59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	77	0	0	0	0	0
WTas	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	152	0	0	0
WTas	7	0	0	0	102	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	241	76	0	0
ETas	Longline	6	0	0	0	13	0	0	44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	336	0	0	0	0	0	0
ETas	6	0	0	0	0	0	108	0	35	0	0	0	65	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ETas	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	491	364	0	0

(Table 2.11 Continued)

(b) Males

Sub-region	Gear-type	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
WSA	Longline	0	0	0	41	38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WSA	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	146	49
WSA	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	66	0	0	299	899
WSA	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	39	66	203	42	0	0	41	497	479	685	1056	374	0	0
WSA	8	0	0	0	429	162	0	51	0	0	0	0	0	0	0	0	0	128	0	0	0	0	0	0	0	0	0	0	0	0
CSA	Longline	0	0	0	0	19	326	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
CSA	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	411	758	96	142	0	181	83	260	0	0	0	74
CSA	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	124	0	0	149	106	280	0	354	2030
CSA	7	0	0	0	0	0	463	19	0	0	0	0	0	0	0	0	59	460	1712	683	186	461	134	270	113	435	871	317	0	0
CSA	8	0	0	0	65	8	188	268	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SAV	Longline	0	0	0	90	0	0	0	0	0	0	0	0	0	0	0	0	0	0	138	0	0	0	0	0	0	57	0	0	0
SAV	6	0	0	0	0	0	0	100	0	0	75	0	285	172	256	0	0	0	0	188	102	483	0	156	0	0	0	0	184	0
SAV	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	321	0	72	0	165	0	0	0	0
SAV	7	0	0	0	368	0	0	0	0	0	0	0	0	0	0	0	0	0	226	363	129	125	0	0	0	0	0	0	0	0
SAV	8	0	0	0	150	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WBas	Longline	36	382	114	86	141	453	421	0	0	0	98	5	0	24	0	1	21	0	40	53	31	0	24	65	56	3	0	0	0
WBas	6	0	0	0	0	1636	2483	2994	2566	1657	1574	1397	1879	3201	1783	0	615	854	1031	1336	961	924	1141	394	1511	1321	603	1132	318	3072
WBas	7	1006	2624	4743	3381	248	46	44	0	0	85	52	98	184	62	96	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EBas	Longline	640	2243	590	1659	3413	733	811	0	43	65	0	0	0	0	0	29	23	23	55	64	0	36	116	278	454	0	0	10	0
EBas	6	0	0	0	1287	7740	13145	9992	4619	2394	1996	3072	5153	2252	2095	68	1236	1229	1132	2256	1764	2204	1953	1581	3599	1396	979	2692	2543	7667
EBas	7	3233	4848	5837	12002	1625	50	0	0	0	43	18	238	31	45	0	35	0	0	0	29	0	0	0	0	0	0	0	0	0
WTas	Longline	0	0	0	17	44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	69	0	66	0	0	0	0	0
WTas	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	115	0	53	0
WTas	7	0	0	0	96	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	613	125	0	0
ETas	Longline	0	0	0	8	0	0	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	321	0	0	0	0	0	0
ETas	6	0	0	0	0	0	223	0	57	0	0	0	52	0	0	0	0	0	0	0	0	0	0	79	0	0	0	0	0	0
ETas	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1119	452	0	0

Table 2.12 : Length-frequency information (parts per ten thousand) for gummy shark in Bass Strait and South Australia. Results are shown separately for males and females. The row ‘No’ indicates the number of animals measured for length in the year concerned.

(a) Bass Strait - Males – 6-inch mesh

Length	Year																						
Class	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
70	17	19	15	1	3	2	0	10	0	0	6	0	3	6	0	20	4	7	25	0	2	2	9
75	61	46	39	14	13	0	6	36	5	0	27	6	6	24	3	26	56	26	41	27	20	22	74
80	137	122	138	88	143	51	81	176	97	3	62	31	70	45	76	131	152	64	99	78	93	153	281
85	255	325	494	265	329	190	309	554	550	231	128	236	250	279	385	301	341	244	364	480	387	632	885
90	470	807	1245	929	1153	947	915	1453	1642	1360	568	768	806	1174	886	726	947	603	963	1134	1072	1240	1471
95	806	1271	1679	1650	1472	1682	1349	1844	2165	2126	978	1468	1468	1970	1509	1413	1597	1146	1576	1758	1676	1784	1708
100	1016	1505	1621	1877	1756	1624	1505	1952	2131	2283	1481	1721	1918	2126	1846	1700	1738	1533	1714	1792	1721	1594	1541
105	1310	1538	1362	1698	1618	1519	1644	1728	1705	2063	1650	1488	1693	1693	1679	1753	1420	1618	1479	1442	1443	1447	1174
110	1374	1265	999	1266	1095	1473	1468	1053	913	1205	1453	1295	1347	1084	1294	1241	1288	1305	1213	1107	1095	956	890
115	1325	1043	807	798	856	966	970	477	411	506	1157	945	915	615	861	860	899	1161	858	763	803	681	611
120	1104	795	598	592	688	656	728	319	171	162	839	755	629	442	556	679	597	907	604	545	594	529	491
125	902	570	445	420	467	416	537	180	97	38	626	608	399	247	370	403	452	585	447	298	479	426	346
130	598	317	262	226	241	311	246	118	61	23	381	306	240	120	212	313	226	323	284	260	271	293	203
135	302	217	186	86	103	106	145	58	29	0	253	178	134	52	153	173	136	250	181	195	168	101	149
140	166	96	71	56	39	37	60	27	15	0	138	130	72	39	93	128	86	142	85	71	114	113	101
145	102	47	31	21	20	15	25	10	4	0	123	53	35	48	39	95	57	71	48	40	41	26	48
150	54	17	9	12	5	5	14	4	2	0	130	13	13	35	39	39	4	17	19	8	21	0	18
155	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
160	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
165	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
170	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
175	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
180	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
No	7526	13884	12526	6527	4109	4333	5296	8575	6722	4703	1757	1601	2826	2141	2491	2392	1643	3954	2197	1349	2833	1897	6763
Ave length	111.7	106.7	103.2	103.2	104.4	105.3	105.9	99.7	98.2	98.5	110.3	104.6	102.7	99.0	103.6	103.7	101.9	103.6	101.7	99.4	101.5	100.9	97.6

(Table 2.12 Continued)

(b) Bass Strait - Females – 6-inch mesh

Length Class	Year																						
	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
70	20	23	12	0	5	0	2	12	0	0	0	0	3	0	3	9	18	8	15	12	0	4	3
75	58	56	40	11	7	0	19	55	20	0	17	0	7	36	40	23	36	31	50	51	35	31	97
80	118	100	121	92	106	45	98	229	207	66	17	31	48	76	77	114	138	108	154	183	123	212	417
85	280	316	422	308	303	172	256	614	697	471	143	367	306	429	373	315	546	332	467	664	472	885	1178
90	428	743	1214	921	1058	732	767	1313	1554	1409	460	776	952	1421	939	1033	950	853	1061	1417	1160	1561	1710
95	832	1188	1611	1636	1376	1443	1196	1734	1900	1949	1111	1499	1655	2226	1678	1557	1777	1494	1816	1960	1837	1890	1683
100	895	1388	1590	1819	1657	1692	1556	1811	1946	2115	1472	1757	2073	2289	1802	1891	1789	1772	1888	1960	1730	1526	1499
105	1160	1412	1322	1662	1488	1576	1517	1715	1587	1897	1579	1645	1618	1472	1606	1512	1468	1532	1370	1186	1571	1098	1131
110	1205	1208	995	1232	1185	1352	1382	1023	979	1180	1312	1216	1117	868	1264	1111	1109	1262	1119	1018	1071	829	769
115	1129	1018	774	739	832	1035	1035	559	502	566	1015	836	805	434	603	791	874	935	725	566	792	491	509
120	1017	823	630	571	659	694	728	322	249	213	673	642	551	329	510	543	418	645	373	349	490	322	314
125	824	581	429	341	507	465	564	234	128	97	513	485	367	143	338	314	296	435	345	223	266	287	213
130	563	406	344	244	298	392	338	119	76	28	404	319	216	117	201	215	212	220	206	120	147	177	181
135	524	258	245	164	201	176	212	83	55	10	277	145	80	36	165	157	132	147	155	126	76	187	144
140	394	177	116	107	107	106	144	64	47	0	292	75	56	13	117	93	82	97	97	80	65	160	62
145	242	140	60	58	66	70	66	44	18	0	179	50	58	15	63	57	64	50	55	6	26	118	35
150	150	76	32	44	71	20	49	24	21	0	197	38	24	34	40	70	27	25	44	34	38	8	15
155	81	40	19	29	35	15	41	14	4	0	101	50	14	13	67	54	9	10	17	23	41	14	25
160	43	29	14	5	29	12	18	10	3	0	58	50	21	21	16	59	22	19	19	0	9	101	10
165	14	6	9	6	7	0	3	8	1	0	66	6	25	25	29	16	19	4	20	12	21	81	0
170	13	11	2	6	2	4	5	11	3	0	51	7	0	0	13	26	4	10	0	12	9	4	5
175	8	4	0	2	2	0	2	2	0	0	28	7	0	4	39	17	4	6	0	0	21	0	0
180	2	1	1	2	0	0	0	0	0	0	34	0	3	0	17	23	4	2	5	0	0	14	0
No	9376	15628	12986	7185	4051	3570	4469	7032	5453	3878	2083	2163	3592	2725	3128	3094	1975	5110	2717	1582	3824	2861	10739
Ave length	109.0	104.7	101.8	102.5	102.4	103.4	104.0	98.8	97.6	98.7	107.6	104.9	103.4	100.7	103.0	104.2	102.7	106.2	103.0	101.8	102.8	101.2	99.7

(Table 2.12 Continued)

(c) Bass Strait – 7-inch mesh

	Males					Females				
Length	Year									
Class	1970	1971	1972	1973	1974	1970	1971	1972	1973	1974
70	31	20	5	3	0	15	22	9	2	0
75	143	78	9	10	0	107	99	19	8	6
80	418	183	17	18	11	322	222	45	19	36
85	682	403	53	68	79	534	417	79	42	95
90	1171	685	158	139	275	829	816	196	141	300
95	1270	792	279	283	530	1141	1029	324	343	554
100	1186	959	509	492	844	1297	1286	606	810	861
105	1109	1101	764	808	1148	1196	1365	871	1084	1149
110	988	1201	1139	1264	1424	1074	1307	1292	1200	1257
115	800	1132	1500	1554	1518	850	1132	1433	1374	1091
120	756	1075	1670	1713	1561	656	953	1428	1226	1014
125	562	893	1567	1518	1070	468	481	1251	966	997
130	389	698	1141	1072	781	361	373	804	855	643
135	228	431	686	618	502	312	159	604	704	555
140	129	230	324	295	113	247	103	400	557	493
145	79	70	121	104	97	184	97	286	329	322
150	57	49	56	42	48	147	62	124	144	259
155	0	0	0	0	0	122	44	73	79	162
160	0	0	0	0	0	72	14	73	39	122
165	0	0	0	0	0	42	16	42	67	56
170	0	0	0	0	0	15	4	37	7	22
175	0	0	0	0	0	11	0	5	2	6
180	0	0	0	0	0	0	0	0	1	0
No	4239	7472	10580	15383	1873	3255	5413	6287	11755	1751
Ave length	102.7	108.6	116.5	116.0	112.6	106.5	105.4	116.7	116.8	115.9

(Table 2.12 Continued)

(d) South Australia

	Females											Males										
Length	Year																					
Class	7-inch mesh									6.5 –inch mesh		7-inch mesh									6.5 –inch mesh	
	1986	1987	1988	1990	1992	1993	1994	1995	1996	1997	1998	1986	1987	1988	1990	1992	1993	1994	1995	1996	1997	1998
70	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
75	0	0	0	37	0	0	0	0	0	0	2	0	0	0	22	0	0	0	0	0	0	4
80	32	32	26	110	16	0	19	17	0	0	28	0	15	40	217	0	0	0	0	0	0	19
85	96	32	61	92	89	0	0	0	0	0	119	0	41	93	130	61	4	0	13	21	0	101
90	32	171	279	753	664	3	70	105	13	52	331	0	112	319	607	367	4	129	73	0	119	383
95	128	349	506	845	903	0	140	138	33	93	764	41	340	453	933	930	4	211	30	60	200	766
100	70	631	1142	973	1256	165	549	353	98	367	1252	20	478	1145	911	1045	457	467	226	194	570	1342
105	134	888	1194	900	1155	230	704	743	303	343	1252	41	747	1291	1085	1297	830	674	738	457	724	1340
110	163	1234	1525	1158	1068	411	1004	976	630	633	1261	143	1174	1571	1150	1443	575	1148	1638	949	1291	1512
115	741	1008	1051	901	965	667	1053	1055	854	1227	1157	781	1041	1072	1150	1380	1355	1923	2125	1786	2123	1456
120	2424	966	1099	1067	935	659	1271	994	1341	1576	864	2180	1239	1354	803	1319	1447	1733	1884	1922	1733	1072
125	1925	1270	925	956	774	1034	1181	1331	1392	1239	763	1926	1805	902	933	1083	2947	1796	1694	2010	1448	967
130	690	1241	689	608	452	581	775	1235	1439	1035	592	883	1409	582	738	439	1201	985	973	1417	817	621
135	934	802	487	461	465	722	640	1059	986	869	410	1399	739	633	456	279	422	270	462	604	466	252
140	401	424	274	294	462	1039	550	474	1151	731	317	1065	408	186	325	183	604	192	59	388	346	106
145	761	302	246	349	289	1351	458	582	776	610	237	1146	227	213	282	88	79	257	64	122	162	33
150	421	267	192	129	183	1110	392	277	513	467	248	376	227	146	260	86	71	216	19	72	0	27
155	439	131	87	74	150	994	296	172	341	284	195	0	0	0	0	0	0	0	0	0	0	0
160	415	69	122	92	57	463	354	146	92	266	108	0	0	0	0	0	0	0	0	0	0	0
165	69	57	78	92	31	236	280	194	0	152	55	0	0	0	0	0	0	0	0	0	0	0
170	43	41	17	73	59	255	89	67	39	51	17	0	0	0	0	0	0	0	0	0	0	0
175	63	44	0	37	20	43	112	33	0	4	13	0	0	0	0	0	0	0	0	0	0	0
180	18	41	0	0	7	38	64	50	0	0	13	0	0	0	0	0	0	0	0	0	0	0
No	402	2965	1083	544	1588	948	1184	1285	1021	1218	4724	526	1915	725	461	767	592	1120	1927	691	653	2929
Ave length	127.4	119.2	114.4	113.0	112.7	135.7	124.7	123.5	127.3	125.5	113.5	127.3	118.3	112.4	111.2	110.4	119.5	117.0	116.3	119.4	115.8	109.4

Table 2.13 : Number of gummy sharks collected and aged (1973–97).

(a) Males

Region	Mesh size	Year								
		1973	1974	1975	1986	1987	1990	1991	1992	1993
Bass Strait	6	18	10	15	76	27	83	141	70	184
Bass Strait	6.5	3	0	19	143	90	0	0	0	0
Bass Strait	7	13	11	4	27	7	0	0	0	6
Bass Strait	8	2	0	0	7	2	0	0	0	0
South Australia	6	0	0	0	29	5	35	11	37	12
South Australia	6.5	0	0	0	53	15	5	0	25	33
South Australia	7	0	0	0	23	4	10	0	81	69
South Australia	8	0	0	0	8	0	0	0	0	0
Tasmania	6	0	0	0	0	0	11	11	0	17

(b) Females

Region	Mesh size	Year								
		1973	1974	1975	1986	1987	1990	1991	1992	1993
Bass Strait	6	24	7	12	72	39	43	179	68	190
Bass Strait	6.5	0	0	7	139	114	0	0	0	0
Bass Strait	7	36	30	4	20	11	0	0	0	10
Bass Strait	8	6	0	7	19	4	0	0	0	0
South Australia	6	0	0	0	93	11	77	58	113	14
South Australia	6.5	0	0	0	97	20	12	0	28	59
South Australia	7	0	0	0	56	6	54	0	79	76
South Australia	8	0	0	0	46	5	0	0	0	0
Tasmania	6	0	0	0	0	0	5	10	0	14

Table 2.13 : Number of gummy sharks collected and aged (1973–97).

(a) Males

Region	Mesh size	Year								
		1973	1974	1975	1986	1987	1990	1991	1992	1993
Bass Strait	6	18	10	15	76	27	83	141	70	184
Bass Strait	6.5	3	0	19	143	90	0	0	0	0
Bass Strait	7	13	11	4	27	7	0	0	0	6
Bass Strait	8	2	0	0	7	2	0	0	0	0
South Australia	6	0	0	0	29	5	35	11	37	12
South Australia	6.5	0	0	0	53	15	5	0	25	33
South Australia	7	0	0	0	23	4	10	0	81	69
South Australia	8	0	0	0	8	0	0	0	0	0
Tasmania	6	0	0	0	0	0	11	11	0	17

(b) Females

Region	Mesh size	Year								
		1973	1974	1975	1986	1987	1990	1991	1992	1993
Bass Strait	6	24	7	12	72	39	43	179	68	190
Bass Strait	6.5	0	0	7	139	114	0	0	0	0
Bass Strait	7	36	30	4	20	11	0	0	0	10
Bass Strait	8	6	0	7	19	4	0	0	0	0
South Australia	6	0	0	0	93	11	77	58	113	14
South Australia	6.5	0	0	0	97	20	12	0	28	59
South Australia	7	0	0	0	56	6	54	0	79	76
South Australia	8	0	0	0	46	5	0	0	0	0
Tasmania	6	0	0	0	0	0	5	10	0	14

Table 2.15 : Values for the parameters of the population dynamics model.

(a) Biological parameters

Quantity	Female	Male	Source
L_∞ (mm)	2019	1387	Moulton *et al*. (1992)
κ (yr^{-1})	0.123	0.253	Moulton *et al*. (1992)
t_0 (yr)	-1.55	-0.90	Moulton *et al*. (1992)
a ($x10^{-9}$)	1.22	4.38	Walker (1994a)
b	3.18	2.97	Walker (1994a)
a' (yr)	-1.8520		Walker (1994a)
b' (yr^{-1})	0.0032		Walker (1994a)
P''_{max}	0.6060		Walker (1994a)
λ''_{50} (mm)	1273.15		Walker (unpublished data)
λ''_{95} (mm)	1593.20		Walker (unpublished data)

b) Gill-net selectivity parameters (Kirkwood and Walker, 1986)

Mesh-size	α	β
6-inch	42.09	26.27
7-inch	56.95	22.65
8-inch	74.08	19.90

Table 2.16 : The five tag-types. Double-tagged animals are treated differently from animals tagged using a single tag because of differences in the rate of tag loss.

Tag-type(s)	# Releases	# Recoveries	Tag loss rate (yr^{-1})	
			Females	Males
Jumbo, Roto, Dart (fin) – single tag	1282	352	0.119	0.152
Dart (muscle) – single tag	957	112	0.975	0.677
Dart (muscle) and Jumbo	373	141	0.072	0.072
Jumbo, Roto, Dart (fin) – double tagged	56	14	0.013	0.020
Internal	1658	370	0	0

Table 2.17 : Maximum likelihood estimates of various management-related quantities for Bass Strait.

Scenario	Quantity												
	SB_0	M_2	$MSYR$	SB_{73}/SB_0	SB_{99}/SB_0	σ_{CPUE}	$\sigma_{len,f}$		$\sigma_{len,m}$		$\sigma_{age,f}$	$\sigma_{age,m}$	$-\ln L$
							6-inch	7-inch	6-inch	7-inch			
Base-case	7055	0.188	0.221	77.2	73.6	0.134	0.067	0.083	0.071	0.098	0.188	0.221	294.97
M age-dependent	6468	0.173	0.228	75.9	72.9	0.134	0.067	0.084	0.071	0.097	0.187	0.221	294.76
Alter effort relationship	6828	0.190	0.225	76.7	73.2	0.135	0.067	0.084	0.072	0.098	0.189	0.221	295.69
Higher catches	7801	0.190	0.187	74.9	70.4	0.135	0.067	0.083	0.071	0.097	0.187	0.221	293.18
With 73-75 CPUE data	7404	0.181	0.248	79.1	76.7	0.176	0.068	0.086	0.072	0.101	0.188	0.224	301.31
Dens-dep M (ages 0-4)	7712	0.169	0.296	71.4	59.6	0.134	0.067	0.084	0.071	0.097	0.186	0.217	290.41
Dens-dep pups	6096	0.174	0.190	81.0	66.4	0.139	0.065	0.078	0.070	0.094	0.192	0.223	284.10
30 day early captures	6441	0.192	0.223	75.9	71.1	0.144	0.066	0.084	0.070	0.098	0.187	0.216	286.43
120 day early recaptures	8134	0.182	0.222	79.2	77.8	0.120	0.068	0.083	0.072	0.097	0.190	0.229	309.46
No age/length data	4636	0.223	0.186	70.0	54.5	0.129	0.156	0.194	0.161	0.198	0.209	0.194	74.46
No age data	6736	0.190	0.212	75.4	70.2	0.121	0.064	0.081	0.072	0.093	0.210	0.276	239.43
No 7-inch mesh	3559	0.256	0.187	65.5	44.8	0.139	0.186	0.221	0.178	0.211	0.159	0.156	112.24
No CPUE data	7292	0.191	0.208	77.5	73.4	0.192	0.065	0.083	0.070	0.097	0.182	0.218	378.81
No tagging data	6622	0.136	0.300	75.5	69.0	0.129	0.061	0.087	0.065	0.104	0.186	0.194	158.72
Tagging data only	3672	0.244	0.272	67.4	58.5	0.280	0.276	0.201	0.295	0.198	0.315	0.333	147.69
Deterministic recruitment	8650	0.183	0.137	79.4	59.0	0.158	0.079	0.114	0.086	0.116	0.209	0.222	377.03
Uniform availability	2229	0.295	0.287	54.6	53.5	0.129	0.114	0.130	0.113	0.132	0.172	0.200	429.80
Restricted availability	2235	0.295	0.282	54.5	53.0	0.129	0.113	0.130	0.112	0.132	0.172	0.200	429.33
Eastern Bas	3367	0.194	0.300	76.7	74.5	0.129	0.075	0.080	0.073	0.106	0.195	0.209	284.92
Western Bas	3196	0.185	0.108	79.7	67.1	0.194	0.078	0.117	0.087	0.080	0.177	0.210	248.57

Table 2.18 : Maximum likelihood estimates of various management-related quantities for South Australia.

Scenario	Quantity												
	SB_0	M_2	$MSYR$	SB_{73}/SB_0	SB_{99}/SB_0	σ_{CPUE}	$\sigma_{len,f}$		$\sigma_{len,m}$		$\sigma_{age,f}$	$\sigma_{age,m}$	$-\ln L$
							7-inch	6.5-inch	7-inch	6.5-inch			
Base-case	5446	0.188	0.221	82.3	76.3	0.130	0.137	0.182	0.178	0.117	0.345	0.229	167.01
	5582	0.188	0.190	81.1	73.9	0.129	0.137	0.181	0.178	0.117	0.344	0.230	166.27
	5344	0.188	0.250	83.2	78.3	0.131	0.137	0.182	0.178	0.118	0.346	0.229	167.65
Dens-dep pups	4234	0.188	0.221	77.9	68.2	0.193	0.139	0.198	0.178	0.138	0.386	0.209	185.95
	4452	0.188	0.190	76.4	67.8	0.193	0.137	0.195	0.177	0.135	0.384	0.211	183.05
	4032	0.188	0.250	78.5	69.1	0.195	0.139	0.195	0.180	0.135	0.389	0.208	188.66
No CPUE data	5371	0.188	0.221	82.0	76.3	0.169	0.134	0.183	0.172	0.119	0.359	0.221	222.90
	5515	0.188	0.190	80.8	73.9	0.164	0.134	0.183	0.171	0.118	0.357	0.221	222.37
	5263	0.188	0.250	82.8	78.2	0.173	0.134	0.183	0.172	0.119	0.361	0.220	223.31
No age/length data	4499	0.188	0.221	73.3	56.2	0.110	0.156	0.190	0.220	0.152	0.373	0.349	33.18
	4687	0.188	0.190	72.1	53.7	0.107	0.155	0.190	0.220	0.152	0.371	0.349	32.79
	4359	0.188	0.250	74.3	58.3	0.113	0.156	0.190	0.220	0.152	0.374	0.349	33.52
No tagging data	7928	0.188	0.221	88.5	86.6	0.131	0.137	0.168	0.172	0.098	0.322	0.245	104.36
	7896	0.188	0.190	87.4	84.3	0.128	0.137	0.168	0.172	0.099	0.322	0.245	104.00
	7979	0.188	0.250	89.4	88.3	0.134	0.137	0.167	0.172	0.098	0.321	0.245	104.66
No age data	5181	0.188	0.221	81.8	76.9	0.131	0.136	0.180	0.182	0.115	0.347	0.240	108.39
	5323	0.188	0.190	80.5	74.4	0.129	0.136	0.180	0.182	0.114	0.346	0.240	107.79
	5072	0.188	0.250	82.7	78.8	0.133	0.136	0.181	0.182	0.115	0.348	0.240	108.90
Deterministic Recruitment	4698	0.188	0.221	77.5	65.8	0.140	0.160	0.188	0.217	0.136	0.373	0.245	202.29
	4900	0.188	0.190	76.4	63.4	0.131	0.160	0.189	0.215	0.138	0.370	0.245	200.46
	4573	0.188	0.250	78.5	68.0	0.147	0.161	0.187	0.218	0.135	0.374	0.246	203.60
CSA only	3395	0.188	0.221	91.6	70.4	0.141	0.144	0.177	0.182	0.115	0.355	0.215	124.09
	3491	0.188	0.190	91.1	67.6	0.139	0.144	0.177	0.182	0.115	0.355	0.216	123.45
	3316	0.188	0.250	91.9	72.6	0.143	0.144	0.177	0.182	0.115	0.356	0.215	124.66

3. HARVEST STRATEGY EVALUATION

3.1 Introduction

A harvest strategy is a set of rules that is used to determine a management action. In the context of the Southern Shark Fishery, the management action is the annual Total Allowable Catch (*TAC*) and the rules should include details of the data to collect, the method of analysing those data, and how the results of the data analysis would be used to set the *TAC*. There is currently a harvest strategy for school shark that involves setting the *TAC* so that there is an estimated probability of 80% that the mature biomass in 2011 exceeds that at the start of 1996. However, this harvest strategy is better described as a management objective coupled with a decision on how reductions in catch are to be phased in because it does not specify the data to collect and how to analyse those data. Harvest strategies may be very simple (e.g. constant catch strategies) or extremely complicated (such as how *TAC*s are currently being set for school shark).

Harvest strategies are evaluated in terms of how well they are able to satisfy the objectives for management, using the Management Strategy Evaluation (MSE) approach (Smith, 1994; Punt *et al*., 2001a). The primary goal of the MSE approach is to identify, in an objective manner, the trade-offs among the management objectives across a range of management actions. Note that it is never possible to perfectly satisfy all of the management objectives, and all harvest strategies consequently achieve some balance among them (e.g. high risk, high catch; low risk, low catch). 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.

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

There are five steps in identifying the advantages and disadvantages of different harvest strategies (Figure 3.1).

1) Identification of the management objectives and representation of these using a set of quantitative performance measures.
2) Identification of the alternative harvest strategies (see Figure 3.2 for the structure of a ‘typical’ harvest strategy).
3) Development and parameterization of a set of alternative structural models (called operating models) of the system under consideration.
4) Simulation of the future use of each harvest strategy to manage the system (as represented by each operating model). For each year of the projection period (usually 15-25 yrs; 25 yrs in the case of this report), the simulations involve the following four steps.

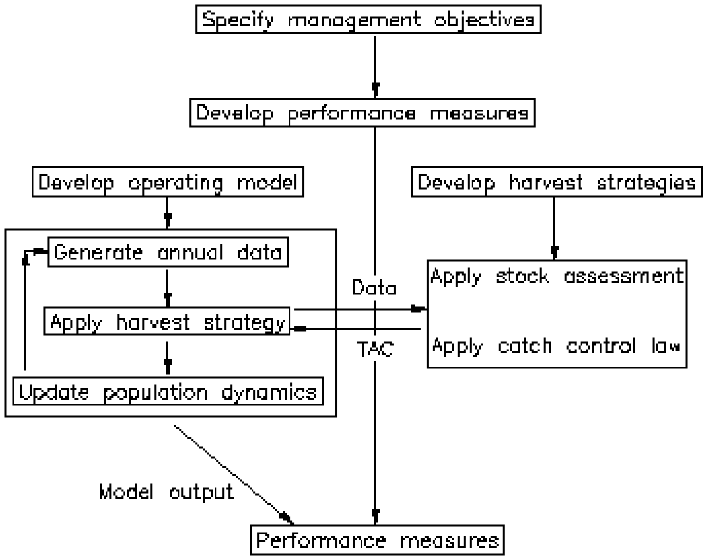

Figure 3.1 : Outline of the MSE approach.

a. Generation of the types of data available for assessment purposes.
b. Application of a method of stock assessment to the generated data set to determine key management-related quantities and the inputs to the 'catch control law'.
c. Application of the catch control law element of the harvest strategy to determine the *TAC* based on the results of the stock assessment.
d. Determination of the (biological) implications of this *TAC* by setting the catch for the 'true' population represented in the operating model based on the *TAC*. This step can include the impact of 'implementation uncertainty' (e.g. Rosenberg and Brault, 1993).

5) Summary of the results of the simulations by means of the performance measures and presentation of the results to the decision makers.

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

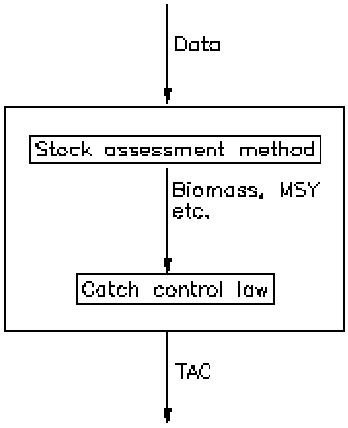

Figure 3.2 : A harvest strategy illustrating the difference between the assessment and catch control law components.

3.2 The management objectives and the performance measures

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

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

Performance measures are statistics that summarise how successfully a harvest strategy is able to satisfy the legislative management objectives (e.g. the total catch over the next 20 years, whether the school shark stock is driven extinct, etc.). Only the first three of these objectives (cost-effective management, economic efficiency and ecologically sustainable development, ESD) are considered in this study because the other two objectives are not related directly to how *TAC*s are to be set for school and gummy shark.

It has been argued (Kaufmann *et al.*, pg. 88) that the second objective (economic efficiency) is satisfied for the target species of a fishery if the Total Allowable Catch 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 of inputs. If this is the case, the complexities of trying to model investment behaviour can be avoided. Dealing with the 'cost effective management' objective is also complicated.

However, 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 the setting of *TAC*s. Since 1 January 2001, school and gummy shark have been managed using an ITQ management system and the costs associated with any candidate harvest strategy can be calculated if needed. Therefore, the performance measures considered in this study are restricted to those related to the ESD objective.

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. Each of these is discussed in turn.

3.2.1 Stock-related performance measures

The ideal stock-related performance measure is the probability that the resource drops below the level at which it is unable to play its appropriate role in the ecosystem (the 'biological bottom line'). However, there is no clear objective basis for specifying such a level for any shark species. Instead, it is conventional to choose a variety of alternative 'biological bottom lines' and to assess the probability of the population dropping below each. The performance measures are designed to reflect concern about the possible consequences of low biomass. Such consequences include stock collapse due to recruitment failure, species replacement, or depensatory processes (Hilborn, 1997), and impacts on the rest of the ecosystem (Corten, 1993). The following represent a set of possible 'biological bottom lines':

a) B_{MSY} the biomass at which *MSY* is achieved – this level is conventional in fisheries management and has been included in several international agreements (e.g. United Nations, 1995) and shark management plans (Appendix 3.1); however, there is no evidence that depleting a resource to below B_{MSY} will lead to severe biological problems.

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

c) $0.4\ B_0$ this level is the current long-term management objective for the fishery (Walker *et al*., 1998). This value is subject all of the criticisms of $0.2\ B_0$.

d) B_{half} this level corresponds to the lowest biomass at which the number of pups is at least half the virgin level; this measure has the advantage that it is lower for more productive stocks and higher for less productive stocks.

e) B_{low} this level is the lowest biomass ever encountered.

f) B_{y} the biomass in a pre-specified year already appears as an objective for the southern shark fishery (1994 for gummy shark and 1996 for school shark – Walker *et al*. (1998)).

It is necessary to specify the time period to consider and the component of the population (pups, total biomass, mature biomass, available biomass, etc.) to which *B* refers to fully specify a 'biological bottom line'. In addition to performance measures that relate to the biomass of the resource, performance measures are also based on the percentage of the landed catch that is discarded, as this relates (to some extent) to some of the broader ecosystem objectives:

$$\text{discard rate} = \frac{100 \sum_{y=2000}^{2024} D_y}{\sum_{y=2000}^{2024} (C_y + D_y)} \tag{3.1}$$

where C_y is the landed catch (in weight) during year *y*, and
D_y is the discarded catch (in weight) during year *y*.

3.2.2 Economic performance measures

There are two approaches to developing performance measures that capture economic issues. The first is to develop a model that explicitly considers fleet dynamics and the costs of harvesting, and can determine the profitability of the fishery for different harvest strategies. The second is to assess economic performance using simple proxies. Development of a detailed economic model is beyond the scope of this project due primarily to the lack of data but also because many operators in the (expanded) Southern Shark Fishery are multiply endorsed. Evaluating the consequences of alternative management actions would necessitate modelling the dynamics of other resources that could be exploited if shark were not available and *vice versa*. Therefore, proxies based on the quantities included in the operating model are considered instead:

a) discounted catch,
b) total fishing effort, and
c) stability of catches.

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

$$AAV = \frac{100 \sum_{y=2000}^{2024} \left| C_y - C_{y-1} \right|}{\sum_{y=2000}^{2024} C_y} \tag{3.2}$$

3.2.3 Selection of performance measures

The selection of appropriate performance measures is the task of the management system. In seeking comment from the Shark Fishery Management Advisory Committee (SharkMAC), SharkFAG (see Appendices 3.2 and 3.3) received the following advice:

- ‘the harvest strategy should aim towards stable average catches in preference to higher average catches with large inter-annual variability’ (16–17 March 2000).
- ‘SharkMAC advised SharkFAG to concentrate on performance measures based on the pup production in 1996 (school shark) and 1994 (gummy shark), and the exploitable biomass available to the fishery’ (26–27 October 2000).

3.3 The operating model

The specifications for the operating model relate to each of the following.

a) The current status, productivity and population dynamics of the gummy and school shark populations off southern Australia.
b) How future *TAC*s for school and gummy shark are allocated to regions and gear-types.
c) The data collected in the future from the fishery.

The details for each of these are discussed below.

3.3.1 The biological scenarios

The specifications for the current status, productivity and population dynamics of school and gummy shark are based on the assessments conducted for school shark by Punt *et al*. (2000a) and for gummy shark in Chapter 2. However, the operating models consider a wider range of scenarios than would be implied by these assessments. Scenarios that are not strongly supported by the assessments are nevertheless examined when evaluating harvest strategies to better assess the robustness of candidate harvest strategies. One reason for doing this is to try to avoid the common problem of under-estimating the true extent of uncertainty (Ludwig *et al*., 1993; Punt and Butterworth, 1993; Walters and Pearse, 1996; Punt and Kennedy, 1997). Table 3.1 lists the biological factors included in the operating models considered in this report.

It is assumed that there are three populations (stocks) of gummy shark (Bass Strait, South Australia, and Tasmania) and two populations of school shark (Bass Strait and dispersed) off southern Australia for consistency with the assumptions underlying the present assessments of school and gummy shark. The base-case simulation trial is based on the specifications for the base-case assessments of school and gummy shark (Table 3.1; Punt *et al*., 2000a; Chapter 2). Sensitivity is explored to changing the specifications of the operating models to examine the implications of violations of the base-case assumptions (Table 3.1). These ‘sensitivity tests’ involve forcing the status of the populations to be more and less optimistic than for the base-case trial.

The final year of the assessment for school shark is 1997 while this year is 1998 for gummy shark. The first year that harvest strategies are applied to set the *TACs* is 2000 so the catches for 1998 and 1999 (school shark) and 1999 (gummy shark) are pre-specified to be equal to the observed catches (by region) for those years.

3.3.1.1 The biological scenarios for gummy shark

The operating model for gummy shark is identical to the population dynamics model used in Chapter 2, except that allowance is made that 26% of the gummy sharks tagged using external tags are ‘lost’ due to initial tag-loss / tagging mortality (Walker *et al*., 2000). The assessments of gummy shark in Chapter 2 only consider the gummy shark populations in Bass Strait and off South Australia. However, it is necessary to provide specifications for the gummy shark population off Tasmania (defined as south of 42^0S) because the *TAC*s for gummy shark set by AFMA are for the whole of southern Australia. The following algorithm is applied to find the model parameters for each of the 100 simulations for each operating model scenario and to specify the status of the population off Tasmania.

a) The gummy shark population dynamics model is fitted to the data for Bass Strait and South Australia. The values for the parameters that determine variability in length-at-age, *MSYR*, and availability are assumed to be the same for the populations of gummy shark in these two regions while the values for the virgin biomass, B_0, and the annual pup survival rates are assumed to be differ between regions. For some of the operating model scenarios, the values for some of these parameters (e.g. *MSYR* and the current (1998) depletion of the pup production) are pre-specified rather than being estimated.
b) 100 parameter vectors are generated from a (multivariate) asymptotic variance co-variance matrix obtained by inverting the Hessian matrix evaluated at the point estimates of the model parameters[1].
c) For each of the 100 simulation trials, the ratios of the actual pup survival rates to those expected from the deterministic stock recruitment relationship (see Equations 2.9 and 2.26) for the gummy shark population off Tasmania are generated independently from a log-normal distribution with mean 1 and coefficient of variation σ_r. The value for the virgin biomass, B_0, for the gummy shark population off Tasmania is then selected so that the current (1998) depletion of the pup production equals that for Bass Strait.

The sensitivity tests for gummy shark (Table 3.1a) include changing the availability function, assuming that only pup survival is density-dependent, fixing *MSYR* and the current depletion of the resources, ignoring the data for 7-inch mesh gear in Bass Strait, replacing the catch series by one that allows for historical mis-reporting, and ignoring initial tag-loss / tagging mortality.

3.3.1.2 The biological scenarios for school shark

The operating model for school shark is identical to the population dynamics model used by Punt *et al*. (2000a), except that allowance is made for the possibility that school sharks tagged using external tags are 'lost' due to initial tag-loss / tagging mortality (Walker *et al*., 2000). Walker *et al*. (2000) report that 44% of school sharks tagged using external tags either die or lose their tags immediately after tagging. SharkFAG evaluated this result and concluded that, although initial tag-loss / tagging mortality was both plausible and likely, the value of 44% seemed very high. Therefore, SharkFAG recommended that the base-case assumption be that 80% of tagged sharks survive and retain their tags and that sensitivity be explored to alternative assumptions.

The biological model for school shark considers the dynamics of school shark in eight regions around southern Australia (Figure 3.3). The fishery for school shark off Western Australia is included in the operating model by adding the catches off Western Australia to those off Western South Australia. The parameters of the school shark model are:

[1] An exception to this occurs for the operating models in which current depletion is pre-specified. The 100 parameter vectors for these trials are all equal to that vector that maximises the (constrained) likelihood function.

MSYR (assumed to be the same for the two stocks), the tag-reporting rates for NSW and those for 1942–54 and 1955–72, the virgin biomass, B_0, for each stock, and the parameters that determine movement among regions. The values for these parameters for each of the 100 simulations are determined by fitting the school shark population dynamics model to the data (catch rates and tagging data). No attempt is made to estimate the 'statistical' uncertainty associated with these parameters since the likelihood function is badly behaved near its maximum which makes methods such as that used to quantify this type of uncertainty for gummy shark unreliable. Instead, the sensitivity of the results is examined to the key parameter that determines productivity (*MSYR*).

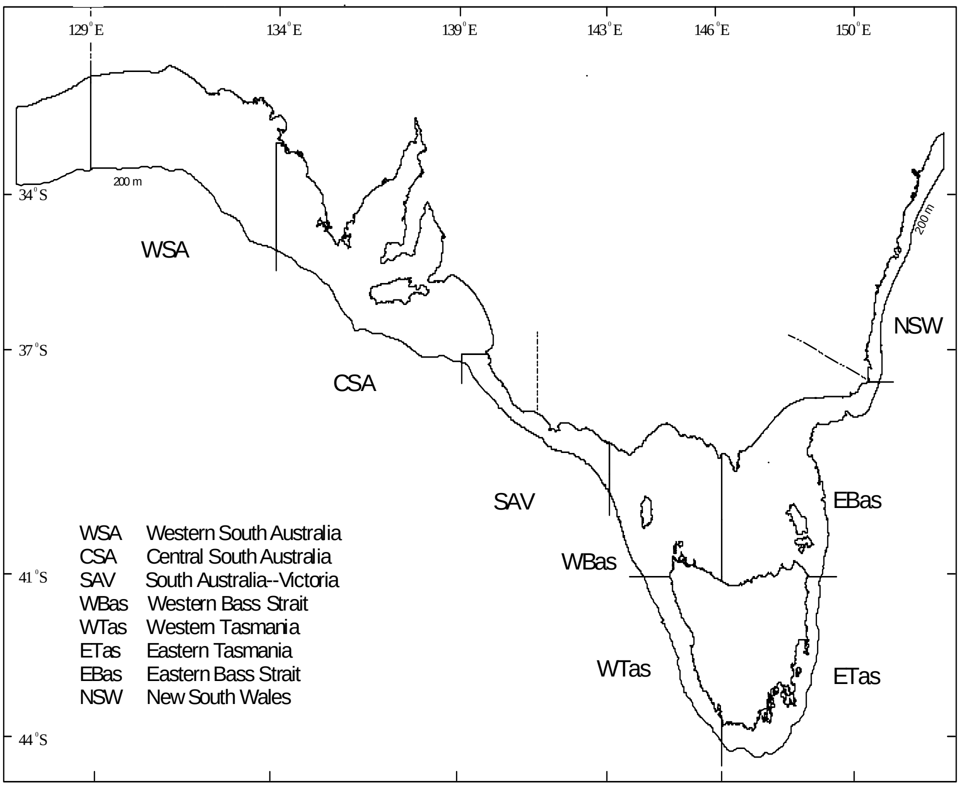

Figure 3.3 : Map of southern Australia showing the eight regions considered for school shark.

The sensitivity tests for school shark (Table 3.1b) include allowing for movement of school shark (temporarily) from New Zealand to Australia, fixing *MSYR*, changing the (assumed) value for adult natural mortality, downweighting the contribution of the tagging data to the likelihood function, replacing the catch series by one that allows for historical mis-reporting, and ignoring initial tag-loss / tagging mortality.

It is known from tagging data (e.g. Hurst *et al.*, 1999) that school sharks in New Zealand move to Australia. The model developed by Punt *et al.* (2000a) therefore includes the possibly of movement of New Zealand school sharks to Australia. Movement from Australia to New Zealand is not included in previous assessments and hence in the operating model because it is believed that the rate of fishing mortality in New Zealand is much lower than that in Australia. It is necessary to specify the pre-exploitation movement rate, the depletion of the New Zealand population in 1997, the relationship between the movement rate and the depletion of the New Zealand stock, and the future level of fishing mortality in New Zealand for the scenarios that include movement from the stock of school shark in New Zealand to Australia. The base-case choice for the depletion of the New Zealand population (0.75) and the assumption that the harvest rate in New Zealand in future will be equal to the average for 1992–99 were selected by SharkFAG. The catch of school shark in New Zealand has been relatively constant over this period. The sensitivity tests consider non-linearity in the relationship between the depletion of the New Zealand population and the rate of movement to Australia. The fraction (by age) of New Zealand school sharks moving to Australia can be modelled as being proportional to:

$$N_{y,a}\,(N_{y,a} / N_{1927,a})^{\alpha} \tag{3.3}$$

where $N_{y,a}$ is the number of New Zealand school sharks of age *a* during year *y*, and

α is a parameter that determines how the rate of movement from New Zealand to Australia depends on the depletion of the population.

3.3.1.3 Maximum possible exploitation rates

There have to be limits on the maximum possible exploitation rate (by species and region) because of the restrictions on the amount of gear in the fishery and the possible impact of 'gear competition'. The maximum possible exploitation rate for school shark (by region and gear-type) is (semi-arbitrarily) taken to be 0.95 because there is no evidence for gear competition effects for school shark. For gummy shark, gear competition is estimated to place an upper bound on the exploitation rate (see Section 2.4). Therefore, the maximum possible exploitation rate (by region and gear-type) for gummy shark is 99%[2] of the maximum possible exploitation rate derived from the estimated relationship between fishing effort and exploitation rate, $F^r_{\max,j,t}$, (see Equation 2.30c):

$$F^r_{\max,j,t} = q^r / (\gamma_1^r\, e^{\varepsilon^r_{j,t} - \sigma_q^2/2}) \qquad\qquad \varepsilon^r_{j,t} \sim N(0;(\sigma^r_q)^2) \tag{3.4}$$

where q^r is the catchability coefficient for region *r*,

γ_1^r is the extent of non-linearity in the relationship between standardized fishing effort and exploitation rate for region *r* (the value assumed for Tasmania is that for Bass Strait – see Section 3.3.1.1), and

σ_q^r is the extent of variation about the fishing effort – exploitation rate relationship for region *r* (the value assumed for Tasmania is again that for Bass Strait).

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[2] 99% is imposed to avoid fishing effort reaching unrealistic levels when the exploitation rate is close to the maximum possible.

The actual fishing effort by gear-type *j* directed towards gummy shark in region *r* during year *t*, $E^{r,act}_{j,t}$, is given by:

$$E^{r,act}_{j,t} = \frac{F^r_{j,t}\, e^{\varepsilon^r_{j,t} - (\sigma^r_q)^2/2}}{q^r - \gamma^r_1\, F^r_{j,t}\, e^{\varepsilon^r_{j,t} - (\sigma^r_q)^2/2}} \tag{3.5}$$

where $F^r_{j,t}$ is the fully-selected exploitation rate in region *r* by gear-type *j* during year *t*.

3.3.2 TACs and catches

The harvest strategies provide *TAC*s by species for all of southern Australia. It is necessary therefore to specify how the *TAC* relates to the actual removals from the population by region and gear-type, and how different levels of *TAC* impact discarding practices. In principle, these effects depend on factors such as individual quota holdings, catch rates, investment strategies, etc. However, there are currently no data upon which a model that includes these factors could be developed. Therefore, a simpler (and more empirical) approach is used.

3.3.2.1 The split of the TAC by gear-type and region

The simplest (yet probably still adequate) assumption about the split of the catch to gear-type (by region) is that it is the same as the last year for which catch data are available (1999). This implies that the bulk of the catch off Tasmania and South Australia is taken using 6.5-inch mesh gill-nets and that the bulk of the catch in Bass Strait is taken using 6-inch gill-nets.

The problem of modelling the split of the catch to region is more complicated and three alternative approaches were discussed by SharkFAG:

a) The split of the catch to region is equal to that for the most recent year for which catch data by gear-type and region are available (1999). This approach assumes that there are essentially no changes to the structure of the fishery over time.
b) The landed catch in Bass Strait is assumed to remain at the average over the previous five years (up to a maximum of 95% of the *TAC*) and the landed catches in the Tasmanian, South Australian and New South Wales regions are scaled to 'take up the slack'.
c) The splits are computed using methods a) and b) and averaged.

Alternative c) forms part of the specifications for the operating model because alternative a) is not dynamic enough (and could lead to much less variability in catches among regions than is already evident in the data for the Southern Shark Fishery) while alternative b) is perhaps too dynamic (and could lead to catches outside of Bass Strait in some years that are close to zero). The catches by region are multiplied by a log-normal random variable with mean 1 and coefficient of variation 0.2 and then renormalised to introduce additional variability into the catches by region.

3.3.2.2 Discarding practices

There are several reasons for discarding in the Southern Shark Fishery. These include the impact of damage to the carcass (due, for example, to predation by sea lice, fish and marine mammals), high-grading and mis-matches between the *TAC*s for school and gummy shark. The base-case extent of discarding due to damage and high-grading is assumed to be 5%. This value is lower than the 9% observed by Walker *et. al*. (1999) during a pilot fixed-station survey off South Australia and in Bass Strait. This is because discarding due to damage already exists (although the extent of this is not fully known) – the 5% reflects additional discarding of damaged fish due to the change from input to output controls.

The discarding that results from mis-matches between the *TAC*s for the two species is accounted for by comparing the ratio for the exploitation rates (standardized to those for 1994–97) for the two species for region-specific choices of chosen gear-types (6-inch mesh in Bass Strait and 6.5-inch mesh off South Australia and Tasmania) and increasing the catches until this ratio falls into a pre-specified range (see Table 3.1c):

$$R_t = \frac{\sum_{r^{school}} C_t^{r^{school}} \sum_{r^{gummy}} B_t^{r^{gummy}}}{\sum_{r^{gummy}} C_t^{r^{gummy}} \sum_{r^{school}} B_t^{r^{school}}} \frac{\sum_{t'=1994}^{1997} \sum_{r^{gummy}} C_{t'}^{r^{gummy}} \sum_{t'=1994}^{1997} \sum_{r^{school}} B_{t'}^{r^{school}}}{\sum_{t'=1994}^{1997} \sum_{r^{school}} C_{t'}^{r^{school}} \sum_{t'=1994}^{1997} \sum_{r^{gummy}} B_{t'}^{r^{gummy}}} \tag{3.6}$$

where $C_t^{r^{school}}$ is the catch of school shark in (school shark) region r^{school} during year t,

$C_t^{r^{gummy}}$ is the catch of gummy shark in (gummy shark) region r^{gummy} during year t,

$B_t^{r^{school}}$ is the exploitable biomass of school shark in (school shark) region r^{school} during year t, and

$B_t^{r^{gummy}}$ is the exploitable biomass of gummy shark in (gummy shark) region r^{gummy} during year t.

The rationale for this is approach is that (for example) school shark is an inevitable by-product catch of fishing for gummy shark (although, even in Bass Strait, the area of greatest fishing intensity for gummy shark, there is evidence for some targeting of school shark – Bruce Taylor (MAFRI), unpublished data). Therefore, even if school shark *TAC*s are (for example) reduced to zero, there will be some by-product catch of school shark while fishing for gummy shark. The base-case ranges for this ratio (by region) (Table 3.1c) are based on the extreme of those estimated for the years 1994–99. Sensitivity is explored to the assumed range, including that the fishery is such that it can modify its behaviour perfectly to avoid any TAC-related discarding.

3.3.3 Future data collection

The information currently collected from the fishery (by region and species) includes landed catches, catch rates, length-frequency (by sex), age-composition (by sex), and tagging data. Future data collection (based on fixed-station surveying, for example) could provide a fishery-independent index of relative abundance.

3.3.3.1 Landed catches

The landed catch for a given region and year is the lower of the total catch for that region and year and the component of the *TAC* for that year assigned to that region (see Section 3.3.2.1). The total catch may be less than the *TAC* if the fishing mortality corresponding to the *TAC* is equal to the maximum possible fishing mortality so that it is not possible to take the entire *TAC*. No estimates of discards are provided to the harvest strategies, which base their assessments on the landed catches.

3.3.3.2 Catch rate data

The relationship between future catch rates and future abundance is currently very speculative and depends on what changes in fishing practices occur after the introduction of output controls into the Southern Shark Fishery. For this study, the relationship between future abundance and future catch rate is given by:

$$(C/E)_t^r = B_t^r \, e^{\phi_t^r - (\sigma_q^r)^2/2} \tag{3.7a}$$

$$(C/E)_t^r = C_t^r / E_t^{r,act} \, e^{\phi_t^r - (\sigma_q^r)^2/2} \tag{3.7b}$$

where $(C/E)_t^r$ is the observed catch rate for region *r* and year *t*,

$E_t^{r,act}$ is the actual fishing effort directed towards gummy shark in region *r* during year *t* (see Equation 3.5),

ϕ_t^r is the extent of sampling error in region *r* and year *t* ($\phi_t^r \sim N(0;(\sigma_q^r)^2)$), and

σ_q^r determines the amount of sampling error in region *r*.

Equation (3.7a) applies to school shark while Equation (3.7b) applies to gummy shark. The equation for gummy shark differs from that for school shark as Equation (3.7b) includes gear competition effects (see Equations 3.4 and 3.5). The base-case choice for σ_q^r = 0.3 is based on fits to actual data. Sensitivity tests consider the implications of varying the value for σ_q^r.

3.3.3.3 Survey data

The survey estimates are generated assuming that N_1 sites within the fishery are selected, that these sites are sampled quarterly, and that N_2 stations are sampled at each site each quarter. One survey site is assumed to be established in each of the WSA, CSA, ESA, WBas and WTas regions and two survey sites are assumed to be established in the EBas region. It is assumed that the survey provides an index of the component of population available to 6.5-inch mesh gear off South Australia and Tasmania and available to 6-inch mesh gear in Bass Strait. There are two sources of measurement error associated with the surveys: the variability that arises from sampling the population in the area being surveyed, and the level of 'additional' variation due to fluctuations in catchability, e.g. in the fraction of the population present in the sites being surveyed. Sampling variability can be reduced by conducting survey shots at additional stations at each site while additional variability can only be reduced by sampling a large number of sites frequently. The coefficients of variation for the two sources of measurement error are denoted σ_s and σ_A respectively.

For this study, it is assumed that 'additional' variation is common to all stations at a survey site (but independent among sites and quarters). The survey index for region *r* and year *t*, $I_t^{r,obs}$, is defined as the average number of sharks caught per station during the survey, and is therefore given by:

$$I_t^{r,\text{obs}} = \frac{1}{4N_1\ N_2}\sum_{z=1}^{N_1}\sum_{q=1}^{4}\sum_{s=1}^{N_2} I\left[\frac{\kappa}{B_{1998}^r} B_t^r\, e^{\varepsilon_{z,q,t}^r - \sigma_A^2/2}\, e^{\eta_{z,q,s,t}^r - \sigma_s^2/2}\right] \tag{3.8}$$

where B_t^r is the biomass in region *r* during year *t* available to the size of gill-net used during the survey (1998 was the year in which the pilot fixed-station survey took place),

$I\left[x\right]$ denotes the nearest integer to *x*,

κ is the average catch rate during the pilot survey (22.6 sharks per station for gummy shark and 2.0 for school shark – see Prince *et al*. (1999) for details on the pilot fixed-station survey),

$\varepsilon_{z,q,t}^r$ is the error due to 'additional' variance when sampling site *z* in region *r* during quarter *q* of year *t* ($\varepsilon_{z,q,t}^r \sim N(0;\sigma_A)$), and

$\eta_{z,q,s,t}^r$ is the sampling error corresponding to sampling station *s* at site *z* in region *r* during quarter *q* of year *t* ($\eta_{z,q,s,t}^r \sim N(0;\sigma_s)$).

The survey index for year *t* is therefore defined as the (arithmetic) average survey catch rate over all stations sampled during year *t*. Equation (3.8) ignores the impact of variation among stations in shot duration as this is minor (Prince *et. al*., 1999) and, in any case, it is straightforward to account for this given the information recorded on shot duration. Changes in biomass over the year are also ignored.

Account is taken in Equation (3.8) that:

a) the catch from a survey station is an integer (given the low expected catch rate for any single station, this needs to be accounted for in the analysis); and
b) the average catch rate during the pilot survey (in 1998) was 22.6 gummy sharks and 2.0 school sharks per station.

This approach to generating catch rates is consistent with that used to analyze the data from the pilot fixed-station survey (Prince *et al*., 1999). Table 3.2 lists the base-case values assumed for N_2, σ_A, and σ_s. The values for σ_s are based on an analysis of the data collected during the pilot surveys (Prince *et al*., 1999). The value assumed for σ_A is largely an educated guess. Sensitivity tests consider the implications of the actual values for these parameters differing from those assumed (Table 3.2).

3.3.3.4 Length-frequency and age-composition data

Length-frequency and age-composition data are only generated for gummy shark for consistency with current assessment practice. The observed length-frequency data for a given region, sex and gear-type are a multinomial sample from the corresponding model-predicted catch length-frequency distribution (see Equation 2.33) and the observed age-composition data for a given region, sex and gear-type are a multinomial sample from the corresponding model-predicted catch age-composition distribution (see Equation 2.35). The base-case length-frequency sample sizes (for gummy shark) are 1000 (Bass Strait) and 850 (South Australia). These values are based on the noise about the fits to the actual length-frequency data using the approach of McAllister and Ianelli (1997). No future age-composition data are generated for the base-case trial as ageing of gummy shark has not occurred since 1993.

3.3.3.5 Tagging data

It is necessary to specify how the processes of tagging, 'early' recapture and tag-reporting operate to generate future tagging data using the operating model. Simulating the release of animals of a given species and sex from a particular region tagged from catches by a pre-specified gear-type involves selecting animals multinomially from the catch of that species and sex by that gear-type in that region. Each tagged animal is assumed to be equally likely to be recaptured "early" so the early recaptures are simply randomly sampled from the tagged animals. The proportion of "early" recaptures is 1.5% and 4% for school and gummy shark respectively based on the actual data. The information on recaptures includes the year of recapture, as well as the tag-type, age and sex of the animal. The observed number of recaptures is a Poisson random variable with mean given by the expected number of recaptures (see Equation 2.39) multiplied by the tag-reporting rate. For consistency with the approach used in the assessment, the tag-reporting rate for the years in which tags are released is assumed to be 0.7 while it is 0.5 for the years in which tags are not released. The possibility of future tagging of gummy and school shark is ignored in the base-case trial.

3.4 The harvest strategies

Most of the harvest strategies considered in this report consist of two parts: an estimator and a catch control law (Figure 3.2). The estimator (or stock assessment) is used to analyse the data collected from the fishery to estimate the key quantities of interest to management (e.g. current biomass, *MSY*) as well as those quantities needed for *TAC* setting. The catch control law takes the results of the assessment (usually the current biomass) and determines the *TAC* from this. Assessments are conducted for Bass Strait and South Australia only for consistency with past practice and because there are insufficient data to conduct reliable assessments for the Tasmanian and NSW regions. The *TAC*s based on the assessments for Bass Strait and South Australia are 'pooled' to determine the global *TAC*. For any year, this pooling process involves multiplying the *TAC*s based on the assessments for South Australia and Bass Strait by the ratio of the global catch (all regions) to that for these regions in the last year for which catches are available. *TAC*s are rounded to the nearest 100*t* (gummy shark) and 25*t* (school shark) to give effect to likely actual *TAC* setting practice.

The *TAC* based on the harvest strategy is only changed once every *n*th year. The base-case choice for *n* is 3. This choice for *n* was recommended by SharkMAC at its October 2000 meeting and means that the assessment group would conduct assessments of gummy and school shark and then have a year to enhance assessments or concentrate on other key issues (such as the management of non-quota species). SharkMAC requested that the *TAC* for year *t* be forced to lie within a pre-specified percentage (20%) of that for the previous year. SharkMAC also requested that the *TAC* be forced to lie within pre-specified bounds (319–2000*t* for school shark, and 1525 (the lowest catch during 1989–98) – 2500*t* for gummy shark).

The management arrangements for the Southern Shark Fishery permit 20% of the *TAC* to be carried over from one year to the next. The actual *TAC* for year *t*+1, TAC_{t+1}^{act}, is therefore determined from TAC_t^{act}, the *TAC* for year *t*+1 from the harvest strategy, TAC_{t+1}, and the landed catch for year *t*, C_t, using the formula:

$$TAC_{t+1}^{act} = TAC_{t+1} + \min\left(TAC_t^{act} - C_t, 0.2\,TAC_t^{act}\right) \tag{3.9}$$

Equation (3.9) reflects the observation in the South East Trawl fishery that operators lease uncaught quota in excess of the 20% maximum permissible carry-over to operators who have caught more than 80% of their allocation near the end of the year and then lease it back at the start of the following year so as to maximise the amount of uncaught quota that can be carried-over (J. Prince, pers. commn).

3.4.1 Estimators

There is little chance that methods of stock assessment that are based on the age-structure of the catch (such as VPA) will be applied to data for the shark populations off southern Australia in the near future. Therefore, the types of estimators on which harvest strategies could be based are restricted to production models (e.g. Butterworth and Andrew, 1984; Punt and Hilborn, 1996) and age-structured production models (e.g. Punt, 1994; Punt and Walker, 1998; Walker, 1994a, b). The former use only catch, catch rate and fishery-independent index data. The age-structured production model (ASPM) can use a much broader range of data types including age-composition, length-frequency, and tagging data.

There are several ways in which age-structured production models can be applied. The options considered in this report (see Section 2.3 for the technical details of the estimator) are:

a) estimate only *MSYR* and B_0,
b) estimate *MSYR*, M_{adult} and B_0, and
c) estimate *MSYR*, M_{adult}, B_0 and the recruitment residuals for the last 10 years of the assessment period.

The last variant is similar to the Integrated Analysis approach (Methot, 1989,1990) as it attempts to identify the strong and weak year-classes. Only the last 10 recruitment residuals are estimated to keep the computation time requirements of the calculations within feasible limits. The values for the parameters not estimated are set equal to the values assumed for the base-case trial, except that unestimated historical recruitment residuals are assumed to be zero. The historical (pre-2000) catches assumed when applying the harvest strategy are taken to be those corresponding to the base-case trial (even if the catches used in the operating model to update the population dynamics differ from these). The uncertainty associated with the parameter estimates and consequently the estimates of the other model outputs, such as biomass, are determined by inverting the Hessian matrix and generating 100 parameter sets from this matrix.

3.4.2 Catch control laws

The *TAC* for year *t* is computed using the formula:

$$TAC_t = F^{t\arg} B_t^{cur} \tag{3.10}$$

where TAC_t is the *TAC* for year *t*,
$F^{t\arg}$ is the 'target' exploitation rate, and
B_t^{cur} is an estimate of the biomass at the start of year *t*.

Several variants of this basic approach exist.

a) Constrain the *TAC* to be less than the estimate of the Maximum Sustainable Yield, *MSY* (Butterworth, 1987).
b) Decrease the target exploitation rate linearly to zero if the current biomass is below a pre-specified threshold biomass:

$$TAC_t = \begin{cases} F^{t\arg} B_t^{cur} & \text{if } B_t^{cur} > B^{thresh} \\ F^{t\arg} B_t^{cur} \left(B_t^{cur} / B^{thresh} \right) & \text{otherwise} \end{cases} \tag{3.11}$$

where B^{thresh} is the threshold biomass.
c) Compute 100 values of Equation (3.10) (or Equation 3.11) corresponding to each of the 100 parameter vectors generated from the variance-covariance matrix obtained by fitting the model to the data and set the *TAC* to a pre-specified percentile of the distribution of the 100 values.
d) Set the *TAC* to zero if the current depletion is less than a pre-specified level.

It is possible to combine these four variants. $F^{t\arg}$ is taken to be $\theta_1 MSYR$ and B^{thresh} is taken to be $\theta_2 B_{MSY}$ for the purpose of this study. The values assumed for θ_1 and θ_2 can be selected to achieve different risk-reward trade-offs and to give greater (or lesser) emphasis to recovery from over-exploitation.

3.4.3 Simple approaches

In addition to the population model-based approaches listed above, simpler (empirical) approaches to setting *TAC*s are also considered. The empirical approach to setting *TAC*s considered in this study is to adjust the *TAC* according to the trend in an index of abundance:

$$TAC_t = TAC_{t-1}(1+\gamma\beta_{t-1}) \tag{3.12}$$

where β_t is the trend in the abundance index (the survey data for the purposes of this report) over the last few (8) years, and

γ is a parameter that relates the change in the abundance index to the change in the *TAC*.

The value of the *TAC* can be constrained to being no larger than the average catch over the previous (say) 10 years to avoid unnecessary fluctuations in *TAC*s.

These simpler approaches allow the 'value' of collecting (and analysing) fisheries and research data to be examined. If the ability to satisfy the management objectives is the same for a simple approach (which requires virtually no monitoring data) and a complicated approach (which requires a large research and monitoring programme), there is little justification for adopting the complex (and expensive) approach to *TAC* setting.

3.5 Results and discussion

3.5.1 Overview of the biological scenarios

Table 3.3 lists summary statistics for the depletion (expressed as a percentage) of the pup production in 1973 and at the start of the last year considered in the most recent assessment, *MSYR*, and natural mortality (gummy shark only) for the operating models that involve modifying the characteristics of the biological component of the operating model. Results are shown in Table 3.3a for gummy shark off South Australia and in Bass Strait separately whereas the results for school shark (Table 3.3b) are pooled across stocks. Figure 3.4 shows medians and 90% intervals for the time-trajectories of total (1+) biomass and pup production for gummy shark for the base-case trial and Figure 3.5 shows the base-case point estimates of the time-trajectories of total (1+) biomass and pup production for school shark for this trial.

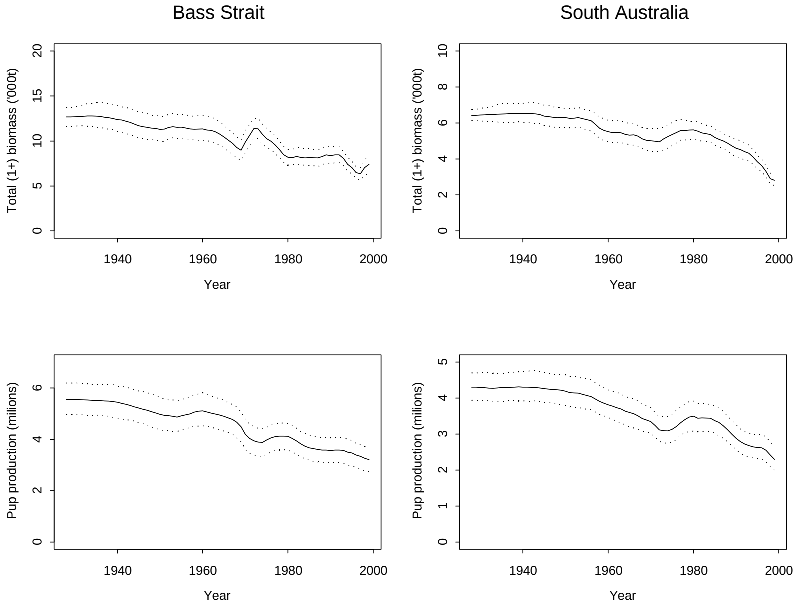

Figure 3.4 : Medians and 90% intervals for total (1+) biomass and pup production for gummy shark for the base-case trial. Results are shown separately for the gummy shark populations in Bass Strait and off South Australia.

The results for gummy shark in Table 3.3a are somewhat less optimistic than those in Tables 2.17 and 2.18. One reason for this is that the estimates of *MSYR* in Table 3.3a are lower than those in Table 2.17. This is not particularly surprising because the estimates of *MSYR* in Chapter 2 are based solely on the data for gummy shark in Bass Strait whereas those in Table 3.3a are based on data for both South Australia and Bass Strait, and the data for South Australia are more consistent with lower values for *MSYR* than the estimates of *MSYR* inferred solely from the data for Bass Strait (Table 2.18). The results for gummy shark become more pessimistic (in terms of the current depletion of the resource) when availability is forced to be uniform, when *MSYR* is reduced below the base-case level, when the base-case catch series is replaced by an alternative series of catches (see Section 2.2.1.3), and when the length-frequency data for 7-inch mesh gear in Bass Strait are left out of the assessment. In contrast, the results become more optimistic if *MSYR* is larger than the base-case value or if the possibility of initial tag-loss / tagging mortality is ignored.

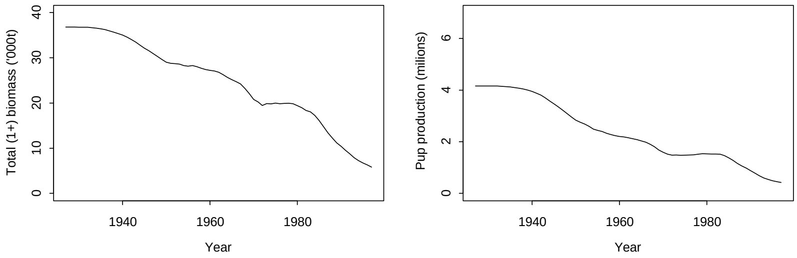

Figure 3.5 : Base-case time-trajectories for total (1+) biomass and pup production for school shark for the base-case trial. Results are shown pooled across movement types (stocks).

The results for school shark indicate a population depleted to between 8 and 14% of the pre-exploitation level in terms of pup production (Figure 3.5; Table 3.3b). The results become more optimistic when initial tag-loss / tagging mortality is ignored, if M_{adult} is reduced from 0.1 to 0.08yr^{-1}, and when less emphasis is placed on the tagging data. The results become more pessimistic when the extent of initial tag-loss / tagging mortality is set to 0.3 (a tag retention / survival rate of 0.6), a value close to that estimated by Walker *et al*. (2000), and when the base-case catch series is replaced by one that attempts to account for known sources for under-reporting of historical catches (see Punt *et al*. (1999) for details). As expected from Punt *et al*. (2000a), allowing for movement of New Zealand school sharks to Australia (temporally) leads to a more pessimistic appraisal of the status of the population in Australia; greater rates of movement from New Zealand to Australia and a more depleted New Zealand population leads to lower values for the current depletion of the pup production of school shark.

3.5.2 Selection of a minimum TAC level for school shark

SharkMAC advised that the minimum *TAC* for school shark should be 319*t* while that for gummy shark should be the lowest catch over the last 10 years (1525*t*). A series of 25-year projections based on the base-case trial and a variant thereof that ignored the possibility of additional discarding due to mismatches between the *TAC*s for school and gummy shark (see Section 3.3.2.2) were therefore undertaken (Table 3.4). The *TAC* from 2000 for gummy shark in these projections was fixed at 1525*t* and the *TAC* from 2000 for school shark was varied from 100 to 319*t*. Results are shown in Table 3.4 for no restrictions on *TAC* changes, a maximum percentage reduction of 20%, and a maximum percentage reduction of 50%. The results of the projections are summarised by the probability of the school shark pup production exceeding the 1996 level in 2024 (abbreviation $P(P_{2024} > P_{1996})$)[3], the median annual catch of school shark, the median of the ratio of the school shark pup production in 2024 to that in 1996 (abbreviation $med(P_{2024} / P_{1996})$), and the fraction of the total catch of school shark that is discarded.

[3] Results are not shown for the probability of the school shark pup production in 2011 being above that in 1996 because this probability is virtually zero for all of the harvest strategies considered.

As expected, lower *TAC*s correspond to greater probabilities of exceeding the 1996 level in 2024. However, the extent of discarding due to mismatches between the gummy and school shark *TAC*s increases substantially as the level of *TAC* is reduced. The impact of this TAC-related discarding (i.e. mismatches between the *TAC*s for school and gummy shark) can be assessed by comparing the two "none" columns in Table 3.4. For example, for a 100*t* annual *TAC*, the value of $med(P_{2024}/P_{1996})$ is 189% if there is no TAC-related discarding but only 115% when there is such discarding. The discarded component of the catch is predicted to be larger than the retained component of the catch for a 100*t* *TAC* from 2000. The impact of the restrictions on changes in *TAC*s can also be substantial. For example, the value of $P(P_{2024} > P_{1996})$ for the 150*t* *TAC* scenario increases from 1% to 52% and then to 67% as the restrictions on *TAC* changes are weakened from 20 to 50% and then to none. It should be noted, however, that the landed catches are higher for the 50 and 20% restrictions because it takes several years of 20% reductions in *TAC* to reach a *TAC* of (say) 100*t*.

None of the minimum *TAC* levels perform particularly successfully in terms of achieving a high value for $P(P_{2024} > P_{1996})$ due to the impact of discarding. Concentrating on the "20% restriction" column suggests that a minimum *TAC* less than 150*t* has little benefit but that there are some benefits in terms of resource conservation of a 150*t* minimium *TAC* compared with a 200*t* minimum *TAC*. Therefore, the remaining calculations in this report are based on a 150*t* minimum *TAC* for school shark.

3.5.3 Selection of a 'reference' harvest strategy

Given the large potential volume of results, it is prudent to select a 'reference' harvest strategy to form the focus for the evaluation of alternative harvest strategies. The 'reference' harvest strategy for this report includes the following specifications.

a) The estimator is the age-structured production model (ASPM) and only B_0 and *MSYR* are treated as estimable parameters; the values for the remaining parameters are set to the values for the base-case trial. The estimator uses all of the tagging, age-composition and length-frequency information, the historical catch-rate data and any future survey data (the surveys are assumed to start in 1998). It ignores any future commercial catch-rate data.
b) The *TAC* is based on the point estimates of the model parameters using Equations 3.10 and 3.11 and the *TAC* is bounded above by *MSY* for school shark. The value of B^{thresh} is set to $0.5B_{MSY}$ so that the target level of fishing mortality is constant above $0.5B_{MSY}$ and declines linearly to zero below this. The *TAC* is set to zero if the expected pup production is less than 5% of the virgin level.

Table 3.5 lists the values for 15 performance measures for the base-case trial for nine variants of the 'reference' harvest strategy constructed by specifying the values of θ_1 (see Section 3.4.2) for school and gummy shark, and whether the *TAC* for gummy shark is bounded above by the estimate of *MSY*. Results are shown for two variants of the base-case trial related to the constraints on the exploitation rates for gummy and school shark: a) the default values (see Table 3.2), and b) none because it is assumed that fishing practices can be modified to avoid any TAC-related discarding (high-grading / additional damaged-related discarding at 5% still occurs, however). The 15 performance measures are:

a) the median of the distribution for the pup production (all stocks combined) at the end of the projection period as a fraction of the virgin level (abbreviation 'Med B_{fin}'),
b) the 5^{th}, 50^{th} and 95^{th} percentiles of the distribution of the average annual catch during 2000–24,
c) the median of the distribution for the fraction of the total catch that is discarded (see Equation 3.1),
d) the median of the distribution for the AAV statistic (see Equation 3.2),
e) the probability that the pup production in 2024 exceeds that in 1996 (school shark only),
f) the ratio of the pup production in 2024 relative to that in 1996 (abbreviation $med(P_{2024} / P_{1996})$) (school shark only), and
g) the probability that the pup production in 2024 exceeds the lower of 40% of the virgin level and the 1994 level (gummy shark only) (abbreviation $P_{2024} > \text{thresh}$).

These 15 performance measures capture the key aspects of catch, catch variability and resource conservation. The lower 5^{th} percentile of the average catch distribution can be considered to reflect the 'guaranteed catch'.

The results for gummy shark are largely insensitive to the constraints on the exploitation rates. This is because school shark rather than gummy shark is the 'limiting' species; the range of catches for gummy shark is such that TAC-related discarding of school shark is likely given the desire to allow some recovery of school shark without deliberately reducing the catches of gummy shark. The results for school shark are highly dependent on the constraints on the exploitation rates. For example, the probability of exceeding the 1996 pup production in 2024 is almost 100% for the harvest strategies in which θ_1 for school shark is 0.4 or 0.7 when fishers are able to avoid school shark, but no greater than 38% when this is not the case.

The results for gummy shark are insensitive to the value assumed for θ_1 but substantially higher catches result when the *TAC* is not bounded by the estimate of *MSY*. For school shark, the probability of being above the 1996 pup production in 2024 is greater if the target exploitation rate (determined by θ_1 for school shark) is lower and if the *TAC* for gummy shark is bounded by the estimate of *MSY*. The 'reference' harvest strategy for the remaining calculations of this paper is based on θ_1 = 0.7 and 1 for school and gummy shark respectively while the *TAC* for gummy shark is not bounded by the estimate of *MSY* for gummy shark. This particular harvest strategy variant was selected for further consideration because it achieves high catches of gummy shark and does not leave the school shark resource far below the 1996 level in 2024 if fishing practices remain essentially unchanged.

Figure 3.6 shows the time-trajectories of catch (landed and total) and *TAC* (as set by the harvest strategy and after adjustment for carryover) for the 'reference' harvest strategy for one simulation for the base-case trial. The *TAC*s for school shark are always fully taken so no carryover of school shark *TAC* occurs (i.e. the results for "TAC" and "TAC (incl. Carryover)" in Figure 3.6 are identical). In contrast, the impact of 'gear competition' (see Equation 3.5) means that the *TAC*s for gummy shark are not fully taken so there is some carryover (see the right panels of Figure 3.6). The level of discarding is small for gummy shark (Figure 3.6 right panels) but this is not the case for school shark when constraints are placed on the relative exploitation rate because the total catch can substantially exceed the landed catch (Figure 3.6 upper left panel).

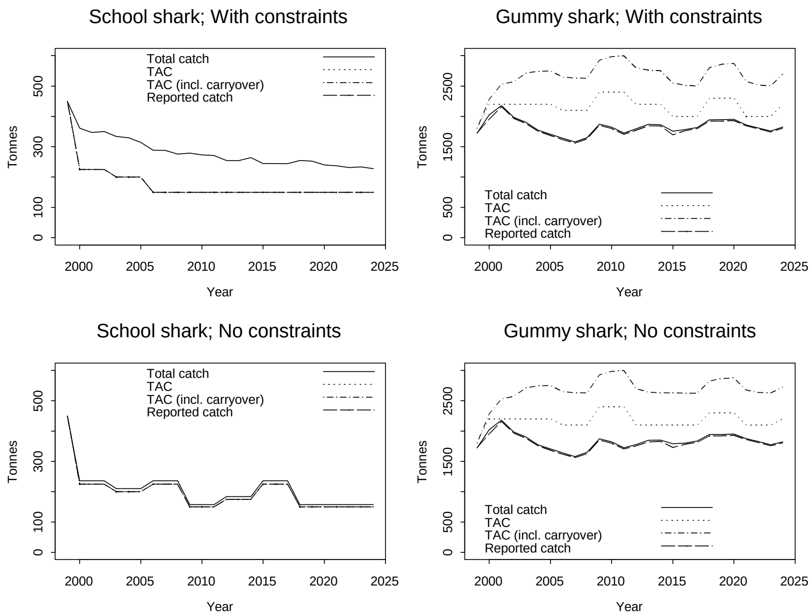

Figure 3.6 : Time-trajectories of the *TAC* set by the harvest strategy, the actual *TAC* allocated (accounts for any carryover), the total catch removed from the population and the catch reported for use in stock assessments (which differs from the total catch due to (un-reported) discards).

3.5.4 Sensitivity to the harvest strategy

Table 3.6 contrasts the performance of the 'reference' harvest strategy selected above with the performances of harvest strategies based on Schaefer and Fox production models for the base-case trial. Results are shown for the variant of the base-case trial in which the default constraints are placed on the relative exploitation rates. The 'reference' harvest strategy clearly outperforms the harvest strategies based on the Fox and Schaefer production models in that the school shark resource is left at a higher proportion of its pre-exploitation level and, simultaneously, the catches of gummy shark are higher. This is a case in which one harvest strategy (the 'reference' harvest strategy) dominates another harvest strategy. Table 3.7 lists results for a set of empirical harvest strategies (see Section 3.4.3) determined by the value assumed for the feedback gain parameter, γ (see Equation 3.12). The 'reference' harvest strategy again achieves greater recovery for school shark and larger catches of gummy shark. The results in Tables 3.6 and 3.7 indicate that there is value in basing harvest strategies for school and gummy shark on stock assessment models that consider the selectivity patterns of the gear-types employed in the fishery and the peculiarities of the pupping process.

Table 3.8 examines the performances of several additional variants of the 'reference' harvest strategy. Estimating the natural mortality rate, *M*, for gummy shark or the recruitment residuals for the last 10 years does not have any impact on the results for school shark. The median of the distribution for the average annual catch of gummy shark is higher when *M* for gummy shark is estimated, but this distribution is also much wider so the 'guaranteed' average catch is actually no larger than is the case for the 'reference' harvest strategy. The median final depletion of the pup production is only 38% (the lowest value in Table 3.8) when *M* for gummy shark is treated as an estimatable parameter; consequently the probability of the gummy shark pup production being above the lower of 40% of the virgin level and the 1994 level ($P_{2024} > \text{thresh}$) is only 0.41.

Results are also shown in Table 3.8 when the *TAC* is set as the median (*P*=0.5) or the lower 30th percentile of the Monte Carlo distribution for the *TAC* (*P*=0.3) (see Section 3.4.2 for details). The '*P*=0.3' variant leads to lower average annual catches of both gummy and school shark but also to increased discarding of school shark. One reason that the results for the '*P*=0.3' variant differ so little from those for the 'reference' harvest strategy is that the Monte Carlo distribution for the *TAC* is very tight because there are only two estimable parameters (B_0 and *MSYR*) in the ASPM that underlies the harvest strategy. Given the extra computational requirements associated with computing the Monte Carlo distribution for the *TAC*, and the minor differences from the 'reference' harvest strategy, there seems little point in pursuing this option.

Increasing the value of θ_2 from 0.5 to 0.7 leads to lower average catches of school shark but has little impact on the probability of being above the 1996 pup production in 2024 because the extent of TAC-related discarding increases when θ_2 =0.7. Decreasing θ_2 from 0.5 to 0.1 leads to the opposite effects. The results for gummy shark are not sensitive to the value assumed for θ_2 because the gummy shark population is hardly ever reduced to levels at which this specification plays a role.

The results for school shark are insensitive to amount of carryover because the school shark *TAC* is always fully caught (Figure 3.6). In contrast, ' $P_{2024} > \text{thresh}$ ' is very sensitive to whether the extent of carryover is 10, 20 of 30%. There is relatively little difference between the average annual catches for 10 and 20% carryover rates but ' $P_{2024} > \text{thresh}$ ' increases by 20% if the carryover is 10 rather than 20%.

3.5.5 Sensitivity to the form of the operating model

Table 3.9 examines the sensitivity of the results to changing the specifications related to the gummy shark component of the operating model (see Tables 3.1 and 3.3a for the specifications and the assessment implications of the changes). Results are not shown in Table 3.9 for the case in which selectivity is assumed to be uniform because this case provides a very poor fit to the data. The discussion of Table 3.9 focuses only on the results for gummy shark because the results for school shark are almost independent of the specifications of the gummy shark component of the operating model.

The ability to leave the gummy shark pup production above the lower of 40% of the virgin level and the 1994 level is compromised if availability is more uniform than estimated by the base-case assessment and / or if density-dependence acts on pup survival rather than on the natural mortality rate of all animals. The harvest strategy does 'learn' that productivity is over-estimated because catches are lower for the 'Constrained availability' and 'Density-dependent pups' trials. The median average annual catches, median final depletion and '$P_{2024} >$ thresh' all increase as *MSYR* is increased from 0.11 to 0.15 and then to 0.25 (Table 3.9). It is noteworthy, however, that the lower 5th percentile for the average catch distribution is lower when *MSYR*=0.25 than for the base-case trial. This presumably arises because, in some simulations with a high *MSYR*, the population recovers before the estimator component of the harvest strategy is able to detect this. Poor performance of harvest strategies when *MSYR* is high has been observed in other cases (e.g. Punt and Butterworth, 1989).

Average catch, final depletion and '$P_{2024} >$ thresh' all increase with the initial depletion of the resource although, whether this is due to the impact of initial depletion or *MSYR* (which is correlated with initial depletion – see Table 3.3a) is unclear. The results for the operating model based on the alternative catch series (see Section 2.2.1.3) and (particularly) when the length-frequency data for 7" mesh gear are ignored are more pessimistic than for the base-case operating model. Ignoring the possibility of initial tag-loss / tagging mortality leads to more optimistic results, presumably because the initial depletion is estimated to be larger when initial tag-loss / tagging mortality is ignored (Table 3.3a).

Tables 3.10 and 3.11 examine the sensitivity of the results to changing the specifications related to the school shark component of the operating model (see Tables 3.1 and 3.3b for the specifications and the assessment implications of the changes). The most important sensitivity in Table 3.10 is to the value assumed for initial tag-loss / tagging mortality. Reducing the fraction of tagged animals that die / lose tags immediately after being tagged to 0 (trial "No initial tag-loss") implies that the 'reference' harvest strategy has a 0.46 probability of allowing recovery to the 1996 pup production by 2024 while increasing this fraction to 0.6 leads to very pessimistic results (for example, a median final depletion only 3% of the pre-exploitation level). This sensitivity test also impacts performance for gummy shark in that the (relatively) high catches of school shark lead to some discarding of gummy shark (rather than the other way around). The performance for school shark becomes somewhat more optimistic when M_{adult} is assumed to be 0.08yr^{-1} rather than 0.1yr^{-1}, when the tagging data are downweighted and when the catch series is replaced by the alternative series of catches. The last result may seem initially surprising because the initial depletion is lower when the base-case catch series is replaced by the alternative series (Table 3.3b). However, this is more than compensated for by the larger value for *MSYR*.

The results generally become more pessimistic when allowance is made for movement from New Zealand to Australia. The effect of this is greater for higher values for the movement rate (e.g. trial 'NZ movement rate=10%') and if the New Zealand population is more depleted.

As expected, the values for the performance measures for school shark are highly sensitive to value assumed for *MSYR* (Table 3.11, Figure 3.7). For *MSYR* values < 4% ("no constraints") and < 6% ("with constraints"), there is a better than even chance that the pup production in 2025 will be less than half of that in 1996. In contrast, the probability of being above the 1996 pup production in 2024 exceeds 80% for *MSYR* values of 9% and above for the "no constraints" case. The discard rate for the "with constraints" case increases with *MSYR* (Figure 3.7). Figure 3.8 indicates the relative likelihood of the different values for *MSYR*; *MSYR* values less than 7% and greater than 11% fall outside the 95% confidence interval.

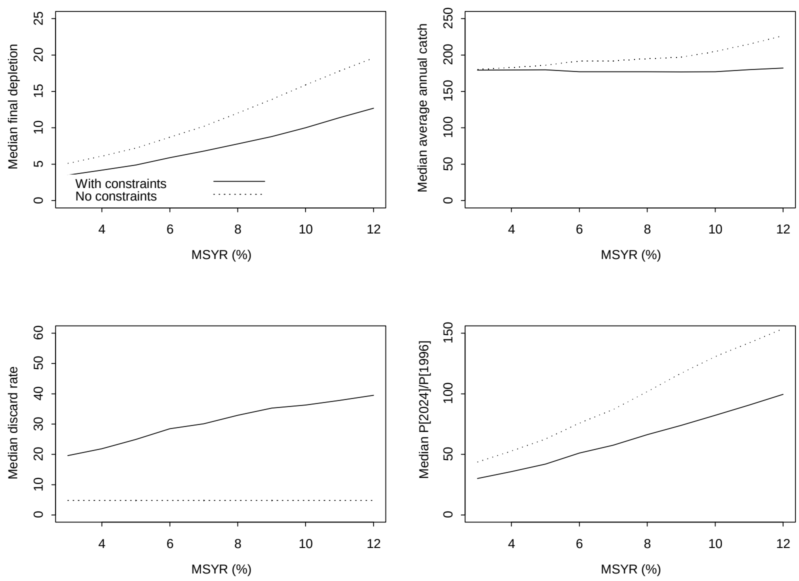

Figure 3.7 : For school shark, median final depletion, median average annual catch, median discard rate and the median of the ratio of P_{2024} to P_{1996} as a function of the value assumed for *MSYR* for school shark. Results are shown for the default constraints on the relative school : gummy exploitation rate and for no constraints on this relative exploitation rate.

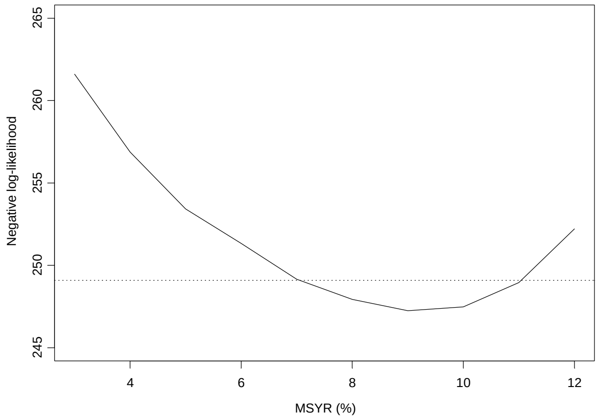

Figure 3.8 : Negative log-likelihood versus *MSYR*. The dotted line indicates the negative log-likelihood corresponding to a 95% confidence interval.

Table 3.12 examines the sensitivity of the performance measures to the frequency with which assessments (and *TAC* updates) are conducted. These results point to shorter periods between *TAC* updates for school shark being desirable (slightly lower average annual catches and slightly higher values for $med(P_{2024}/P_{1996})$ at the expense of higher inter-annual catch variability) while for gummy shark longer periods between *TAC* updates lead to slightly higher catches without any noticeable deterioration in resource conservation.

The sensitivity of the results to a range of assumptions regarding the constraint placed on the relative gummy : school exploitation rate is examined in Table 3.13 and Figure 3.9. The trial "No discarding" ignores all sources of discarding (i.e. no TAC-related discarding and no high-grading or additional damage-related discarding). As expected, performance in terms of allowing recovery of the school shark resource (and, in fact, in terms of the catches of school shark) improves as the extent of discarding due to mis-matches in *TAC*s is reduced.

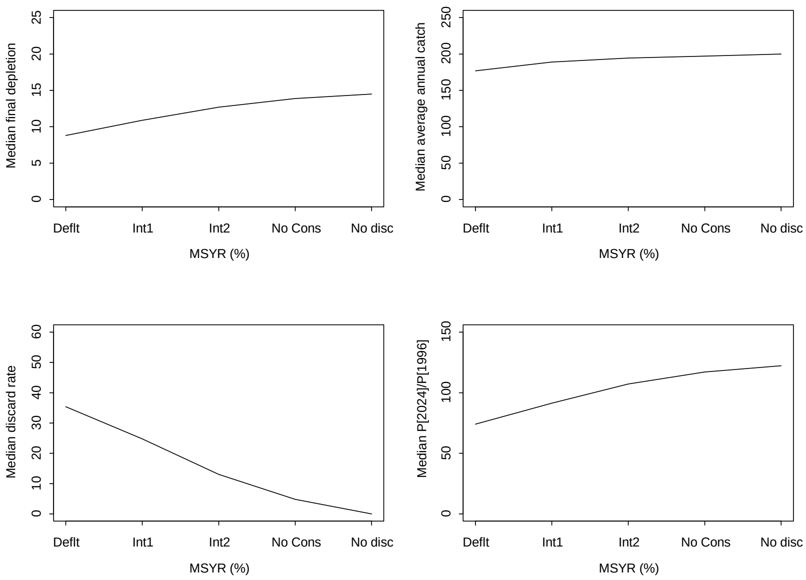

Figure 3.9 : For school shark, median final depletion, median average annual catch, median discard rate and the median of the ratio of P_{2024} to P_{1996} as a function of assumptions regarding the constraints placed on the relative gummy : school exploitation rate.

3.5.6 Sensitivity to the data used when setting TACs

Table 3.14 examines the sensitivity of the performance measures to changing the data available for *TAC* setting. Ignoring the length-frequency data leads to lower average annual catches of gummy shark while ignoring the age-composition data leads to higher average annual catches of gummy shark but also to a greater than 50% chance of the gummy shark pup production not being above the lower of 40% of the virgin level and the 1994 level. The results are not very sensitive to halving or doubling the survey sample size; catches of gummy shark are, however, slightly higher if the sample sizes are doubled for the “default constraints” case. Lower sample sizes or more additional variation (see Section 3.3.3.3 for details) lead to a slightly lower probability of leaving the pup production of school shark above the 1996 level in 2024 for the “no constraints” case.

Including the CPUE data (along with the survey, length-frequency and age-composition data) in the assessment leads to markedly lower catches of gummy shark and consequently better recovery of school shark (Table 3.14). Basing the assessments solely on the CPUE data leads to lower but more variable landed catches of school shark as well as increased discarding of this species. As expected, when the harvest strategy uses only CPUE data the distribution of average annual gummy shark catches is wider than for the base-case with, for the “default constraints” case, a lower probability of gummy shark being above the lower of 40% of the virgin level and the 1994 level in 2024.

3.6 General discussion

The ultimate aim of any harvest strategy for school and gummy shark is to promote the recovery of the school shark resource without impacting substantially on the catches of gummy shark. The 'reference' harvest strategy examined in Tables 3.6 – 3.14 was chosen because it achieves a 'tolerable' balance between risk and reward. Any such balance is, however, subjective to some extent and, in this case, is simply one chosen by the authors of this report. Any final decision regarding a harvest strategy will be made by AFMA based on advice from SharkMAC and other relevant advisory bodies.

None of the harvest strategies considered in this report perform well at allowing the school shark resource to recover in the short term. This is partly because of the poor status of the resource and the relatively low productivity of school shark but also because of the interaction between gummy and school shark. In order to achieve a higher probability of recovery, the constraints suggested by SharkMAC (minimum *TAC* levels, maximum inter-annual percentage changes in *TAC*, etc.) will need revision. If fishers are unable (or unwilling) to modify their targeting practices to avoid TAC-related discarding of school shark, it may be necessary to reduce the catches of gummy shark to lower levels than would be appropriate if gummy shark was the target of a single species fishery. An option, not considered in this report, would be to close areas where catches of school shark are known to be high. Calls have been made to close all known and potential pupping grounds by several groups, including SharkFAG, but, to date, pupping ground closures have not occurred in all parts of the fishery (the State of Victoria being a notable exception).

As expected from observations of the process of developing harvest strategies in other fishery jurisdictions (Butterworth and Punt, 1999), the results of the application of the Management Strategy Evaluation framework to the problem of setting *TAC*s for gummy and school shark highlight that there are only a few key uncertainties to which candidate harvest strategies are particularly sensitive.

a) The extent of future TAC-related discarding. Recovery of school shark pup production to above the level in 1996 depends critically on whether fishers can modify their targeting practices to avoid school shark (e.g. Figure 3.9). Taylor (unpublished data) reports that up to 60% of the catch of school shark in Bass Strait is the result of targeted fishing rather than being incidental whilst fishing for gummy shark.
b) The value of the *MSYR* parameter. Although it is not unexpected from previous studies that the values for the performance measures are highly sensitive to the value for the key parameter that determines productivity, *MSYR*, this is the key uncertainty once an assumption regarding the extent of future TAC-related discarding is made (Figure 3.7; Tables 3.9 and 3.11).
c) The extent of initial tag-loss / tagging mortality. The impact of this factor was ignored for the 1999 assessment of school shark and the 2000 assessment of gummy shark but can have a marked impact on performance, in that final depletions and annual catches are lower when there is initial tag-loss / tagging mortality (Tables 3.9 and 3.10). The estimates of initial tag-loss / tagging mortality obtained by Walker *et al*. (2000) seem to be too high so the base-case analyses are based on lower values than those obtained by Walker *et al.* (2000).

It should be noted that the minimum *TAC* for school shark was set to 150*t* rather than the 319*t* specified by SharkMAC (although SharkMAC were warned that it might not be possible to include all their suggestions in harvest strategies). Communication with SharkMAC and AFMA assisted the harvest strategy evaluation process by restricting the possible constraints (minimum *TAC*s, inter-assessment period, etc.) Further communication is necessary to finalise the selection of a harvest strategy.

The 'reference' harvest strategy is based on a simple variant of the Integrated Analysis framework; only two parameters (B_0 and *MSYR*) are estimated, and no account is taken of the uncertainty of the assessment results when providing *TAC* recommendations. Nevertheless, this harvest strategy outperforms harvest strategies based on production models and those that are purely empirical. Presumably, this is because the model underlying the harvest strategy explicitly considers the selectivity patterns used in the fishery and the peculiarities of shark pupping and because all of the available data (catch, catch-rate, length-frequency, age-composition and tagging) are included when estimating the parameters of the model.

The bulk of the analyses of this report are based on ignoring future catch-rate data and using the results from the fishery-independent survey. The results in Table 3.14 indicate that relying solely on future catch rate data is likely to lead to more variable outcomes.

Table 3.1 : The factors and levels considered in the operating models. The levels indicated in bold typeface are part of the specifications for the base-case trial.

Factor	Levels
(a) Gummy shark	
Length-specific availability	**Estimated**, uniform, constrained > 0.1
Density-dependent component	**Natural mortality**, pup survival
MSYR	**Estimated**, 11%, 15%, 25%
Current depletion of pup production (Bass Strait and South Australia)	**Estimated**, 0.5, 0.6, 0.7, 0.8
Use 7-inch mesh gear data	**Yes**, No
Catch series	**Base-case**, alternative
Ignore initial tag loss	**No**, yes
(b) School shark	
Movement rate from New Zealand	**0%,** 2%, 5%, 7%, 10%
MSYR	**Estimated**, 3%, 4%, 5%, 6%, 7%, 8%, 10%, 11%, 12%
Adult natural mortality, M_{adult}	0.08yr^{-1}, **0.1yr^{-1}**
Historical catches	**Base-case**, alternative
Tagging contribution to the likelihood	**Base-case**, halved
Depletion of the New Zealand stock	50%, **75%**, 100%
Bucket relationship between NZ and Aus	**No (α=0)**, yes (α=2)
Initial tag loss fraction	**20%**, 0, 40%
(c) Both species	
Exploitation rate ratio – South Australia	**[0.3, 1]**, [0, 0]
Exploitation rate ratio – Bass Strait	**[0.8, 0.5]**, [0, 0]
Exploitation rate ratio – Tasmania	**[0.3, 0.5]**, [0, 0]
Frequency of *TAC* updates	Every 2nd yr, **every 3rd yr** , every 5th yr

Table 3.2 : The specifications for the generation of future data. The values indicated in bold typeface form part of the specifications for the base-case trial.

Model parameter	Value – school shark	Value – gummy shark
Catch-rate data		
Sampling error, σ_q	0.212, **0.3**, 0.424	0.212, **0.3**, 0.424
Survey data		
Stations per survey site, N_2	3, **6**, 12	3, **6**, 12
Sampling error, σ_s	**1.132**	**0.849**
Additional variance, σ_A	**0.2**, 0.4	**0.2**, 0.4
Length frequency sample size		
Bass Strait	**0**	0, **1000**
South Australia	**0**	0, **850**
Tagging data		
Number released annually	**0**	**0**

Table 3.3 : Status of the gummy and school shark resources at the start of the population projections. The values presented for gummy shark are the medians and 90% intervals (in parenthesis) for quantities based on the 100 simulations, while the values listed for school shark are point estimates.

(a) Gummy shark

Scenario	Bass Strait		South Australia		*MSYR*	M_2
	P_{1973}/P_0 (%)	P_{1999}/P_0 (%)	P_{1973}/P_0 (%)	P_{1999}/P_0 (%)		(yr^{-1})
Base-case	69.9	57.8	72.2	53.7	0.173	0.192
	[65.7, 73.7]	[52.9, 62.2]	[67.0, 77.2]	[49.5, 58.0]	[0.159, 0.187]	[0.183, 0.202]
Uniform availability	51.5	41.3	58.0	38.9	0.253	0.294
	[48.3, 54.5]	[36.9, 45.1]	[51.3, 63.8]	[33.5, 43.2]	[0.240, 0.267]	[0.291, 0.297]
Constrained availability	60.7	47.0	64.8	43.2	0.178	0.251
	[56.2, 64.5]	[41.6, 51.3]	[58.1, 71.3]	[38.2, 48.3]	[0.160, 0.197]	[0.235, 0.268]
Density-dependent pups	63.7	45.5	67.5	42.7	0.115	0.167
	[56.4, 71.8]	[37.6, 51.2]	[59.3, 75.9]	[36.2, 48.1]	[0.102, 0.133]	[0.151, 0.184]
MSYR = 0.11	66.8	50.5	71.3	49.0	0.11*	0.187
	[61.1, 72.1]	[45.6, 54.2]	[64.2, 78.1]	[44.4, 53.4]		[0.178, 0.197]
MSYR = 0.15	69.1	55.3	72.5	52.5	0.15*	0.190
	[64.7, 73.2]	[50.1, 59.3]	[67.0, 78.4]	[47.8, 57.1]		[0.175, 0.208]
MSYR = 0.25	72.0	66.4	74.2	60.2	0.25*	0.190
	[68.8, 75.1]	[63.1, 69.6]	[67.0, 81.0]	[52.1, 67.7]		[0.177, 0.202]
Current depletion = 0.5	66.5	50.1	69.4	49.9	0.146	0.197
Current depletion = 0.6	69.4	60.1	74.0	59.9	0.204	0.191
Current depletion = 0.7	94.5	70.1	88.9	69.9	0.252	0.171
Current depletion = 0.8	80.5	79.9	84.0	79.9	0.300*	0.148
Ignore 7-inch mesh data for BS	78.3	50.2	68.1	47.3	0.130	0.192
	[72.4, 83.9]	[43.5, 55.7]	[61.4, 74.4]	[42.4, 52.0]	[0.106, 0.163]	[0.176, 0.209]
Alternative catches	67.2	54.1	68.0	50.6	0.144	0.192
	[62.1, 72.3]	[43.8, 60.5]	[60.8, 74.9]	[43.3, 56.5]	[0.115, 0.185]	[0.174, 0.212]
No initial tag-loss	73.9	69.3	78.4	66.8	0.160	0.202
	[70.3, 77.1]	[65.8, 72.2]	[72.9, 82.9]	[62.8, 70.2]	[0.153, 0.168]	[0.199, 0.206]

* Pre-specified values

(Table 3.3 continued)

(b) School shark

Scenario	P_{1973} / P_0 (%)	P_{1997} / P_0 (%)	*MSYR*
No New Zealand movement			
Base-case	35.6	11.0	0.090
No initial tag-loss	37.2	14.3	0.087
Initial tag-loss = 0.6	34.0	8.3	0.087
M_{adult} = 0.08yr^{-1}	35.9	12.5	0.092
Halve tagging contribution	34.9	11.6	0.090
Alternative catches	37.9	10.0	0.098
MSYR = 0.03	41.6	10.6	0.03*
MSYR = 0.04	40.4	10.7	0.04*
MSYR = 0.05	39.1	10.6	0.05*
MSYR = 0.06	37.7	10.6	0.06*
MSYR = 0.07	37.1	10.8	0.07*
MSYR = 0.08	36.3	10.9	0.08*
MSYR = 0.10	35.1	11.3	0.10*
MSYR = 0.11	34.9	11.7	0.11*
MSYR = 0.12	35.3	11.9	0.12*
With New Zealand movement			
Base-case (NZ depletion = 0.75; NZ movemnt rate = 5%)	34.9	10.5	0.082
NZ depletion = 1	34.7	10.5	0.082
NZ depletion = 0.5	34.6	9.2	0.082
NZ movemnt rate = 2%	35.5	10.8	0.080
NZ movemnt rate = 7%	35.1	9.9	0.079
NZ movemnt rate = 10%	34.3	9.5	0.079
With bucket model	35.1	10.5	0.081

* Pre-specified values

Table 3.4 : Probability of the pup production of school shark exceeding the 1996 level in 2024, the median annual catch of school shark during 2000–24, the median of the ratio of the pup production in 2024 to that in 1996, and the percentage of the catch during 2000–24 that will discarded. Results are shown for a series of harvest strategies that pre-specify the annual *TACs*. The *TAC* for gummy shark is 1525*t* for all of the analyses in this Table.

	Restrictions on reductions in *TAC*			
	None	None (no discarding)	20%	50%
Median catch				
319*t TAC*	317	317	319	317
200*t TAC*	200	200	230	203
150*t TAC*	150	150	201	159
100*t TAC*	100	100	184	118
Fraction discarded				
319*t TAC*	5	5	5	5
200*t TAC*	21	5	11	20
150*t TAC*	39	5	18	35
100*t TAC*	56	5	23	49
$P(P_{2024} > P_{1996})$				
319*t TAC*	0	0	0	0
200*t TAC*	17	100	0	12
150*t TAC*	67	100	1	52
100*t TAC*	100	100	2	99
$med(P_{2024} / P_{1996})$				
319*t TAC*	42	43	38	42
200*t TAC*	95	122	81	94
150*t TAC*	103	155	87	101
100*t TAC*	115	189	90	111

Table 3.5 : Performance measures for school and gummy shark for the base-case trial for a set of harvest strategies based on ASPM.

(a) With default constraints on the relative gummy : school exploitation rates

Harvest strategy variant			School shark performance measures								Gummy shark performance measures						
Bound by *MSY*	θ_1 Sch	θ_1 Gum	Med B_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob $P_{2024} > P_{1996}$	Med P_{2024}/P_{1996}	Med B_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob P_{2024}> thresh
No	0.4	1	11	159	159	165	36	8	38	96	56	1525	1550	1630	3	5	100
No	0.7	1	11	174	189	210	26	8	8	91	56	1525	1550	1630	3	5	100
No	1	1	9	189	213	237	17	9	1	79	56	1522	1550	1629	4	5	100
No	0.4	1.5	11	159	159	165	36	8	35	96	56	1527	1552	1638	3	5	100
No	0.7	1.5	11	174	189	210	27	8	8	91	56	1527	1552	1638	3	5	100
No	1	1.5	9	189	213	237	17	9	1	79	56	1522	1552	1638	3	5	100
Yes	0.4	1	9	159	159	162	41	8	2	76	42	1633	1788	1941	1	6	61
Yes	0.7	1	9	165	177	195	35	8	2	74	42	1633	1788	1941	1	6	61
Yes	1	1	8	177	204	231	26	9	1	66	42	1633	1785	1941	2	6	59

(b) With no constraints on the relative gummy : school exploitation rates

Harvest strategy variant			School shark performance measures								Gummy shark performance measures						
Bound by *MSY*	θ_1 Sch	θ_1 Gum	Med B_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob $P_{2024} > P_{1996}$	Med P_{2024}/P_{1996}	Med B_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob P_{2024}> thresh
No	0.4	1	17	159	165	181	5	9	100	141	56	1525	1549	1618	3	5	100
No	0.7	1	14	182	197	218	5	9	99	117	56	1525	1549	1618	3	5	100
No	1	1	11	201	226	242	5	10	35	92	56	1525	1549	1618	3	5	100
No	0.4	1.5	17	159	165	181	5	9	100	141	56	1527	1551	1616	3	5	100
No	0.7	1.5	14	182	197	218	5	9	99	117	56	1527	1551	1616	3	5	100
No	1	1.5	11	201	226	242	5	10	35	92	56	1527	1551	1616	3	5	100
Yes	0.4	1	17	159	165	181	5	9	100	141	42	1633	1785	1941	1	6	65
Yes	0.7	1	14	182	197	218	5	9	99	117	42	1633	1785	1941	1	6	65
Yes	1	1	11	201	226	242	5	10	35	92	42	1633	1785	1941	1	6	65

Table 3.6 : Performance measures for school and gummy shark for the variant of the base-case trial that imposes the default constraints on the relative gummy : school exploitation rates for a set of harvest strategies based on the Schaefer and Fox production models. The results for 'reference' harvest strategy are shown in bold typeface.

Harvest strategy		School shark performance measures								Gummy shark performance measures						
θ_1 Sch	θ_1 Gum	Med B_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob $P_{2024} > P_{1996}$	Med P_{2024}/P_{1996}	Med B_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob P_{2024}> thresh
Schaefer production model																
Reference		**9**	**165**	**177**	**195**	**35**	**8**	**2**	**74**	**42**	**1633**	**1788**	**1941**	**1**	**6**	**61**
1	1	4	280	313	342	17	15	0	30	37	1571	1743	1899	8	6	33
0.8	1	3	272	312	348	17	16	0	25	37	1585	1729	1899	8	6	28
0.6	1	3	293	325	352	17	16	0	21	37	1578	1723	1889	9	6	24
0.4	1	5	273	296	316	21	13	1	45	39	1606	1742	1899	7	6	39
0.2	1	7	253	260	312	29	16	1	59	40	1612	1759	1905	8	8	48
0.1	1	7	228	260	310	30	16	2	59	41	1617	1759	1905	8	8	52
1	0.5	4	284	319	346	15	15	0	37	42	1559	1654	1779	8	6	63
0.8	0.5	4	271	322	353	16	16	0	31	41	1581	1650	1783	9	6	55
0.6	0.5	3	299	332	359	16	15	0	24	41	1578	1645	1776	9	6	55
0.4	0.5	6	264	299	314	19	13	1	52	44	1601	1656	1791	7	6	75
0.2	0.5	8	206	260	312	29	16	1	66	46	1603	1662	1813	9	8	80
0.1	0.5	8	206	259	306	29	15	2	67	47	1605	1662	1814	8	8	80
Fox production model																
Reference		**9**	**165**	**177**	**195**	**35**	**8**	**2**	**74**	**42**	**1633**	**1788**	**1941**	**1**	**6**	**61**
1	1	0	283	322	349	10	17	0	0	33	1565	1710	1893	10	6	4
0.8	1	0	278	323	349	11	18	0	0	33	1534	1714	1861	10	6	3
0.6	1	0	278	324	353	14	21	0	0	32	1564	1710	1878	10	6	3
0.4	1	2	279	323	349	18	17	0	19	34	1585	1744	1891	9	6	13
0.2	1	4	278	304	324	25	19	1	32	35	1594	1757	1914	11	8	20
0.1	1	4	258	295	320	28	18	1	35	36	1606	1768	1928	9	8	24
1	0.5	0	294	324	351	9	16	0	3	35	1560	1695	1833	10	6	14
0.8	0.5	0	288	325	349	11	18	0	0	34	1533	1704	1831	10	6	12
0.6	0.5	0	285	325	353	14	21	0	0	34	1559	1700	1832	10	6	13
0.4	0.5	2	291	325	349	17	17	0	20	36	1585	1723	1862	9	6	22
0.2	0.5	4	286	307	324	25	18	1	34	38	1594	1736	1869	11	8	35
0.1	0.5	4	258	300	321	27	17	1	36	39	1606	1742	1869	10	8	38

Table 3.7 : Performance measures for school and gummy shark for the base-case trials for a set of empirical harvest strategies. The results for 'reference' harvest strategy are shown in bold typeface.

Harvest strategy		School shark performance measures								Gummy shark performance measures						
γ Sch	γ Gum	Med B_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob $P_{2024} > P_{1996}$	Med P_{2024}/P_{1996}	Med B_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob P_{2024}> thresh
(a) With default constraints on the relative gummy : school exploitation rates																
Reference		**9**	**165**	**177**	**195**	**35**	**8**	**2**	**74**	**42**	**1633**	**1788**	**1941**	**1**	**6**	**61**
TAC not bounded by the average catch																
0.6	0.6	3	289	301	309	5	5	0	27	42	1539	1609	1681	11	6	70
0.8	0.8	6	260	281	301	5	4	0	46	47	1537	1606	1684	9	6	92
1.0	1.0	6	241	266	289	6	5	0	54	49	1542	1605	1693	7	6	95
1.2	1.2	8	216	244	271	10	5	0	67	52	1547	1606	1704	4	6	98
1.4	1.4	9	201	229	256	14	5	0	72	53	1542	1597	1713	3	6	100
TAC bounded by the average catch																
0.6	0.6	3	289	301	309	5	5	0	28	46	1504	1552	1578	13	6	88
0.8	0.8	6	259	281	299	5	4	0	46	51	1508	1551	1580	9	6	99
1.0	1.0	7	243	268	289	6	5	0	55	53	1506	1551	1580	8	6	100
1.2	1.2	8	216	244	268	9	5	0	70	55	1509	1549	1582	4	6	100
1.4	1.4	9	201	231	256	11	5	0	75	57	1507	1541	1563	4	5	100
(b) With no constraints on the relative gummy : school exploitation rates																
Reference		**14**	**182**	**197**	**218**	**5**	**9**	**99**	**117**	**42**	**1633**	**1785**	**1941**	**1**	**6**	**65**
TAC not bounded by the average catch																
0.6	0.6	3	290	302	309	5	5	0	28	52	1562	1635	1712	3	6	99
0.8	0.8	6	263	284	299	5	4	0	48	52	1555	1627	1721	3	6	99
1.0	1.0	7	248	270	289	5	5	0	57	52	1555	1620	1721	3	6	100
1.2	1.2	9	222	245	272	5	5	0	75	53	1554	1612	1721	3	6	100
1.4	1.4	10	210	237	264	5	5	5	80	53	1545	1602	1713	3	6	100
TAC bounded by the average catch																
0.6	0.6	3	289	301	309	5	5	0	28	56	1520	1558	1587	3	6	100
0.8	0.8	6	259	283	299	5	4	0	48	57	1520	1554	1581	3	6	100
1.0	1.0	7	247	269	289	5	5	0	57	57	1520	1552	1588	3	6	100
1.2	1.2	9	222	244	269	5	5	0	76	57	1517	1550	1582	3	6	100
1.4	1.4	10	207	235	258	5	5	6	81	57	1510	1541	1564	3	5	100

Table 3.8 : Performance measures for school and gummy shark for two variants of the base-case trial for a set of variants of the 'reference' harvest strategy. The results for the 'reference' harvest strategy are shown in bold typeface.

Harvest strategy	School shark performance measures								Gummy shark performance measures						
	Med B_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob $P_{2024} > P_{1996}$	Med P_{2024}/P_{1996}	Med B_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob P_{2024}> thresh
(a) With default constraints on the relative gummy : school exploitation rates															
Reference	**9**	**165**	**177**	**195**	**35**	**8**	**2**	**74**	**42**	**1633**	**1788**	**1941**	**1**	**6**	**61**
Estimate Gummy *M*	9	165	174	189	36	8	2	73	38	1629	1827	2046	1	5	41
Estimate Rec resides	9	165	177	195	35	8	2	74	43	1627	1781	1924	1	6	70
Bootstrap															
P=0.5	9	162	171	189	37	8	2	75	42	1633	1788	1939	1	6	62
P=0.3	9	162	168	183	38	9	2	76	43	1633	1780	1917	2	6	69
θ_2 = 0.1	9	169	183	201	33	8	1	73	42	1633	1788	1941	1	6	61
θ_2 = 0.7	9	162	168	183	37	11	2	75	42	1633	1785	1941	1	6	62
Extent of carryover															
30%	9	165	177	195	35	8	2	74	40	1642	1802	1960	1	6	50
10%	9	165	177	195	35	8	2	75	44	1630	1772	1915	2	6	83
(b) With no constraints on the relative gummy : school exploitation rates															
Reference	**14**	**182**	**197**	**218**	**5**	**9**	**99**	**117**	**42**	**1633**	**1785**	**1941**	**1**	**6**	**65**
Estimate Gummy *M*	14	180	194	218	5	10	100	119	38	1628	1827	2037	1	6	42
Estimate Rec resides	14	182	197	218	5	9	99	117	43	1629	1779	1924	1	6	73
Bootstrap															
P=0.5	14	180	195	214	5	9	99	120	42	1633	1785	1930	1	6	65
P=0.3	15	175	190	210	5	10	100	123	43	1633	1777	1915	2	6	70
θ_2 = 0.1	13	186	201	220	5	8	95	112	42	1633	1785	1941	1	6	65
θ_2 = 0.7	15	170	190	213	5	12	100	124	43	1633	1785	1941	1	6	65
Extent of carryover															
30%	14	182	197	218	5	9	99	117	40	1632	1795	1956	1	6	53
10%	14	182	197	218	5	9	99	117	44	1634	1770	1915	2	6	85

Table 3.9 : Sensitivity of the performance measures for the ‘reference’ harvest strategy to modifying the specifications of the gummy shark component of the operating model. The results for the base-case trial are shown in bold typeface.

Operating model	School shark performance measures								Gummy shark performance measures						
	Med B_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob $P_{2024} > P_{1996}$	Med P_{2024}/P_{1996}	Med B_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob P_{2024}> thresh
(a) With default constraints on the relative gummy : school exploitation rates															
Base-case	**9**	**165**	**177**	**195**	**35**	**8**	**2**	**74**	**42**	**1633**	**1788**	**1941**	**1**	**6**	**61**
Constrained availability	9	165	177	195	34	8	0	73	27	1394	1614	1809	1	6	2
Density-dependent pups	10	165	179	195	32	8	0	80	26	1358	1578	1792	1	6	2
MSYR = 0.11	9	168	177	195	33	8	0	77	27	1347	1489	1642	1	6	0
MSYR = 0.15	9	168	177	192	33	8	0	76	38	1601	1714	1854	1	6	29
MSYR = 0.25	9	168	177	195	34	8	6	73	56	1131	1934	2006	2	6	100
Current depletion = 0.5	9	168	180	195	32	8	0	79	33	1565	1671	1744	1	5	3
Current depletion = 0.6	9	168	177	195	34	8	0	78	50	1813	1882	1941	1	6	100
Current depletion = 0.7	9	168	177	195	36	8	0	73	62	1917	1968	2029	2	7	100
Current depletion = 0.8	9	168	177	195	35	8	0	75	75	1927	1976	2041	2	7	100
Ignore 7-inch mesh data	9	165	177	195	33	8	1	77	31	1354	1576	1798	1	6	8
Alternative catches	9	168	177	195	34	8	1	77	38	1397	1754	1936	1	5	42
No initial tag-loss	8	165	174	189	42	8	0	63	42	1681	1814	1957	1	5	70
(b) With no constraints on the relative gummy : school exploitation rates															
Base-case	**14**	**182**	**197**	**218**	**5**	**9**	**99**	**117**	**42**	**1633**	**1785**	**1941**	**1**	**6**	**65**
Constrained availability	14	182	197	218	5	9	99	117	27	1394	1615	218	1	6	2
Density-dependent pups	14	182	197	218	5	9	99	117	26	1358	1577	1792	1	6	2
MSYR = 0.11	14	182	197	218	5	9	99	117	27	1347	1489	1642	1	6	0
MSYR = 0.15	14	182	197	218	5	9	99	117	38	1601	1713	1839	1	6	31
MSYR = 0.25	14	182	197	218	5	9	99	117	57	1128	1934	1998	2	6	100
Current depletion = 0.5	14	182	197	218	5	9	99	117	33	1566	1665	1744	1	5	3
Current depletion = 0.6	14	182	197	218	5	9	99	117	51	1812	1880	1935	1	6	100
Current depletion = 0.7	14	182	197	218	5	9	99	117	63	1911	1962	2021	2	7	100
Current depletion = 0.8	14	182	197	218	5	9	99	117	75	1920	1971	2035	2	7	100
Ignore 7-inch mesh data	14	182	197	218	5	9	99	117	31	1354	1572	1798	1	6	8
Alternative catches	14	182	197	218	5	9	99	117	39	1397	1751	1936	1	5	44
No initial tag-loss	14	182	197	218	5	9	99	117	42	1681	1812	1957	1	5	70

Table 3.10 : Sensitivity of the performance measures for the 'reference' harvest strategy to modifying the specifications of the school shark component of the operating model. The results for the base-case trial are shown in bold typeface.

(a) With default constraints on the relative gummy : school exploitation rates

Operating model	School shark performance measures								Gummy shark performance measures						
	Med B_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob $P_{2024} > P_{1996}$	Med P_{2024}/P_{1996}	Med B_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob P_{2024}> thresh
No New Zealand movement															
Base-case	**9**	**165**	**177**	**195**	**35**	**8**	**2**	**74**	**42**	**1633**	**1788**	**1941**	**1**	**6**	**61**
No initial tag-loss	15	165	186	210	46	9	46	99	42	1633	1788	1941	1	6	61
Initial tag-loss = 0.6	3	161	174	185	17	10	0	31	36	1582	1729	1877	10	6	21
M_{adult} = 0.08yr^{-1}	12	171	186	210	42	9	10	90	42	1633	1788	1941	1	6	61
Halve tag contribution	11	168	183	204	41	8	6	88	42	1633	1788	1941	1	6	61
Alternative catches	9	165	177	195	40	8	2	81	42	1633	1788	1941	1	6	61
With New Zealand movement															
NZ depletion = 0.75	6	165	171	180	27	8	0	55	41	1632	1783	1938	3	6	51
NZ depletion = 1	7	165	180	198	41	8	1	63	42	1633	1788	1941	1	6	61
NZ depletion = 0.5	2	143	156	165	15	12	0	19	35	1582	1732	1862	10	6	16
NZ movemnt rate = 2%	7	165	174	189	30	8	0	60	41	1632	1785	1941	2	6	58
NZ movemnt rate = 7%	6	165	168	180	27	7	0	54	42	1633	1788	1941	2	6	60
NZ movemnt rate = 10%	5	165	168	180	24	8	0	49	41	1632	1786	1940	2	6	56
With bucket model	6	164	168	177	25	8	0	51	39	1623	1780	1937	4	6	47

(Table 3.10 Continued)

(b) With no constraints on the relative gummy : school exploitation rates

Operating model	School shark performance measures								Gummy shark performance measures						
	Med B_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob $P_{2024} > P_{1996}$	Med P_{2024}/P_{1996}	Med B_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob P_{2024}> thresh
No New Zealand movement															
Base-case	**14**	**182**	**197**	**218**	**5**	**9**	**99**	**117**	**42**	**1633**	**1785**	**1941**	**1**	**6**	**65**
No initial tag-loss	22	203	234	275	5	10	100	145	42	1633	1785	1941	1	6	65
Initial tag-loss = 0.6	5	174	180	195	5	9	0	55	42	1633	1785	1941	1	6	65
M_{adult} = 0.08yr^{-1}	19	202	223	263	5	10	100	139	42	1633	1785	1941	1	6	65
Halve tag contribution	17	197	221	258	5	10	100	135	42	1633	1785	1941	1	6	65
Alternative catches	14	195	211	237	5	10	100	132	42	1633	1785	1941	1	6	65
With New Zealand movement															
NZ depletion = 0.75	10	168	177	189	5	8	0	87	42	1633	1785	1941	1	6	65
NZ depletion = 1	11	180	202	224	5	10	39	99	42	1633	1785	1941	1	6	65
NZ depletion = 0.5	3	166	171	173	5	10	0	33	42	1633	1785	1941	1	6	65
NZ movemnt rate = 2%	11	174	180	195	5	8	13	96	42	1633	1785	1941	1	6	65
NZ movemnt rate = 7%	9	165	177	180	5	8	0	86	42	1633	1785	1941	1	6	65
NZ movemnt rate = 10%	8	165	174	180	5	7	0	77	42	1633	1785	1941	1	6	65
With bucket model	9	165	174	177	5	7	0	81	42	1633	1785	1941	1	6	65

Table 3.11 : Sensitivity of the performance measures for the ‘reference’ harvest strategy to the value of *MSYR* for school shark. The results for the base-case trial are shown in bold typeface.

MSYR	School shark performance measures								Gummy shark performance measures						
	Med B_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob $P_{2024} > P_{1996}$	Med P_{2024}/P_{1996}	Med B_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob P_{2024}> thresh
(a) With default constraints on the relative gummy : school exploitation rates															
Estimated	**9**	**165**	**177**	**195**	**35**	**8**	**2**	**74**	**42**	**1633**	**1788**	**1941**	**1**	**6**	**61**
0.03	4	168	179	192	20	9	0	30	39	1623	1776	1933	4	6	48
0.04	4	168	180	192	22	9	0	36	41	1629	1784	1939	3	6	53
0.05	5	168	180	195	25	8	0	42	41	1632	1784	1941	2	6	58
0.06	6	168	177	195	29	8	0	51	41	1633	1785	1941	2	6	58
0.07	7	168	177	195	30	8	0	58	42	1633	1788	1941	1	6	60
0.08	8	165	177	195	33	8	1	66	42	1633	1788	1941	1	6	61
0.09	9	165	177	195	35	8	2	74	42	1633	1788	1941	1	6	61
0.1	10	165	177	195	36	8	2	82	42	1633	1788	1941	1	6	61
0.11	11	165	180	198	38	8	17	91	42	1633	1788	1941	1	6	61
0.12	13	168	182	204	40	8	49	100	42	1633	1788	1941	1	6	61
(b) With no constraints on the relative gummy : school exploitation rates															
Estimated	**14**	**182**	**197**	**218**	**5**	**9**	**99**	**117**	**42**	**1633**	**1785**	**1941**	**1**	**6**	**65**
0.03	5	177	180	198	5	8	0	44	42	1633	1785	1941	1	6	65
0.04	6	177	183	198	5	8	0	53	42	1633	1785	1941	1	6	65
0.05	7	177	186	198	5	8	0	63	42	1633	1785	1941	1	6	65
0.06	9	177	192	198	5	8	0	76	42	1633	1785	1941	1	6	65
0.07	10	177	192	201	5	8	0	87	42	1633	1785	1941	1	6	65
0.08	12	177	195	216	5	9	67	102	42	1633	1785	1941	1	6	65
0.09	14	182	197	218	5	9	99	117	42	1633	1785	1941	1	6	65
0.1	16	185	205	227	5	10	100	131	42	1633	1785	1941	1	6	65
0.11	18	194	215	247	5	10	100	142	42	1633	1785	1941	1	6	65
0.12	20	202	227	270	5	10	100	154	42	1633	1785	1941	1	6	65

Table 3.12 : Sensitivity of the performance measures for the ‘reference’ harvest strategy to the frequency with which *TAC*s are updated.

Frequency of *TAC* updates	School shark performance measures								Gummy shark performance measures						
	Med B_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob $P_{2024} > P_{1996}$	Med P_{2024}/P_{1996}	Med B_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob P_{2024}> thresh
With default constraints on the relative gummy : school exploitation rates															
Annually	9	161	173	187	35	12	1	76	42	1633	1781	1939	1	6	67
Every 3 yrs	9	165	177	195	35	8	2	74	42	1633	1788	1941	1	6	61
Every 5 yrs	9	175	180	205	33	7	1	73	42	1633	1789	1923	1	6	64
With no constraints on the relative gummy : school exploitation rates															
Annually	14	178	192	210	5	13	100	120	43	1625	1775	1920	2	6	70
Every 3 yrs	14	182	197	218	5	9	99	117	42	1633	1785	1941	1	6	65
Every 5 yrs	13	180	205	220	5	8	97	111	43	1633	1791	1940	1	6	65

Table 3.13 : Sensitivity of the performance measures for the ‘reference’ harvest strategy to the assumptions regarding how future fishing practices will impact TAC-related discarding.

Constraint	School shark performance measures								Gummy shark performance measures						
	Med B_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob $P_{2024} > P_{1996}$	Med P_{2024}/P_{1996}	Med B_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob P_{2024}> thresh
Default	9	165	177	195	35	8	2	74	42	1633	1788	1941	1	6	61
Int-1	11	174	189	201	25	8	17	91	42	1633	1788	1941	1	6	61
Int-2	13	177	195	216	13	9	81	107	42	1633	1785	1941	1	6	62
No constraints	14	182	197	218	5	9	99	117	42	1633	1785	1941	1	6	65
No discarding	15	184	200	220	0	9	100	122	43	1651	1800	1957	0	6	72

Table 3.14 : Sensitivity of the performance measures for the ‘reference’ harvest strategy to the assumptions regarding the data available in the future.

Operating model	School shark performance measures								Gummy shark performance measures						
	Med B_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob $P_{2024} > P_{1996}$	Med P_{2024}/P_{1996}	Med B_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob P_{2024}> thresh
(a) With default constraints on the relative gummy : school exploitation rates															
Base-case	**9**	**165**	**177**	**195**	**35**	**8**	**2**	**74**	**42**	**1633**	**1788**	**1941**	**1**	**6**	**61**
No Length frequency data	9	165	177	195	34	8	2	76	45	1614	1734	1881	2	6	87
No age-composition data	9	165	177	195	35	8	2	73	37	1639	1827	2077	1	5	37
Halve survey sample size	9	168	177	192	35	8	2	74	42	1633	1786	1931	1	6	62
Double survey sample size	9	168	177	192	35	8	2	74	42	1633	1795	1945	1	6	63
More additional variation	9	165	177	195	36	8	2	74	42	1633	1790	1941	1	6	63
Use CPUE data	10	165	177	192	34	8	5	83	48	1583	1662	1798	2	6	98
Use CPUE (lower CV)	10	165	177	195	34	8	5	83	48	1583	1664	1798	2	6	98
Use CPUE (higher CV)	10	165	177	189	34	8	5	83	48	1583	1661	1798	2	6	98
CPUE data only	9	159	162	176	41	9	2	78	39	1639	1808	2002	2	5	41
(b) With no constraints on the relative gummy : school exploitation rates															
Base-case	**14**	**182**	**197**	**218**	**5**	**9**	**99**	**117**	**42**	**1633**	**1785**	**1941**	**1**	**6**	**65**
No Length frequency data	14	182	197	218	5	9	99	117	48	1596	1706	1844	2	6	92
No age-composition data	14	182	197	218	5	9	99	117	37	1639	1827	2078	1	5	37
Halve survey sample size	14	177	196	222	5	9	95	118	42	1633	1785	1931	1	6	63
Double survey sample size	14	180	195	215	5	9	100	118	42	1633	1785	1941	1	6	65
More additional variation	14	182	197	220	5	9	97	116	42	1633	1785	1940	1	6	64
Use CPUE data	15	174	189	206	5	9	100	122	48	1583	1649	1794	2	6	98
Use CPUE (lower CV)	15	170	189	210	5	9	100	122	49	1583	1649	1794	2	6	98
Use CPUE (higher CV)	15	174	189	204	5	9	100	122	48	1583	1648	1794	2	6	98
CPUE data only	17	159	165	185	5	9	100	141	39	1629	1793	2001	2	5	48

Appendix 3.1: Shark assessment and management practices

Although there is widespread recognition of the need for stock assessment and management for shark species, there is little or no uniformity in these practices across chondrichthyan fisheries worldwide. Historically, most targeted chondrichthyan fisheries have been unregulated and have rapidly become unsustainable. By 1994, about 105 countries reported shark landings to FAO and some 26 nations landed more than 10,000*t* of shark per year[7]. Table App 3.1.1 summarises a literature survey of management practices for over 30 fisheries, representing more than 20 countries.

Most chondrichthyan fisheries appear to have no stock assessment or management plans (e.g. China, Guatemala, Indonesia, Pakistan, Peru, Phillipines, Uraguay, former-USSR)[4].

For those fisheries that do have management plans, assessment of the status of stocks can be as rudimentary as collection of colloquial information, although the predominant method is to rely on trends in catches and particularly catch rates as input to various (usually simple) stock assessment models. Many of the surveyed fisheries do not systematically record the data necessary for stock assessment. Although not shown in Table App 3.1.1, Japan assesses trends in shark stocks by examining trends in shark by-catch from other larger finfish fisheries (e.g. tuna) in addition to catch rates from fishery-independent surveys. The majority of shark fisheries have not attempted stock assessment and this may be because most of the fisheries do not record data for the different shark species caught and record catches simply as ‘shark’. In the absence of a thorough stock assessment, declining catch rates are universally accepted as a signal that a fishery may need additional management controls.

Canada has carried out a fishery-independent survey of dogfish. The USA has carried out a long-term (1974–91) fishery-independent survey of sandbar, dusky, sand tiger, and tiger shark in the Chesapeake Bay region using longlines[20]. The stocks targeted in other fisheries (Caribbean, Malaysia, New Zealand and South Africa) have also been surveyed, typically by bottom trawling, but it is not clear if this was targeted fishery-independent work.

Some fisheries jurisdictions (Brazil, the Mediterranean, South Africa and the USA Atlantic) have proposed future management plans for their major commercial shark species. Other fisheries jurisdictions (Ireland, Mexico, Norway, Oman, Portugal, Peurto Rico, and the Virgin Islands) have minimal or only partial management of their shark species. With the exception of South Africa, New Zealand, the USA and Australia, the countries surveyed do not have integrated research and management plans. Only Canada, New Zealand and Australia have well defined, quantifiable, biological reference points that can be used to evaluate the success, or otherwise, of implemented management strategies.

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Table App 3.1.1 : Overview of shark assessment and management practices.

Country / Region	*Species*	*Assessment*		*Management*	*Reference Points*
		Data	*Method*		
Africa[18]	School, shortfin mako, blue, hound	Crude total catch estimates		None	
South Africa[7,15]	School, smoothhound, St Joseph	Catch and effort, biological data, fishery-independent surveys		Quotas, gear restrictions, bag limits, limited entry	
Argentina[10]	Smoothhound, school, copper	Catch and effort, Length frequencies		None	
Brazil[7]	Various			Proposed gear restrictions, proposed finning prohibition	
Canada Atlantic[16]	Porbeagle, spiny dogfish, blue	Catch and effort	Preliminary catch rate analysis using Analysis of Variance for porbeagles.	Quotas, gear restrictions, limited entry	
Canada Pacific[5,17]	Spiny dogfish	Catch and effort, tagging data, fishery-independent surveys	Delay difference model, age-structured model	Quotas	*MSY*
Canada Grand Banks[19]	Skate	Catch and effort		Quotas, gear restrictions, limited entry, closures	
Caribbean[27]	Various	Catch, biological data, fishery-independent surveys		Gear restrictions	
European Union[7]	Basking, porbeagle, skates, various	Catch		Quotas	
Falkland Islands[1]	Various	Catch and effort, biological data	Production model with constant recruitment, GLM standardised catch rate series.	Limited entry, gear restrictions, closures	*MSY*
India[4,13]	Various	Catch and effort, biological data, length frequencies	VPA, Thomson & Bell model, Schaefer model	None	
Ireland[7]	Various			Recreational minimum sizes (self regulated)	
Japan[11]	Piked dogfish, skates and rays	Catch and effort (lumped by shark or batoid), tagging data		None	
Malaysia[2]	Various	Catch, fishery-independent surveys		Gear restrictions, limited entry, vessel restrictions	
Maldives[7]	Various			Area closures, gear restrictions	
Mediteranean Sea[7]	Shortfin mako, porbeable, blue			In development	

(Table App 3.1.1 continued)

Country / Region	*Species*	*Assessment*		*Management*	*Reference Points*
		Data	*Method*		
Mexico[8]	Atlantic sharpnose, bonnethead, blacktip, blacknose, scalloped hammerhead	Monitoring of artisanal landings, catch and effort		Limited entry	
New Zealand[11,12]	Spiny dogfish, school, skates, rig, ghost, elephant fish, blue porbeagle, shortfin mako	Catch and effort, recreational catch, tagging data, fishery-independent surveys	Catch-rate analyses	Quotas, species prohibitions, bag limits, gear restrictions, closures, limited entry	Catch-rate decline, *MCY*
Norway[7]	Spiny dogfish			Minimum sizes	
Oceania[23]	Various	Catch and effort		None except in NZ and Australia waters	Relative Abundance, *MSY*
Oman[7]	Various			Finning prohibited	
Portugal[7]	Kitefin			Gear restrictions	
Puerto Rico, and the Virgin Islands[3,9]	Large coastal, small coastal, pelagic		Assessment by shark groups	Finning prohibited, discarding discouraged	
United Kingdom[7]	Rays			Minimum sizes	
U.S.A. [21]	Dogfish	Catches		None	
U.S.A. West Coast[14]	Thresher, shortfin mako	Catch and effort, biological data, length-frequencies	Catch-rate trends	Gear restrictions	Fishing mortality
U.S.A. Atlantic[6,22,24]	Sandbar, dusky, sandtiger, tiger, spurdog various	Catch and effort, biological data, fishery-independent surveys	Production models for northern Spurdog.	Proposed: quotas, trip limits, bag limits, closures, prohibited species, finning prohibition	*MSY*

Appendix 3.2 : Brief provided to the 16–17 March 2000 meeting of SharkMAC

Introduction

SharkFAG completed its spatially-structured stock assessment of school shark in July 1999, and work on the spatially-structured stock assessment of gummy shark is nearing completion. SharkMAC have selected a management objective for school shark (that there be an 80% probability that the mature biomass at the start of 2011 exceeds that at the start of 1996) and have agreed how Total Allowable Catches (*TAC*s) should be modified over time to achieve this objective. It has, however, not recently agreed to any management objectives for gummy shark nor is there a clear process for setting *TAC*s for this species. SharkMAC and AFMA have requested SharkFAG to evaluate alternative approaches for setting *TAC*s (referred to as harvest strategies) for gummy shark. SIRLC and SharkMAC assigned this work high priority and a research project for supporting this work was submitted to, and funded by, FRDC.

The development of a harvest strategy for gummy shark necessarily involves interaction between SharkFAG (who conduct the technical aspects of the work) and SharkMAC (who will have to make any final recommendations to the AFMA Board on harvest strategies for the SSF). SharkFAG expect to provide SharkMAC with a range of alternative harvest strategies and their advantages and disadvantages. These harvest strategies will differ in terms of how conservative they are, how much they emphasise stable catches, and how much they attempt to make use of good year-classes when they become available. It will be up to SharkMAC to decide what trade-off it desires among these issues.

This document first outlines some of the technical aspects of the work (what exactly is a harvest strategy and how SharkFAG will evaluate different harvest strategies). It then outlines how SharkFAG intends to quantify the performance of different harvest strategies (in terms of the three issues listed above and AFMAs legislative objectives). Finally, it lists what input SharkFAG will be expecting from SharkMAC members while it conducts the technical work.

Technical overview of harvest strategy evaluation

The term ‘harvest strategy’ is used to refer to the combination of two processes: the stock assessment and the *TAC* decision rule (Fig. 1). The objective of the stock assessment component of a harvest strategy is to use the information collected from the fishery (e.g. catch, CPUE, length-frequency, etc.) to obtain estimates of the quantities that are needed for *TAC* setting (e.g. the current biomass and the current sustainable yield). The objective of the *TAC* decision rule component is to use the information provided by the stock assessment to determine a *TAC*. The stock assessments considered by SharkFAG will be typical of those used in the past for assessments in the SSF (i.e. allowance will be made for the spatial structure of the fishery and the nature of gill-net selectivity). An example of a *TAC* decision rule is shown in Fig. 2. In this case, the *TAC* changes in proportion to the biomass.

Harvest strategies are evaluated using a process that is rather like a flight simulator. A model that represents the real world (including the stocks to be fished, the fishery, and some aspects of the environment) is developed. This model will be chosen by SharkFAG but will essentially be a variant of the stock assessment with refinements that allow future data to be generated and the biological consequences of the *TAC*s to be determined. The model will include issues such as how catches will be taken spatially given changes over time in *TAC* levels.

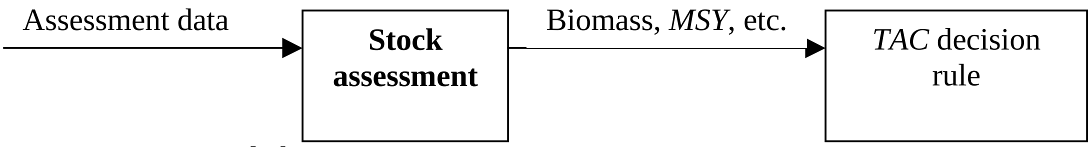

Figure 1 : An example harvest strategy.

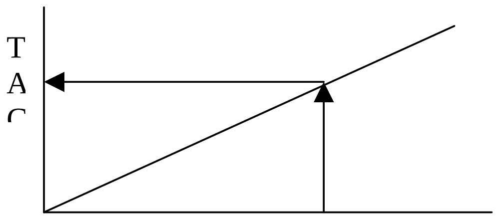

Figure 2 : A simple relationship be **Biomass** *TAC*.

The data generated by the model is analysed by means of the stock assessment and the *TAC* decision rule to produce a *TAC* and the *TAC* is used to move the model forward one further year. The process of data generation, application of the harvest strategy and evaluation of the consequences of the *TAC* is repeated for several years (Fig. 3). The analogy with the flight simulator is that a flight simulator generates information on height, speed etc and determines the consequences of the pilot's actions, which are based on that information. The whole process in Fig. 3 is repeated many times for each model (say 100–250) and for several alternative models of reality. The alternative models are considered so that harvest strategies that do well for some scenarios but poorly for others can be identified.

Quantifying performance

The key information that SharkFAG requires from SharkMAC is an indication of how the performance of a harvest strategy should be evaluated. SharkMAC has some experience in doing this. For example, for school shark, the risk to the resource has been quantified by the probability of the mature biomass in 2011 being above the 1996 level and by the discounted total catch over the period 1996–2011.

Ideally, the statistics used to measure performance should be based directly on AFMAs' three key legislative objectives:

a) economic efficiency,

b) cost effective management, and
c) ecologically sustainable development.

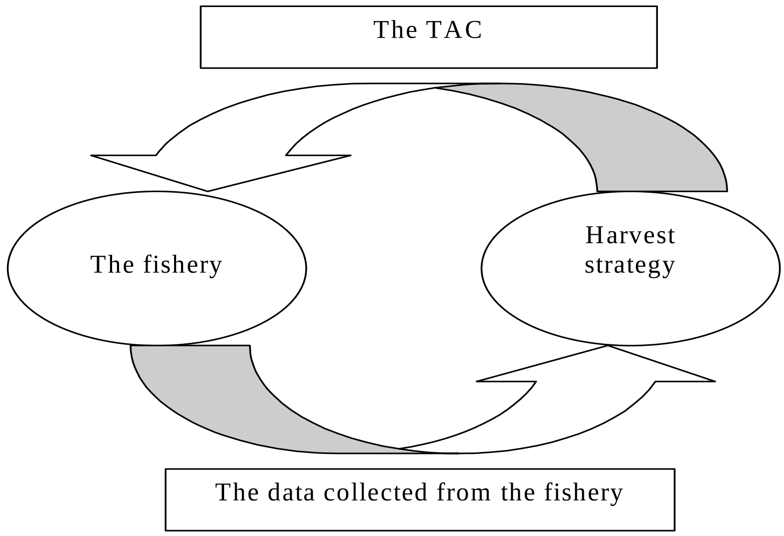

Figure 3 : The assessment and TAC cycle.

Consideration of economic efficiency should ideally involve the development of a detailed model of the fishery (including how fishers make investment decisions). Unfortunately, there is currently no funding for the development of such a model and, in any case, the data needed to use the model (e.g. how well the market for school and gummy shark quota will operate) is simply not available. This same problem arose in 1996 during the development of the school shark assessment and it is proposed that the same solution to that problem be adopted now. This solution involves providing SharkMAC with information related to how catch and effort changes over time (and by region within the fishery) rather than modelling the dynamics of the fishery directly.

Similarly it is impossible to develop a model of management costs as these involve issues (such as how future governments might change the cost-recovery policy, for example) that are beyond the scope of SharkFAG. Instead, a less ambitious approach will be adopted, which will attempt to quantify how much data is needed for assessments and hence the provision of management advice. Different harvest strategies can then be compared in terms of their monitoring costs.

Assessing performance relative to the objective of Ecologically Sustainable Development can also not be addressed fully. This is because, for example, it is currently impossible to develop models of how catches of shark impact the overall ecosystem. Therefore, in common with how this issue is dealt with internationally, attention will only be focussed on the target species. The types of statistics to measure the performance of a harvest strategy will therefore consist of how catches change over time and whether the resources are reduced to undesirably low levels. The risk to the ecosystem is captured to some extent by consideration of this latter issue because the magnitude of the impact of the fishery on the ecosystem will be larger the more depleted the population is.

There is, at present, no objective basis for identifying the ‘biomass that we must not drop below because something bad will happen’ although it is certain that there must be such a biomass. This is one of the reasons SharkMAC agreed to a reference point for school shark that the stock should not go below where it is now (irrespective of what that might be). SharkFAG has reviewed the literature for shark and other fisheries. The ways in which the risk to the resource has been measured include: whether the biomass drops below that at which *MSY* is achieved (referred to as B_{MSY}), whether it drops below some pre-specified fraction (20% or 40%) of the virgin biomass, and whether it drops below the point at which at which it is estimated recruitment to the fishery is halved (B_{50}). Naturally, it is not as worrying if the biomass drops below B_{MSY} than if it drops below B_{50}.

What SharkFAG expects from SharkMAC

There is still much work that needs to be done before SharkFAG expects to be presenting any results to SharkMAC. For example, it is necessary to first complete the spatially-structured assessment of gummy shark. It should also be noted that the process of evaluating harvest strategies is intended to be iterative so that any decisions made now are not set in stone forever. However, SharkFAG needs guidance now on several issues so that it can focus its work.

a) Should emphasis be placed on finding harvest strategies that lead to the highest average catches or on lower but more stable catches (Fig. 4)? Discussions with fishers have indicated that stability of catches is a key objective for many in the fishery.

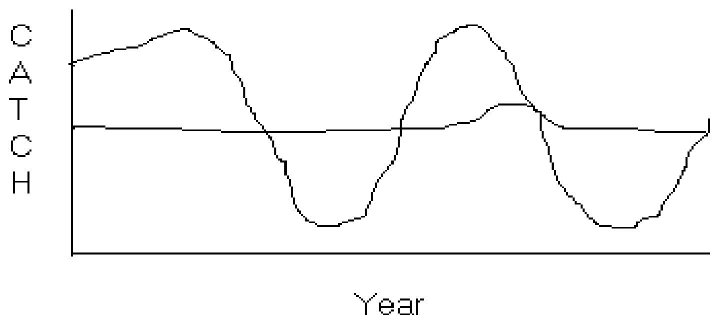

Figure 4 : Time-series of annual catches for two options: one that has a higher average catch but is more variable and another that has a lower average catch but is much less variable.

b) The process of evaluating harvest strategies usually involves looking at scenarios that are not considered very likely at present but may have important future consequences. SharkFAG would appreciate guidance on such scenarios. For example, it might be worth considering scenarios in which environmental degradation has impacted pup production of school shark and relationships between school sharks in New Zealand and those in Australia that are more complicated than currently assumed (e.g. the ‘bucket model’ of Trevor Gilmore).

c) What other types of information would SharkMAC like when comparing harvest strategies (and the consequences of future *TAC*s in general).
d) Given the importance of this issue for the long-term management of the fishery, SharkFAG would like guidance on which groups, other than SharkMAC, the States, and AFMA, should be kept aware of this work.

Appendix 3.3 : Brief provided to the 26-27 October 2000 meeting of SharkMAC

As requested by SharkMAC, SharkFAG are developing the technical basis for evaluating alternative harvest strategies for school and gummy shark. It is anticipated that the process of developing advice on the advantages and disadvantages of alternative harvest strategies will be completed by mid-2002. This task has a large technical (i.e. modelling) component. However, to achieve a satisfactory outcome (i.e. the selection of appropriate harvest strategies), SharkFAG require guidance from SharkMAC and AFMA on several key issues. This brief document outlines what a harvest strategy is, the process of evaluating harvest strategies (highlighting the tasks to be accomplished by SharkMAC and SharkFAG), and some issues on which SharkFAG would appreciate preliminary guidance. SharkFAG intend to provide SharkMAC with regular reports to facilitate the interaction necessary to achieve a satisfactory outcome.

What is a harvest strategy (in the context of the SSF)

At the most fundamental level, a harvest strategy is 'a set of rules', selected by SharkMAC (and the AFMA Board) that provide the annual *TAC*s for school and gummy shark. A harvest strategy is chosen so that it achieves a satisfactory balance among AFMA's legislative objectives. Harvest strategies can be very simple. For example, the *TAC* could be adjusted upwards or downwards based on recent trends in catch rate. However, they can also be very complicated. An example of a complicated harvest strategy is the current harvest strategy for school shark. This involves applying a complex and data intensive stock assessment model and then selecting a *TAC* such that it is estimated that the probability is 80% in 2011 that the mature biomass exceeds that in 1996.

The use of a harvest strategy to select annual *TAC*s provides an objective and transparent basis for the management of a fishery. As the harvest strategy is pre-agreed, all the stakeholders are aware of the procedure for changing the *TAC* given the data collected from the fishery. For some simple harvest strategies (e.g. those not based on an assessment model), the *TAC* can be calculated as part of a SharkMAC meeting. Alternatively, this would need to be accomplished by members of SharkFAG interssessionally. The likely performance of the harvest strategy is evaluated relative to AFMA's legislative objectives in the medium-term and so all stakeholders are aware of the likely medium-term consequences of using the harvest strategy, and this can form the basis for the selection of a harvest strategy.

The steps involved in the selection of a harvest strategy

There are four key steps to selecting a harvest strategy. All depend on SharkFAG and SharkMAC input to some extent, although some steps are the prime responsibility of one or the other body.

1) Selection of quantitative performance measures. It is necessary to have clear (and quantitative) performance measures to assess whether a particular harvest strategy performs acceptably. AFMA's legislative objectives provide some guidance in this regard but are insufficiently clearly specified. The fishery objectives are clearer but even they are not sufficient. For example, if the objective was 'to keep the

population above 40% of the virgin level' it is necessary to define 'population' (for example, mature or 1+ biomass), to state over what period this objective must be satisfied (for example, 5, 10, or 20 years) and to state an acceptable probability (for example, 50, 75 or 90%). The school shark harvest strategy is based on a fully specified management objective: 'that there be an 80% probability that the mature biomass in 2011 exceeds that in 1996'. The performance measures should not just be biological but should also include economic considerations. The ability to model the economics of the Southern Shark Fishery is lacking so the economic implications of a harvest strategy could be evaluated using proxies (average catch, 'discounted' catch and how variable catches are). Some members of SharkMAC have already expressed the view that lower, more stable, *TAC*s are preferable to higher, but more variable, *TAC*s. The task of selecting performance measures is complex and involves interaction between the SharkFAG and SharkMAC.

2) Identification of the biological (and economic) scenarios against which candidate harvest strategies should be tested. This is primarily a SharkFAG responsibility – the scenarios to be considered will be variants of those considered in recent assessments of school and gummy shark.
3) Identification of candidate harvest strategies. This is also primarily a SharkFAG responsibility and SharkFAG started the process of identifying a range of possible harvest strategies at its 6–7 September 2000 meeting. If SharkMAC members have ideas for harvest strategies, SharkFAG members will work with them to develop fully specified harvest strategies that could be tested.
4) Selection of a final harvest strategy. This is clearly a SharkMAC responsibility. The task of SharkFAG will be to develop approaches to assist SharkMAC understand the trade-offs achieved by different harvest strategies. For example, two harvest strategies may be equal in terms of risk but one may achieve higher but more variable catches. It is the responsibility of SharkFAG to develop tools to highlight such trade-offs clearly.

Issues about which the SharkFAG would like preliminary guidance

A harvest strategy can consist of a large number of components, and the work of SharkFAG and SharkMAC will be reduced substantially if the range of options for some of these can be reduced now:

a) How frequently should *TAC*s be updated (every year, every second year, every third year,…). SharkFAG already works on a two-year cycle for assessments, so the minimum frequency at which *TAC*s would be changed would therefore be once every second year. The *TAC* would be 'rolled over' if a formal assessment is not conducted (i.e. *TAC*s would be constant over the period between *TAC* updates giving industry some additional stability).
b) Should there be maximum and minimum *TAC*s for school and gummy shark? If so, what should the range for these be? Note that the minimum *TAC* would be overridden if the status of the stock was assessed to be so low that the minimum *TAC* would be biologically risky.
c) Should there be a maximum permissible change in *TAC* (e.g. no more than a 10% increase and a 20% decrease – unless the stock is assessed to be very overexploited)? Note that as *TAC*s would not be changed each year, there is an

interaction between the maximum permissible change in *TAC* and the frequency with which *TAC*s are updated (i.e. changing the *TAC* every year and allowing a 10% change each time the *TAC* is changed is equivalent to changing it every second year and allowing a 20% change)

d) Can SharkMAC provide SharkFAG with guidance on how it should begin to develop candidate performance measures (e.g. the time period to consider and perhaps the population component (mature biomass, total biomass) to concentrate on)?

4. BENEFITS

The benefits of this project will flow to the fishers in the expanded Southern Shark Fishery, the Great Australian Bight Trawl Fishery and the South East Trawl Fishery who hold quota for school and gummy shark. These benefits result from a better understanding of the likely trade-offs associated with alternative harvest strategies as well as the possible implications of the impact of changes in targeting practices and *TAC*s on the ability to permit the over-exploited school shark resource to recover.

The results confirm the value of conducting assessments using the methods currently employed by SharkFAG and the value of having a fishery-independent survey of abundance. Use of these methods and this data source should lead to an increased ability to satisfy the legislative management objectives for the Southern Shark Fishery.

5. FURTHER DEVELOPMENT

5.1 Gummy shark stock assessment

The gummy shark assessment represents a major advance when compared with previous assessments because it makes use of a broader range of data inputs, considers sensitivity to alternative hypotheses about the population dynamics, and because it attempts to estimate the relative strength of incoming year-classes. Nevertheless, there are several areas where additional modelling work / data analyses are needed.

a) Lack of data currently preclude conducting gummy shark assessments at finer spatial scales than by region. However, the results obtained when the EBas and WBas sub-regions are assessed separately suggest that there is probably population structure at fine spatial scales (e.g. annual recruitment differs by sub-region). Future data collection should aim at collecting representative data from all areas that may contain local populations of gummy shark.
b) The gummy shark assessment presented in this report attempts to account for the impact of availability. The estimates of availability as a function of length based on this assessment differ, however, from those obtained by Punt (2000) using survey data. An attempt should be made to re-examine the survey length-frequency data and / or include it in future assessments.
c) The length-frequency data include data for ‘aggregated’ and ‘background’ shots. Availability almost certainly differs between these two types of shots and it would be desirable to find a way to distinguish ‘aggregated’ from ‘background’ shots in the length-frequency data so that these two types of length-frequency data can be fitted separately.
d) The results are based on the assumption that the length-frequency and age-composition data are multinomially distributed about the model-predictions. Sensitivity to alternative assumptions should be considered.
e) Although the assessment makes use of more data than previous assessments, some data remain unused. In particular, future assessments should consider the use of the data from the length-frequency sampling programme related to the sex ratio of the catches (by gear-type and region).

5.2 Harvest strategy evaluation

The future work related to harvest strategy evaluation can be divided into that relating to the operating model, the alternative harvest strategies and communication with AFMA / SharkMAC.

5.2.1 The operating model

The operating model developed to conduct the evaluation of harvest strategies is spatial and explicitly considers hypotheses regarding the technical interaction between gummy and school shark. There are, however, some areas where the operating model should be extended / alternative hypotheses developed.

a) The approach for splitting future catches among sub-regions (see Section 3.3.2.1) is based on inferring what would happen once management based on *TAC*s is introduced into the fishery. Once sufficient data become available analyses should be conducted to refine this approach.

b) The estimates of initial tag-loss / tagging mortality are based roughly on the values obtained by Walker *et al*. (2000). SharkFAG have, however, expressed concern about those estimates. The data for gummy and school shark should be re-analysed with a view to reviewing the estimates. In addition, data for other (similar) species should be examined to place bounds on the likely rate of initial tag-loss / tagging mortality.
c) The analyses in this report are based on a range for the rate of movement of school sharks from New Zealand to Australia. Data are now available that could be used to estimate this rate (subject to a variety of assumptions) and such analyses formed part of the basis for the 2001 assessment of school shark (Punt and Pribac, 2001). Future evaluations of harvest strategies should include this information. Furthermore, the approach used to model the school shark population in New Zealand is relatively crude given an absence of detailed data related to the shark fishery in New Zealand. Attempts should therefore be made to conduct joint Australia-New Zealand assessments of school shark. A joint assessment process could also allow revisions to be made to the hypotheses related to how future *TAC*s in New Zealand will be set.
d) Analyses should be conducted to refine the approach used to constrain the relative gummy : school exploitation rates once sufficient data (from the fishery and from a soon-to-be-implemented fishery-independent survey programme) become available. These analyses should be assigned a very high priority as the results of the harvest strategy evaluation are highly sensitive to assumptions regarding future targeting practices.
e) Industry members of SharkFAG have highlighted the potential importance of past habitat degradation. Additional sensitivity tests based on a “simple” model of the impact of habitat degradation should be considered if some bounds can be placed on the parameters related to the possible impact of habitat degradation.

5.2.2 Alternative harvest strategies

The harvest strategies considered in this report are all based on setting a target exploitation rate. An alternative approach (suggested by SharkFAG members, but too late to be considered for this report) would be to select the *TAC* so that it is estimated to be consistent with a pre-specified management goal. The basic approach involves selecting a management goal that has to be achieved over the next twenty years, conducting population projections based on 100 parameter vectors generated from the variance-covariance matrix for a range of (constant) levels of *TAC*, and selecting that *TAC* level that satisfies the management goal. Possible management goals are:

a) That there be an x% chance that the pup production in 20 years exceeds the current pup production.
b) That there be an x% chance that the pup production does not fall below y% of that at which *MSY* is achieved over the next 20 years.
c) That there be an x% chance that the pup production does not fall below y% of B_0 over the next 20 years.

If the value for *x* is chosen to be larger than 50, these strategies are ‘explicitly precautionary’ in that greater uncertainty leads to lower *TAC*s.

5.2.3 Communication with SharkMAC and AFMA

The ultimate decision regarding harvest strategies for school and gummy shark is not scientific. Rather, it is a decision that needs to be made by AFMA who will be advised by SharkMAC and other relevant advisory bodies. There is therefore a need for SharkFAG to continue the process of informing SharkMAC and AFMA regarding progress related to harvest strategy evaluation and obtaining from them their desired properties for harvest strategies and their preference among the conflicting management objectives. Substantial progress was made in obtaining advice from SharkMAC during this project. However, SharkMAC’s focus on harvest strategies dropped recently because issues (e.g. future limitations on fishing effort) of more immediate consequence were discussed. It is important therefore that matters related to the selection of harvest strategies be included routinely on SharkMAC agendas.

Finally, the information produced from an evaluation of harvest strategies remains complicated and it is important that more attention is placed on developing methods to display the key information to groups such as SharkMAC.

6. CONCLUSIONS

Objective 1. To provide the information necessary for the development of an operational definition of ESD for gummy and school shark, in collaboration with SharkFAG, SharkMAC and AFMA.

- The Principal Investigator gave two formal presentations to SharkMAC regarding harvest strategy evaluation and requested information on performance measures (the operational definition of ESD) and on the desirable features of a harvest strategy.
- SharkMAC agreed that the operational definition for ESD for school and gummy shark will be based on the probability of being above the 1996 pup production (school shark) and the 1994 pup production (gummy shark). SharkMAC also highlighted the importance of taking due consideration of the size of the biomass available to the fishery (the fishable biomass).
- SharkMAC advised on minimum and maximum *TAC* levels and that stability of catches was preferable to higher but more variable catches.

Objective 2. To complete a spatially-structured stock assessment of gummy shark for use as the biological basis for an evaluation of harvest strategies for this species.

- A spatially-structured stock assessment of gummy shark which considered the population of gummy shark off South Australia and in Bass Strait was conducted. This assessment formed the basis for the 2000 assessment of gummy shark presented to SharkMAC.
- Qualitatively, the populations of gummy shark in Bass Strait and off South Australia are both estimated to be currently above the level at which *MSY* would be achieved, B_{MSY}, and recruitment to the fisheries in both areas is estimated to be stable.
- The assessment made use of a wider range of data (catch, catch-rate, length-frequency, age-composition and tagging data) than has been the case in the past. The assessment highlighted the potential for the length-frequency data to provide information about the size of year-classes,
- The assessment presented to SharkMAC was refined by including initial tag-loss / tagging mortality and by assuming that the key productivity related parameter (*MSYR*) was common to Bass Strait and South Australia. This refined assessment formed the basis for the evaluation of harvest strategies.

Objective 3. To provide SharkMAC and AFMA with an evaluation of the trade-offs associated with a range of harvest strategies for gummy and school shark.

- As expected, the results confirmed that the key aim for any harvest strategy is to achieve a reasonable probability of recovering the school shark resource without substantially impacting the catches of gummy shark.
- None of the harvest strategies considered in this report perform well at allowing the school shark resource to recover in the short term. This is partly because of the poor status of the resource and the relatively low productivity of school shark but also because of the technical interaction between gummy and school shark.

- If fishers are unable (or unwilling) to modify their targeting practices to avoid TAC-related discarding of school shark, it may be necessary to reduce the catches of gummy shark to lower levels than would be appropriate if gummy shark was the target of a single species fishery.
- The uncertainties that have the greatest impact on the performance of a harvest strategy are: the extent of TAC-related discarding, the inherent productivity of school and gummy shark, and the extent of initial tag-loss / tagging mortality.
- The approach of basing assessments (and harvest strategies) on assessment models that include gear-selectivity and the peculiarities of the pupping process and that use as much of the available data as possible should form the focus for final calculations regarding harvest strategies for school and gummy shark.

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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. Any intellectual property associated with this project will be shared 81 : 13 : 6 between the Fisheries Research and Development Corporation, CSIRO Marine Research, and the Australian Fisheries Management Authority.

APPENDIX B. STAFF

André E. Punt	Senior Research Scientist, CMR	20%
Fred Pribac	Analyst / Programmer, CMR	100%
Terence Walker	Program Manager, Modelling and Data Management, MAFRI	10%
Bruce Taylor	Fisheries Modeller and Data Manager	10%