

## Harvest strategy evaluation for the eastern stock of gemfish (*Rexea solandri*)

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The eastern stock of gemfish in south-eastern Australia is currently assessed to be overfished and to be depleted below the performance criterion established by the Australian Fisheries Management Authority (AFMA). Assessments of the stock indicate that there was a substantial decline in abundance during the late 1970s and early 1980s and that the year classes spawned at the end of the 1980s were much weaker than expected from the (estimated) stock–recruitment relationship. The performances of a variety of alternative management procedures are contrasted. The factors considered in the operating models include uncertainty about historical catches, the comparability of recent survey estimates, the form of the stock–recruitment relationship, whether variations in recruitment about the stock–recruitment relationship are auto-correlated, and the quantity and quality of the data available for assessment purposes. The management procedures differ in terms of their data needs (survey data only, survey and age-composition data) and their target levels. The results indicate that, even though yields from the fishery are likely to be low, the benefits of conducting annual surveys exceed the costs. The value of collecting age-composition data is less clear. Management procedures based on Virtual Population Analysis achieve more variable catches and are less likely to satisfy AFMA performance criteria than management procedures based on a Schaefer production model, but they achieve higher levels of “guaranteed” catch for the industry.

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### Introduction

The fishery for the eastern stock of gemfish (*Rexea solandri*) is part of the multi-species South-East Fishery, and is managed by the Australian Fisheries Management Authority (AFMA). The stock is harvested by a variety of gears. The bulk of the historical catch has been taken using bottom trawl gear on the upper continental slope in depths ranging from 300 to 500 m, although, in recent years, a sizeable fraction of the catch has been taken using dropline. Traditionally, most of the catch has been taken during the winter spawning run when gemfish migrate from waters off Tasmania to southern Queensland (Rowling, 1990). The fishery commenced in the late 1960s as open access. Quota management was introduced in 1988, initially as a competitive quota, and subsequently based on Individual Transferable Quotas (Rowling, 1990). The first assessments of

the resource were made during the late 1980s on the basis of Virtual Population Analysis (VPA) (e.g. Allen, 1989) and on trends in standardized catch rates (e.g. Rowling, 1990). These and subsequent assessments indicated that the biomass had been reduced substantially by fishing during the late 1970s/early 1980s and that a series of weak year classes had been spawned in the late 1980s. A total allowable catch (TAC) for the trawl sector of zero was set in 1993 and maintained until 1996 when assessments (Punt, 1996, 1997a; Smith and Punt, 1998) indicated that a relatively strong year class had entered the population. AFMA set as a criterion for reopening the gemfish fishery that there be a greater than 50% chance that the current biomass (of 5<sup>+</sup> males and 6<sup>+</sup> females) exceeds 40% of the corresponding biomass in 1979. Although a zero TAC for the trawl sector was set from 1993 to 1996, catches were not zero over these years. This is because trip limits were set for trawlers and

because some sectors (e.g. dropliners off New South Wales) are not included in the TAC system.

Decisions regarding the management of those fisheries managed by the Australian Federal Government are ultimately made by the AFMA Board, who are advised by a relevant Management Advisory Committee (MAC). MACs comprise the manager of the fishery, a research member, a member representing the State governments, industry members and, in many instances, a conservation member. For gemfish, the advisory committee is the South-East Trawl MAC. Assessments and management recommendations for eastern gemfish have been highly contentious, with industry disagreeing with the results from the VPA. For this reason, a subcommittee, the Eastern Gemfish Assessment Group (EGAG) was established in early 1996. EGAG comprises fishery managers, industry (catching and processing sectors), scientists (government and independent), an economist, and a conservation member. EGAG's principle objectives are to undertake stock assessments, to evaluate future harvest regimes, and to set research priorities.

A trawl survey, designed to provide a catch rate comparable with those prior to the closure of the fishery, was undertaken in winter 1996. The results indicated some recovery and confirmed early indications in the length–frequency of by-catch that a strong cohort had entered the population. EGAG adopted an assessment approach based on maximum likelihood and Bayesian methods (Smith and Punt, 1998). Industry and management members of EGAG, together with the scientific members, have played a critical role in the assessment process through review of data, identification of key assumptions and uncertainties, and in constructing prior distributions for the parameters of the Bayesian assessment. The assessment is conducted using an age- and sex-structured population dynamics model. The values for the parameters of that model not determined from auxiliary information are obtained using data on catch rates, the fraction of females in the winter fishery catches and information about the age composition and length frequency of the catches (Smith and Punt, 1998).

For 1997 a TAC of 1200 t was recommended. This TAC was selected so that if the fishery had to be closed again in 1998 (resulting in an incidental kill expected at that time to be approximately 500 t annually), the population was estimated to continue to satisfy AFMA's criterion. However, the 1997 fishing season was poor and the total trawl catch was only 346 t (Punt *et al.*, 1997). It is unclear whether the reason for the poor season was because the biomass was substantially smaller than estimated during the March 1997 assessment or because of adverse environmental factors (or a combination of both). Using the same strategy as used to set the 1997 TAC, the 1998 TAC for targeted fishing was set at zero. A 500-t kill was expected to result from

a zero TAC given the multi-species nature of the fishery. A total of 400 t of the 500 t was “allocated” to fishers to assist them to manage their by-catch of eastern gemfish and the remaining 100 t was set aside for a further survey during the 1998 winter fishery.

There is a need to develop a long-term management procedure for the eastern stock of gemfish (defined here to be a combination of the rules that define the data to be collected and the rules that specify how those data are to be used to provide a TAC recommendation). The same approach was used to set the 1997 and 1998 TACs. However, this approach has not been evaluated formally and, being similar to a fixed escapement strategy, should seem likely to result in very high levels of interannual variation in catch. Such variation would seem undesirable from the viewpoint of industry stability. An important reason for formally considering the benefits of alternative management procedures is that the research costs associated with eastern gemfish are currently very high relative to the value of the fishery. Surveys were conducted in 1996, 1997, and 1998 (time constraints precluded inclusion in this paper of the results from the 1998 survey and other data from the 1998 fishing season). Although the costs of the surveys are offset to some extent by the value of the catch, running them annually means that other important research projects cannot be funded. It is crucial therefore to assess the trade-off between survey frequency (and hence cost) and performance in terms of satisfying AFMA's objective of Ecologically Sustainable Development.

## Methods

The methods for formally comparing alternative management procedures and for evaluating the benefits of research are described elsewhere (e.g. Hilborn, 1979; Fournier and Warburton, 1989; Punt, 1992; McDonald and Smith, 1997; McDonald *et al.*, 1997; Cooke, 1999), so they will not be described in detail here. The results reported are based on 100 simulations for each trial scenario.

### The operating model

The model used to describe the dynamics of the resource (the “operating model”, Appendix A) is age- and sex-structured and takes account of a summer and a winter fishery in each year. Smith and Punt (1998) document the values for the parameters determined from auxiliary information and the scheme used to estimate the values for the free parameters of the operating model (i.e. how the simulation trials are “conditioned”).

The assessments of eastern gemfish conducted by EGAG are based on identifying a set of key uncertainties and a set of “plausible hypotheses” related

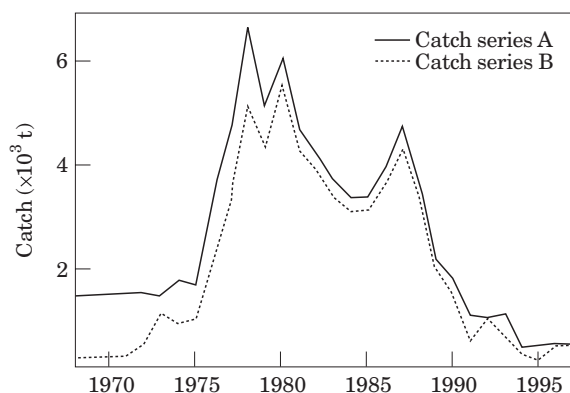


Figure 1. The two series of historical catches for the eastern stock of gemfish ("A" and "B").

to each uncertainty. The major sources of uncertainty for eastern gemfish are as follows.

- The series of historical (1968–1997) catches (either series A or series B, Fig. 1). Series B reflects recorded catches only, whereas series A makes some allowance for under-reporting of catches and discarding. There is disagreement in EGAG regarding the relative merits of these two series of catches, although it is agreed that they span the plausible range adequately.
- Whether the abundance index for 1996, that for 1997, or perhaps both, are representative of abundance. The (optimistic) 1996 index was based on a survey with considerable support from industry, whereas the (pessimistic) 1997 index occurred during one of the warmest years on record. The uncertainty regarding the comparability of the catch rate for 1996 with those for the period 1973–1991 is not explicitly considered in the operating models, because it is reflected adequately by the other hypotheses.
- Whether the deviations about the stock–recruitment relationship are correlated ( $\tau$  – see Equation A.4 = 0.7), or uncorrelated ( $\tau=0$ ). The choice  $\tau=0.7$  is based on the results of fits to the data in which the extent of correlation among the recruitment residuals is treated as a free parameter.
- Whether selectivity changes as a function of abundance (see Equations A.5 and A.6).
- The form of the stock–recruitment relationship: Beverton–Holt, Ricker “depensatory” and “regime-shift” (see Section A.2 of Appendix A).

This range of uncertainties/hypotheses gives rise to a total of 64 possible simulation trials (based on selecting from two options for each of the first four uncertainties and from four options for the last uncertainty).

Density-dependence in selectivity (equivalent in the model to density-dependence in maturity) is considered because smaller/younger fish have been observed in the spawning run since the severe reduction in biomass. Fits

to the data allowing for density-dependent selectivity are statistically superior to those that assume density-independent selectivity. Helser and Brodziak (1998) note for *Merluccius bilinearis* that allowing for density-dependent maturity in projections affects the estimated risk associated with different target levels of fishing mortality. The depensatory stock–recruitment relationship allows for the possibility that recruitment drops off faster than expected from the more conventional relationships, while the “regime shift” relationship involves assuming that the virgin biomass (carrying capacity) of eastern gemfish changed in 1987. This relationship and the depensatory relationship are considered because the Ricker and Beverton–Holt relationships are unable to mimic changes in estimated numbers of births particularly well.

The operating model is used to generate future catch, catch rate, and catch-at-age data (see Section A.4 of Appendix A). The base-case values assumed for the parameters that determine the extent of observational error ( $\sigma_q$ ,  $\sigma_c^s$  and  $\sigma_c^w$ ; Equations A.8, A.11, and A.12) are taken to be 0.15, 0.17, and 0.1, respectively. The values for these parameters are based on fits to the actual data. Sensitivity is explored into increasing the values for  $\sigma_q$ ,  $\sigma_c^s$  and  $\sigma_c^w$ . The first year in which the management procedure is used to calculate the TAC is 1999. The TAC is assumed to include both targeted fishing and by-catch. The current assessment only goes as far as the start of 1998, but the targeted TAC for 1998 has already been set at 0, which leads to a TAC for purposes of this paper of 500 t. TACs are assumed to be taken exactly.

All of the analyses are based on the assumption that the catch rates from the surveys are related linearly to abundance. This assumption is clearly subject to considerable uncertainty (e.g. Walters and Ludwig, 1994). However, such a source of uncertainty is not considered because fits of the model assuming alternative relationships (e.g. that catch rate is proportional to the square root of abundance) lead to notably poorer fits.

The simulations start from the “best” (i.e. posterior modal) estimates of the parameters conditioned on specific hypotheses about the five key uncertainties. This is primarily for computational ease, but it also implies that the simulations for a given operating model all start from the same biomass at the start of 1998. Differences in future biomasses are therefore a consequence of stochastic fluctuations in recruitment and the behaviour of the management procedure. They cannot be attributed to differences in the values for the model parameters.

### Management procedures

The “raw” catch limits produced by the management procedures considered can be highly variable inter-annually, so constraints have to be placed on the extent

of change in TAC from one year to the next. The TAC is constrained to lie between 250 and 2000 t and is also not permitted to vary up by more than 50% or down by more than 25% from one year to the next. The lower limit for the TAC has been chosen as 250 t because some by-catch will be taken even if the targeted trawl fishery is closed.

The management procedures are based on production model and VPA estimators. The production-model management procedures are based on fitting a Schaefer production model to the catch and catch rate data. They assume that all of the error between the model and the data is due to observational error (Butterworth and Andrew, 1984; Punt, 1994). The “raw” catch limits from these management procedures are based on variants of the  $f_{0,n}$  strategy (Punt, 1994) which involve setting future fishing effort to  $\phi E_{MSY}$ , where  $\phi = 0.1, 0.2, \dots, 0.5, \dots, 2$ .

Two types of management procedure, based on *ad hoc* tuned VPA, that use age composition and catch-rate data are considered (Appendix B). One bases catch limits (and hence TACs) on the “best estimates” of the model parameters, whereas the other determines those from some percentile of a distribution designed to reflect the uncertainty associated with the parameter estimates. The form of the model underlying the VPA is similar to that underlying the operating model and it assumes perfect information about mass-at-age. Therefore, given data with no measurement error, the VPA would yield the correct values for the model parameters. The VPA estimators are used to estimate the numbers-at-age from 1973 and the values for the parameters of the (Beverton–Holt) stock–recruitment relationship. The catches for the years 1973–1997 are taken to be historical series A (irrespective of the “true” catch series underlying the operating model). This choice is made here because the performance of a management procedure is not notably sensitive to the choice of catch series (Punt and Smith, 1998).

Two types of harvest strategy are considered in conjunction with the VPA estimators. The first type involves the  $F_{0,n}$  strategy, a strategy based on fixing future fishing effort at the level at which the slope of the yield versus exploitation rate curve is 0.n of that at the origin (Smith *et al.*, 1996). This strategy therefore takes both yield-per-recruit and stock–recruitment effects into account. For  $n=0$ , this strategy corresponds to selecting catches in order to move the resource towards a  $B_{MSY}$  target level of biomass. The other type of strategy is based on that used by the SETMAC TAC Sub-committee when it recommended TACs for the eastern stock of gemfish for 1997 and 1998 (Appendix C). Fixed escapement strategies are not considered because management procedures based on these strategies have been shown to produce appreciably higher interannual variation in catches without notable improvements in terms

of resource conservation and total catches (e.g. Butterworth and Bergh, 1993; Smith *et al.*, 1996; Punt and Smith, 1998).

## Performance measures

The performance measures considered in this study attempt to quantify performance relative to conservation- and utilization-related management objectives:

- the median and 90% limits for the average catch over the 20-year (1998–2017) projection period
- the median and 90% limits for interannual variation in catches, AAV, defined as the average absolute change in catch divided by the average total catch, and expressed as a percentage
- the median and 90% limits for the size of the winter biomass (see Equation A.9) at the end of the projection period, expressed as a percentage of the virgin biomass  $B_0$
- the lower 5th, 25th, and 50th percentiles of the lowest size that the winter biomass drops to over the projection period expressed as a percentage of  $B_0$
- the probability that the winter biomass does not drop below  $0.2B_0$  some time during the projection period
- the probability that the winter biomass at the end of the projection period exceeds the biomass at which MSY is achieved,  $B_{MSY}$
- the probability that the  $5^+/6^+$  biomass at the end of the projection period exceeds the 1979 level – the “AFMA criterion” corresponds to this probability exceeding 0.5.

These performance measures are typical of those used in previous evaluations of alternative management procedures (e.g. Bergh and Butterworth, 1987; Donovan, 1989; Butterworth and Bergh, 1993; Punt, 1995, 1997b; Francis and Shotton, 1997), but some are specific to the eastern stock of gemfish.

## Results and discussion

### Trade-off among management procedures

It is not feasible for the purposes of initial procedure selection to consider all 64 trials. Instead of selecting a “base-case” set of specifications and considering a set of sensitivity tests as is common when evaluating management procedures (e.g. De Oliveira *et al.*, 1998), four trials based on each of the five factors (stock–recruitment relationship, true catch series, true catch rate series, an assumption related to  $\tau$ , and an assumption regarding density dependence of selectivity) were selected (Table 1). The four trials are based on the assumption  $\tau=0.7$  and were selected so that the levels for



Table 1. Specifications for the four trials considered for initial screening of management procedures. All trials are based on the assumption  $\tau=0.7$ .

Trial	Catch series	Stock-recruitment relationship	Density-dependent selectivity	Use 1997 catch rate
1	A	Beverton-Holt	Yes	Yes
2	B	Ricker	Yes	No
3	A	Depensatory	No	No
4	B	Regime shift	No	Yes

each of the other four factors are included in the four trials. The specific combinations were chosen using the results of preliminary analyses that showed that these four trials captured both high (trial 3) and low (trials 1 and 4) productivity scenarios. The trials are based on the choice  $\tau=0.7$  only because Punt (1997b) found that ignoring the consequences of autocorrelation in the recruitment anomalies can lead to overly optimistic appraisals of the ability of management procedures to achieve conservation objectives.

Figures 2 and 3 show the trade-off between median final depletion and median average catch and between median final depletion and median AAV for a variety of management procedures. Each symbol in Figures 2 and 3 represents the trade-off achieved by a particular management procedure. These figures therefore provide information on the trade-offs among different classes of management procedure and among variants within each class. They also provide information on the trade-off among trial scenarios. Results are shown in Figure 2 for management procedures based on the Schaefer production model and the non-bootstrap *ad hoc* tuned VPA, and in Figure 3 for the “bootstrap variants” of the VPA-based procedures. Results are shown in Figures 2 and 3 for trials 1, 2, and 3 only, because the results for trial 4 are virtually insensitive to the choice of a management procedure (the management procedures all reduce the catch limit to 250 t as quickly as possible).

Results are shown in Figure 2 for SETMAC strategies for  $x=0.4$ , 0.5, and 0.6 (see Appendix C for the definition of  $x$ ), and for variants of a VPA management procedure based on the  $F_{MSY}$  strategy where the  $F_{MSY}$  strategy catch limit is multiplied by 0.2, 0.4, ... 2. Results are shown in Figure 3 for “raw” catch limits based on the 30th, 40th, 50th, 60th, and 70th percentiles of the bootstrap distribution for the  $F_{MSY}$  and  $x=0.4$ , 0.5, and 0.6 strategies. For simplicity, each procedure will henceforth be referred to by its strategy ( $F_{MSY}$ ,  $x=0.5$ , etc.) and (if relevant) its percentile. The relative ranking of the variants in terms of median final depletion does not change from one trial to the next. This means that the variant of the production model procedure that achieves the third smallest median

final depletion for trial 2 is the same as that which achieves the third smallest median final depletion for trial 3.

There is a clear (and expected) trade-off between median average catch and median final depletion. However, the trade-off between median final depletion and median AAV is less clear. In general the production model management procedures outperform those based on VPA in terms of reducing interannual variation in catch (Fig. 2). Unexpectedly, of the non-bootstrap VPA-based procedures, the variants of the SETMAC strategy lead to lower interannual variation in catches than those based on variants of the  $F_{MSY}$  strategy for the same level of median final depletion. This is most notable for trial 3. However, the median AAV for a given median final depletion increases as the value of  $x$  for the bootstrap strategies is increased. For example, the “70%  $x=0.6$ ” procedure achieves almost the same median final depletion as the “50%  $x=0.5$ ” procedure, but leads to notably more variable catch limits (Fig. 3).

Performance depends notably on the scenario underlying the simulation trial. For trial 1, all of the management procedures leave the resource in median terms below  $0.165B_0$  (0.165 is the median final depletion if the catch limit is reduced by 25% each year from 1999 until it reaches the minimum of 250 t in 2001). In contrast, some of the production-model-based management procedures underutilize trial 3 and leave the resource at median final depletions of 0.7 or larger. Somewhat surprisingly, the relative ranking of different procedures in terms of the trade-off between median final depletion and median average catch differs among trials. For example, the production-model-based management procedure with  $\phi=2$  leads to the lowest median final depletion for trial 2, but underutilizes the resource for trial 3.

The performances of most of the variants of the bootstrap  $F_{MSY}$  procedure are poor and lead, for example, to median final depletions for trial 1 below  $0.1B_0$  (Fig. 3). The procedures based on the  $x=0.5$  and  $x=0.6$  harvest strategies permit recovery for trial 2, but underutilize the resource for trial 3. The results for the variants based on the  $x=0.4$  harvest strategy are intermediate between those for the  $F_{MSY}$  and the  $x=0.5/0.6$  harvest strategies.

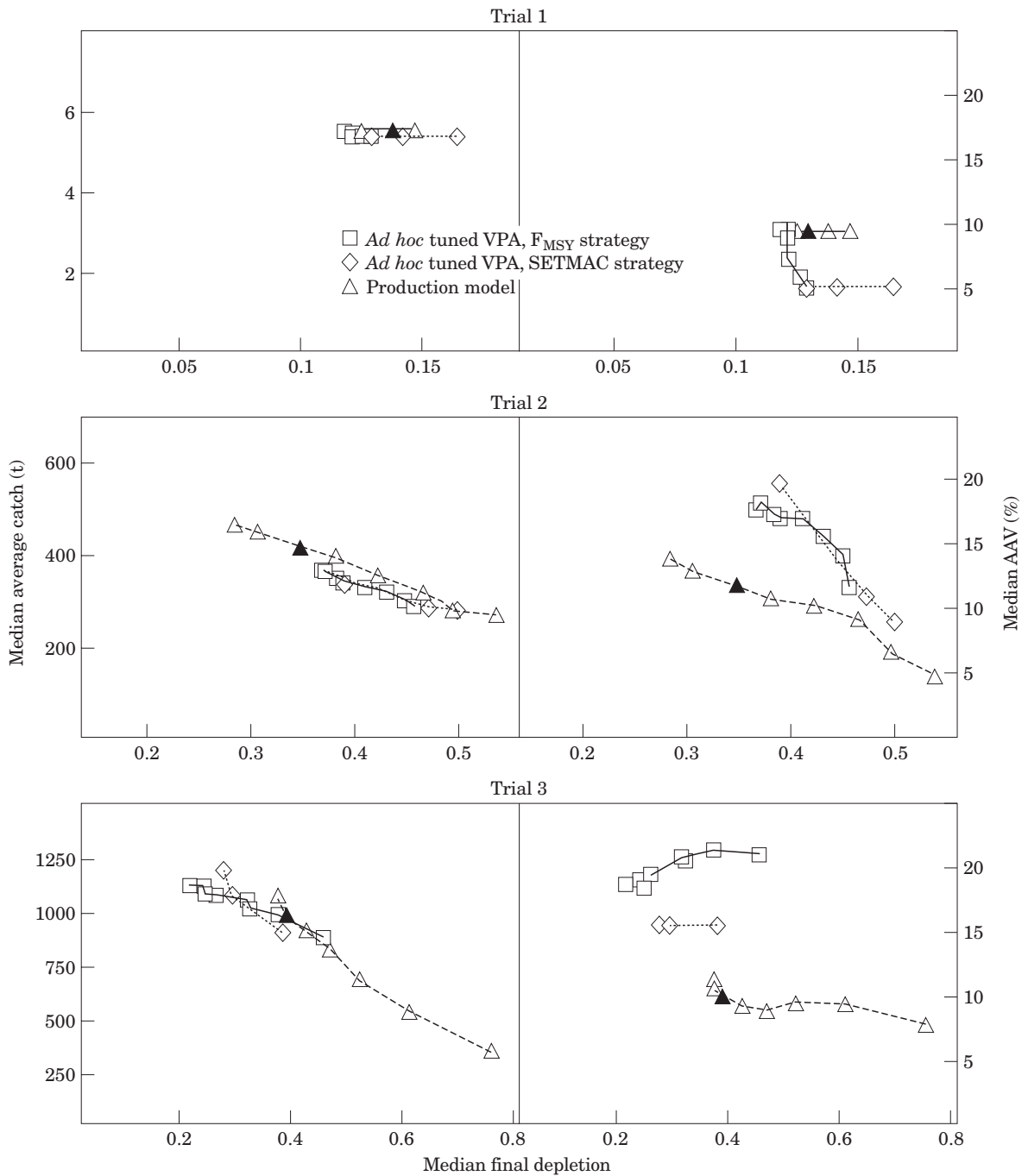


Figure 2. Relationship between median final depletion and median average catch, and between median final depletion and median AAV for three classes of management procedure. Results are shown for three of the four trials in Table 1. The closed symbols indicate the management procedures considered in detail.

#### Selection of candidate management procedures

The results in Figures 2 and 3 permit the number of management procedures to be reduced. Two management procedures (indicated by the closed symbols) are considered further:

- The “30%  $x=0.4$ ” procedure. This management procedure performs satisfactorily for all four trials although it leads to relatively high interannual variation in catches. It is, however, explicitly precautionary because increased uncertainty implies lower catch limits.

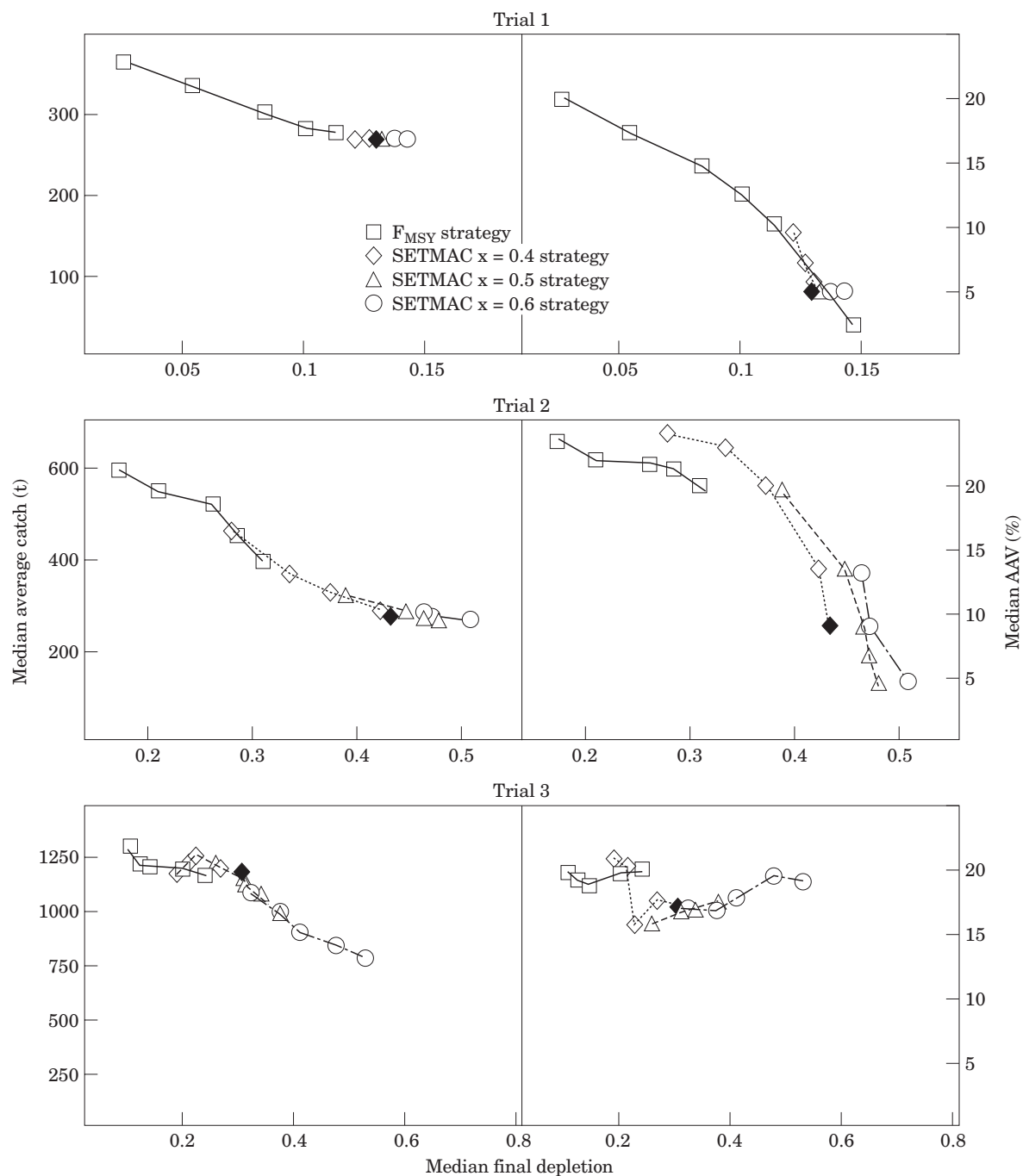


Figure 3. As for Figure 2 except that results are shown for four classes of management procedure based on the bootstrap VPA estimator (squares  $F_{MSY}$  strategy; diamonds  $x=0.4$  strategy; triangles  $x=0.5$  strategy; circles  $x=0.6$  strategy).

- (b) The  $\phi=1.5$  production model procedure. This procedure achieves a similar median average catch to the “30%  $x=0.4$ ” procedure for trial 3 but leads to much lower interannual variation in catch limits (e.g. 11% compared to 17% for trial 3).

Figure 4 plots results for four key performance measures based on 24 trials for those two procedures. The values for the probability of exceeding 40% of the 1979 5<sup>+</sup>/6<sup>+</sup> biomass are indicated by closed or open circles, depending on whether or not a strategy of setting

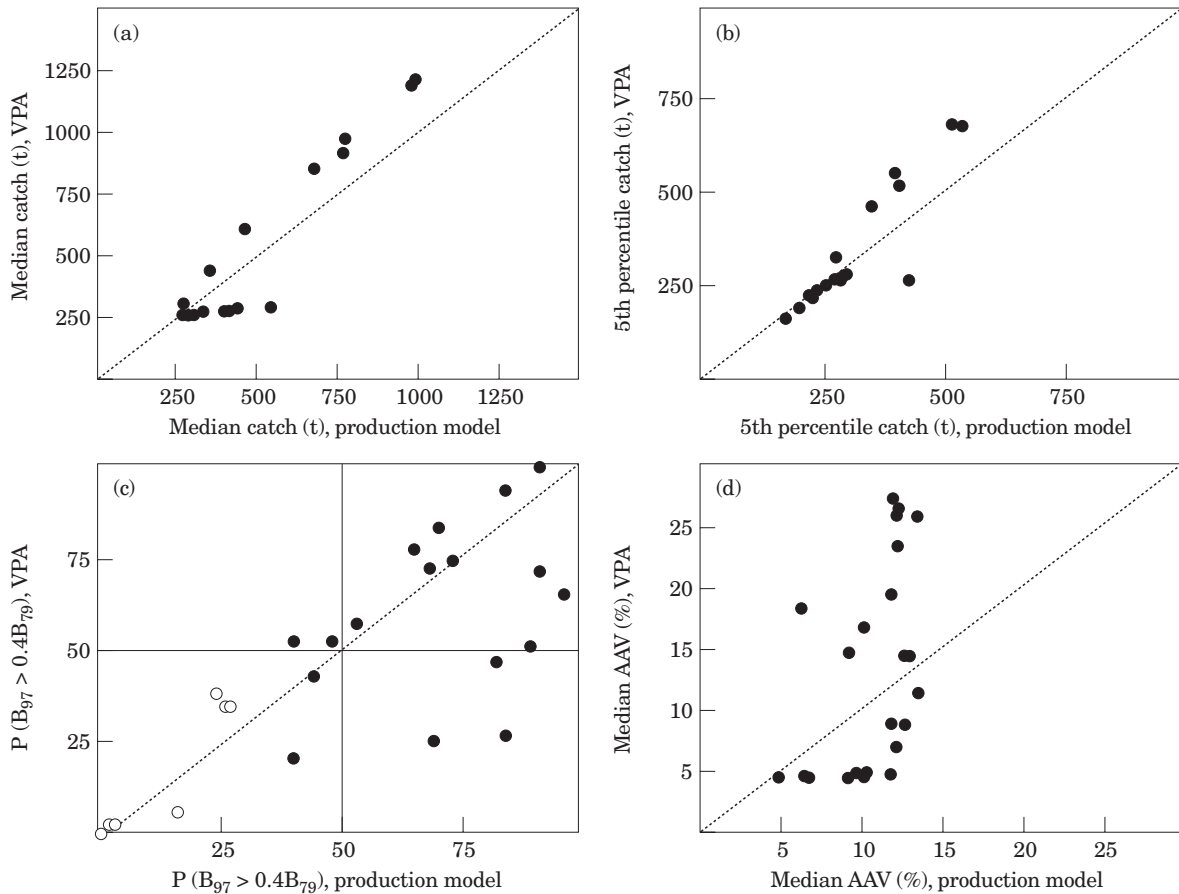


Figure 4. Relationships between the values of four key performance measures for 24 trials for two candidate management procedures.

a 250 t constant TAC would satisfy the AFMA criterion that this probability exceeds 0.5. The 24 trials are the subset of the 32 trials for  $\tau=0.7$  for which the median final depletion under a 250 t constant catch strategy exceeds  $0.1B_0$ .

The VPA procedure outperforms the production model procedure in terms of median average catch for 8 of the 24 trials, whereas the median average catch is the same for 2 of the trials (Fig. 4a). The most notable difference in median average catch occurs for the trial in which the stock–recruitment relationship is depensatory, the true catch series is “A”, the 1997 catch rate is ignored, and selectivity is independent of density. For that trial, the production model procedure achieves a median average catch that is 459 t greater than that achieved by the VPA procedure. Averaged over the 24 trials, the production model procedure achieves a higher median average catch although the difference is slight (463 compared to 457 t). The lower 5%ile of the average catch distribution can be seen as representing the guaranteed catch. The VPA procedure outperforms

the production model procedure for this performance measure by an average of 24 t (Fig. 4b).

The production model and VPA procedures fail to satisfy the AFMA criterion for 11 and 12 trials, respectively (Fig. 4c). For seven of those trials, even a strategy of reducing the TAC to 250 t in 1999 and keeping it at that level is unable to satisfy this performance criterion. The production model procedure is closest to satisfying the AFMA criterion for those trials for which this was possible. Of note is the poor performance of the VPA procedure for two of the three trials in which the production model procedure satisfies the performance criterion but the VPA procedure does not.

The production model procedure never results in values for the median AAV statistic above 15%. In contrast, the VPA procedure achieves a median AAV of more than 25% for 4 of the 24 trials (Fig. 4d). The relatively variable nature of catch limits based on VPA procedures has been noted in previous investigations into the performance of management procedures (Punt, 1993, 1997b).



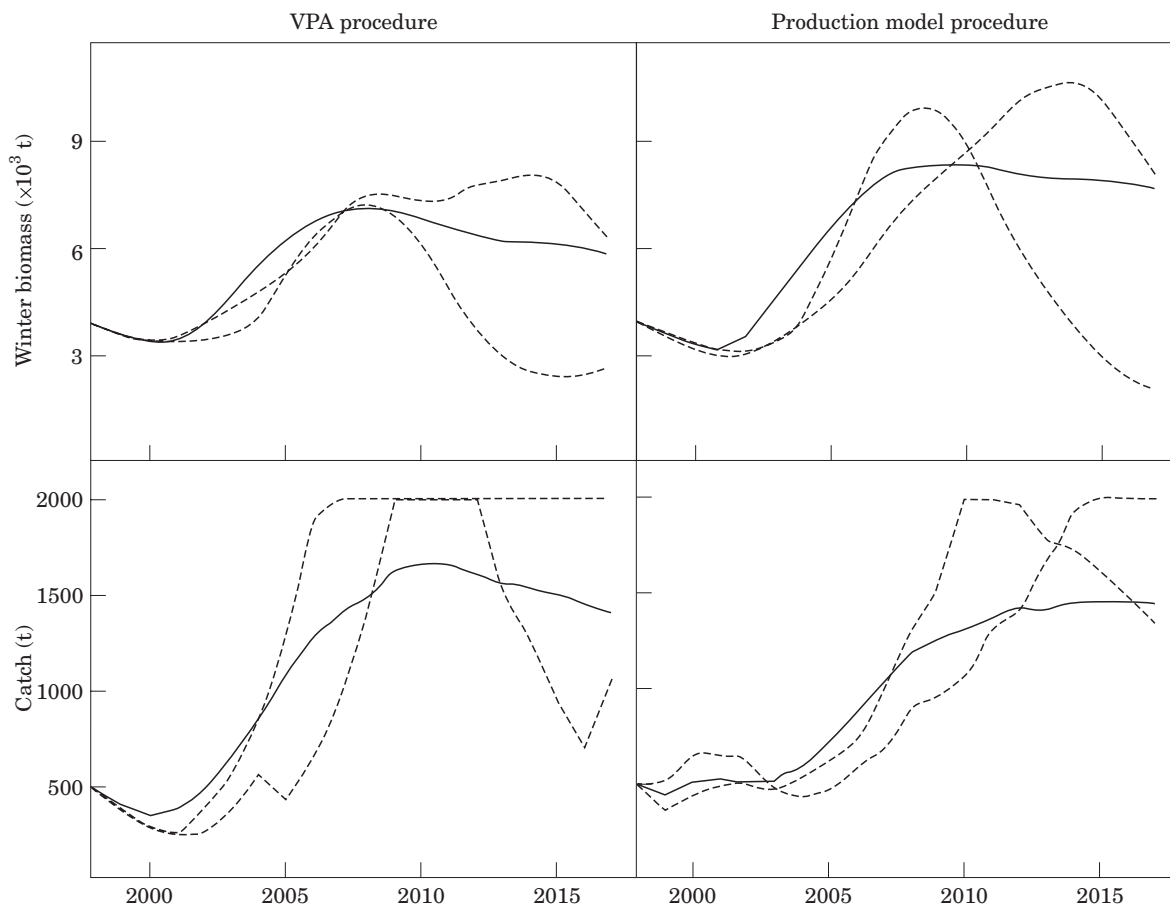


Figure 5. Average trajectories for trial 3 of catch and winter biomass (solid lines) and the trajectories for these quantities for two randomly selected simulations (dashed lines). Results are shown for the VPA and production model procedures.

Figure 5 shows the average time trajectories of winter biomass and catch for the two management procedures for trial 3 (Table 1). It also shows the time trajectories for these quantities for two individual (and randomly selected) simulations. In terms of average trajectories, the production model procedure achieves virtual stability by the end of the 20-year projection period, whereas the VPA procedure results in slight downward trends in catch and biomass after roughly 13 years. The trajectories for the two simulations are notably more variable than the average trajectories. For one simulation, both management procedures overshoot the long-term catch and are forced to reduce catches as the biomass declines in response to overharvesting.

The behaviour of the management procedures in the first few years of the projection is of particular interest. Both procedures allow some drop in catch in 1999 on average, but soon realize that this is a trial scenario in which productivity is relatively high. The production model procedure reacts quicker initially but then does

not increase the catch to quite the same extent as the VPA procedure.

Figure 6 shows performance plots for trials 2 and 3 (Table 1) for the base-case values for the parameters that determine the variation in the observed data and two scenarios in which the observational error variances are doubled. Results are not shown for the case in which the variation in the catch-at-age data is doubled for the production model procedure, because this procedure ignores the catch-at-age data. In general, the results for the production model procedure are affected little by doubling the variation in the catch rate–abundance relationship,  $\sigma_q^2$ , although the catch limits are slightly more variable interannually. In contrast, the results for the VPA procedure are fairly sensitive to changing the level of observation error. For example, doubling  $\sigma_q^2$  leads to lower average catches and higher final sizes. For trial 3, it also results in greater variation in catch limits. Increasing the noise about the catch-at-age data does not impact the results as much as increasing  $\sigma_q$ ,

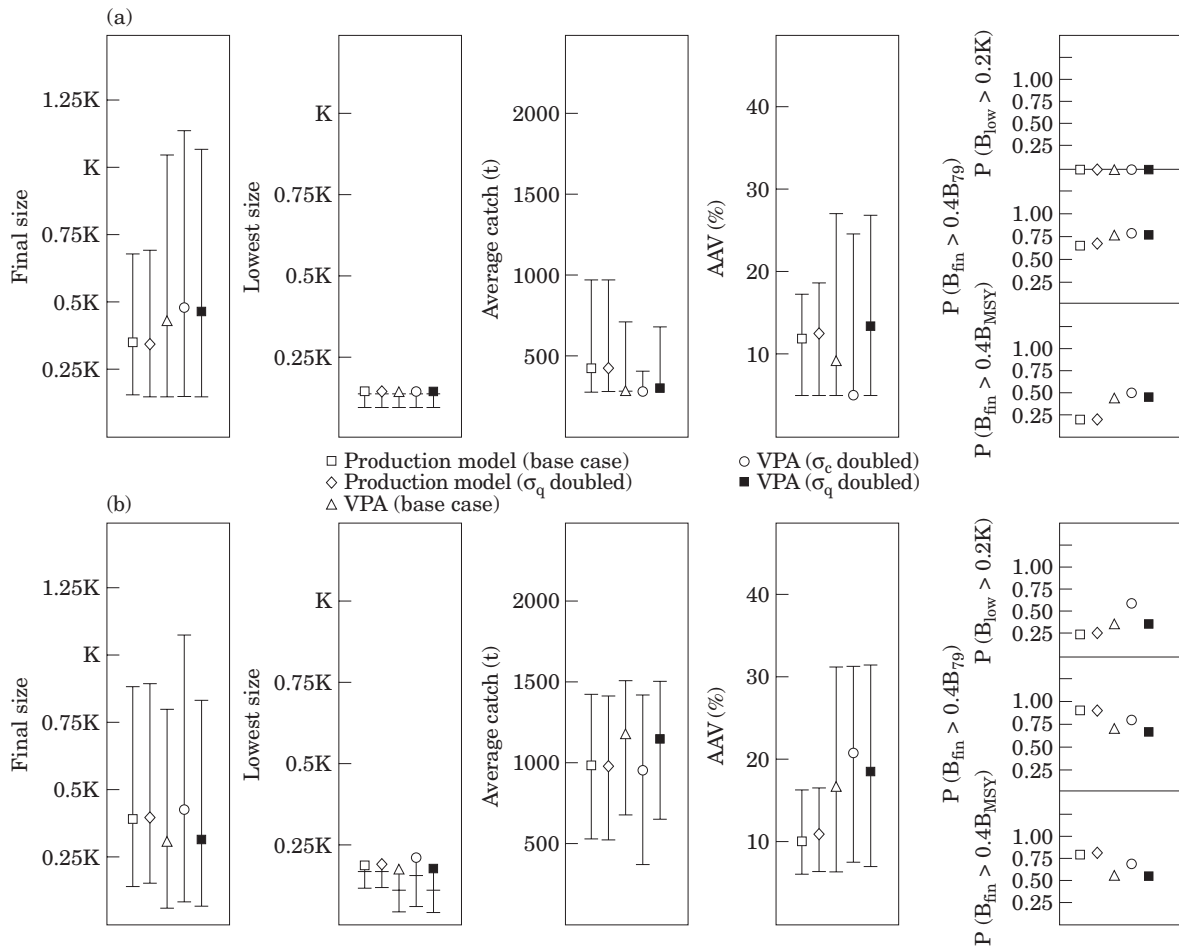


Figure 6. Performance plots for (a) trial 2 and (b) trial 3. Results are shown for the VPA and production model procedures for trial scenarios that involve changing the extent of variation in the observational data. For the final size, average catch, and AAV panels, the symbols and bars represent medians and 90% intervals, whereas for the lowest size panel they represent medians and lower 5 and 25 percentiles. K is the virgin biomass.

although the distributions are wider and the amount of variation in catch limits greater.

### Value of information

The results indicate clearly that improved resource utilization can be expected from conducting annual surveys of the resource to provide an index of relative abundance. The difference in annual catch between a scenario of setting a constant catch of 250 t (the level necessary to achieve reasonable performance in terms of leaving the resource above 40% of the 1979  $5^+/6^+$  biomass) and one of the management procedures considered in Figures 4–6 is close to 200 t. The value of this extra catch greatly exceeds the cost of running the surveys on an annual basis. Further analyses should examine the impact of conducting surveys less regularly. The results in Figure 6 suggest that even if the survey frequency were reduced to

one survey every 4 years (equivalent to doubling the variation about the catch rate-abundance relationship), performance would not deteriorate markedly.

The value of collecting annual information about the age structure of the catch is less clear. The VPA procedure does achieve a slightly greater “guaranteed” catch but performs worse than the production model procedure in terms of satisfying AFMAs performance criterion and in terms of the level of interannual variation in catch (Fig. 4). The VPA procedure is based on the Laurec-Shepherd tuning algorithm. Other estimators that utilize age-structure data (e.g. Deriso *et al.*, 1985; Gavaris, 1988; Methot, 1989) have yet to be evaluated. Management procedures based on these estimators will be more difficult to evaluate because of their computational demands, but they may perform better. For example, Patterson and Kirkwood (1995) demonstrate that ADAPT VPA (Gavaris, 1988) can outperform

*ad hoc* tuned VPA in estimation ability and management performance, although they did not consider any uncertainty in the catch-at-age data so it is not clear how general their result is likely to be.

The age-composition data have a second use that is not assessed directly in this study, namely that they form the basis for the parameterization of the operating model used to assess alternative management procedures. Had the age-composition data not been available, it would have been impossible to characterize the uncertainty regarding the status of the resource effectively.

## Final remarks

In principle, the performance of the management procedures should have been evaluated after weighting the various trial scenarios. Such weighting might involve assessing the relative credibility of the hypotheses underlying each trial scenario or examining the quality of the fit of the model corresponding to each trial scenario to the data. A more sophisticated but computationally intensive approach would be through a fully Bayesian method. Such a weighting process has not been undertaken for this study. This is primarily because any hypotheses that led to outcomes considered “implausible” (e.g. a value for the steepness of the stock–recruitment relationship less than 0.3) were completely excluded. The utility of comparing different trial scenarios in terms of the value of the likelihood function is questionable in this case. This is because, as is the case for many assessments based on fitting several data sets simultaneously, the data were given *a priori* “weights” prior to inclusion in the assessment (Punt, 1996, 1997a). In any case, the values for the likelihood function for some of the trial scenarios (e.g. those based on different catch/catch rate series) would not be directly comparable.

The simulations are based on projecting the population from the “best estimates” corresponding to each trial scenario. This may seem surprising given the increased emphasis in recent years on quantifying parameter uncertainty (see, for example, references in Smith *et al.*, 1993). However, the level of uncertainty about the values for the model parameters is relatively minor (except for that about recent recruitment, which is handled explicitly – see Section A.2) and its impact is totally dominated by uncertainty about model structure. Incorporating parameter uncertainty is therefore not likely to have impacted any of the qualitative conclusions.

All of the trial scenarios considered mimic the actual observational data for eastern gemfish reasonably well and suggest roughly the same size for the current biomass. However, their implications in terms of productivity differ quite markedly. The results indicate

that the relative performance of management procedures can differ among trial scenarios quite markedly, which implies that a wide range of hypotheses needs to be considered when evaluating management procedures for a specific case and that hypotheses should not be excluded merely on the basis of model-selection criteria. The performances of the two management procedures selected above can be considered to be relatively robust to the uncertainties regarding model structure identified by EGAG. These procedures are able to determine the level of productivity relatively effectively within the first few years of management (Fig. 4). The result that the average catch achieved by the VPA procedure dropped when the extent of variation in the catch–effort relationship was increased reflects its precautionary nature.

One of the indirect benefits of the evaluation of management procedures for the eastern stock of gemfish is the impact that this has had on furthering the process of “quantification” of the management objectives for federally managed fisheries in Australia. At the start of this research, AFMA’s criterion for re-opening the fishery was that “the biomass recover to 40% of the 1979 level”. In order to include this criterion in the evaluation, it was necessary to define “biomass” and what is meant by “recover”.

The next step in the evaluation process is to present the results of this evaluation to industry and management through EGAG, to obtain further direction regarding the desirable trade-offs among the management objectives. Further consideration of sources of uncertainty is needed to ensure that a key uncertainty likely to impact performance has not been ignored. In particular, additional relationships between catch rate and abundance need to be examined.

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## Appendix A: The operating model

The operating model is age- and sex-structured, takes account of two pulse fisheries, and assumes that the number of births is related to the egg production by means of a stock–recruitment relationship. The “year” considered in this model is defined so that the winter spawning run fishery occurs in a pulse at the end of the year (i.e. each year is defined to run from July to June). The operating model is a slight generalization of the model described by [Smith and Punt \(1998\)](#). Therefore, this appendix only provides specifications for the basic dynamics of the resource, the relationship between egg production and births, selectivity to the winter fishery, and how the data used by the management procedures are generated. Readers interested in how the initial conditions are specified, and how the catches-at-age are computed from the catches in mass should consult [Smith and Punt \(1998\)](#).

### A.1 Basic population dynamics

The resource dynamics are modelled using the equations:

$$N_{y+1,a}^g = \begin{cases} N_{y+1,0}^g & \text{if } a=0 \\ \tilde{N}_{y,a-1}^g & \text{if } 1 \leq a \leq x-1 \\ \tilde{N}_{y,x}^g + \tilde{N}_{y,x-1}^g & \text{if } a=x \end{cases} \quad (\text{A.1})$$

where  $N_{y,a}^g$  is the number of fish of sex  $g$  and age  $a$  at the start of year  $y$ ,  $\tilde{N}_{y,a}^g$  is the number of fish of sex  $g$  and age  $a$  at the end of year  $y$ ,

$$\tilde{N}_{y,a}^g = (N_{y,a}^g e^{-t_1 M_a^g - C_{y,a}^{s,g}}) e^{-t_2 M_a^g - C_{y,a}^{w,g}} \quad (\text{A.2})$$

$M_a^g$  is the rate of natural mortality on fish of sex  $g$  and age  $a$ ,  $C_{y,a}^{s,g}$  is the catch (in number) of fish of sex  $g$  and age  $a$  during the summer fishery of year  $y$ ,  $C_{y,a}^{w,g}$  is the catch (in number) of fish of sex  $g$  and age  $a$  during the winter fishery of year  $y$ ,  $t_1$  is the time between the start of the year and the midpoint of the summer fishery,  $t_2$  is the time between the midpoint of the summer fishery and that of the winter fishery ( $t_1 + t_2 = 1$  because the winter

fishery is assumed to be at the end of the year), and  $x$  is the maximum age considered (taken to be a plus-group).

### A.2 Births

Three alternative relationships between egg production and subsequent births are considered:

- (a) Beverton–Holt:  $N_{y,0}^g = 0.5 \text{ SB}_{y-1} / [\alpha + \beta \text{ SB}_{y-1}] e^{\varepsilon_y}$
- (b) Ricker:  $N_{y,0}^g = 0.5 \alpha \text{ SB}_{y-1} e^{-\beta \text{ SB}_{y-1}} e^{\varepsilon_y}$
- (c) Depensatory:  $N_{y,0}^g = 0.5 \text{ SB}_{y-1}^{\gamma} / [\alpha + \beta \text{ SB}_{y-1}^{\gamma}] e^{\varepsilon_y}$

where  $\text{SB}_y$  is proportional to the egg production at the end of year  $y$ :

$$\text{SB}_y = \sum_{a=1}^x w_a^{w,f} (S_{y,a}^{w,f} (N_{y,a}^f e^{-t_1 M_a^f - C_{y,a}^{s,f}}) e^{-t_2 M_a^f - C_{y,a}^{w,f}}) \quad (\text{A.3})$$

$S_{y,a}^{w,g}$  is the selectivity of the fishing gear used during the winter fishery of year  $y$  on fish of sex  $g$  and age  $a$ ,  $\varepsilon_y$  is the recruitment anomaly for year  $y$ :

$$\varepsilon_y = \tau \varepsilon_{y-1} + \sqrt{(1 - \tau^2)} \varepsilon'_y \quad (\text{A.4})$$

$\varepsilon'_y$  is the recruitment residual for year  $y$  ( $\varepsilon'_y \sim N(0; \sigma_r^2)$ ),  $\tau$  determines the extent of interannual autocorrelation in the recruitment anomalies,  $w_a^{w,g}$  is the mass of a fish of sex  $g$  and age  $a$  during the winter fishery,  $\sigma_r$  is the standard deviation of the logarithms of the multiplicative fluctuations in births (approximately the coefficient of variation of these fluctuations), and  $\alpha, \beta, \gamma$  are the parameters of the stock–recruitment relationship.

This formalism assumes that egg production is determined by the biomass of females that survives the winter spawning-run fishery and that maturation is the same as selectivity to the winter fishery. Some of the catches during the winter fishery are made after spawning (the “back run”). However, those catches are generally a small fraction of the total winter catch when they occur ( $\sim 5$ – $10\%$ , K. Rowling, pers. comm.), and a “back run” only takes place in some years, so this complication has been ignored here. The particular form for the depensatory stock–recruitment relationship follows the choices by [Myers \*et al.\* \(1995\)](#) and [Liermann and Hilborn \(1997\)](#). A fourth stock–recruitment relationship based on the Beverton–Holt form that assumes that the virgin number of births changed in 1987 is also considered. The year classes from 1995 onwards are not estimated as part of the process of “conditioning” the trial scenarios but are instead generated using the above equations. Therefore, each simulation involves generating year-class strengths for all cohorts from 1995.



### A.3 Selectivity to the winter fishery

The selectivity functions are sex- and fishery-specific. The selectivity function for the winter fishery is assumed to have the logistic form:

$$S_{y,a}^{w,g} = \begin{cases} 0 & \text{if } a < 2 \\ \left(1 + \exp\left(-\frac{\ln(19)(L_a^{w,g} - L_{50y}^{w,g})}{(L_{95y}^{w,g} - L_{50y}^{w,g})}\right)\right)^{-1} & \text{otherwise} \end{cases} \quad (\text{A.5})$$

where  $L_a^{w,g}$  is the length of a fish of sex  $g$  and age  $a$  during the winter fishery,  $L_{50y}^{w,g}$  is the length-at-50%-selectivity for fish of sex  $g$  during the winter fishery of year  $y$ , and  $L_{95y}^{w,g}$  is the length-at-95%-selectivity for fish of sex  $g$  during the winter fishery of year  $y$ .

The selection of the logistic form was made because selectivity to the winter fishery is equivalent to being mature and the probability of a fish being mature increases with size and/or age. The selectivities for ages 0 and 1 are set equal to zero because fish younger than 2 years have never been encountered during the winter spawning run.

It seems plausible that maturation (and hence selectivity to the winter fishery) is density-dependent. One way to model this is to assume that density impacts the length-at-50%-selectivity to the winter fishery. One possible functional form to model this is:

$$L_{50,y}^{w,g} = L_{50,B_0}^{w,g} - \Omega^g(1 - \tilde{B}_y^g/\tilde{B}_{B_0}^g) \quad (\text{A.6})$$

where  $\Omega^g$  is the parameter which controls density dependence for sex  $g$ , and  $\tilde{B}_y^g$  is the “spawning biomass” (5+ biomass for males and 6+ biomass for females) at the start of year  $y$ .

For these calculations, it is assumed that the width of the selectivity function does not change even if the length-at-50%-selectivity changes, i.e.:

$$L_{95,y}^{w,g} = L_{95,B_0}^{w,g} + (L_{50,y}^{w,g} - L_{50,B_0}^{w,g}) \quad (\text{A.7})$$

### A.4 Generation of future data

The simulations assume that future catch, catch rate, and catch-at-age data are available for all years from 1998.

Catchability is assumed to be log-normally distributed, i.e.:

$$(C/E)_y^w = q B_y^w e^{v_y - \sigma_q^2/2} \quad v_y \sim N(0; \sigma_q^2) \quad (\text{A.8})$$

where  $(C/E)_y^w$  is the catch rate during the winter fishery of year  $y$ , and  $B_y^w$  is the exploitable biomass in the middle of the winter fishery of year  $y$ ,

$$B_y^w = \sum_{g=a=0}^x w_a^{w,g} [S_{y,a}^{w,g} (N_{y,a}^g e^{-t_1 M_a^g - C_{y,a}^{s,g}}) e^{-t_2 M_a^g - C_{y,a}^{w,g}/2}] \quad (\text{A.9})$$

$q$  is the catchability coefficient, and  $\sigma_q$  is the standard deviation of the observation errors.

The total catches by fleet  $f$  (s/w) and year (in mass and aggregated over ages and sexes),  $\tilde{C}_y^f$ , are assumed to be measured without error. In contrast, the observed catches-at-age,  $\tilde{C}_{y,a}^{f,g}$ , are assumed to be log-normally distributed about their true values:

$$\tilde{C}_{y,a}^{f,g} = \tilde{C}_{y,a}^{f,g} \frac{\tilde{C}_y^f}{\sum_{g'} \sum_{a'=0}^x w_{a'}^{f,g'} \tilde{C}_{y,a'}^{f,g'}} \quad (\text{A.10})$$

$$\tilde{C}_{y,a}^{f,g} = C_{y,a}^{f,g} e^{\phi_{y,a}^{f,g} - (\sigma_{c,y,a}^{f,g})^2/2} \quad (\text{A.11})$$

where  $C_{y,a}^{f,g}$  is the catch (in number) of fish of sex  $g$  and age  $a$  by fleet  $f$  during year  $y$ , and  $\phi_{y,a}^{f,g}$  is from  $N(0; (\sigma_{c,y,a}^{f,g})^2)$ .

The second term on the right side of equation (A.10) is necessary so that the relationship  $\tilde{C}_y^f = \sum_g \sum_{a'=0}^x w_{a'}^{f,g} \tilde{C}_{y,a'}^{f,g}$  is satisfied. The coefficients of variation of estimates of catch-at-age are largest for ages that make up relatively small contributions to the catch. To mimic this, the observation error coefficient of variation for the catch of fish of age  $a$  during year  $y$  depends on the proportion which  $C_{y,a}^{f,g}$  makes up of the total catch in number of fish of sex  $g$  by fishery  $f$  during year  $y$  (Punt, 1997b):

$$\sigma_{c,y,a}^{f,g} = \sigma_c^f \sqrt{\sum_{a'} C_{y,a'}^{f,g} / C_{y,a}^{f,g}} \quad (\text{A.12})$$

where  $\sigma_c^f$  is the standard deviation of the catch-at-age for fishery  $f$ .

### A.5 Historical data

The historical (pre-1998) catch data used by the management procedures are taken to be those corresponding to catch series A (Fig. 1), even though for half of the trial scenarios the “true” catch series may differ from that underlying the management procedure. Age-composition data are assumed to be available from 1973. The age-composition data are taken to be the actual age-composition data for eastern gemfish. For those years for which catch-at-age data are unavailable, those data are taken to be the predictions from an assessment based on the assumptions that selectivity is not density-dependent, that the stock–recruitment relationship is Beverton–Holt, that the catch rates for 1996 and 1997 are comparable with those for the years 1973–1991, and that the recruitment anomalies are temporally uncorrelated (Smith and Punt, 1998). This



assumption is correct for one of the 64 trial scenarios, but incorrect for all the others. The historical catch rate data are taken to be those in Table 2 of Punt *et al.* (1997).

## Appendix B: The *ad hoc* tuned VPA estimator

The standard VPA back calculations for each cohort, together with the selected tuning algorithms, are applied until convergence takes place to obtain the estimates of the exploitation rate and numbers-at-age (N) matrices. The *ad hoc* tuned VPA can be used to provide “best estimates”. Measures of uncertainty can be obtained by means of a bootstrap approach. The “raw” catch limit is calculated from the tuned N-matrix when using the “best estimates”, and it is taken to be a pre-specified percentile of the distribution for the catch limit for the bootstrap-VPA approach. The estimates of mass-at-age are taken to be the actual values while the rates of natural mortality for males and females are taken to 0.5 and 0.4 year<sup>-1</sup> respectively.

### B.1 The VPA back calculations

The VPA back-calculation process is used to calculate the entire numbers-at-age matrix from the numbers-at-age for the oldest-age (age  $x$ , taken to be a plus group and equal to 10) and the most-recent-year (year  $t$ ). The equation used to calculate  $N_{y,a}^g$ , the number of fish of sex  $g$  and age  $a$  at the start of year  $y$ , from  $N_{y+1,a+1}^g$  is:

$$N_{y,a}^g = ((N_{y+1,a+1}^g + \ddot{C}_{y,a}^{w,g})e^{t_2 M_a^g} + \ddot{C}_{y,a}^{s,g})e^{t_1 M_a^g} \quad a < x - 1 \quad (B.1)$$

where  $M_a^g$  is the rate of natural mortality on fish of sex  $g$  and age  $a$ ,  $\ddot{C}_{y,a}^{s,g}$  is the observed catch (in number) of fish of sex  $g$  and age  $a$  during the summer fishery of year  $y$ ,  $\ddot{C}_{y,a}^{w,g}$  is the observed catch (in number) of fish of sex  $g$  and age  $a$  during the winter fishery of year  $y$ ,  $t_1$  is the time between the start of the year and the midpoint of the summer fishery, and  $t_2$  is the time between the midpoint of the summer fishery and that of the winter fishery.

The exploitation rate on animals of age  $a$  and sex  $g$  by fishery  $k$  during year  $y$ ,  $F_{y,a}^{k,g}$  is given by:

$$F_{y,a}^{k,g} = \begin{cases} \frac{\ddot{C}_{y,a}^{s,g}}{N_{y,a}^g e^{-t_1 M_a^g}} & \text{if } k = s \\ \frac{\ddot{C}_{y,a}^{w,g}}{(N_{y,a}^g e^{-t_1 M_a^g} - \ddot{C}_{y,a}^{s,g}) e^{-t_2 M_a^g}} & \text{if } k = w \end{cases} \quad (B.2)$$

Back-projection of the plus group is achieved using appropriate modifications to the equations derived by Powers and Restrepo (1992).

### B.2 Tuning procedure

The algorithm used to tune the oldest-age terminal exploitation rates is based on the assumption that the age-specific selectivity function for the winter fishery is flat over the oldest  $r+1$  ages (where  $r$  is taken to be 2). The equation specifying the exploitation rate on the plus group as a function of those on the  $r$  younger ages is:

$$\hat{F}_{y,x}^{w,g} = \left[ \prod_{a=x-r}^{x-1} F_{y,a}^{w,g} \right]^{1/r} \quad y = 1, 2, \dots, t \quad (B.3)$$

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

$$\hat{F}_{t,a}^{w,g} = \overline{q_{a}^{w,g}} E_t^w \quad a = a_{low}, \dots, x \quad (B.4)$$

where  $q_a^{w,g}$  is the catchability coefficient for age  $a$  and sex  $g$ ,

$$\overline{q_a^{w,g}} = \left[ \prod_y (F_{y,a}^{w,g} / E_y^w) \right]^{1/(n_y - 1)} \quad (B.5)$$

$E_y^w$  is the fishing effort for the winter fishery for year  $y$ ,  $n_y$  is the number of years for which fishing effort data are available, and  $a_{low}$  is the lowest age considered in the tuning algorithm (age 3).

The product in Equation (B.5) is taken over all years for which effort data are available (except the most recent year).

### B.3 Estimation of the parameters of the stock–recruitment relationship

The number of 0-year-olds for year  $y$  is assumed to be related to the spawning biomass at the end of year  $y-1$  according to the Beverton–Holt stock–recruitment relationship. The estimates of the parameters of the stock–recruitment relationship are obtained by fitting to the estimates of 0-year-class strength provided by the VPA. This involves minimizing the function:

$$SS = \sum_{y=y_{min}+1}^{t-3} (\ln(N_{y,0}^m + N_{y,0}^f) - \ln \hat{N}_{y,0})^2 \quad (B.6)$$

where  $y_{min}$  is the first year considered in the analysis (1973), and  $\hat{N}_{y,0}$  is the estimate of the 0-year-class strength (both sexes combined) for year  $y$  from the stock–recruitment relationship.

The estimates of 0-year-class strength for the years  $t-2$ ,  $t-1$  and  $t$  are omitted from this regression because their variances are usually very large (see, for example, Butterworth *et al.*, 1990). The summation in Equation (B.6) starts in year  $y_{min}+1$  because the

spawning biomass at the end of year  $y - 1$  is used when predicting the year-class strength for year  $y$ .

#### B.4 Variance estimation

A bootstrap procedure is used to quantify the uncertainty associated with the VPA assessment. This procedure involves the generation of 100 bootstrap replicate exploitation rate matrices, which are conditioned on the assumption that the catch-at-age matrix and the natural mortality rates are exact (see Butterworth *et al.*, 1990, for details).

### Appendix C: The harvest strategy

A deterministic variant of the strategy applied by the TAC subcommittee of the South East Trawl Management Advisory Committee to recommend a TAC for eastern gemfish for 1997 and 1998 can be defined using the results of the *ad hoc* tuned VPA. This strategy sets the “raw” catch limit for year  $t+1$  using the following algorithm.

- Set the “target” biomass to  $x\%$  of the VPA estimate of the  $5^+/6^+$  biomass at the end of 1979.
- Project the VPA-estimated age structure at the end of the last year for which data are available, year  $t$ ,

ahead 20 years with catches of  $Q_{\min}$  (the minimum catch limit, 250 t) in each year and find the lowest level to which the  $5^+/6^+$  biomass drops over the 20-year projection period. If this value is less than the “target” biomass, the “raw” catch limit is  $Q_{\min}$  and the algorithm ends.

- Project the VPA-estimated age structure at the end of the last year for which data are available ahead 20 years with a catch of 2000 t for year  $t+1$  and catches of  $Q_{\min}$  in each year thereafter and find the lowest level to which the  $5^+/6^+$  biomass drops over the 20-year projection period. If this value is greater than the “target” biomass, the “raw” catch limit is 2000 t and the algorithm ends.
- Apply a bisection algorithm to find the catch during year  $t+1$  which, if followed by 19 years of catches of  $Q_{\min}$ , leads to the lowest  $5^+/6^+$  biomass over the next 20 years being equal to the “target” level.

Note that, like all of the other management procedures considered, this one is applied each year. This implies that, although it is assumed that the catch for years  $t+2$  onwards will be  $Q_{\min}$  when determining the TAC for year  $t+1$ , the actual TAC for year  $t+2$  may be larger than  $Q_{\min}$  when this algorithm is applied based on data up to year  $t+1$ .