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Harvest Strategy Evaluation for School and Gummy Shark

(Elasmobranch Fisheries – Oral)

by

Andre E. Punt, Fred Pribac

CSIRO Marine Research, GPO Box 1538, Hobart, TAS 7001, Australia

and

Bruce L. Taylor, Terence I Walker

Marine and Freshwater Research Institute, Department of Natural Resources and Environment
Box 114, Queenscliff, VIC 3225, Australia

Abstract

The Management Strategy Evaluation (MSE) approach is used to evaluate the benefits of alternative harvest strategies to set annual Total Allowable Catches *TAC*s for school shark, *Galeorhinus galeus*, and gummy shark, *Mustelus antarcticus*. The harvest strategies are based on a stock assessment method that includes the gear-types employed in the fishery and the peculiarities of the shark pupping process. The harvest strategies are evaluated in terms of performance measures that relate to average catches, catch variability and resource conservation. The uncertainties that impact performance to the largest extent are the technical interaction between fishing for school shark and for gummy shark, the productivity of the overexploited school shark resource, and the extent to which tagged animals lose tags (or die) immediately after tagging.

Keywords: Australia, gummy shark, harvest strategy, Monte Carlo simulation, school shark

Introduction

School shark, *Galeorhinus galeus*, and gummy shark, *Mustelus antarcticus* Günther, form the major part of Australia's Southern Shark Fishery. Since 1 January 2001, this fishery has been managed by the Australian Fisheries Management Authority (AFMA) using output controls implemented as Individual Transferable Quotas (ITQs). The main gear-types employed in this fishery are baited longlines and monofilament gill-nets (presently 6-inch and 6.5-inch mesh), although small amounts of school and gummy shark are also taken using bottom trawl and other gear-types (Walker, 1999). The fishery is therefore unusual in that most of the shark catch is a result of targeted fishing rather than being by-product in fisheries for other species.

There is wide-spread agreement in Australia (Smith *et al*., 1999; Punt *et al*., 2001a) and elsewhere (Butterworth *et al*., 1997) that the tactical decisions related to fisheries management (e.g. the setting of annual Total Allowable Catches, *TAC*s) should be based on pre-specified harvest strategies[1] while the decision makers should focus primarily on strategic issues such as the selection of operational management objectives and appropriate harvest strategies. A harvest strategy is a set of rules that defines the data to be collected from a fishery, how those data are

[1] The term 'harvest strategy' is used throughout this paper due, primarily, to its use in Australia. The terms 'decision rule' (e.g. Starr *et al*., 1997) and 'management procedure' (Butterworth and Punt, 1999) have been used elsewhere for the same concept.

to be analysed, and how the results of the data analyses are to be used to determine management actions. A key feature of the Management (or Harvest) Strategy Evaluation approach to fisheries management (Smith, 1994; Punt *et al*., 2001a; Butterworth *et al*., 1997) is that candidate harvest strategies are evaluated using computer simulation in terms of their ability to satisfy the objectives for management and their robustness to uncertainty. The use of harvest strategies is therefore consistent with the precautionary approach to fisheries management (FAO, 1995).

There are five legislative objectives for the fisheries managed by the Australian Commonwealth Government (Anon, 1998). Two of these objectives (Ecological Sustainable Development, ESD, and Economic Efficiency) relate directly to day-to-day management of fisheries. The second of these objectives is not considered explicitly in this study because it has been argued (Kaufmann *et al*., 1999) that it will be satisfied if, through quota trading, the fishery moves over time to a situation in which the catch is taken with a minimum of inputs – allowing quota shares to be transferable allows the most efficient operators to obtain the greatest shares of the *TAC*. The ESD objective is extremely broad and includes consideration of *inter alia* the impact of fishing gear on non-target as well as target species. In the context of this study, however, performance relative to this objective is restricted to issues related solely to school and gummy shark.

Selection of harvest strategies for a fishery requires not only technical input from scientists but also input from fishers on their likely reaction to changed management arrangements, and from the decision makers on their preferences for features to include in harvest strategies (such as minimum and maximum levels of *TAC*s and maximum percentage changes in *TAC*s). Management of fisheries in Australia involves broad participation at all levels by the key stakeholders (fishers, scientists, managers and members of conservation groups) (Smith *et al*., 1999). Several of the assumptions made during the development of the models that underlie the calculations of this paper were guided by the Southern Shark Fishery Assessment Group (SharkFAG) while issues of policy (e.g. guidelines on operational management objectives) were provided by the Shark Fishery Management Advisory Committee (SharkMAC) and AFMA.

This paper evaluates candidate harvest strategies for school and gummy sharks in terms of their performance relative to operational definitions for the ESD objective. The harvest strategies all involve two components. The estimator (or stock assessment method) is used to analyze 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. Only harvest strategies based on the age-structured production model (ASPM) approach to fisheries stock assessment (Punt, 1994; Walker, 1994a,b) are considered in this paper. This is because it will be impossible in the short- to medium-term to apply techniques such as Virtual Population Analysis and Integrated Analysis due to lack of ageing data for school and gummy shark, while harvest strategies based on simpler stock assessment methods (such as production models) perform more poorly than those based on the ASPM approach.

Materials and Methods

The conceptual basis and rationale for the approach used to evaluate the performances of alternative harvest strategies has been described elsewhere (e.g. Southward, 1968; Hilborn, 1979; Donovan, 1989; McAllister *et al*., 1999; Smith *et al*., 1999; Punt *et al*., 2001a). Briefly, there are five steps in identifying the advantages and disadvantages of different harvest strategies (Fig. 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.
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 study), the simulations involve the following four steps.
    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*.

5) Summary of the results of the simulations (100 simulations for each scenario) by means of the performance measures and presentation of the results to the decision makers.

The following sections outline how the management objectives have been quantified in this case, the details of the operating model, how future data are generated, and the alternative harvest strategies for the school and gummy shark fishery.

Performance measures

The following 15 performance measures were selected to evaluate candidate harvest strategies (each measure is computed separately for school and gummy shark unless indicated otherwise).

a) The lower 5th percentile of the distribution of the average annual catch during 2000–24.
b) The median of the distribution of the average annual catch during 2000–24.
c) The upper 95th percentile of the distribution of the average annual catch during 2000–24.
d) The median of the distribution for the average absolute variation in catch, AAV:

$$AAV = 100 \sum_{t=2000}^{2024} \left| C_t - C_{t-1} \right| / \sum_{t=2000}^{2024} C_t$$

where C_t is the catch during year *t*.

e) The median of the distribution for the number of pups produced (all stocks combined) at the end of the projection period as a fraction of the virgin level (abbreviation 'Med $P_{\rm fin}$').
f) The probability that the number of pups produced in 2024 exceeds that in 1996 (abbreviation $P(P_{2024} > P_{1996})$) (school shark only).
g) The median of the distribution of the ratio of the number of pups produced in 2024 relative to that in 1996 (abbreviation $med(P_{2024} / P_{1996})$) (school shark only).
h) The probability that the number of pups produced in 2024 exceeds the lower of 40% of the virgin level and the 1994 level (abbreviation $P_{2024} > \text{thresh}$) (gummy shark only).
i) The median of the distribution for the fraction of the total catch that is discarded.

These 15 performance measures capture the key aspects of catch (measures a) – c)), catch variability (statistic d)) and resource conservation (statistics e) – i)). The lower 5th percentile of the average catch distribution can be considered to reflect the 'guaranteed catch' while statistic i) can be considered to capture some of the broader ecosystem implications of the fishery management system. These measures were chosen based on comments from SharkMAC and AFMA, agreed management reference points for the fishery, and the performance measures used in previous evaluations of harvest strategies. The choice of the 1996 pup production for school shark and the 1994 pup production and 40% of the virgin level for gummy shark are based on agreed short- and long-term management objectives for the fishery (Walker *et al*., 1998).

The operating model

The operating model consists of a biological component and a fishery component. In the interests of brevity, the full technical details of the operating model are not provided here. Rather, the following sections overview some of the key features of the operating model; the interested reader can consult Punt *et al*. (2001b) for the full mathematical specifications for the operating model.

<u>The biological component of the operating model</u>

The specifications for the current status, productivity and population dynamics of school and gummy shark are based on the assessments undertaken by Punt *et al.* (2000) and Punt *et al.* (2001b) for school and gummy shark respectively. Each operating model therefore involves specifications for certain of its aspects (e.g. the value assumed for natural mortality) with the remaining parameters estimated by fitting the operating model to the actual data for school and gummy shark. The operating models consider a wider range of scenarios than would be implied by conventional stock assessments. Scenarios that are not strongly supported by the assessments (e.g. low and high values for the maximum sustainable yield rate, MSYR[2]) (see Table 1) are nevertheless examined when evaluating harvest strategies to better assess the robustness of candidate harvest strategies to uncertainty. One reason for doing this is due to the common problem of under-estimating the true extent of uncertainty when carrying out fishery stock assessments (Ludwig *et al*., 1993; Punt and Butterworth, 1993; Walters and Pearse, 1996; Punt and Kennedy, 1997). The school and gummy shark operating models are spatially-structured. The school shark operating model considers eight regions (Fig. 2) while the gummy shark operating model considers three regions (South Australia, Bass Strait and Tasmania). Separate stocks of gummy shark are assumed to be found in each of the three gummy shark regions while two stocks of school shark that mix are assumed to be found off southern Australia. Few data are available for the gummy shark population off Tasmania (Punt *et al*., 2001b; Pribac *et al*., in prep) so the values for the parameters for the gummy shark population off Tasmania are assumed to be the same as those for the gummy shark population in Bass Strait.

It is known from tagging data (e.g. Hurst *et al*., 1999) that school sharks in New Zealand waters move to Australia. The school shark model developed by Punt *et al.* (2000) 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 school shark 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 (time-independent)[3] movement rate from New Zealand to Australia, the depletion of the New Zealand population in 1997, 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 status of the two species at the start of the projection period (2000) differs substantially. For the base-case scenario, the gummy shark population is close to 55% of its virgin level while the school shark population is 11% of this level. These specific percentages are sensitive to the specifications of the operating model but the qualitative impression of a highly depleted school shark resource and a gummy shark resource close to (or possibly above) conventional target levels is robust.

<u>The fishery component of the operating model</u>

The harvest strategies provide *TAC*s for school and gummy shark 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 instead.

a) The split of the *TAC* to gear-type (within a region) is the same as it was in the last year for which actual data are available (1999).
b) The split of the *TAC* to region is determined by averaging the split to region for 1999 and the split which arises if the catch for Bass Strait (the historical center of the fishery) remains at its average level over the last five years (subject to being less than 95% of the *TAC*) and the catches off Tasmania, South Australia and New South Wales are scaled to 'take up the slack'. The splits to regions are further modified by adding log-normal error with a coefficient of 0.2.

[2] *MSYR* is the ratio of *MSY* to B_{MSY}.
[3] Sensitivity tests (not shown here) indicate that the results are robust to some non-linearity in the relationship between the movement rate from New Zealand to Australia and the depletion of the New Zealand population.

c) The maximum possible exploitation rate for gummy shark is based on the relationship between catch rate and abundance, which allows for gear competition (see Pribac *et al*. (in prep) for details) while the maximum possible exploitation rate for school shark is assumed (semi-arbitrarily) to be 0.95 (in the absence of evidence for gear-competition).

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%.

The discarding that results from mis-matches between the *TAC*s for the two species is modeled by assuming that fishers modify their fishing practices to attempt to fully satisfy their *TAC*s without over-catching (and hence discarding) either species. However, there are limits on the extent to which this is possible and, given some *TAC* mixes (in particular low school shark *TAC*s and high gummy shark *TAC*s) and the desire to fully catch the *TAC*s. Discarding is therefore inevitable even given the best intentions. The extent of discarding has been modeled by placing constraints on the ratio of the gummy to the school shark exploitation rate (by region). If the value for this ratio fails to satisfy these constraints when catches are set to the *TAC*s, the catch of one species is increased until the ratio of the exploitation rates falls within the pre-specified constraints. This formulation mimics fishers targeting the species that is not fully caught leading to discarding of the "constraining" species. The constraints on the ratio of the exploitation rates for the base-case trial are set to the extremes observed over the period 1994–97 (the "default" constraints) and sensitivity to alternative bounds (including no bounds whatsoever; i.e. perfect targeting by fishers) is examined during the tests of sensitivity.

Future data collection

The information that could be used by harvest strategies includes landed catches, catch rates, survey indices of relative abundance, length-frequency (by sex), age-composition (by sex), and tagging data (by sex). 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. 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 because there is currently no program to estimate discards. Also, no future tagging or age-composition data are generated by the operating model because there are no plans to collect these data on a regular basis in the future. The future catch-rate data are not used by the 'reference' harvest strategy considered in this study. When used, these data are assumed to be log-normally distributed about the model-predicted catch rate, with a non-linear relationship between catch-rate and abundance for gummy shark (Pribac *et al*., in prep). The data (catches, catch-rates, length-frequencies, etc.) for the years prior to the first application of the harvest strategy are taken to be the actual historical data.

The approach used to generate the survey estimates of relative abundance follows that used by Punt *et al*. (2001c), viz. 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 (Fig. 2) and two survey sites are assumed to be established in the EBas region (i.e. $N_1 = 7$). It is assumed that the survey provides an index of the component of the 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 undertaking 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 s_s and s_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:

$$I_t^{r,\mathrm{obs}} = \frac{1}{4N_1\ N_2}\sum_{z=1}^{N_1}\sum_{q=1}^{4}\sum_{s=1}^{N_2} I\left[\frac{k}{B^r_{1998}} B_t^r\ e^{e^r_{z,q,t} - s_A^2/2}\ e^{h^r_{z,q,s,t} - s_s^2/2}\right]$$

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 a pilot fixed-station survey took place),

$I[x]$ denotes the nearest integer to x,

k 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),

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

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

The survey index for year t is therefore defined as the (arithmetic) average survey catch rate over all stations sampled during year t. The impact of variation among stations in shot duration is ignored as this is minor (Prince *et. al*., 1999). Changes in biomass over the year are also ignored. Table 2 lists the base-case values assumed for N_2, s_A, and s_s. The values for s_s are based on an analysis of the data collected during the pilot survey (Prince *et al*., 1999). The value assumed for s_A is largely an educated guess. Sensitivity tests consider the implications of the actual values for these parameters differing from those assumed.

Length-frequency data are generated for only 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. The base-case length-frequency sample sizes (for gummy shark), 1000 (Bass Strait) and 850 (South Australia), were determined using the approach developed by McAllister and Ianelli (1997).

The harvest strategies

Setting of global (i.e. southern Australia-wide) *TAC*s for school and gummy shark involves several steps. These steps mimic the actual practice of setting *TAC*s for the Southern Shark Fishery. First stock assessments are conducted and initial *TAC*s determined. These initial *TAC*s are then modified to conform with rules on the maximum extent to which *TAC*s may change from one year to the next and then rounded to the nearest 100*t* (gummy shark) and 25*t* (school shark). After this, any carryover of (uncaught) quota from the previous year is added to the *TAC*. The following sections outline each of the steps in more detail.

Stock assessments are undertaken and initial *TAC*s calculated for only Bass Strait (WBas and EBas combined) and South Australia (WSA and CSA combined) for consistency with past practice and because there are insufficient data to obtain reliable assessments for the Tasmanian and NSW regions. The global (i.e. southern Australia-wide) initial *TAC*s for year t are then determined by multiplying the sum of the initial *TAC*s for Bass Strait and South Australia for year t by the ratio of the global catch for year t-1 to the catch for year t-1 for Bass Strait and South Australia.

The *TAC* based on the harvest strategy is only changed once every 3$^{\mathrm{rd}}$ year as suggested by SharkMAC. SharkMAC also requested that the *TAC* for year t be forced to lie within a pre-specified percentage (20%) of that for the previous year and that it also 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^{act}_{t+1}, is therefore determined from TAC^{act}_{t}, 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:

$$TAC^{\text{act}}_{t+1} = TAC_{t+1} + \min\left(TAC^{\text{act}}_{t} - C_t, 0.2\, TAC^{\text{act}}_{t}\right)$$

This equation assumes that the maximum possible carryover of *TAC* occurs. This assumption is based on the observation in Australia's 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, Biospherics Pty Ltd, pers. comm..).

There are several ways in which the ASPM method of stock assessment can be applied. The options considered in this study 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 so as to keep the computation time requirements of the calculations within feasible limits. The values for the pre-specified parameters of the assessment model (such as growth rates, the selectivity pattern of the gear, etc.) are set equal to the base-case trial values, 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). Given the results from an ASPM assessment, the initial *TAC* for year *t* is then computed using the formula:

$$TAC_t = \begin{cases} 0 & \text{if } B^{\text{cur}}_t < B^{\text{limit}} \\ F^{\text{targ}}\, B^{\text{cur}}_t & \text{if } B^{\text{cur}}_t > B^{\text{thresh}} \\ F^{\text{targ}}\, B^{\text{cur}}_t \left(B^{\text{cur}}_t / B^{\text{thresh}}\right) & \text{otherwise} \end{cases}$$

where TAC_t is the initial *TAC* for year *t*,
F^{targ} is the 'target' exploitation rate,
B^{limit} is the biomass below which the initial *TAC* is set equal to zero,
B^{thresh} is a threshold biomass below which the target exploitation rate is reduced linearly to zero, and
B^{cur}_t is an estimate of the biomass at the start of year *t*.

It is also possible to constrain the initial *TAC* to be less than the estimate of the Maximum Sustainable Yield, *MSY* (Butterworth, 1987). F^{targ} is taken to be $q_1\, MSYR$ and B^{thresh} is taken to be $q_2\, B_{MSY}$ for the purpose of this study. The values assumed for q_1 and q_2 can be selected to achieve different risk-reward trade-offs and to give greater (or lesser) emphasis to recovery from over-exploitation.

Results and Discussion

Selection of a minimum TAC level for school shark

A series of 25-year projections based on the base-case trial (Table 1) were undertaken (Table 3). The initial *TAC* from 2000 onwards for gummy shark in these projections was fixed at 1525*t* (the minimum suggested by SharkMAC) and the initial *TAC* from 2000 onwards for school shark was varied from 100 to 319*t*. Note that being initial (constant) *TACs*, they are subject to the rules regarding the maximum extent of change and carryover of uncaught quota. Results are shown in Table 3 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 quantity $P(P_{2024} > P_{1996})$), the median annual catch of school shark, $med(P_{2024} / P_{1996})$, and the fraction of the total catch of school shark that is discarded.

As expected, lower initial *TAC*s correspond to greater probabilities of exceeding the 1996 level in 2024. However, the extent of discarding due to mismatches between the school and gummy shark *TAC*s increases substantially as the level of initial *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. For example, for a 100*t* annual initial *TAC*, the value of $med(P_{2024} / P_{1996})$ is 189% when 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* initial *TAC* from the year 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* initial *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* given a 1999 catch of 450*t*.

None of the minimum *TAC* levels perform particularly well in terms of achieving stock recovery [i.e. a high value for $P(P_{2024} > P_{1996})$] because of the impact of discarding. Concentrating on the "20% restriction" column suggests that an initial *TAC* less than 150*t* has little benefit but that there are some benefits in terms of resource conservation of a 150*t* minimum initial *TAC* compared with a 200*t* minimum initial *TAC*. Therefore, the remaining calculations in this paper are based on a 150*t* minimum *TAC* for school shark.

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 paper includes the following specifications.

a) Only B_0 and *MSYR* are treated as estimable parameters when applying ASPM; the values for the remaining parameters are set to those 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 initial *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 initial *TAC* is set to zero if the expected number of pups is less than 5% of the virgin level.

Table 4 lists the values for the 15 performance measures for the base-case trial for nine variants of the 'reference' harvest strategy constructed by specifying the values of q_1 for school and gummy shark, and whether the initial *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 school and gummy shark: a) the default values, and b) none because it is assumed that fishing practices can be modified to avoid any TAC-related discarding (high-grading / additional damage-related discarding at 5% still occurs, however).

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 q_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 q_1 but substantially higher catches result when the initial *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 q_1 for school shark) is lower and if the initial *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 q_1 = 0.7 and 1 for school and gummy shark respectively while the initial *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. It also achieves a high probability of recovering the school shark resource to above the 1996 level if fishing practices can be modified to avoid TAC-related discarding.

Figure 3 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 Fig. 3 are identical). In contrast, the impact of 'gear competition' means that the *TAC*s for gummy shark are not fully taken so there is some carryover (see the right panels of Fig. 3). The level of discarding is small for gummy shark (Fig. 3 right panels) but this is not the case for school shark when constraints are placed on the relative exploitation rate because the total catch of school shark can substantially exceed the landed catch of this species (Fig. 3 upper left panel).

Sensitivity to the harvest strategy

Table 5 examines the performances of several additional variants of the 'reference' harvest strategy for the variant of the base-case trial in which the default constraints are placed on the relative gummy: school exploitation rates. Estimating the natural mortality rate, *M*, for gummy shark or the recruitment residuals for the last 10 years has virtually no 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 for gummy shark is only 38% (the lowest value in Table 5) 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.

Increasing the value of q_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 q_2=0.7. Decreasing q_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 q_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 (Fig. 3). In contrast, ' $P_{2024} > \text{thresh}$ ' is very sensitive to whether the extent of carryover is 10, 20 (base-case) or 30%. There is relatively little difference (20*t*) between the average annual catches for gummy shark for 10 and 20% carryover rates but ' $P_{2024} > \text{thresh}$ ' increases by 20% if the carryover is 10% rather than 20%.

Sensitivity to the form of the operating model

Table 6 examines the sensitivity of the results for gummy shark to changing the specifications related to the gummy shark component of the operating model. Results are not shown for the case in which selectivity is assumed to be uniform because this case provides a very poor fit to the data. Table 6 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 number of gummy shark pups 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 ('Constrained availability') and / or if density-dependence acts on pup survival rather than on the natural mortality rate of all animals ('Density-dependent pups'). The harvest strategy does 'learn' that productivity is over-estimated because average catches are lower for the 'Constrained availability' and 'Density-dependent pups' trials. The median average annual catches, median final depletion and '$P_{2024} > \text{thresh}$' all increase as *MSYR* is increased from 0.11 to 0.15 and then to 0.25 (Table 6). 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 '$P_{2024} > \text{thresh}$' all increase with the initial (2000) depletion of the resource, although whether this is due to the impact of initial depletion or *MSYR* (which is correlated with initial depletion) is unclear. The results for the operating model based on the alternative catch series (which is based on hypotheses regarding the extent of historical under-reporting of catches) and (particularly) when the length-frequency data for 7-inch mesh gear when estimating the parameters of the operating model are ignored are more pessimistic than those for the base-case operating model. Ignoring the possibility of initial tag-loss / tagging mortality (i.e. setting the fraction of tagged animals that die or lose tags immediately after being tagged to zero when estimating the parameters of the operating model) leads to more optimistic results, presumably because the initial depletion is estimated to be larger when initial tag-loss / tagging mortality is ignored.

Table 7 and Fig. 4 examine the sensitivity of the results for school shark to changing the specifications related to the school shark component of the operating model. The most important sensitivity is to the value assumed for initial tag-loss / tagging mortality. Reducing initial tag-loss / tagging mortality 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 an alternative series of catches that attempts to account for historical under-reporting. 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. However, this is more than compensated for by a larger estimated 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 the value assumed for *MSYR* (Fig. 4). For *MSYR* values < 4% ("no constraints") and < 6% ("with constraints"), there is a better than even chance that the number of pups in 2024 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* (Fig. 4).

The sensitivity of the results for school shark to a range of assumptions regarding the constraints placed on the relative gummy : school exploitation rate is examined in Fig. 5. The options "Alt-1" and "Alt-2" in Fig. 5 are intermediate between the “default” constraints and ignoring any TAC-related discarding and involve linearly interpolating the exploitation rates constraints between the default value and none. The option “No discarding” in Fig. 5 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.

Sensitivity to the data used when setting TACs

Table 8 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 number of gummy shark pups 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 (N_2); catches of gummy shark are, however, slightly higher if the sample sizes are doubled for the “default 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 8). 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, the distribution of average annual gummy shark catches is wider than for the base-case when the harvest strategy uses only CPUE data. For the “default constraints” case, this leads to a lower probability of gummy shark being above the lower of 40% of the virgin level and the 1994 level in 2024.

General discussion

Ultimately, any harvest strategy for school and gummy shark should promote the recovery of the school shark resource without impacting substantially on the catches of gummy shark. The ‘reference’ harvest strategy examined in Tables 5 – 8 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 paper. Any final decision regarding a harvest strategy will be made by AFMA based on advice from SharkMAC and other relevant advisory bodies.

One outcome from an evaluation of harvest strategies is that the uncertainties that most impact the ability to satisfy the management objectives are identified. In principle, this could be used to prioritize future management-related research (Butterworth and Punt, 1999). 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 school and gummy shark highlight that there are only a few key uncertainties to which candidate harvest strategies are particularly sensitive. For the Southern Shark Fishery these are:

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. Fig. 5). For example, 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. Taylor (pers. obs.)).
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 parameter that determines productivity, *MSYR*, this is the key uncertainty once an assumption regarding the extent of future TAC-related discarding is made (Fig. 4, Tables 6 and 7).
c) The extent of initial tag-loss / tagging mortality. This factor 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 6 and 7).

The result that the performances of harvest strategies are highly sensitive to the extent of (technical) interaction between school and gummy shark is perhaps intuitive. Nevertheless, shark species are commonly by-catch or by-product species. The results presented in this paper indicate that ignoring technical interactions may severely over-estimate the ability to recover species that are not major target species. Unfortunately, apart from a few notable exceptions (anchovy and pilchard off South Africa (e.g. Cochrane *et al*., 1998; Geromont *et al*., 1999) and species in Australia's South East Fishery (e.g. Punt *et al*., 2002)) evaluations of harvest strategies have ignored technical interactions.

None of the harvest strategies considered in this paper performed 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 school and gummy 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.

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TABLE 1. The factors and levels considered in the biological component of the operating models (see Punt *et al*. (2001b) for the full technical details of these 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%
Initial 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}	$0.08yr^{-1}$, $\mathbf{0.1yr^{-1}}$
Historical catches	**Base-case**, alternative
Tagging contribution to the likelihood	**Base-case**, halved
Depletion of the New Zealand stock	50%, **75%**, 100%
Initial tag loss fraction	**20%**, 0, 40%

TABLE 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, S_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, S_s	**1.132**	**0.849**
Additional variance, S_A	**0.2**, 0.4	**0.2**, 0.4
Length frequency sample size		
Bass Strait	**0**	0, **1000**
South Australia	**0**	0, **850**

TABLE 3. The probability of the number of school shark pups exceeding the 1996 level in 2024, the median annual catch of school shark during 2000–24, the median of the ratio of the number of pups in 2024 to that in 1996, and the percentage of the catch during 2000–24 that is discarded. Results are shown for a series of harvest strategies that pre-specify the annual (initial) *TACs*. The initial *TAC* for gummy shark is 1525*t* for all of the analyses in this Table.

	Restrictions on annual reductions in *TAC*			
	None	None (no discarding)	20%	50%
$P(P_{2024} > P_{1996})$				
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
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
$med(P_{2024} / P_{1996})$				
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
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

TABLE 4. 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
(b)

Harvest strategy variant			School shark performance measures								Gummy shark performance measures						
Bound by *MSY*	q_1 Sch	q_1 Gum	Med P_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob $P_{2024} > P_{1996}$	Med P_{2024}/P_{1996}	Med P_{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*	q_1 Sch	q_1 Gum	Med P_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob $P_{2024} > P_{1996}$	Med P_{2024}/P_{1996}	Med P_{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 5. Performance measures for school and gummy shark for the variant of the base-case trial in which the default constraints are placed on the relative gummy : school exploitation rates 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 P_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob $P_{2024} > P_{1996}$	Med P_{2024}/P_{1996}	Med P_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob P_{2024}> thresh
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
q_2 = 0.1	9	169	183	201	33	8	1	73	42	1633	1788	1941	1	6	61
q_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

TABLE 6. Sensitivity of the performance measures for gummy shark 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	Constraints on the relative gummy : school shark exploitation rate													
	Default							None						
	Med P_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob P_{2024}> thresh	Med P_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob P_{2024}> thresh
Base-case	**42**	**1633**	**1788**	**1941**	**1**	**6**	**61**	**42**	**1633**	**1785**	**1941**	**1**	**6**	**65**
Constrained availability	27	1394	1614	1809	1	6	2	27	1394	1615	218	1	6	2
Density-dependent pups	26	1358	1578	1792	1	6	2	26	1358	1577	1792	1	6	2
MSYR = 0.11	27	1347	1489	1642	1	6	0	27	1347	1489	1642	1	6	0
MSYR = 0.15	38	1601	1714	1854	1	6	29	38	1601	1713	1839	1	6	31
MSYR = 0.25	56	1131	1934	2006	2	6	100	57	1128	1934	1998	2	6	100
Initial depletion = 0.5	33	1565	1671	1744	1	5	3	33	1566	1665	1744	1	5	3
Initial depletion = 0.6	50	1813	1882	1941	1	6	100	51	1812	1880	1935	1	6	100
Initial depletion = 0.7	62	1917	1968	2029	2	7	100	63	1911	1962	2021	2	7	100
Initial depletion = 0.8	75	1927	1976	2041	2	7	100	75	1920	1971	2035	2	7	100
Ignore 7-inch mesh data	31	1354	1576	1798	1	6	8	31	1354	1572	1798	1	6	8
Alternative catches	38	1397	1754	1936	1	5	42	39	1397	1751	1936	1	5	44
No initial tag-loss	42	1681	1814	1957	1	5	70	42	1681	1812	1957	1	5	70

TABLE 7. Sensitivity of the performance measures for school shark 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.

Operating model	Constraints on the relative gummy : school shark exploitation rate															
	Default								None							
	Med P_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob $P_{2024} > P_{1996}$	Med P_{2024}/P_{1996}	Med P_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob $P_{2024} > P_{1996}$	Med P_{2024}/P_{1996}
	No New Zealand movement															
Base-case	**9**	**165**	**177**	**195**	**35**	**8**	**2**	**74**	**14**	**182**	**197**	**218**	**5**	**9**	**99**	**117**
No initial tag-loss	15	165	186	210	46	9	46	99	22	203	234	275	5	10	100	145
Initial tag-loss = 0.6	3	161	174	185	17	10	0	31	5	174	180	195	5	9	0	55
M_{adult} = 0.08yr^{-1}	12	171	186	210	42	9	10	90	19	202	223	263	5	10	100	139
Halve tag contribution	11	168	183	204	41	8	6	88	17	197	221	258	5	10	100	135
Alternative catches	9	165	177	195	40	8	2	81	14	195	211	237	5	10	100	132
	With New Zealand movement															
NZ depletion = 0.75	6	165	171	180	27	8	0	55	10	168	177	189	5	8	0	87
NZ depletion = 1	7	165	180	198	41	8	1	63	11	180	202	224	5	10	39	99
NZ depletion = 0.5	2	143	156	165	15	12	0	19	3	166	171	173	5	10	0	33
NZ movemnt rate = 2%	7	165	174	189	30	8	0	60	11	174	180	195	5	8	13	96
NZ movemnt rate = 7%	6	165	168	180	27	7	0	54	9	165	177	180	5	8	0	86
NZ movemnt rate = 10%	5	165	168	180	24	8	0	49	8	165	174	180	5	7	0	77

TABLE 8. 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 P_{fin}	5% Catch	Med Catch	95% Catch	Med Disc	Med AAV	Prob $P_{2024} > P_{1996}$	Med P_{2024}/P_{1996}	Med P_{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

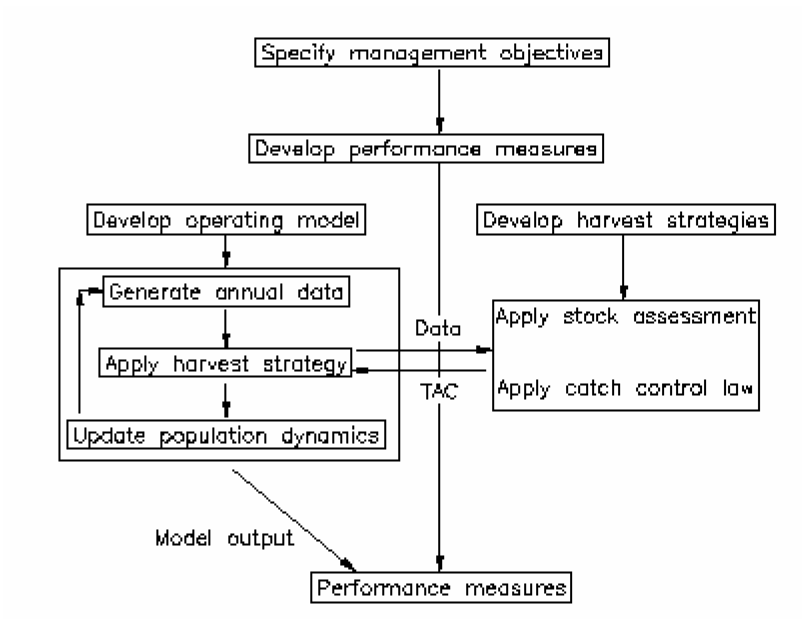

Fig. 1. Outline of the MSE approach.

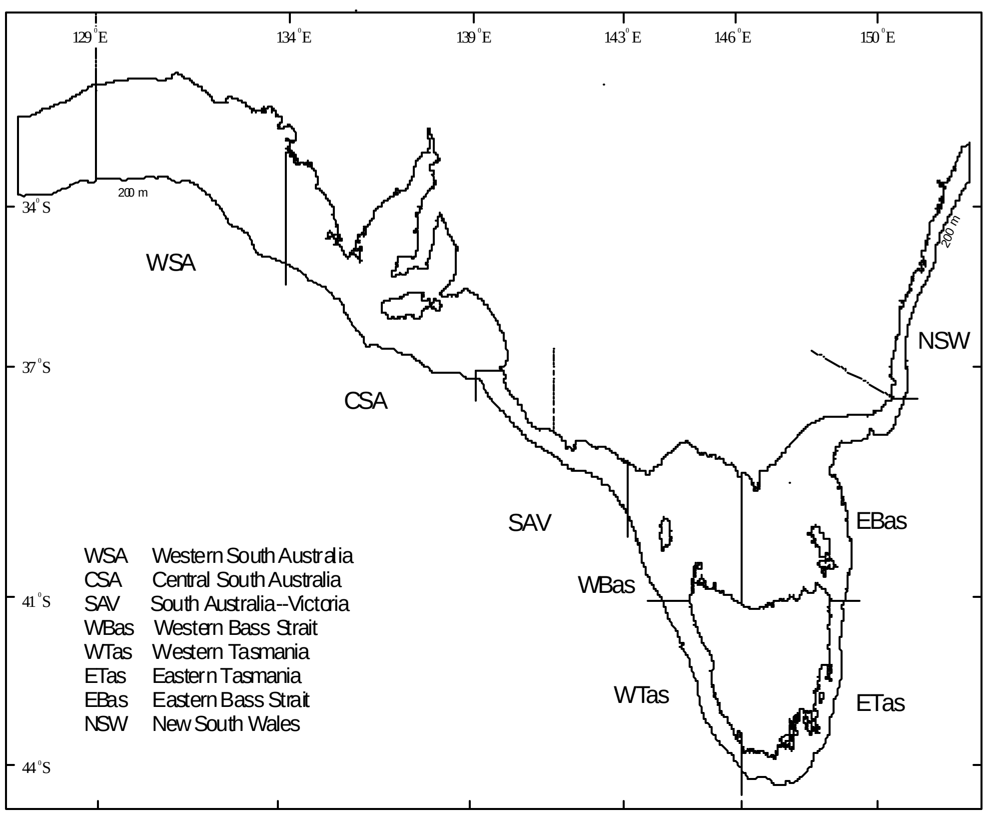

Fig. 2. Map of southern Australia showing the eight regions considered for school shark.

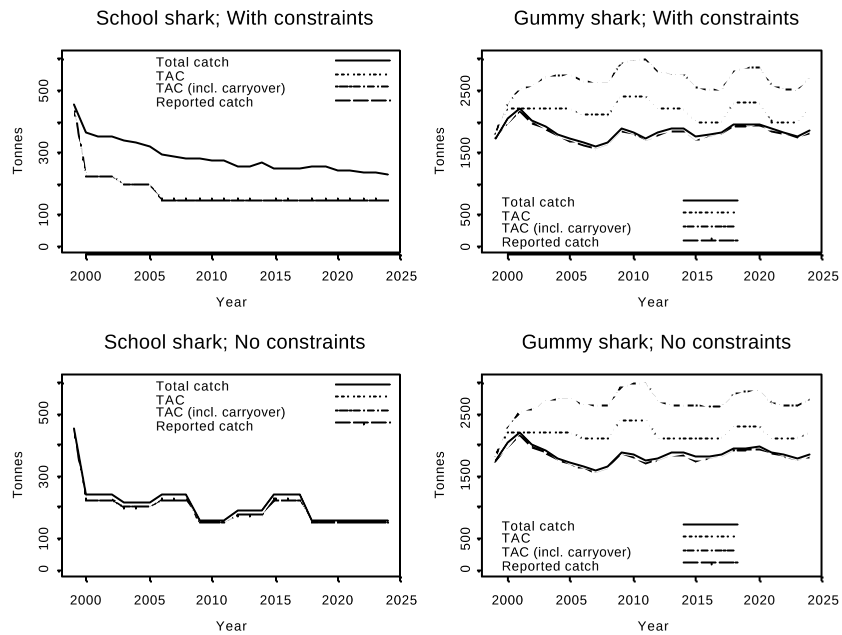

Fig. 3. Time-trajectories of the *TAC* set by the harvest strategy (the initial *TAC* modified by the constraints on the extent of change in *TAC* and rounding), the actual *TAC* allocated (accounts for any carryover), the total catch removed from the population and the catch reported for use in stock assessments (which differs from the total catch due to (un-reported) discards).

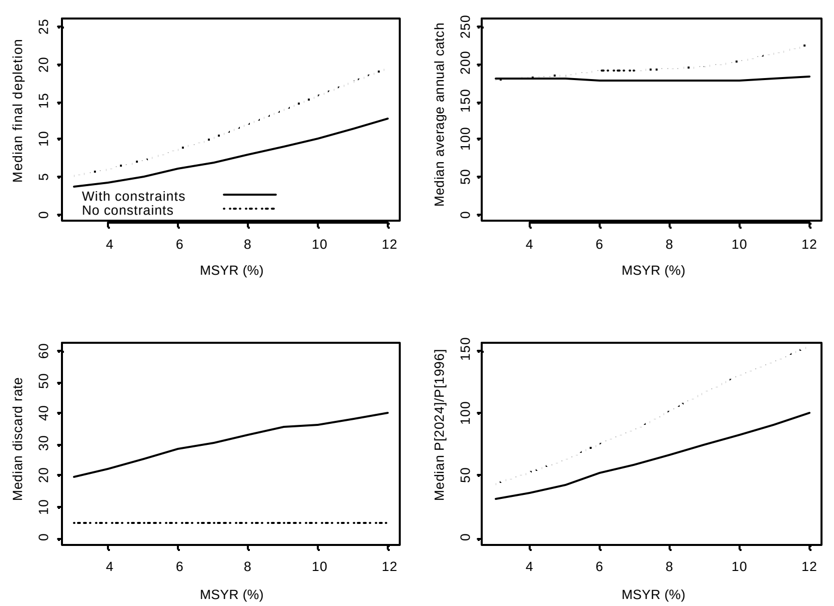

Fig. 4. For school shark, median final depletion, median average annual catch, median discard rate and the median of the ratio of P_{2024} to P_{1996} as a function of the value assumed for *MSYR* for school shark. Results are shown for the default constraints on the relative school : gummy exploitation rate and for no constraints on this relative exploitation rate.

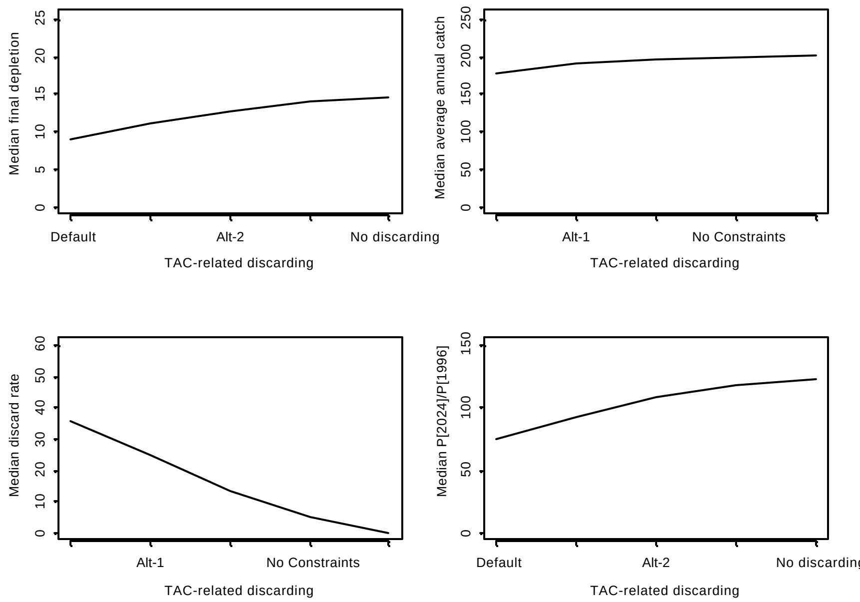

Fig. 5. For school shark, median final depletion, median average annual catch, median discard rate and the median of the ratio of P_{2024} to P_{1996} as a function of assumptions regarding the constraints placed on the relative gummy: school exploitation rate.