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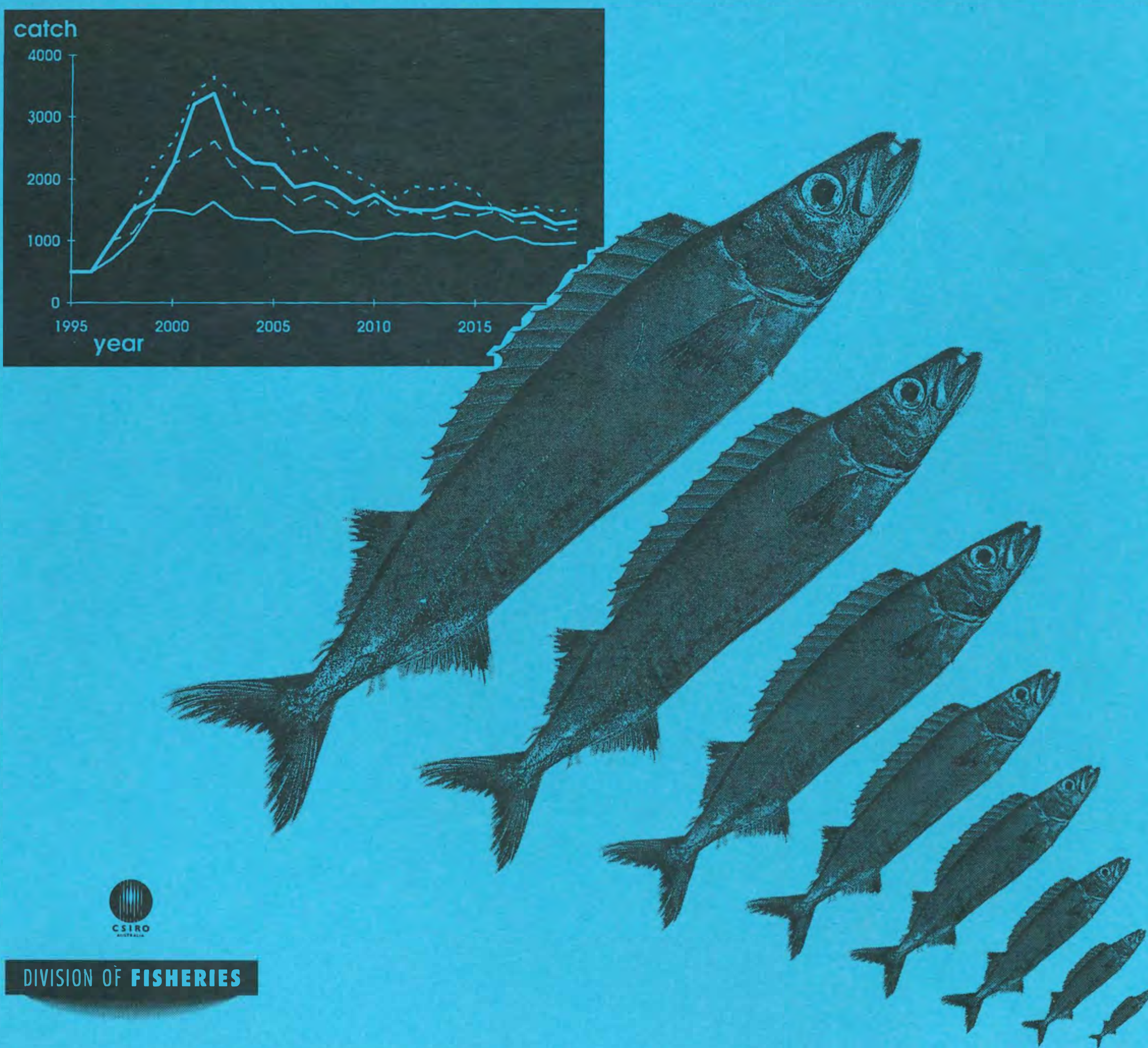
FINAL REPORT TO FISHERIES RESEARCH AND DEVELOPMENT CORPORATION

PROJECT NUMBER T93/238

EVALUATION OF HARVESTING STRATEGIES FOR AUSTRALIAN FISHERIES AT DIFFERENT LEVELS OF RISK FROM ECONOMIC COLLAPSE



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Final Report to Fisheries

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Evaluation of Harvesting Strategies for Australian Fisheries at Different Levels of Risk from Economic Collapse

Project Number T93/238

CSIRO
AUSTRALIA

DIVISION OF FISHERIES

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PART ONE

SUMMARY

SUMMARY

Management of a marine renewable resource involves selecting a trade-off between conflicting objectives related to conservation and utilization. This problem is complicated by uncertainty about the current status and productivity of the resource being managed, and hence about the implications of alternative management measures. A general quantitative framework for evaluating these trade-offs in the face of uncertainty is developed. This framework allows for uncertainty about the current state of the resource and the observational error associated with future data. It can assess the performances of a variety of harvest strategies based on setting total allowable catches (TACs). These include constant catch, fixed escapement and constant fishing effort strategies. It is possible to constrain the changes in TAC from one year to the next. This framework is illustrated using the eastern stock of gemfish.

It is necessary to quantify the status of the resource to apply this framework. In this project, the historical trends in, current status of, and productivity of the eastern gemfish population is evaluated using two age-structured assessment approaches tailored to the specifics of the gemfish resource. These methods take account of the two-fishery nature of the resource, explicitly consider sex-structure, and use the catches, the catch rates in the winter fishery, the length frequency data and the age-length keys. This resource is estimated to have declined markedly during the 1980s as a consequence of unsustainable catches and a long series of weak year-classes. However, the assessments cannot distinguish among alternatives for the relationship between spawning stock size and future recruitment. The two assessments arrive at different conclusions regarding the size of the resource relative to AFMAs harvesting target of 40% of virgin level.

The harvest strategy evaluation is restricted to constant catch and constant fishing effort strategies. The current status of the resource is summarized from the results of the Bayesian variant of one of the stock assessments. A range of performance measures (including the average catch and the probability of the resource being above AFMA's target by 2020) are used to assess the performance of each strategy. Most of the strategies considered allow the resource to recover between 1995 and 1999, but only the relatively conservative strategies of a 1000 t constant catch or an $F_{0.4}$ strategy perform well relative to AFMAs target. The constant catch strategies result in less variability in TAC from one year to the next, but do not take as much catch on average as strategies which adjust the TAC each year based on an annual stock assessment. A notable result is that strategies which use assessment models which aim at specific target biomass levels do not necessarily achieve them, even on average. In this example, the resource tends to stabilize below the targets built into the assessment models.

The results of the harvest strategy evaluation are not notably sensitive to a variety of sources of uncertainty, including whether recruitment fluctuates randomly about the stock-recruitment relationship and whether there is auto-correlation between the deviations from the stock-recruitment relationship from one year to the next.

Although the harvest strategy evaluation has been developed using gemfish as an example, the results should be regarded as preliminary and illustrative. Their possible application for management advice awaits further consultation on the stock assessment results which underlie them.

BACKGROUND

Most harvesting strategies aim to maintain fished stocks at levels which are both biologically and economically productive. For fisheries managed using output controls such as TACs or ITQs, a harvest strategy is a rule or method for setting an annual TAC. Examples of harvest strategies which have been used in such instances include fixed catches, constant exploitation rates, or attempts to maintain stocks at some target level. The latter two of these general classes of harvest strategy will usually require some type of annual quantitative stock assessment as input to the decision rule underlying the strategy. Strategies will vary in the extent to which they satisfy alternative management objectives such as maximizing long term catch (or profits), minimizing year to year variations in catch, minimizing risks to the stock, and rebuilding depleted stocks.

Use of output controls for fisheries management in Australia is of relatively recent origin, and is so far limited to a handfull of fisheries. Nevertheless, there seems to be an increasing trend towards use of this particular form of management. This has resulted in turn in an increasing emphasis on annual stock assessments. These are used in the quota setting process, but the way in which they are used is *ad hoc* to say the least. Two stocks which are currently managed under a quota (ITQ) system are orange roughy and gemfish.

NEED

At the outset of this project, there had been no serious attempt to develop a longer term feedback harvest strategy for an Australian fishery, nor to evaluate the performance of such a strategy against management objectives. The objective of the project was to develop the framework and software for such an evaluation, based around one or more case studies. Initially, the fisheries for orange roughy and for the eastern stock of gemfish were selected as possible examples around which to develop such an evaluation. These were selected on the basis that some preliminary stock assessments were available, and that they offered a contrast in current levels of depletion. Orange roughy was seen as a still developing fishery, while gemfish were regarded as overexploited. A zero TAC had been set for the eastern stock of gemfish in 1993.

During the course of the study, further assessments for orange roughy showed that these stocks were already fully exploited, and therefore offered less contrast to gemfish than was first anticipated. Although some fixed quota harvest strategies were investigated for this species, and some economic analyses were undertaken, the main focus of the framework development is based around the gemfish case study, and the orange roughy results are not discussed further in this report.[1]

OBJECTIVES

The aim of this study was to develop an integrated biological and economic framework that can be applied to a number of Australian fisheries. The framework would allow the evaluation of the relative costs, benefits and risks of alternative harvesting strategies for both developing fisheries, and for fisheries in a recovery phase following stock depletion.

As noted above, gemfish was chosen as the main case study for the analyses, with less attention payed to orange roughy. For this reason there was also less focus on the economic analyses, as no recent economic data were available for gemfish due to the closure of the fishery. The proxy for economic performance in the analyses reported here is long term catch.

The main objective, to develop and demonstrate a framework for harvest strategy evaluation, was successfully achieved.

METHODS

There are three components of the work described in this report. The first is the development of the framework for harvest strategy evaluation, and its implementation as a general purpose computer program. The framework, and the computer software which implements it, are described in the Appendix to this report.

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[1] The results of the orange roughy analyses were presented to managers and industry in 1994 through the South East Fishery Assessment Group (SEFAG). They constitute the principal advice to managers in the annual stock assessment reports for orange roughy for 1994 and 1995. These analyses were the subject of an international review of Australian orange roughy assessments, undertaken by Professors Hilborn and Deriso on behalf of AFMA.

The second component needed for the successful completion of the work is an initial assessment of the current status of the stock (in this case the eastern stock of gemfish). This assessment needs to incorporate as many of the uncertainties about the status of the resource as possible because these uncertainties will guide the choice of a suitable harvesting strategy. Three stock assessments for eastern gemfish are described in this report. Chapter 1 of Part Two of this report describes the methods for the Bayesian and maximum likelihood assessments, while Chapter 2 describes an assessment using Stock Synthesis.

The third component is the evaluation of the harvest strategies for eastern gemfish. The method involves simulating the future management of the resource under each harvest strategy using Monte Carlo simulation, and an underlying operating model derived from the Bayesian stock assessment. The details are descibed in Chapter 3 of Part Two of this report.

DETAILED RESULTS

The detailed results of this study are described in Part Two of this report.

BENEFITS

The direct beneficiaries of this research are the fishers and other users of the South East Fishery, in particular the quota holders for eastern gemfish. The results have provided a framework for developing a stock recovery plan for this fishery, and a set of strategies for a possible re-opening of the fishery. Implementation of any plans or strategies will require extensive discussion of the results of this study through the forum of the South East Fishery Assessment Group, and will almost certainly involve some reassessment of data and re-specification of assumptions. A workshop of industry, managers and scientists to undertake these further analyses is planned for early 1996. Rapid progress should be possible at this workshop since the computer programs developed for the analyses described in this report should require little modification for the further work to be undertaken.

The results of this research should also find broader application across a range of Australian fisheries. In particular, the framework and strategy for a stock recovery plan for gemfish should find application in the southern shark and southern bluefin tuna fisheries.

An important finding of this research is that the assessment techniques and harvesting strategies currently used in some Australian and many international fisheries may be inherently unlikely to attain their target exploitation rates. This is an area that will require further research to develop robust harvesting strategies for marine fisheries.

INTELLECTUAL PROPERTY

There is no commercially significant intellectual property arising from this research.

FURTHER DEVELOPMENT

As indicated under benefits, further application of these results and analyses to management of gemfish will occur in the SEFAG workshop in April 1996. This will involve review and revision of both the gemfish assessments and the harvest strategy evaluation, but the framework and software for both these tasks is now well established and should require little modification. Key tasks for this workshop will be to clarify management objectives, and to identify a wider range of harvest strategies for consideration.

The framework and software described in the Appendix is being modified currently for application to evaluate feedback harvest strategies for Southern Bluefin Tuna. This will require some modification to the VPAs which are simulated in the harvest strategies, but the overall structure of the program is well suited to this new application.

Further development of the software should incorporate a wider range of assessment techniques and harvest strategies, as well as additional performance indices to measure key economic variables which are relevant to management objectives.

STAFF

The following CSIRO Division of Fisheries staff were employed on this project:

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PART TWO

DETAILS OF THE STUDY

CHAPTER ONE

PRELIMINARY STOCK ASSESSMENTS OF EASTERN GEMFISH (REXEA SOLANDRI) USING BAYESIAN AND MAXIMUM LIKELIHOOD METHODS

PRELIMINARY STOCK ASSESSMENTS OF EASTERN GEMFISH (*REXEA SOLANDRI*) USING BAYESIAN AND MAXIMUM LIKELIHOOD METHODS

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ABSTRACT

Maximum likelihood and Bayesian stock assessments of the eastern population of gemfish are conducted. The values of the parameters of an age- and sex-structured population dynamics model are estimated using information on catch rates, the fraction of winter fishery catches consisting of females, and the age-composition and length-frequency of the catches. The assessments do not interpolate catch-at-ages for years for which these data are unavailable. The sensitivity of the results to a variety of assumptions, priors and weights for the data is examined. The results confirm earlier analyses which suggest that the abundance of eastern gemfish was reduced markedly as a result of unsustainable catches and a long series of weak year-classes. The analyses are unable to shed much light on the shape of the stock-recruitment relationship and hence the cause for the severe decline in year-class strength during the late 1980s. The ability to provide reliable and precise estimates for the years after 1991 is hampered by the lack of an abundance index after this year, and urgent consideration must be given to the development of such an index. However, unless this index provides an estimate of *absolute* abundance, it cannot be incorporated into the analyses for several years even if collection of data started this year. The analyses indicate fairly robustly that the size of the population's relative fecundity has increased since 1993, and is now likely to be greater than the target level of 40% of the 1979 level[1]. Some suggestions for further model development are outlined.

[1] The harvesting target level is taken to refer to relative fecundity in this paper, although this target is formally defined in terms of spawner biomass.

1. INTRODUCTION

The gemfish (*Rexea solandri*) resource off Australia is divided into two stocks. The eastern stock occurs from the SEF boundary at Barrenjoey Point to western Tasmania (Chesson in press). A variety of age-structured stock assessment techniques, including Allen's cohort analysis (Allen 1989), CAGEAN (Deriso *et al.* 1985) and *ad hoc* tuned VPA (Pope and Shepherd 1985) have been applied to data for this stock in the past. This document gives preliminary stock assessments based on the discrete separable population dynamics model described in Appendix A.

The values for the parameters of the population dynamics model are obtained in this paper 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. The sensitivity of the results to applying maximum likelihood and Bayesian estimation approaches is examined. The methodology upon which the maximum likelihood analyses are based is similar to the "stock synthesis" approach (Methot 1989, 1990) while the Bayesian analyses use an extension of the methodology described in Punt *et al.* (1994) and McAllister *et al.* (1994). Although Bayesian stock assessment methods are relatively new in fisheries (for instance, see Hilborn *et al.* 1994; McAllister *et al.* 1994; Givens *et al.* 1995; Walters and Ludwig 1994), they allow the analyst to incorporate (subjective) prior distributions for model parameters. One of the main features of the assessments in this paper is that they use the age-compositions only for those years for which both length-frequency data and age-length keys are available.

2. METHODS

2.1 POPULATION DYNAMICS MODEL

The population dynamics model considered in this analysis (Appendix A) is age- and sex-structured and takes account of ages up to 20 years, with ages over 20 being pooled into a plus-group. The summer and winter fisheries are modelled as pulses at the start of December and in the middle of July respectively. The number of 0-year-olds at the start of the year (December) is taken to be related to the egg production at the end of the preceding year by a Beverton-Holt stock-recruitment relationship, which allows for lognormally-distributed recruitment anomalies. The sex ratio at birth is taken to be 1:1.

The model assumes that the population was distributed about its unexploited equilibrium level at the start of 1969 when the first substantial catches were taken during winter. The selectivity pattern for the winter fishery is assumed to follow a logistic form, while that for the summer fishery is assumed to be dome-shaped. Both selectivity patterns are assumed to be time-invariant. Natural mortality is assumed to be independent of age, but sex-specific. The assumption of sex-specific natural mortality rates is needed to mimic the age-composition of the catches by sex. Natural mortality has been assumed to be independent of age because of the absence of reliable data to specify its age-dependence.

2.2 PARAMETER VALUES

Tables 1 and 2 list the values for the model parameters which are taken to be known exactly (L_∞, κ, t_0, the parameters of the length-mass relationship and fecundity-at-age), and the priors chosen for the remaining parameters. The priors are largely arbitrary and were selected by consensus by a group consisting of Nic Bax, Neil Klaer, Tony Smith and André Punt. They simply reflect a first attempt at specifying prior distributions for the parameters of the model.

2.3 THE LIKELIHOOD FUNCTION

The data available for stock assessment purposes include catches by fishery since 1969, the fraction of the winter catch (in number) which consists of females, catch rate-based indices of relative abundance, catch-at-age data and length-frequency data (length-frequencies are available for some of the years for which age-length keys are missing). Appendix B details the contributions of the various data sources to the negative of the logarithm of the likelihood function.

The catches, and the fraction of the winter catch which consists of females, are given in Table 3. The fraction of females for year y is calculated from the sex-split of the length-frequency data for that year. Table 4 lists the two catch rate-based relative abundance indices. The winter-1 series is based on information on catch-per-standard-day and the winter-2 series on catch-per-hour data from the SEF logbook database. It is inappropriate to use these two series simultaneously in an assessment because they are based on the same data. The base-case analysis (and the bulk of the sensitivity tests) use the winter-1 series, although the sensitivity of the results to using the winter-1 series from 1973 to 1985 and the winter-2 thereafter is examined in one of the sensitivity tests.

When fitting the model, it is necessary to provide specifications for q and c in Equation (B.2). For the maximum likelihood analyses, the estimate of the catchability coefficient, q, is obtained by differentiating Equation (B.2) with respect to q and solving the resultant equation. There are two ways to deal with c, the *CV* of the catch rate data. One of these is to estimate this quantity as a parameter along with q and the other model parameters (labelled "CV Estimated" in the Tables), and the other is to specify the value of this parameter on *a priori* grounds (labelled "CV Fixed" in the Tables). The base-case choice for c for the analyses in which it is fixed has been taken to be 0.15, which is close to its maximum likelihood estimate. The sensitivity of the results to fixing c equal to 0.05 and 0.25 is also examined.

For the Bayesian analyses, it is necessary to specify prior distributions for q and c. The prior for q is taken to be uniform on a log-scale. It can be shown that this choice of prior is non-informative for B_0 (Pikitch *et al.* 1993). Numerical integration across the prior for q has been avoided by using the approach outlined by Walters and Ludwig (1994). The prior for c has been taken to be uniform across the interval [0.1, 0.2].

Table 5 lists the proportion of the catch by the winter fishery (in number) falling into each age-class by sex. The catch-at-age data, upon which the values in Table 5 are based, were obtained by multiplying the annual age-length keys by the length-frequencies. The latter contain values for lengths which are not covered by the age-length keys (usually the smallest and largest size classes). An average age-length key was used to overcome this difficulty. However, as the estimates for ages 0 and 1 are very small and the estimates for old (>10-year-old) fish are pooled, this should not bias the results substantially. In order to include the age-composition data in the analysis, it is necessary to specify the effective number of fish aged each year (see Equation B.6). This must be substantially less than the actual number which are aged each year, because the ageing sample is rarely a simple random sample of the catch. For consistency with some of the analyses conducted by Nic Bax, the effective sample size has been set to 50 for every year for which age-composition data are available.

Length-frequency data are available for some of the years for which age-composition data are unavailable, in addition to being available for all of the years for which age-composition data are available. The approach used to incorporate the contribution of the length-frequency data into the log-likelihood function (see Appendix B) is similar to the "stage 1" method of Methot (1990). Length-frequencies are available by sex for the winter fishery and for both sexes combined for the summer fishery. The effective number of fish sized, N_y'', for the winter fishery is set to 50 for all years which are included in the analysis. It is set to 5 for the summer fishery. The lesser weight given to the data for the summer fishery reflects the lesser confidence in these data expressed by scientists familiar with this fishery. One of the sensitivity tests involves ignoring the age-composition data altogether and using all of the available length-frequency data instead.

K. Rowling (pers. comm.) has suggested that the large contribution of the 1990 and 1991 year-classes in the 1992 and 1993 age-compositions (see Table 5) may reflect early maturation (and hence recruitment to the winter fishery) rather than two large year-classes. Use of the age-composition data for the youngest age-classes may therefore lead to positively biased estimates of year-class strength for those age-classes which have yet to fully-recruit because the model, which assumes that the selectivity pattern is time-invariant, would interpret early maturation as strong recruitment. In order to avoid this possible source of bias, the data for ages 2-4 for females and 2-3 for males are excluded from the likelihood (i.e. $a_{c,y}^1 = 4$ and $a_{c,y}^2 = 5$ for the years for which catch-at-age data are available). For similar reasons, only the contributions from animals larger than

64 cm (summer fishery), 54 cm (winter fishery males) and 64 cm (winter fishery females) are included in the likelihood (see Equations B.8a and B.8b). One of the sensitivity tests ("Use all age/length data") involves dropping these restrictions.

2.4 ESTIMATION PROCEDURES

The prior distributions listed in Table 1 are also incorporated into the maximum likelihood analyses to enhance the comparability of these and the Bayesian analyses. This is achieved by using the limits of the uniform distributions in Table 1 as bounds for the estimates of the model parameters; if a parameter is outside its bounds (for example, if B_0 exceeds 80,000 t), the negative log-likelihood is set to a very large value. The lognormal prior distributions for the recruitment anomalies (both those which constitute the initial conditions and those which apply to births after 1969) are included in the maximum likelihood analyses by adding the following component to the negative of the log-likelihood function:

$$\sum_y \frac{\varepsilon_y^2}{2\sigma_r^2} \qquad (1)$$

where the summation is taken over all 46 recruitment anomalies, and σ_r is assumed to be 0.6 for the base-case analysis (see Table 1).

This is equivalent to treating the recruitments (in absolute terms) as parameters while at the same time allowing for a stock-recruitment relationship (e.g. Fournier and Archibald 1982; Methot 1989, 1990). The implication of the inclusion of Equation (1) in an analysis is that a recruitment anomaly will be assumed to be zero (i.e. recruitment is equal to the prediction from the deterministic component of the stock-recruitment relationship) unless there are data which indicate otherwise. Another way of interpreting the maximum-likelihood results is that they are Bayesian modal results. This is because the maximum-likelihood parameter estimates correspond to the maximum of the posterior distribution.

In summary then, for the base-case maximum likelihood analysis, the values for 62 parameters (B_0, M^m, M^f, h, q, c, the 46 recruitment anomalies (20 for the initial year and one for each of the years 1970 to 1995) and 10 selectivity parameters) are obtained by maximizing the sum of the negative of the log-likelihood function (see Equation B.9) and Equation (1), while the base-case posterior distributions for these parameters are obtained by integrating the likelihood function over the prior distributions. The Metropolis algorithm (see Appendix C) is used to perform the numerical integration needed to calculate the posterior distribution for the Bayesian calculations.

2.5 SENSITIVITY TESTS

2.5.1 MAXIMUM LIKELIHOOD ANALYSIS

The sensitivity of the results to the weight given to the various data sources is examined by dropping the age-composition data ("No age-data") and by changing the (fixed) *CV* assigned to the catch rate series to 0.05 and 0.25 ("CV_{cpue}=0.05" and "CV_{cpue}=0.25" respectively). The other sensitivity tests related to data selections are.

a) Dropping the restriction to age and length data older/larger than pre-specified minimums ("Use all age/length data").

b) Replacing the contribution of the age-composition data to the likelihood by that of the length-frequency data ("Length data only").

c) Omitting the winter-1 catch rates for 1986 onwards from the likelihood and including the winter-2 catch rate series instead ("With winter-2").

d) Omitting the length-frequency data for 1994 ("No 1994 data").

The sensitivity of dropping the term involving the recruitment anomalies (Equation 1) is examined to assess the impact its inclusion into the likelihood ("$\sigma_r=\infty$"). Additional sensitivity tests involve setting the steepness parameter (*h* - see Equation (A.9)) to 0.9, assuming that the natural mortality rates for males and females are the same, assuming that the selectivity pattern for the summer fishery is flat-topped, and changing the *CV* assumed for the recruitment anomalies to 0.8 and 0.4 (labels "Steepness = 0.9", "$M^f = M^m$", "Slope = 0", "σ_r = 0.8" and "σ_r = 0.4" respectively).

2.5.2 BAYESIAN ANALYSES

The Bayesian analyses are much more intensive computationally than the maximum likelihood analyses, so only a small subset of the earlier sensitivity tests is conducted.

a) The age-composition data are ignored ("No age-data").

b) The length-frequency data for 1994 are ignored ("No 1994 data")[2].

c) Allowance is made for correlation among the recruitment anomalies ("With correlation").

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[2] The results for this sensitivity test have been computed from those for the base-case analysis using the resampling technique outlined by Givens *et al.* (1994).

Sensitivity test c) is necessary because the base-case results indicate that there is considerable covariance between successive recruitment anomalies — this is hardly surprising if the reason for the recruitment anomalies is the impact of some (autocorrelated) environmental variable (or variables). However, the (joint) prior distribution for the recruitment anomalies (Equation 1) assumes that these anomalies are independent and this could potentially bias the results. Sensitivity test c) is implemented by replacing the contribution of recruitment anomalies (Equation 1) by an expression which allows for the possibility of inter-annual correlation (see Appendix D for details):

$$\ell n \sqrt{\sigma_r^2 \det \begin{pmatrix} 1 & \tau & \tau^2 \\ \tau & & \tau \\ \tau^2 & \tau & 1 \end{pmatrix}} + \frac{1}{2\sigma_r^2} \begin{pmatrix} \varepsilon_1 \\ \varepsilon_i \\ \varepsilon_{46} \end{pmatrix}^T \begin{pmatrix} 1 & \tau & \tau^2 \\ \tau & & \tau \\ \tau^2 & \tau & 1 \end{pmatrix}^{-1} \begin{pmatrix} \varepsilon_1 \\ \varepsilon_i \\ \varepsilon_{46} \end{pmatrix} \qquad (2)$$

where τ is the correlation between recruitment anomalies for adjacent years.

It is necessary to specify prior distributions for τ and σ_r^2 in order to implement this sensitivity test. There are, however, few data available which can be used to specify informative priors for these parameters (though the data reported by Myers and Barrowman (1995) could, in principle, be used to develop such priors). Instead of specifying informative priors for τ and σ_r^2 based on data for other species, "noninformative" priors ($\tau \sim U[-1,1]$ and $\sigma_r \sim U[0,1.2]$) have been used.

3. RESULTS

3.1 MAXIMUM LIKELIHOOD ANALYSES

Table 6 lists the estimates of eleven management-related quantities and values for two diagnostic statistics for the base-case maximum likelihood analysis and the sensitivity tests. Unless specified otherwise, the parameters estimated for each analysis are: B_0, M^m, M^f, the recruitment residuals, steepness, q, c, and the parameters which define the selectivity ogives. The thirteen statistics reported in Table 6 are:

a) B_0 the virgin exploitable biomass[3].

b) B_{1969}/B_0 the ratio of the exploitable biomass at the start of 1969 to the virgin level (expressed as a percentage).

[3] Exploitable biomass is defined here by the selectivity pattern for the winter fishery and the mass-at-age vector for the summer fishery.

c) B_{1991}/B_0 the ratio of the exploitable biomass at the start of 1991 to the virgin level (expressed as a percentage).

d) B_{1994}/B_0 the ratio of the exploitable biomass at the start of 1994 to the virgin level (expressed as a percentage).

e) B_{1994} the exploitable biomass at the start of 1994.

f) SB_{1991}/SB_{1979} the ratio of egg production at the start of 1991 to that at the start of 1979 (expressed as a percentage).

g) SB_{1994}/SB_{1979} the ratio of egg production at the start of 1994 to that at the start of 1979 (expressed as a percentage).

h) SB_{1995}/SB_{1979} the ratio of egg production at the start of 1995 to that at the start of 1979 (expressed as a percentage).

i) σ the (estimated) *CV* of the residuals about the winter-1 catch rate series.

j) M^m the (age-independent) rate of natural mortality on males.

k) M^f the (age-independent) rate of natural mortality on females.

l) h the "steepness" of the stock-recruitment relationship.

m) -LnL the negative log-likelihood corresponding to the parameter values presented.

3.1.1 BASE-CASE ANALYSIS

The fit of the base-case model (*CV* fixed) to the winter-1 catch rate series is shown in Figure 1(a) and the fit to the catch proportion-at-age data in Figure 2. Figure 3 shows the fit to the length-frequency data for the winter fishery for the years for which age-length keys are unavailable. The fit to the winter-1 catch rate series is good by marine fisheries standards (σ = 0.144). The fits to the age-composition data are also good, although the fits to the data for males are somewhat poorer than those for females (Figure 2). The fits to the length-frequencies (Figure 3) are noticeably poorer than those to the age-composition data, although there is no evidence for systematic patterns in the residuals which might suggest model mis-specification.

Table 6 and Figure 4(a) indicate that the population was at its virgin level in 1969 and increased between 1974 and 1979 in response to the strong 1970-1975 year-classes. Weaker than average year-classes between 1977 and 1979 combined with relatively large catches between 1977 and 1982 led to a marked decline in biomass over the latter period (Figure 4a). Although the catches after

1983 are somewhat lower than those between 1977 and 1982, there is no increase in biomass owing to another sequence of weak year-classes which led to an ever increasing exploitation rate in the winter fishery (Figure 5). The 1990 year-class is very much larger (237%) than that predicted by the (deterministic) fitted stock-recruitment relationship. This is a consequence of the need to fit the high proportion of animals in the 54-64 cm length-class in the length-frequency distribution for males for 1994 (see Figure 3). If the data for 1994 are ignored (Figure 4b; Table 6 "No 1994 data"), the estimates of the recruitment anomalies for the years prior to 1990 are almost the same as those for the base-case. However, the 1990 year-class is much smaller. Note that there is evidence that the 1990 year-class is substantially larger than expected in the age-composition data (a high proportion of two-year-olds in the 1992 catch followed by a high proportion of three-year-olds in the 1993 catch), but these data are not used in the base-case analysis (see Equation B6) for the reason given in Section 2.3.

The base-case estimate of virgin exploitable biomass (17,700 t) is larger than previous estimates of this quantity, although care needs to be taken when comparing estimates from different analyses to ensure that "like is being compared with like". The estimate of current (1994) exploitable biomass is 31% of this at 5,500 t, down slightly from 33% in 1991. The harvesting target level established for this stock is 40% of the relative fecundity (spawner biomass) at the start of 1979 (Chesson in press). The current (1995) relative fecundity is larger than this target level. SB_{1995} is 14% larger than the relative fecundity at the start of 1994 and almost twice as large as the 1991 relative fecundity — the lowest relative fecundity is predicted to have occurred at the start of 1992 when it was 29.3% of the 1979 level. One of the reasons that the relative fecundity is a larger fraction of the 1979 level in 1995 than is exploitable biomass, is that animals of ages 4 and 5 (the very strong 1990 and above-average 1991 year-classes) make a notable contribution to the relative fecundity, whereas they make a much smaller contribution to the exploitable biomass. This occurs because the fecundity (Table 2) of 4- and 5-year-olds is much greater relative to other ages than the product of age-specific selectivity and mass-at-age.

The natural mortality rate for males ($0.484 yr^{-1}$) is larger than that for females ($0.373 yr^{-1}$). This is a consequence of the age-composition data in which males dominate the catch of the younger (<5-year-old) individuals while females comprise the bulk of the catch of older (>7-year-old) animals. The estimate of steepness for the base-case analysis is 0.5 (the minimum value permitted). However, the value for the negative log-likelihood for the "steepness = 0.9" sensitivity test (Table 6) indicates that the data have little power to discriminate among alternative values for this quantity.

As was the case in the past, the stock-recruitment plot suggests that poor recruitment occurred at a comparatively high relative fecundity (Figure 4a) and that the apparently very good 1990 year-class occurred at a smaller relative fecundity. Note that the 1992-1995 year-classes are all assumed to be "average" because, although some of these cohorts have entered the population and some even the fishery, none of the data used in the base-case analysis provides information about how strong these year-classes are.

3.1.2 THE SENSITIVITY TESTS

In general, the qualitative features of the assessment are insensitive to the weight assigned to the various data sources and the specifications of the model (Table 6). The discussion below focuses on the results for "CV fixed" because the results for "CV estimated" are qualitatively the same.

As expected, the fit to the winter-1 catch rate series improves markedly if the age-composition and length-frequency data are ignored altogether (row "No age/length data" in Table 6; Figures 1b and 4c). The fit to these data is also sensitive to the *CV* assumed when evaluating the likelihood (rows "CV_{cpue} = 0.05" and "CV_{cpue} = 0.25" in Table 6; Figures 1c and 1d). It is notable that the declining trend in catch rate from 1987 onwards can only be mimicked if the catch rate data are given greater weight than that assigned by the base-case analysis (contrast the results for "No age/length data" and "CV_{cpue} = 0.05" with those for "base-case" and "CV_{cpue} = 0.25" in Figure 1). Including the winter-2 catch rate series in the analysis leads to a much more pessimistic assessment and the suggestion that the exploitable biomass has declined since 1991 (Figure 4d). The 1995 relative fecundity is again larger than that for 1994 because this analysis also suggests that the 1990 year-class is very strong.

Including all of the age-composition data (i.e. $a^f_{c,y} = a^m_{c,y} = 2$) in the analysis has almost no impact on the estimates for the years before 1991, but suggests that the 1991 year-class is markedly larger than expected (488% of the value predicted by the fitted stock-recruitment relationship) — Figure 4e. This estimate is also evident in a much larger relative fecundity at the start of 1995 (Table 6). Dropping the age-length keys from the analysis has a relatively small impact on the results, although there is an indication of a continued reduction in biomass (Figure 4f). This confirms the view that most of the information in the age-composition data comes from the length-frequency data (or alternatively that the information in the age-length keys complements that in length-frequencies).

Setting the slope of the selectivity function for the summer fishery (γ in Equation A.14) equal to zero has virtually no impact on the results. This is hardly surprising because the length-frequency data for the summer fishery are given very little weight in the fitting process. On the other hand, the other sensitivity test which involves simplifying the model ("$M^f = M^m$") provides a fit which is significantly poorer than that of the base-case model, showing that it is inappropriate to consider the natural mortality rates for males and females as the same. Changing the *CV* assumed for the recruitment anomalies from 0.6 to 0.4

and 0.8 does not affect the results markedly, although increasing it does allow the model to fit the catch rate series slightly better and *vice versa*.

Setting the value of $\sigma_r = \infty$ (effectively dropping the term involving the recruitment anomalies from the likelihood) results in markedly different behaviour (Figure 4g). Without the constraint (prior) on the recruitment anomalies, the estimates of these parameters for 1984 -1990 are much less than the base-case values, and the 1991 year-class is estimated to be over 10 times larger than the value predicted by the stock-recruitment relationship. The recruitment anomalies for the first few years are also larger than the base-case values. Setting $\sigma_r = \infty$ allows the recruitment anomalies to be chosen to fit the data without being constrained by the stock-recruitment relationship in any way. This can lead to extreme values being selected to fit "quirks" in the data (as is the case for the 1991 year-class) which is, of course, undesirable.

3.2 BAYESIAN ANALYSES

3.2.1 BASE-CASE ANALYSIS

The results of the base-case Bayesian analysis are shown in Figures 5 and 6(a). In terms of medians, the results are qualitatively (and quantitatively) the same as those for the base-case maximum likelihood analysis shown in Figure 4(a). This suggests that the results of the Bayesian analysis are dominated by the data rather than by the choice of priors.

As expected, the 90% probability intervals for the early and most recent recruitment anomalies are very wide — the posterior distributions for the recent (post-1992) recruitment anomalies are essentially identical to their priors (Figure 6a) because the available data do not provide information about these recruitments. However, for most of the parameters of the model, the prior distributions are updated markedly by the data (e.g. Figures 7a and 7d). This is also illustrated in Table 7(a) which lists posterior medians, 90% intervals and the ratios of the posterior variances to those of the priors for several parameters. The values of the steepness parameter and the parameters of the selectivity functions for the summer fishery are not well determined by the available data, as illustrated by the near-100% variance ratios. The former is not surprising, because the relative fecundity does not drop into the region where the effect of the stock-recruitment relationship is marked, and the latter is a consequence of the low weight given to the data for the summer fishery. The lack of updating is reflected in Figures 7(b) and (c) which indicate that the prior and posterior distributions are very similar. As expected from the results in Table 6, the model shows a preference for lower rather than higher values for steepness. Although the marginal posteriors for M^f and M^m overlap, the posterior for M^f/M^m (Figure 8) indicates that the model provides strong evidence that the natural mortality rate for females is less than that for males.

The posterior median for B_{1969}/B_0 is larger than unity (although the 90% probability intervals overlap unity) and consequently the posterior medians for B_{1991}/B_0 and B_{1994}/B_0 are larger than the maximum likelihood estimates. Scaling the results to 1969 leads to virtual agreement between the posterior medians and the estimates in Table 6. The estimate of the ratio of 1995 to 1979 relative fecundity is also somewhat more optimistic than the estimates of this ratio in Table 6. The probability that the 1995 relative fecundity is less than 40% of the 1979 level is only 3.5%, although the probability that the 1993 relative fecundity was less than this level is 92.1% (before the strong 1990 year-class entered the spawning population).

Figure 9 shows the marginal posterior distributions for four quantities that are of interest for fisheries management: B_0, B_{1994}, B_{1994}/B_0, and SB_{1995}/SB_{1979}. Although the posterior for B_0 is roughly normal, that for B_{1994} and consequently those for the other two quantities are skewed towards positive values. The posterior for SB_{1995}/SB_{1979} is particularly skew, which explains why the 90% intervals in Table 7(a) for this quantity are markedly nonsymetric. Although the posterior for B_0 is fairly tight (posterior CV = 15.1%), that for B_{1994}/B_0 and particularly that for SB_{1995}/SB_{1979} are less so (posterior CVs of 19.2 and 29.6% respectively). The marked difference in estimation precision between the last two quantities might suggest a preference for basing harvest targets on exploitable biomass rather than relative fecundity.

3.2.2 SENSITIVITY TESTS

The results for the three sensitivity tests are summarised in Figures 6(b) - (d) and Tables 7(b) - (d). The posterior distributions for the "No age/length data" sensitivity test are, as expected, much less tight than those for the base-case analysis. This is most noticeable for the recruitment anomalies (Figure 6b), the model parameters (Table 7b) and B_0 (Figure 10b). Unlike the situation for the base-case analysis, the results of the "No age/length data" analysis do not indicate a substantial reduction in recruitment during the late 1980s and a strong 1990 cohort. Qualitatively, however, the base-case pattern in the recruitment anomalies is captured by this analysis even though it does not use age-composition data. The usefulness of the age-composition data is best highlighted by the results in Table 7(b) — the posterior distributions for the selectivity parameters are virtually identical to their priors and the posterior distributions for the natural mortality rates are markedly wider than for the base-case analysis. Thus, the results of this sensitivity test confirm the intuitive notion that age-composition data are needed to estimate selectivity and natural mortality.

The mean of the posterior for virgin biomass for the "No age/length data" sensitivity test is almost twice as large as the base-case value. However, it is far less precisely determined (Table 7b; Figure 10b) and is relatively close to the prior mean of 45,000 t. This suggests that the posterior distribution for B_0 (and consequently the absolute magnitude of the biomass trajectory) is driven to a considerable extent by the choice of the B_0 prior.

The posterior means for the "No 1994 data" sensitivity test (Figures 6c and 10c and Table 7c) are similar to the point estimates for the corresponding maximum likelihood analysis (Figure 4c), although the mean of the posterior for B_0 is slightly smaller than the point estimate from the maximum likelihood analysis. The posterior distributions for this sensitivity test are generally as tight as those for the base-case. As expected, the results for this sensitivity test differ quite markedly (in terms of posterior medians and widths) from those for the base-case analysis for the more recent recruitment anomalies (Figures 6a and 6c)

Qualitatively, the results of the "With correlation" sensitivity test (Figures 6d and 10d and Table 7d) are similar to those for the base-case analysis. However, there are some notable quantitative differences. For example, the posterior mean for the current (1994) exploitable biomass is 26.7% smaller than the base-case value and is only 26.8% of B_0 (the base-case value is 36.6%). The posterior for B_0 (Figure 10d) is wider than that for the base-case. However, this is a consequence of correlation between B_0, σ_r and τ. Eliminating this correlation results in a posterior for B_0 which is comparably as precise as that for the base-case analysis. The probability that the 1995 relative fecundity is less than 40% of the 1979 level is 44.1% for this sensitivity test (compared with 3.5% for the base-case analysis). This more pessimistic appraisal of current status is a consequence of the much weaker 1990 year-class (Figure 6d). Although the length-frequency data for 1994 suggest that this is a strong year-class, the estimate of the correlation between recruitment anomalies is high (see Figure 11). This high correlation implies that the likelihood of a very strong 1990 year-class after a long sequence of weak year-classes should be relatively small. The "with correlation" sensitivity test thus "downweights" the probability of this occurring through Equation (2).

Figure 11 indicates that the data are able to update the uniform prior distributions assumed for σ_r and τ markedly. The posterior mean for σ_r is 0.80, or 33.3% larger than the value assumed for this parameter in the base-case analysis, although the 90% intervals for σ_r [0.53, 1.12] include the base-case value. The posterior mean for τ is very large although this is not unexpected given similar estimates of this quantity for other marine fish species (Myers and Barrowman 1995, Table 4). Not unexpectedly, the 90% confidence intervals for τ exclude the assumption of a white-noise process (i.e. $\tau = 0$).

4. DISCUSSION

The results of the analyses indicate that the eastern gemfish population declined markedly between 1980 and 1991. The point estimates / posterior means of the ratio of 1991 biomass to B_0 are relatively insensitive to the specifications of the model and range from 7% ("With winter-2/no age data" - ML) to 41% ("No age/length data" - Bayesian). Restricting the results to those which used at least use some of the age-composition and length-frequency data suggests a much narrower range from 22% ("With winter-2" - ML) to 40% ("No 1994 data" - Bayesian). The suggestion that the 1991 relative fecundity was below the harvesting target level of 40% of the 1979 level is indicated by all but one of the analyses which used at least some of the age-composition and length-frequency data ("CV_{cpue} = 0.25" - ML).

The situation in 1994 and beyond is less clear because the results depend rather critically on whether or not the 1990 year-class was much stronger than expected. The majority of the analyses indicate that the 1994 biomass was larger than that in 1991, although the base-case analysis indicates otherwise. The results for relative fecundity are more consistent for recent trends and suggest that this quantity should have increased from its 1991 level. The inability to make strong statements about the status of the population after 1991 is a consequence of the lack of an abundance index for these years. This problem will not be solved by the acquisition of further age-composition and length-frequency information, and urgent consideration must be given to the development of a reliable index of abundance. Unless such an index provides estimates of absolute abundance, it will take several years before it can be incorporated into the stock assessment, with the implication that for the next several years, the reliability of estimated trends in abundance will be relatively poor and sensitive to model assumptions.

The method applied in this document could be extended by basing the calculations on a length-structured rather than an age-structured population dynamics model. Cooke *et al.* (1983) develop a length-structured estimation procedure for sperm whales which could probably be modified for application to eastern gemfish. The application of this approach would be computationally complex, but would simplify the process of specifying prior distributions for the selectivity parameters (selectivity would be a function of length rather than age) and developing the model-estimates of the length-frequencies. The analyses in this document are all based on a single population dynamics model and, in particular, a single functional form for the stock-recruitment relationship. There is a need to examine different models further.

The prior distributions specified in this document are very preliminary, but it appears from Figures 6 and 7 and Table 7 that the results should not be markedly sensitive to alternative specifications for most of them. The results are sensitive to the prior assumed for B_0 (especially if the age/length data are not included in the analysis) and the data provide little information about steepness (h) so that the posterior for this quantity is essentially the same as its prior (Figure 7). The prior selected for the analyses in this paper restricts h to the range 0.5 to 1. This selection is consistent with the estimates of h derived by

Punt *et al.* (1994) for 43 stocks of gadoids, only one of which (NAFO 5Ze silver hake) had an estimate of h less than 0.5. Consideration should be given in future to basing Bayesian analyses on a prior which allows for correlation among recruitment anomalies, even though this is computationally much more intensive than an analysis which assumes the extent of correlation. This is because the estimated performance of alternative harvest regimes can be very sensitive to the level of this correlation (unpublished data).

The analyses in this paper are all based on the assumption that the winter catch rate series are linearly proportional to abundance. If this were not the case and, for example, they were proportional to the square-root of abundance (i.e. catch rate declines more slowly than abundance), the estimates presented here will be overly optimistic (see, for example, the analyses of Andrew and Butterworth (1987) and Patterson and Kirkwood (1995)). Although every effort has been made to select "standard" vessels, areas and times when constructing the catch rate series, the warning of Walters and Ludwig (1994) that "almost all catch rate series contain misleading trends due to temporal changes in gear efficiency and increasing catchability as stock size declines" cannot be ignored. Note that the problems associated with a violation of this assumption pertain not only to the results of this document but to all of the assessments of eastern gemfish presented to SEFAG.

None of the stock assessment methods which have been applied to gemfish have been examined by simulation to assess their likely levels of bias. Such analyses (e.g. Punt 1989; Cordue and Francis 1994) could indicate that some of the methods which have been applied to this stock are either markedly biased or highly imprecise. For example, the analyses presented here are restricted to the use of age-composition data for the years for which age-length keys are available. Other assessments of this stock (e.g. Allen 1989; Chesson in press) are based on a catch-at-age data set for the entire 1969-1994 period. For these assessments, therefore, the age-compositions for the years for which age-length keys are unavailable have to be interpolated (or guessed). Although this might provide unbiased estimates of age-compositions, it is questionable whether it is an appropriate procedure to develop age-compositions for use in age-structured stock assessment methods, because the age-compositions for adjacent years will be highly correlated and this cannot be directly accounted for in the analyses. It would seem reasonable that an approach which uses only the available data should be less likely to provide biased results, but this cannot be shown conclusively without conducting some simulation tests.

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APPENDIX A : THE POPULATION DYNAMICS MODEL

The model considered in this appendix is age- and sex-structured, takes account of two pulse fisheries, and assumes that the number of births is related to the total egg production of the population by means of a Beverton-Holt stock recruitment relationship.

BASIC POPULATION DYNAMICS

The resource dynamics are modelled using the equations:

$$N^s_{y+1,a} = \begin{cases} N^s_{y+1,0} & a = 0 \\ \tilde{N}^s_{y,a-1} & a = 1,\ldots,x-1 \\ \tilde{N}^s_{y,x} + \tilde{N}^s_{y,x-1} & a = x \end{cases} \tag{A.1}$$

where

$N^s_{y,a}$ is the number of fish of sex s and age a at the start of year y,

$\tilde{N}^s_{y,a}$ is the number of fish of sex s and age a at the end of year y,

$$\tilde{N}^s_{y,a} = ((N^s_{y,a}\, e^{-t_1 M^s} - C^{1,s}_{y,a})e^{-t_2 M^s} - C^{2,s}_{y,a})e^{-(1-t_1-t_2)M^s} \tag{A.2}$$

$N^s_{y,0}$ is the number of 0-year-olds of sex s at the start of year y,

M^s is the (age-independent) rate of natural mortality on fish of sex s,

$C^{1,s}_{y,a}$ is the catch (in number) of fish of sex s and age a during the summer fishery of year y,

$C^{2,s}_{y,a}$ is the catch (in number) of fish of sex s and age a during the winter fishery of year y,

t_1 is the time between the start of the year and the mid-point of the summer fishery,

t_2 is the time between the mid-point of the summer fishery and that of the winter fishery, and

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

BIRTHS

$$N^s_{y,0} = 0.5[E_{y-1} / (\alpha + \beta\ E_{y-1})]e^{\varepsilon_y - \sigma_r^2/2} \tag{A.3}$$

where E_y is total egg production at the end of year y:

$$E_y = \sum_{a=1}^{x} f_a\ \tilde{N}^f_{y,a} \tag{A.4}$$

f_a is the fecundity of a female of age a,

ε_y is the recruitment anomaly for year y ($\varepsilon_y \sim N(0;\sigma_r^2)$),

σ_r is the standard deviation of the logarithm of the multiplicative fluctuations in births (approximately the coefficient of variation of the fluctuations in recruitment), and

α, β are the stock-recruitment relationship parameters.

INITIAL CONDITIONS

Were there no fluctuations in recruitment, the resource would be assumed to be at its pre-exploitation equilibrium level, with the corresponding age-structure, at the start of exploitation (year y_1). Instead, because of historic recruitment fluctuations, the sizes of the cohorts at the start of year y_1 are drawn from distributions that allow for this fluctuation, and the initial biomass is thus similarly distributed about the corresponding deterministic equilibrium level. The initial numbers-at-age are given by the equations:

$$\begin{aligned} N^s_{y_1,a} &= 0.5R_0 \exp(-aM^s)e^{\varepsilon_a - \sigma_r^2/2} & 0 \le a \le x-1 \\ N^s_{y_1,x} &= 0.5R_0 \exp(-xM^s) / \{1-\exp(-M^s)\} & a = x \end{aligned} \tag{A.5}$$

where R_0 is the number of 0-year-olds at the deterministic equilibrium that corresponds to an absence of harvesting, and ε_a is a random variable from $N(0{:}\sigma_r^2)$. A value for R_0 is calculated from the value for the virgin biomass at the start of the year, B_0 (where this biomass is defined using the selectivity pattern for the winter fishery and the mass-at-age vector for the summer fishery), using the equation:

$$R_0 = 2\,B_0 \,/\, \sum_s \left\{ \sum_{a=1}^{x-1} w^s_{a-t_2}\, S^{2,s}_a \exp(-aM^s) + w^s_{x-t_2}\, S^{2,s}_x \exp(-xM^s) \,/\, \{1-\exp(-M^s)\} \right\} \quad \text{(A.6)}$$

where $S^{2,s}_a$ is the selectivity of the fishing gear used during the winter fishery on fish of sex s and age a, and

w^s_a is the mass of a fish of sex s and age a during the winter fishery:

$$w^s_a = b^s_1 (L^s_a)^{b^s_2} \quad \text{(A.7)}$$

$$L^s_a = L^s_\infty (1 - e^{-\kappa^s (a - t^s_0)}) \quad \text{(A.8)}$$

Note that the equation for the plus-group does not incorporate a recruitment variability term because this group comprises a large number of age-classes which will largely damp out this effect. Values for the stock-recruitment function parameters α and β are calculated from the values of R_0 and the "steepness" of the stock-recruit relationship (h). The "steepness" is the fraction of R_0 to be expected (in the absence of recruitment variability) when the total egg production is reduced to 20% of its pristine level (Francis 1992), so that:

$$\alpha = \tilde{B}^S_0 \frac{1-h}{4h}$$

$$\beta = \frac{5h-1}{4hR_0} \quad \text{(A.9)}$$

$$\tilde{B}^S_0 = \frac{1}{2} \left\{ \sum_{a=1}^{x-1} f_a \exp(-(a+1)M^f) + f_x \exp(-(x+1)M^f) \,/\, \{1-\exp(-M^f)\} \right\}$$

CATCHES

The catch (in number) of fish of sex s and age a during the summer fishery in year y, $C^{1,s}_{y,a}$, is calculated from $\tilde{C}^1_y$, the catch (in mass) during the summer fishery, using the equation:

$$C^{1,s}_{y,a} = S^{1,s}_a F^1_y N^s_{y,a} e^{-t_1 M^s} \quad \text{(A.10)}$$

where $S_a^{1,s}$ is the selectivity of the gear used during the summer fishery on fish of sex s and age a, and

F_y^1 is the exploitation rate on fully-selected fish during the summer fishery of year y:

$$F_y^1 = \tilde{C}_y^1 / \sum_s \sum_{a=0}^{x} w_{a-t_2}^s \, S_a^{1,s} N_{y,a}^s e^{-t_1 M^s} \tag{A.11}$$

The catch (in number) of fish of sex s and age a during the winter fishery in year y, $C_{y,a}^{2,s}$, is calculated from $\tilde{C}_y^2$, the catch (in mass) during the winter fishery, using the equation:

$$C_{y,a}^{2,s} = \begin{cases} C_{y,a}^{2,s,obs} & \text{if } a < a_{c,y}^s \\ S_a^{2,s} F_y^2 (N_{y,a}^s e^{-t_1 M^s} - C_{y,a}^{1,s}) e^{-t_2 M^s} & \text{otherwise} \end{cases} \tag{A.12}$$

where $a_{c,y}^s$ is the lowest age included in the likelihood for sex s and year y (catches of ages less than this are removed directly under the assumption that they are measured exactly),

$C_{y,a}^{f,s,obs}$ is the observed catch during year y of animals of sex s and age a by fishery f (summer or winter).

F_y^2 is the exploitation rate on fully-selected fish during the winter fishery of year y:

$$F_y^2 = \left(\tilde{C}_y^2 - \sum_s \sum_{a=0}^{a_{c,y}^s - 1} w_a^s \, C_{y,a}^{2,s,obs} \right) / \sum_s \sum_{a=a_{c,y}^s}^{x} w_a^s \, S_a^{2,s} (N_{y,a}^s e^{-t_1 M^s} - C_{y,a}^{1,s}) e^{-t_2 M^s} \tag{A.13}$$

SELECTIVITY

The selectivity pattern (for each fishery / sex) is given by:

$$S_a = \begin{cases} \left(1 + e^{-(a-a_{50})*\delta}\right)^{-1} & \text{if } a < a_{95} \\ \left(1 + e^{-(a-a_{50})*\delta}\right)^{-1} e^{-\gamma(a-a_{95})} & \text{if } a \ge a_{95} \end{cases} \tag{A.14}$$

where a_{50} is the age-at-50%-selectivity,

a_{95} is the age-at-95%-selectivity,

δ is the parameter which defines the width of the selectivity ogive (calculated from the age-at-50%-selectivity and that of 95%-selectivity using the formula: $\delta = \ell n 19 / (a_{95} - a_{50})$), and

γ is a parameter which allows selectivity-at-age to drop off with age.

Eyeballing the data suggests that γ=0 for the winter fishery. There are thus three parameters for each sex for the summer fishery: the age-at-50%-selectivity, the age-at-95%-selectivity, and the selectivity slope parameter, and two for each sex for the winter fishery: the age-at-50%-selectivity, and the age-at-95%-selectivity.

DATA SERIES

The catch rate data for the winter fishery are assumed to be proportional to the exploitable biomass in the middle of the winter fishery:

$$B_y^2 = \sum_s \sum_{a=0}^{x} w_a^s S_a^{2,s} \left[(N_{y,a}^s e^{-t_1 M^s} - C_{y,a}^{1,s}) e^{-t_2 M^s} - C_{y,a}^{2,s} / 2 \right] \tag{A.15}$$

The age-structure information is taken to be proportional to the model-predicted catches-at-age (i.e. $\{C_{y,a}^{1,s}$ and $C_{y,a}^{2,s}\}$). The estimate of the fraction of the catch in 2cm length-class L (L=1,2, .. 43) in year y (for a given sex and fishery) is calculated using the equation:

$$\hat{C}_{y,L} = \sum_a \hat{C}_{y,a} \Phi(a, L) \tag{A.16}$$

where $\Phi(a, L)$ is the probability that a fish of age a lies in length-class L (where length-class L ranges from 28+2*L to 30+2*L cm):

$$\Phi(a, L) = \int_{\ell n(28+2L)}^{\ell n(30+2L)} \frac{1}{\sqrt{2\pi}\,\sigma_a} e^{-\frac{(\ell n\tilde{L} - \ell n L_a)^2}{2(\sigma_a)^2}} d\ell n\tilde{L} \tag{A.17}$$

L_a is the mean length of a fish of age a (computed using the Von Bertalanffy growth equation parameters), and

σ_a is the standard deviation of the logarithm of the length of a fish of age a (the standard deviation of the length of a fish of age 1 is taken to be 3.5cm and that of a fish of age 20, 5cm; the standard deviations for ages 2 to 19 are calculated by linear interpolation between ages 1 and 20).

APPENDIX B : THE LIKELIHOOD FUNCTION

The catch rate time series is assumed to provide indices which are log-normally distributed about their expected values with a constant coefficient of variation, i.e.

$$\ell nO_i = \ell n(qE_i) + \eta_i \qquad \eta_i \sim N(0;c^2) \tag{B.1}$$

where O_i is the i'th catch rate,

E_i is the model-estimate corresponding to O_i,

q is the catchability coefficient, and

c is the coefficient of variation.

The contribution of the catch rate information to the negative log-likelihood function is thus given by:

$$\lambda^1 = -0.5n\ell n(2\pi c^2) - \tfrac{1}{2c^2}\sum_i \left(\ell nO_i - \ell n(qE_i)\right)^2 \tag{B.2}$$

where n is the number of catch rate data points.

The estimates of the fraction of the catch during the winter fishery (in numbers) consisting of females are assumed to be normally distributed about the model-estimates with a standard deviation of σ_f (taken to be 0.2 for all the analyses of this document). The contribution of the datum for year y to the negative of the log-likelihood is thus given by:

$$\lambda_y^2 = -0.5n_f \ell n(2\pi\,\sigma_f^2) - \tfrac{1}{2\sigma_f^2}\left(Q_y - \hat{Q}_y\right)^2 \tag{B.3}$$

where Q_y is the estimate of the fraction of the winter catch during year y (in numbers) which consists of females,

$\hat{Q}_y$ is the model-estimate of Q_y:

$$\hat{Q}_y = \sum_{a=0}^{x} C_{y,a}^{2,f} \Big/ \sum_s \sum_{a=0}^{x} C_{y,a}^{2,s} \tag{B.4}$$

n_f is the number of years for which values of Q_y are available.

The age-structure data contains information on the total number of fish landed as well as the age-composition of the catch. The former is used (implicitly) when projecting the model forward (Equations A.11 and A.13) so only the information about the age-composition of the catches is included in the likelihood function. The observed fraction of the catch (by number) taken in year y comprised of fish of age a is assumed to be multinomially distributed about its expected value, so the contribution to the log-likelihood function of the catch by the winter fishery during year y of animals of sex s and age a is given by:

$$\lambda^{3,s}_{y,a} = N'^{,s}_{y}\, \rho^{s,obs}_{y,a}\, \ell n \hat{\rho}^{s}_{y,a} \tag{B.6}$$

where $N'^{,s}_{y}$ is the effective number of fish aged for sex s during year y,

$\rho^{s,obs}_{y,a}$ is the observed proportion of the catch by the winter fishery during year y of sex s (by number) which animals of age a make up of the catch of animals not younger than age $a^{s}_{c,y}$:

$$\rho^{s,obs}_{y,a} = C^{2,s,obs}_{y,a} \Big/ \sum_{a'=a^{s}_{c,y}}^{x} C^{2,s,obs}_{y,a'} \tag{B.6a}$$

$\hat{\rho}^{s}_{y,a}$ is the model-predicted value of $\rho^{s,obs}_{y,a}$:

$$\hat{\rho}^{s}_{y,a} = C^{2,s}_{y,a} \Big/ \sum_{a'=a^{s}_{c,y}}^{x} C^{2,s}_{y,a'} \tag{B.6b}$$

In order to improve the numeric stability of the calculations, an "offset adjust" (Bergh 1986) is added to the contribution to the log-likelihood function:

$$\lambda^{3,s}_{y,a} = N'^{,s}_{y}\, \rho^{s,obs}_{y,a}\, \ell n(\hat{\rho}^{s}_{y,a} / \rho^{s,obs}_{y,a}) \tag{B.7}$$

The length composition data are also assumed to be multinomially distributed about their expected values. The contribution to the log-likelihood function (including the offset adjustment) of the length composition data for 2cm length-class L for year y, sex s and fishery f is given by:

$$\lambda^{4f,s}_{y,L} = N''^{,f,s}_{y}\, \theta^{f,s,obs}_{y,L}\, \ell n(\hat{\theta}^{f,s}_{y,L} / \theta^{f,s,obs}_{y,L}) \tag{B.8}$$

where $N''^{,f,s}_{y}$ is the effective number of fish sized for sex s and fishery f in year y,

$\theta_{y,a}^{f,s,obs}$ is the observed proportion of the catch by fishery f during year y of sex s (by number) which animals in length-class L make up of the catch of animals not smaller than $L_{c,y}^{f,s}$

$$\theta_{y,a}^{f,s,obs} = C_{y,L}^{f,s,obs} / \sum_{L'=L_{c,y}^{f,s}}^{L_{\max}} C_{y,L'}^{f,s,obs} \tag{B.8a}$$

$\hat{\theta}_{y,a}^{f,s}$ is the model-predicted value of $\theta_{y,a}^{f,s,obs}$:

$$\hat{\theta}_{y,a}^{f,s} = C_{y,L}^{f,s} / \sum_{L'=L_{c,y}^{f,s}}^{L_{\max}} C_{y,L'}^{f,s} \tag{B.8b}$$

The length-frequencies for the summer fishery are not disaggregated by sex so when determining the contribution of these data to the log-likelihood, the sex superscript in Equation (B.8) is ignored and Equations (B.8a) and (B.8b) are modified so that the catches of both sexes combined are used in the calculation of θ and $\hat{\theta}$.

In summary then, for the base-case analyses, the negative log-likelihood has contributions from four sources: the catch rate series for the winter fishery, the estimates of the fraction of the catch during the winter fishery which consists of females, the age-composition data, and the length-frequency data:

$$-\ell nL = \lambda^1 + \sum_y \lambda_y^2 - \sum_s \sum_y \sum_a \lambda_{y,a}^{3,s} - \sum_f \sum_s \sum_y \sum_L \lambda_{y,L}^{4,f,s} \tag{B.9}$$

The summations in Equation (B.9) are restricted to years / ages / lengths for which data are available (for example, age-composition data are available for the years 1980, 1982, 1984, 1986, 1988, 1990, 1991, 1992 and 1993 only)

APPENDIX C: THE METROPOLIS ALGORITHM

The purpose of the Metropolis algorithm (Hastings 1970) is to sample random variables from an arbitrary distribution, $g(X)$. In this case, the distribution $g(X)$ is the posterior distribution (i.e. $g(X) = P(X|D) \propto L(D|X)p(X)$, where $L(D|X)$ is likelihood of the data set D given a parameter vector X, and $p(X)$ is the prior probability of the parameter vector X). The values in the sample can then be used to calculate expected values and variances for functions of the parameter vector X (e.g. current biomass, risk, etc.).

For the implementation considered in this document, evaluation of $L(D|X)$ involves projecting the age- and sex-structured population dynamics model forward, using known catches, to predict stock biomasses and then calculating the likelihood for the projection. If any of the exploitation rates (see Equations

(A.11) and (A.13)) rise above the maximum possible (0.99), the likelihood is set to zero.

The Metropolis algorithm involves selecting an initial parameter vector X_0 and generating a Markov chain $X_1, X_2, \ldots$. The sample from $g(X)$ is every n'th value in the chain (where n is selected so that the covariance between X_{in} and $X_{(i+1)n}$ is sufficiently small that it can be ignored safely - in this case n is taken to be 20).

The algorithm proceeds by specifying the initial state X_0 (where X is a vector of length m), calculating $Y_0 = g(X_0)$ and defining a vector of tolerances Δ. To update X_0 to X_1 (or more generally to update X_i to X_{i+1}), the following steps are carried out for each element of X ($X_{i,j}$).

a) Generate a "proposal" $X'_{0,j}$ from the uniform distribution on the interval $\left[X_{0,j} - \Delta_j, X_{0,j} + \Delta_j\right]$.

b) Calculate $Y'_0 = g(X'_0)$.

c) Generate a random variable U from the uniform distribution on the interval [0,1]. If $Y'_0 / Y_0 > U$ the "proposal" is accepted, $X_1 = X'_0$ and $Y_1 = Y'_0$, end.

d) The "proposal" X'_0 was not accepted so $X_1 = X_0$ and $Y_1 = Y_0$, end.

Steps a) - d) [referred to as a cycle] are repeated a large number of times (200,000 in this document). The vector of tolerances Δ is updated dynamically. The algorithm for doing this is to keep a record of the proportion of times the "proposal" for element j is accepted and increase the jth element of Δ by 1% if this proportion is greater than 0.5 and *vice versa*. This updating is conducted every 5 - 10 cycles. The results of the first 1,000 cycles are ignored, as this is a "burn-in" period for the algorithm to set itself up.

APPENDIX D : THE DERIVATION OF EQUATION (2)

The "with correlation" sensitivity test is based on the assumption that the recruitment anomaly for year y, ε_y, is correlated with those for all previous years. Reasons for such a correlation include correlations among the environmental variables which are likely to impact the size of the deviation from the stock-recruitment relationship. For the purposes of the analyses of this paper, it is assumed that this correlation structure can be modelled by a ARMA-1 process:

$$\varepsilon_y = \tau\, \varepsilon_{y-1} + \chi \varepsilon'_y \tag{D.1}$$

where $\varepsilon_y^{'}$ is a independent random variate from $N(0;1^2)$.

The variance of ε_y: y=1,2, ... ∞ is defined to be equal to σ_r^2 so

$$\begin{aligned}\sigma_r^2 &= E(\varepsilon_y \varepsilon_y) \\ &= E\left((\tau\,\varepsilon_{y-1} + \chi\varepsilon_y^{'})(\tau\,\varepsilon_{y-1} + \chi\varepsilon_y^{'})\right) \\ &= E(\tau^2\varepsilon_{y-1}^2) + 2E(\tau\,\chi\,\varepsilon_{y-1}\varepsilon_y^{'}) + E(\chi^2\varepsilon_y^{'2}) \\ &= \tau^2 E(\varepsilon_{y-1}^2) + 2\tau\,\chi\,E(\varepsilon_{y-1}\varepsilon_y^{'}) + \chi^2 E(\varepsilon_y^{'2}) \\ &= \tau^2\sigma_r^2 + 0 + \chi^2\end{aligned} \tag{D.2}$$

The term $E(\varepsilon_{y-1}\varepsilon_y^{'})$ is equal to zero because ε_{y-1} and $\varepsilon_y^{'}$ are independent and both have expectation zero. Solving for σ_r^2 leads to an expression for χ:

$$\chi = \sqrt{1-\tau^2} \tag{D.3}$$

Equation (D.1) can therefore be re-written as:

$$\varepsilon_y = \tau\,\varepsilon_{y-1} + \sqrt{1-\tau^2}\varepsilon_y^{'} \tag{D.4}$$

As the recruitment anomalies are not uncorrelated, their joint prior is not simply the product of the individual (independent) priors; Equation (1) of the main text is the negative of the logarithm of such a prior after the removal of constants. It is necessary to construct a joint multivariate normal prior for the recruitment anomalies which incorporates the correlation structure of Equation (D.4). The generic form for such a prior is given by:

$$P(\underline{\varepsilon}) = \frac{1}{(2\pi)^{n/2}\sqrt{\det \mathbf{V}}}\exp\left(-\tfrac{1}{2}\underline{\varepsilon}^T\,\mathbf{V}^{-1}\,\underline{\varepsilon}\right) \tag{D.5}$$

where n is the number of elements in $\underline{\varepsilon}$

$\mathbf{V}$ is the variance-covariance matrix ,i.e.:

$$\mathbf{V} = \begin{pmatrix} E(\varepsilon_1\varepsilon_1) & E(\varepsilon_1\varepsilon_2) & E(\varepsilon_1\varepsilon_3) \\ E(\varepsilon_2\varepsilon_1) & E(\varepsilon_2\varepsilon_2) & E(\varepsilon_2\varepsilon_3) \\ E(\varepsilon_3\varepsilon_1) & E(\varepsilon_3\varepsilon_2) & E(\varepsilon_3\varepsilon_3) \end{pmatrix} \tag{D.6}$$

for case of n = 3.

The elements of **V** are determined as follows (for $i > j$):

$$\begin{aligned}
E(\varepsilon_i \varepsilon_j) &= E(\varepsilon_j \varepsilon_i) \\
&= E\left(\varepsilon_j (\tau\, \varepsilon_{i-1} + \sqrt{1-\tau^2}\varepsilon_i^{'})\right) \\
&= E\left(\varepsilon_j ((\tau^2 \varepsilon_{i-2} + \sqrt{1-\tau^2}\varepsilon_{i-1}^{'}) + \sqrt{1-\tau^2}\varepsilon_i^{'})\right) \\
&= E\left((\varepsilon_j (\tau^{(i-j)} \varepsilon_j + \sum_{k=j+1}^{i} \tau^{i-k} \sqrt{1-\tau^2}\varepsilon_k^{'})\right) \\
&= \tau^{(i-j)} E(\varepsilon_j \varepsilon_j) \\
&= \tau^{(i-j)} \sigma_r^2
\end{aligned} \tag{D.7}$$

Substituting Equation (D.7) into Equation (D.5), taking logarithms, negating and dropping the 2π term leads to Equation (2).

TABLE 1 : THE BASE-CASE VALUES OF / PRIOR DISTRIBUTIONS FOR THE MODEL PARAMETERS.

Parameter	Male	Female	Both sexes
B_0			U[10 000, 80 000t]
M (yr^{-1})	U[0, 0.6]	U[0, 0.6]	
Steepness - h			U[0.5, 1]
ℓnq			U[-∞,∞]
c			U[0.1, 0.2]
L_∞ (cm)	97.5	109.0	
κ (yr^{-1})	0.212	0.18	
t_0 (yr)	-0.54	-0.63	
b_1 (gm cm^{-3})			$0.143.10^{-5}$
b_2			3.39
ε_v			$N(0;\sigma_r^2)$
σ_r			0.6
plus-group - x (yr)			20
a_{50} - summer fishery	U[2, 4]	U[2, 4]	
a_{95} - summer fishery	U[2, 6]	U[2, 6]	
γ - summer fishery	U[0.1, 0.3]	U[0.1, 0.3]	
a_{50} - winter fishery	U[4, 6]	U[4, 6]	
a_{95} - winter fishery	U[4, 8]	U[4, 8]	
Start of year			begin-December
Summer fishery			begin-December
Winter fishery			mid-July

TABLE 2 : ESTIMATES OF RELATIVE FECUNDITY-AT-AGE.

Age	1	2	3	4	5	6	7	8	9	10	11	12+
Relative fecundity	0	0	0	0.7	1.0	1.3	1.7	2.0	2.4	2.7	3.4	4.0

TABLE 3:

The catch data. The catch-by-mass for each year (in tons) is broken down into that taken during the summer fishery and that taken during the winter fishery. The column "fraction female" provides estimates for some years of the fraction of the catch (in number) which is made up by females.

	Fishery		
	Summer	Winter	
Year	Catch (in mass) $\tilde{C}_y^1$	Catch (in mass) $\tilde{C}_y^2$	Fraction female Q_y
1969	20	200	
1970	30	200	
1971	40	230	
1972	60	420	
1973	20	1 110	
1974	20	900	
1975	40	920	
1976	40	2 100	
1977	170	3 100	
1978	450	4 700	
1979	460	3 900	
1980	440	5 100	0.562
1981	190	4 100	
1982	270	3 600	0.547
1983	305	3 100	0.560
1984	300	2 800	0.567
1985	205	2 900	0.505
1986	130	3 450	0.565
1987	80	4 200	0.484
1988	175	3 500	0.500
1989	175	2 2C0	0.575
1990	80	1 200	0.573
1991	50	300	0.611
1992	30	790	0.728
1993	70	450	0.577
1994	25	175	

TABLE 4 :

The indices of relative abundance for the winter fishery. Entries indicated by asterisks are ignored in the analyses of this document. Source: K. Rowling (NSW, Fish. Res. Inst., pers commn).

Year	Winter-1	Winter-2
1969	462*	-
1970	311*	-
1971	689*	-
1972	1214*	-
1973	3403	-
1974	3732	-
1975	3039	-
1976	3873	-
1977	3715	-
1978	4078	-
1979	3109	-
1980	3414	-
1981	2716	-
1982	1982	-
1983	1059	-
1984	1131	-
1985	1391	-
1986	1269	279
1987	1535	358
1988	-	349
1989	1297	242
1990	1151	203
1991	1021	114
1992	-	147*
1993	-	33*
1994	-	-

TABLE 5:

Catch proportion-at-age matrices by sex for the winter fishery. The proportions are pooled at the largest age given (i.e. age-class "10+" includes all fish aged 10 and older).

(a) Males

Year	Age								
	2	3	4	5	6	7	8	9	10+
1980	0	0	0.057	0.290	0.334	0.205	0.095	0.017	0.002
1982	0	0.007	0.104	0.255	0.399	0.141	0.062	0.026	0.007
1984	0.005	0.049	0.228	0.365	0.253	0.076	0.020	0.004	0.000
1986	0.003	0.035	0.220	0.392	0.240	0.091	0.013	0.006	0.000
1988	0.007	0.058	0.150	0.483	0.237	0.057	0.006	0.003	0.000
1990	0.006	0.018	0.150	0.171	0.367	0.212	0.053	0.022	0.002
1991	0.009	0.039	0.281	0.313	0.154	0.071	0.094	0.028	0.012
1992	0.049	0.016	0.045	0.136	0.277	0.270	0.106	0.070	0.032
1993	0.064	0.273	0.070	0.071	0.113	0.218	0.123	0.059	0.009

(b) Females

Year	Age								
	2	3	4	5	6	7	8	9	10+
1980	0	0	0.012	0.090	0.254	0.295	0.151	0.085	0.113
1982	0	0.003	0.016	0.088	0.364	0.254	0.121	0.076	0.077
1984	0	0.002	0.022	0.174	0.344	0.220	0.126	0.059	0.053
1986	0	0.006	0.037	0.194	0.387	0.209	0.090	0.042	0.035
1988	0	0.015	0.017	0.239	0.396	0.201	0.075	0.033	0.025
1990	0	0.002	0.020	0.074	0.286	0.329	0.165	0.076	0.048
1991	0	0.006	0.065	0.206	0.283	0.247	0.127	0.038	0.027
1992	0.001	0.003	0.012	0.101	0.308	0.284	0.156	0.096	0.039
1993	0.005	0.032	0.014	0.035	0.100	0.262	0.277	0.173	0.102

TABLE 6 :

Estimates of management-related quantities and values of diagnostic statistics for the base-case maximum likelihood analysis and the sensitivity tests.

(a) CV Fixed

Acronym	B_0	B_y/B_0(%)			B_{1994}	SB_y/SB_{1979} (%)			σ	M^m	M^f	h	-LnL
		1969	1991	1994		1991	1994	1995					
Base-case	17734	99	33	31	5473	33	50	57	0.144	0.484	0.373	0.500	75.2
$\sigma_r=\infty$	17359	233	36	23	3991	22	25	141	0.120	0.600	0.485	0.461[4]	81.9
σ_r=0.8	18031	100	33	28	4965	30	45	55	0.135	0.510	0.400	0.500	83.1
σ_r=0.4	18777	98	34	35	6564	39	54	61	0.162	0.480	0.367	0.500	67.1
Steepness = 0.9	17107	98	34	33	5724	34	54	66	0.146	0.468	0.359	0.9	76.0
Slope=0	18775	97	31	29	5528	33	50	58	0.144	0.477	0.373	0.500	75.3
$M^f=M^m$	18137	95	30	30	5452	34	56	63	0.141	0.385	0.385	0.500	80.7
CV_{cpue}=0.05	17452	96	28	22	3879	24	34	41	0.098	0.510	0.401	0.500	115.6
CV_{cpue}=0.25	19187	99	38	37	7085	42	64	72	0.187	0.488	0.373	0.500	68.8
With winter-2	17199	97	22	19	3351	24	33	40	0.138	0.435	0.336	0.500	90.2
With winter-2/ No age data	18777	91	7	31	5838	32	36	39	0.060	0.393	0.346	0.500	-12.9
No age/length data	17945	98	27	55	9894	47	53	57	0.047	0.600	0.554	0.501	-18.4
Use all age/length data	18444	98	34	33	6132	32	62	135	0.141	0.513	0.403	0.984	103.7
Length data only	16704	96	30	25	4103	30	44	50	0.142	0.401	0.318	0.500	75.3
No 1994 data	17784	98	32	31	5520	35	38	43	0.143	0.474	0.366	0.501	63.4

[4] This sensitivity test was implemented by dropping all "priors" from the analysis, including that which restricts steepness to lie between 0.5 and 1.

(TABLE 6 CONTINUED)

(b) CV Estimated

Acronym	B_0	B_y/B_0(%)			B_{1994}	SB_{1995}/SB_{1979}			σ	M^m	M^f	h	-LnL
		1969	1991	1994		1991	1994	1995					
Base-case	17898	99	32	30	5309	32	48	56	0.139	0.481	0.371	0.500	41.0
$\sigma_r=\infty$	17188	66	36	22	3782	21	22	128	0.113	0.620	0.501	0.593	46.5
$\sigma_r=0.8$	18233	98	30	26	4722	29	44	53	0.130	0.488	0.384	0.500	48.7
$\sigma_r=0.4$	19481	98	35	36	7106	42	58	65	0.178	0.473	0.358	0.500	32.7
Steepness = 0.9	16949	98	33	33	5568	34	54	65	0.143	0.459	0.352	0.9	41.8
Slope=0	18149	98	32	30	5367	32	49	57	0.140	0.474	0.371	0.500	41.0
$M^f=M^m$	18077	95	29	29	5306	33	54	61	0.137	0.371	0.371	0.500	46.1
No age/length data	21086	84	20	37	7856	41	72	79	0.000	0.417	0.383	0.853	-285.9
Use all age/length data	17956	100	34	32	5800	31	57	122	0.134	0.528	0.417	0.730	69.4
Length data only	17434	93	28	22	3913	29	42	48	0.134	0.399	0.309	0.500	41.3
No 1994 data	18010	97	31	30	5409	34	37	42	0.140	0.470	0.365	0.500	29.2

TABLE 7 :

Posterior means, ratios of the posterior variances to prior variances and posterior 90% intervals for the base-case Bayesian analysis and the three sensitivity tests.

(a) Base-case

Quantity	Posterior Mean	Variance ratio	Lower 5% Point	Upper 95% Point
B_0	17139	1.6	13241	21553
B_{1994}	6191	-	4516	8219
B_{1969}/B_0	1.152	-	0.815	1.584
B_{1991}/B_0	0.396	-	0.276	0.533
B_{1994}/B_0	0.366	-	0.265	0.489
SB_{1991}/SB_{1979}	0.392	-	0.314	0.485
SB_{1994}/SB_{1979}	0.543	-	0.522	0.817
SB_{1995}/SB_{1979}	0.681	-	0.651	1.050
M^m	0.501	10.0	0.407	0.586
M^f	0.388	8.2	0.303	0.468
h	0.706	97.8	0.513	0.961
Summer fishery				
a_{50} (males)	2.99	98.3	2.10	3.90
a_{95} (males)	4.10	102.3	2.23	5.83
a_{50} (females)	2.99	100.2	2.09	3.89
a_{95} (females)	4.19	102.0	2.24	5.86
Winter fishery				
a_{50} (males)	4.75	3.6	4.56	4.93
a_{95} (males)	6.18	4.8	5.76	6.59
a_{50} (females)	5.68	4.6	5.48	5.89
a_{95} (females)	7.19	7.3	6.69	7.73

(TABLE 7 CONTINUED)

(b) No age/ length data

Quantity	Posterior Mean	Variance ratio	Lower 5% Point	Upper 95% Point
B_0	33175	37.1	18262	59827
B_{1994}	20190	-	8918	41918
B_{1969}/B_0	1.197	-	0.873	1.637
B_{1991}/B_0	0.414	-	0.270	0.397
B_{1994}/B_0	0.605	-	0.369	0.941
SB_{1991}/SB_{1979}	0.474	-	0.320	0.684
SB_{1994}/SB_{1979}	0.577	-	0.369	0.870
SB_{1995}/SB_{1979}	0.632	-	0.404	0.984
M^m	0.337	49.2	0.153	0.548
M^f	0.307	49.2	0.129	0.530
h	0.735	99.0	0.522	0.969
Summer fishery				
a_{50} (males)	3.00	99.6	2.10	3.90
a_{95} (males)	4.22	100.7	2.26	5.86
a_{50} (females)	2.99	100.2	2.10	3.90
a_{95} (females)	4.22	98.2	2.29	5.86
Winter fishery				
a_{50} (males)	5.01	93.6	4.12	5.89
a_{95} (males)	6.05	96.5	4.21	7.79
a_{50} (females)	4.91	92.8	4.09	5.86
a_{95} (females)	6.13	97.4	4.22	7.83

(TABLE 7 CONTINUED)

(c) No 1994 data

Quantity	Posterior Mean	Variance ratio	Lower 5% Point	Upper 95% Point
B_0	17185	1.3	13490	20855
B_{1994}	6381	-	4598	8368
B_{1969}/B_0	1.158	-	0.853	1.574
B_{1991}/B_0	0.399	-	0.293	0.511
B_{1994}/B_0	0.375	-	0.276	0.482
SB_{1991}/SB_{1979}	0.364	-	0.286	0.446
SB_{1994}/SB_{1979}	0.470	-	0.311	0.702
SB_{1995}/SB_{1979}	0.572	-	0.368	0.908
M^m	0.502	9.0	0.406	0.582
M^f	0.397	8.0	0.309	0.461
h	0.711	99.5	0.515	0.973
Summer fishery				
a_{50} (males)	2.98	100.6	2.08	3.88
a_{95} (males)	4.26	93.7	2.35	5.90
a_{50} (females)	3.04	117.9	2.09	3.92
a_{95} (females)	4.26	97.5	2.25	5.80
Winter fishery				
a_{50} (males)	4.76	3.4	4.59	4.95
a_{95} (males)	6.16	4.2	5.79	6.53
a_{50} (females)	5.71	4.5	5.51	5.90
a_{95} (females)	7.25	7.6	6.78	7.78

(TABLE 7 CONTINUED)

(d) With correlation

Quantity	Posterior Mean	Variance ratio	Lower 5% Point	Upper 95% Point
B_0	19488	21.0	10919	37320
B_{1994}	4536	-	3175	6223
B_{1969}/B_0	1.128	-	0.451	2.079
B_{1991}/B_0	0.360	-	0.157	0.583
B_{1994}/B_0	0.268	-	0.113	0.441
SB_{1991}/SB_{1979}	0.321	-	0.256	0.401
SB_{1994}/SB_{1979}	0.313	-	0.189	0.490
SB_{1995}/SB_{1979}	0.467	-	0.234	0.839
M^m	0.535	5.7	0.435	0.596
M^f	0.422	5.7	0.331	0.497
h	0.739	41.1	0.517	0.970
Summer fishery				
a_{50} (males)	2.99	106.9	2.09	3.90
a_{95} (males)	4.10	85.2	2.25	5.85
a_{50} (females)	3.02	101.2	2.11	3.91
a_{95} (females)	4.18	106.7	2.23	5.86
Winter fishery				
a_{50} (males)	4.74	3.5	4.55	4.93
a_{95} (males)	6.18	4.8	5.75	6.62
a_{50} (females)	5.68	6.0	5.48	5.89
a_{95} (females)	7.16	9.7	6.66	7.71

FIGURE CAPTIONS

Figure 1 : Observed and model-predicted winter-1 catch rates for (a) the base-case, (b) the "No age/length data", (c) the "CV_{cpue} = 0.05" and (d) the "CV_{cpue} = 0.25" analyses. Results are shown for the "CV fixed" variant of the maximum-likelihood estimator.

Figure 2 : Observed (solid lines) and "CV fixed" base-case model-predicted catch-proportions-at-age (dotted lines). Results are shown in (a) for males and in (b) for females.

Figure 3 : Observed (solid lines) and "CV fixed" base-case model-predicted length-frequency distributions for the winter fishery (dotted lines).

Figure 4 : Plots of exploitable biomass as a fraction of virgin level (upper left panel), exploitable biomass for the summer and winter fisheries and the biomass corresponding to B_0 (upper right panel), EXP(recruitment anomaly) (lower left panel) and the relative fecundity - births plot (lower right panel). Results ("CV fixed") are shown for (a) the base-case, (b) the "No 1994 data", (c) the "No age/length data", (d) the "With winter-2", (e) the "$\sigma_r = \infty$", (f) the "Use all/length age data", and (g) the "Length data only" analyses.

Figure 5 : Trajectories of exploitation rate for the winter fishery (F_y^1 in Equation A.10) for the base-case maximum likelihood (upper panel) and Bayesian (lower panel) analyses. The dotted lines in the lower panel are 90% intervals.

Figure 6 : Plots of exploitable biomass as a fraction of virgin level (upper left panel), exploitable biomass corresponding to B_0 (upper right panel), EXP(recruitment anomaly) (lower left panel) and the relative fecundity (lower right panel). Results are shown for (a) the base-case, and (b) the "No age/length data", (c) the "No 1994 data" and (d) the "With correlation" analyses. The solid lines represent trajectories of distribution medians while the dotted lines are 90% probability intervals.

Figure 7 : Histograms reflecting prior and base-case posterior distributions for four population model parameters: (a) M^m, (b) h, (c) a_{50}^m for the summer fishery and (d) a_{50}^m for the winter fishery. The posterior distributions are shown by the open hatched bars and the priors by the solid bars.

Figure 8 : Base-case posterior distribution for the ratio M^f/M^m.

Figure 9 : Base-case posterior distributions for four management-related quantities: B_0, B_{1994}, B_{1994}/B_0, and SB_{1995}/SB_{1979}.

Figure 10 : Histograms reflecting prior distributions (solid bars) and posterior distributions (open hatched bars) for B_0. Results are shown for the base-case Bayesian analysis and for the three tests of sensitivity.

Figure 11 : Histograms reflecting prior and "with correlation" posterior distributions for the population model parameters σ_r and τ. The posterior distributions are shown by the open hatched bars and the priors by the solid bars.

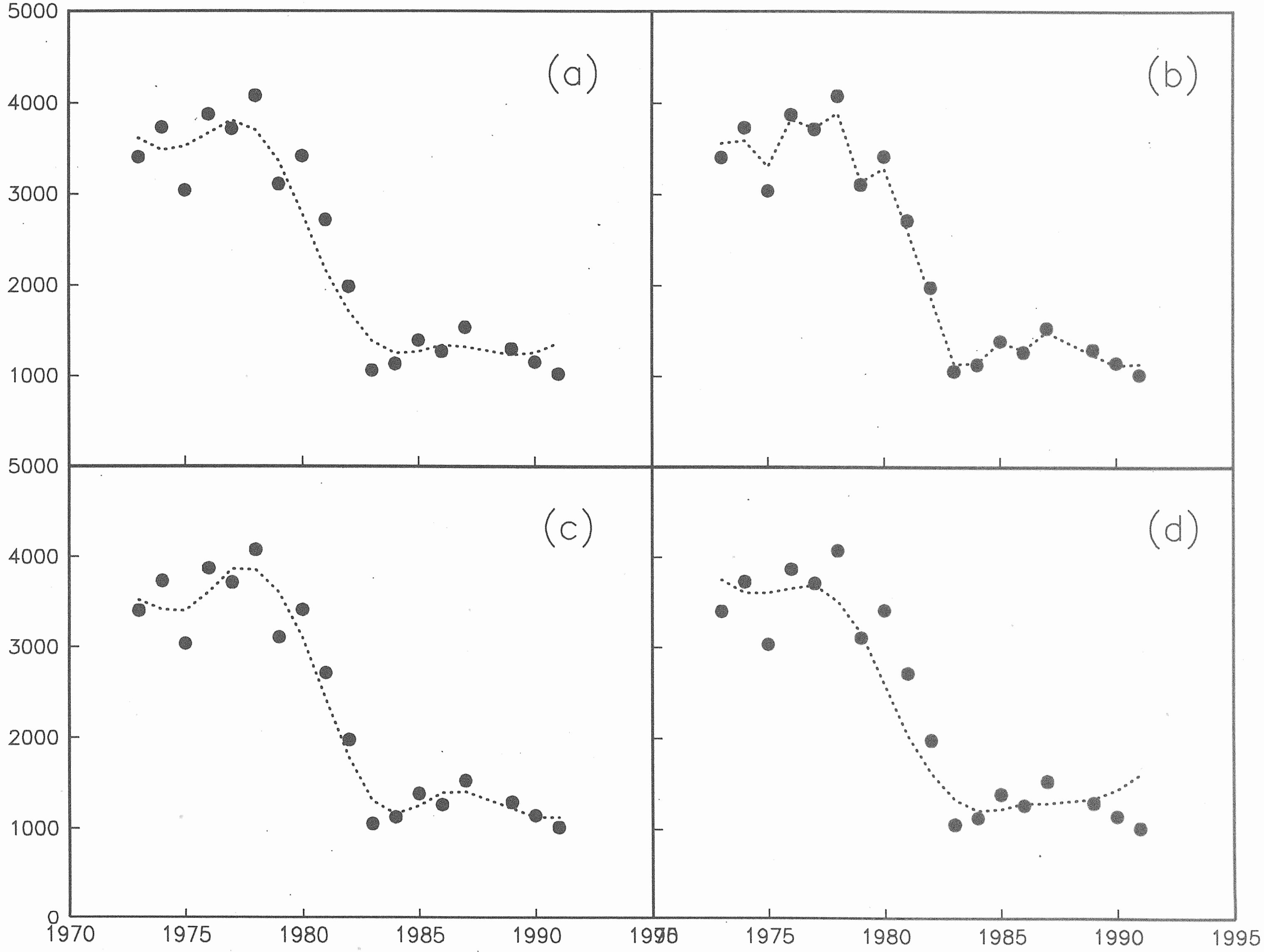

5000
4000
3000
2000
1000
(a)
(b)
5000
4000
3000
2000
1000
0
(c)
(d)
1970
1975
1980
1985
1990
1995

Figure 1

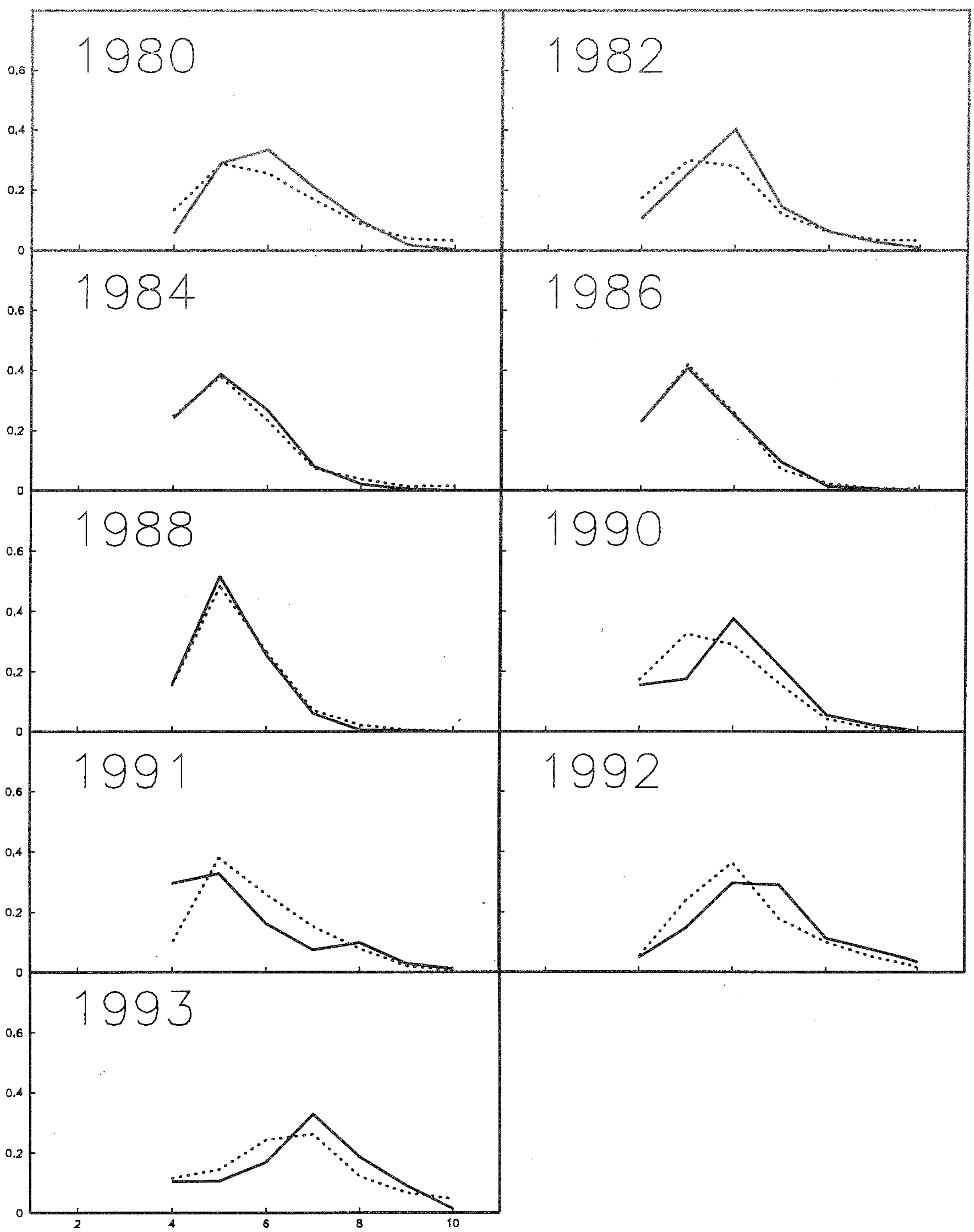


Figure 2(a)

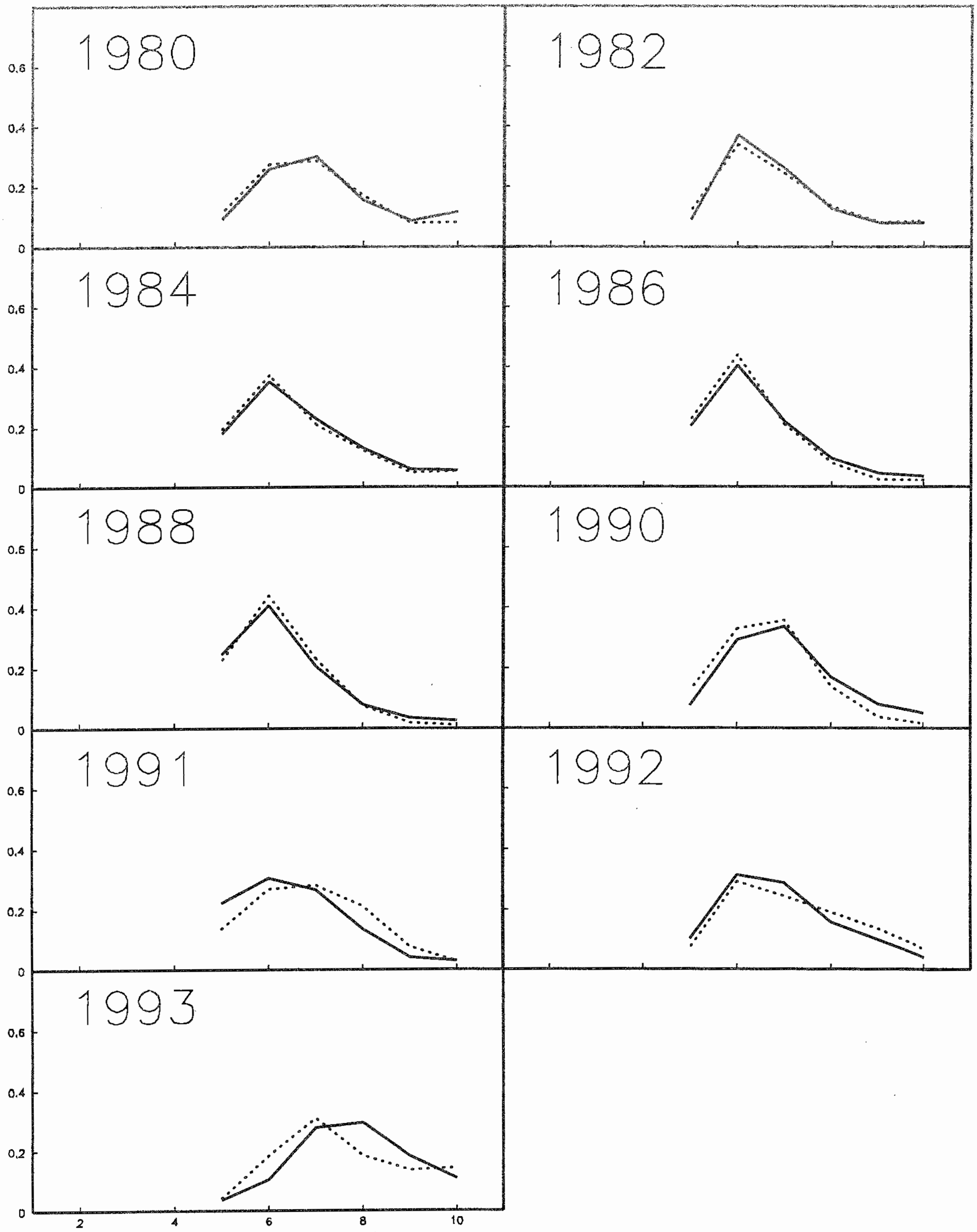


Figure 2(b)

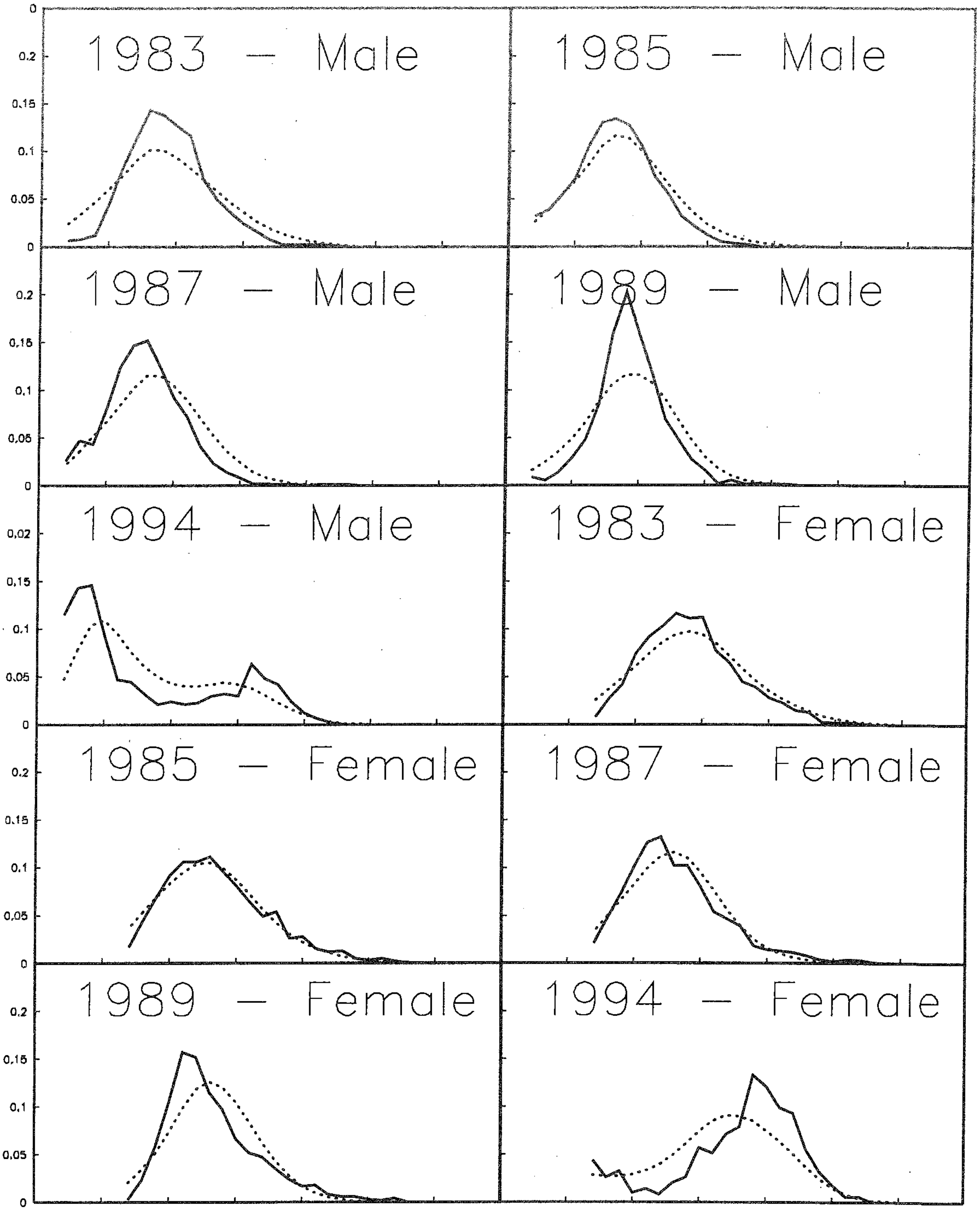

1983 - Male
1985 - Male
1987 - Male
1989 - Male
1994 - Male
1983 - Female
1985 - Female
1987 - Female
1989 - Female
1994 - Female
0
0.2
0.15
0.1
0.05
0.02

Figure 3

Base-case

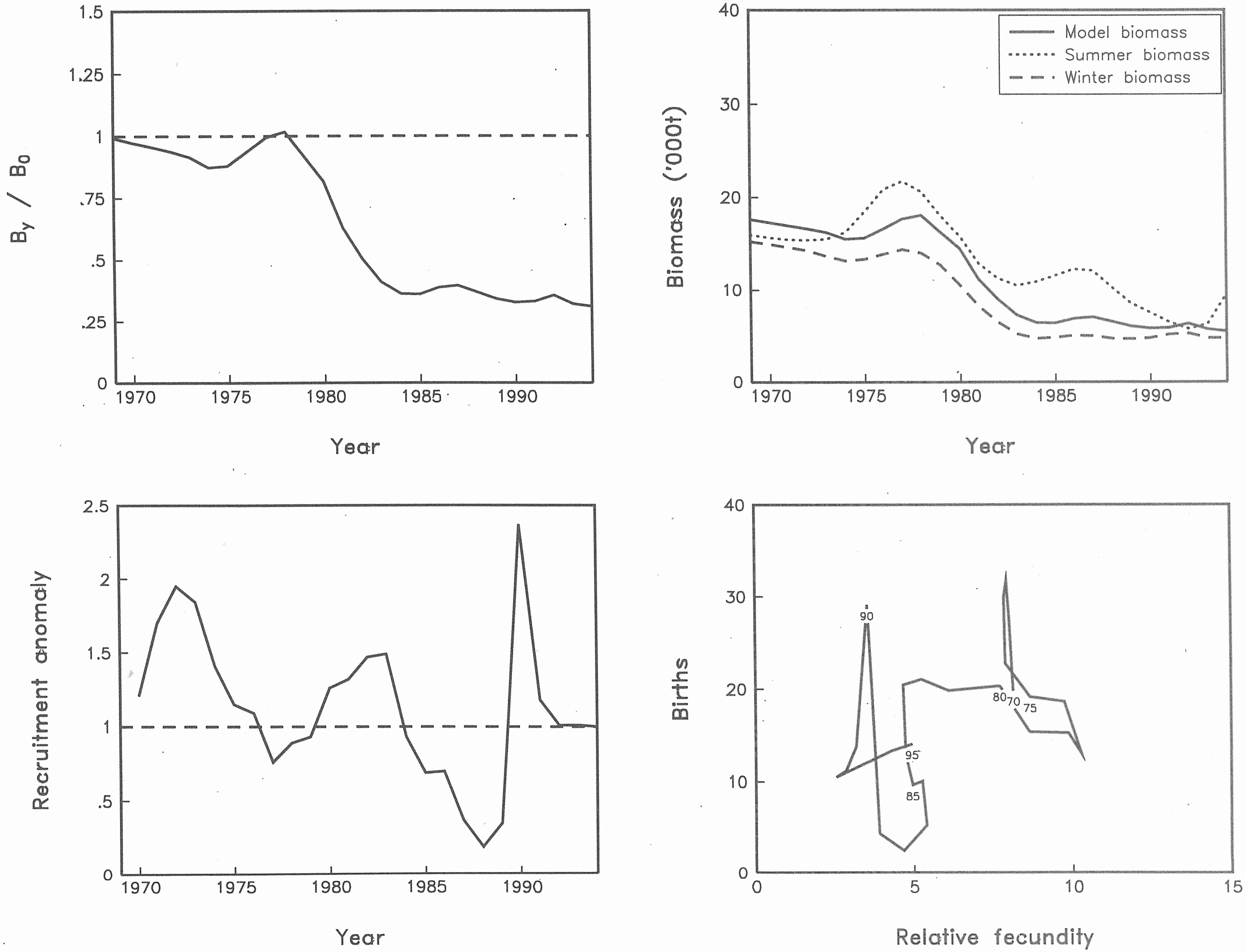


Figure 4(a)

No 1994 data

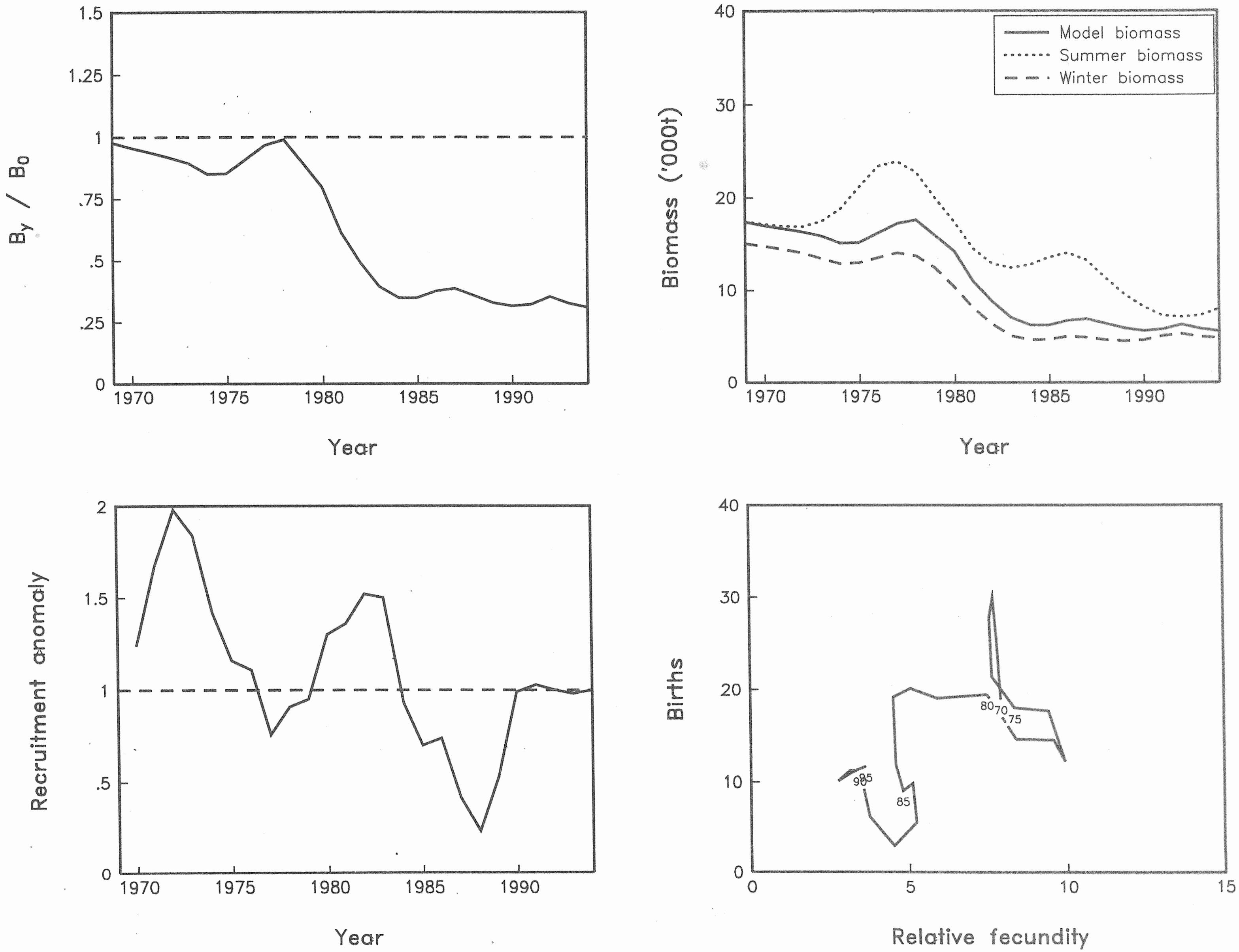


Figure 4(b)

No age/length data

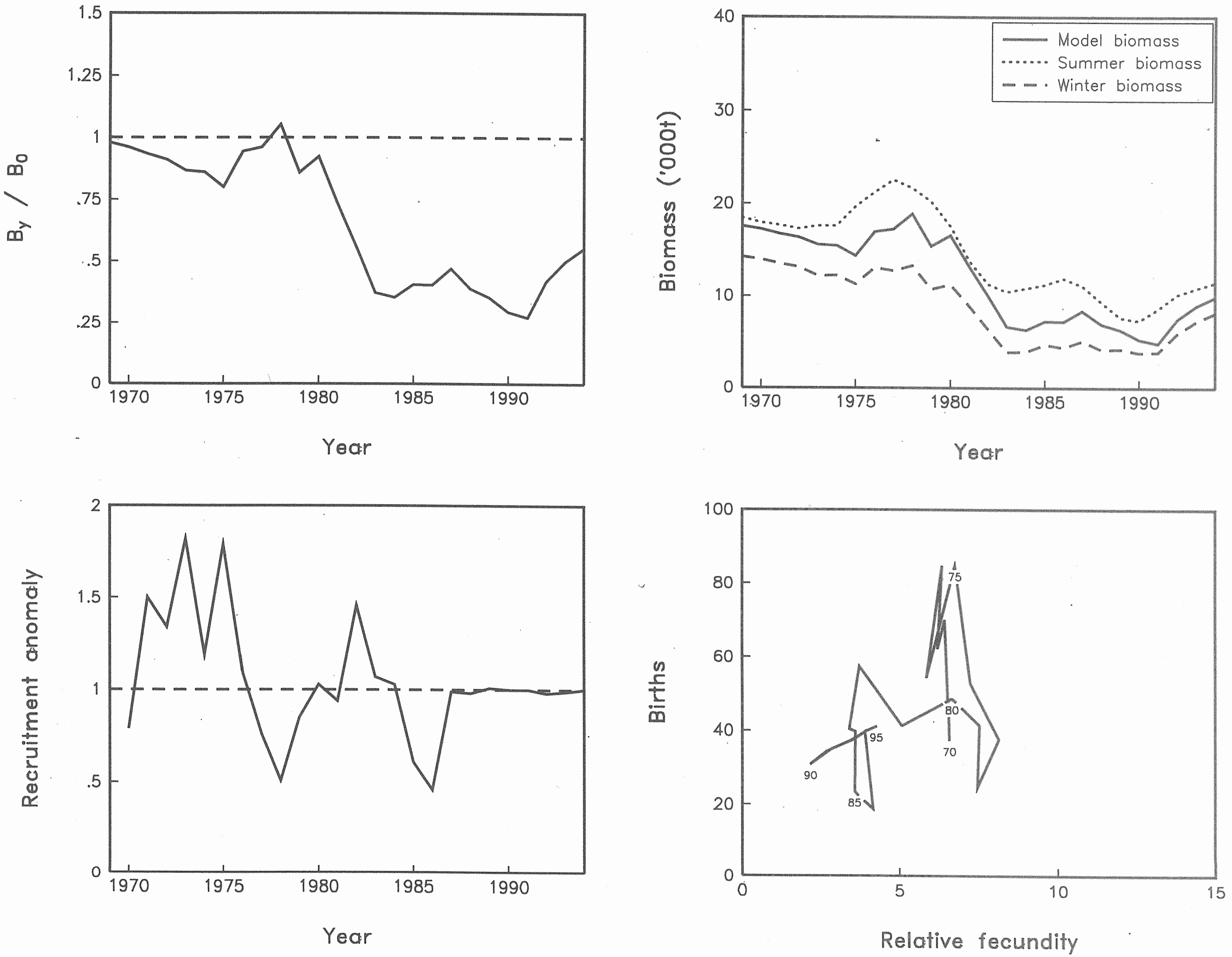


Figure 4(c)

With winter-2

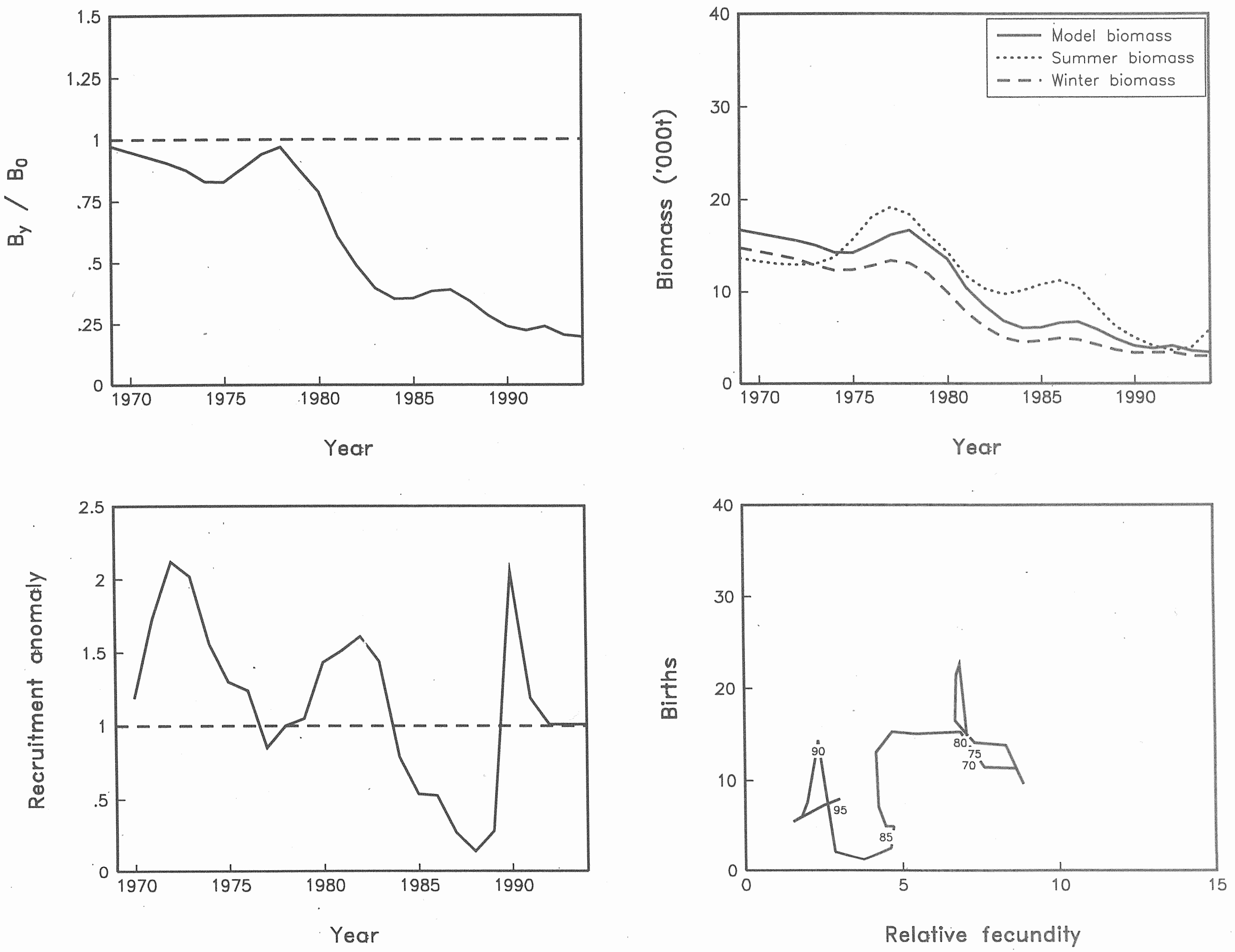


Figure 4(d)

Use all age/length data

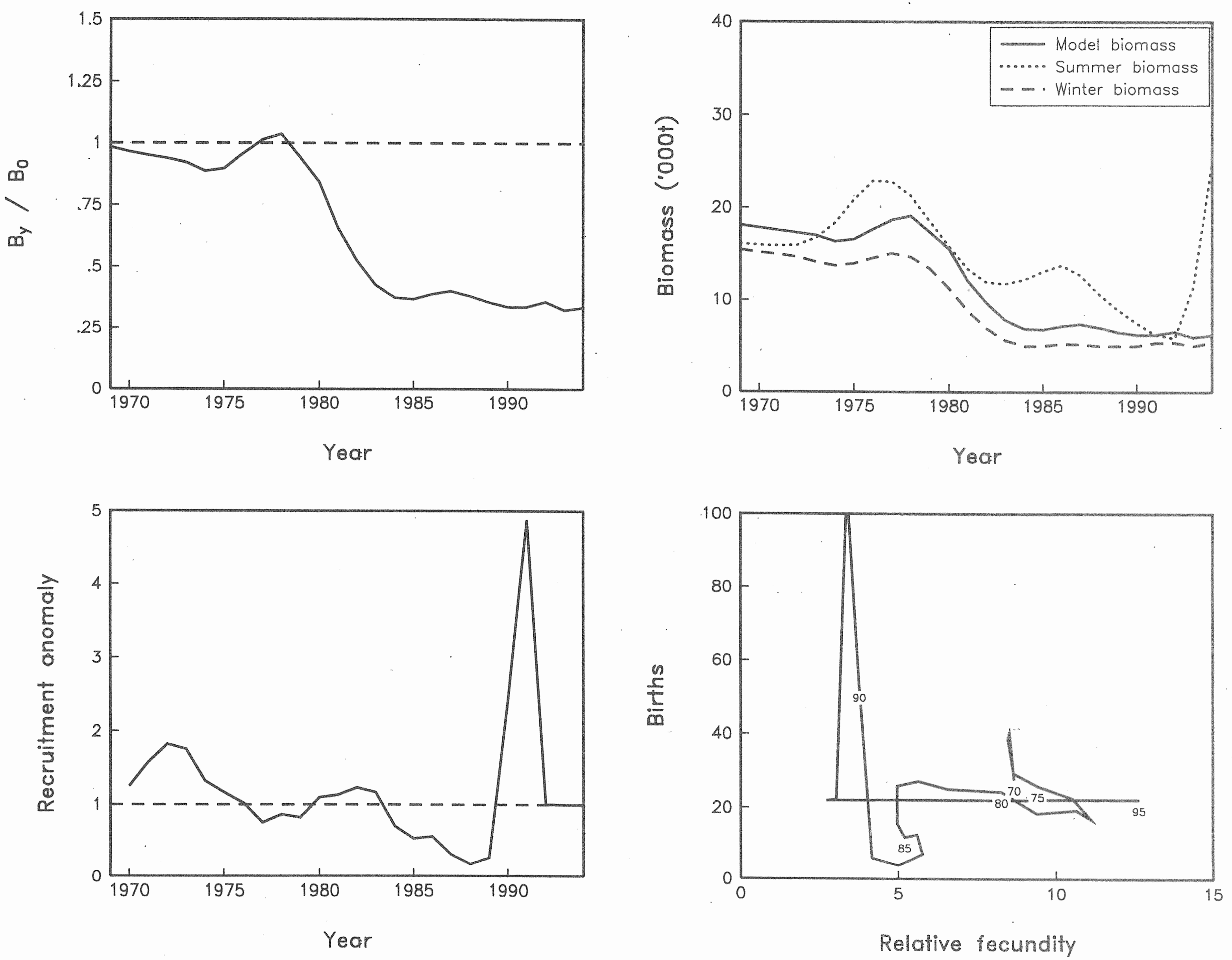


Figure 4(e)

Length data only

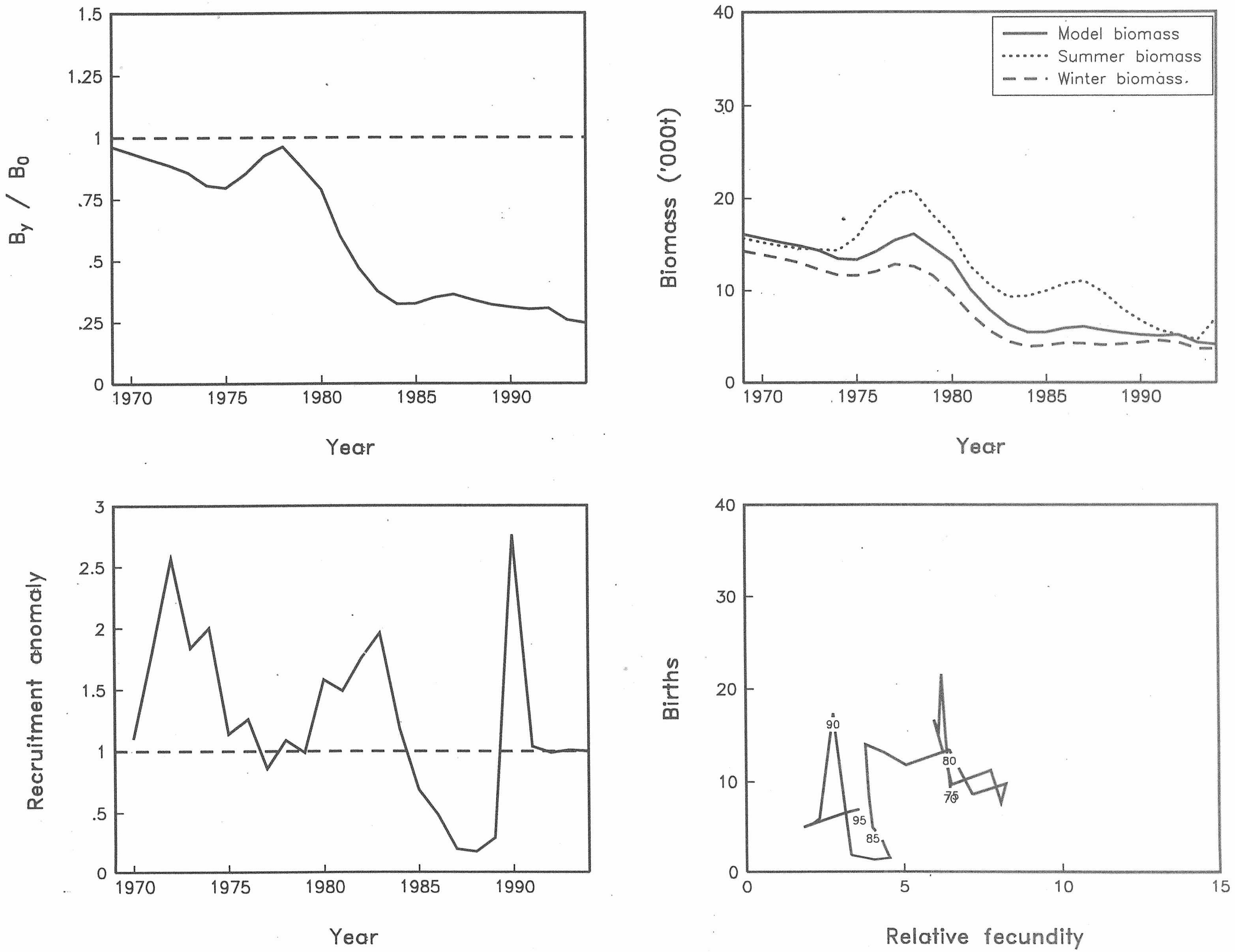


Figure 4(f)

$\sigma_r = \infty$

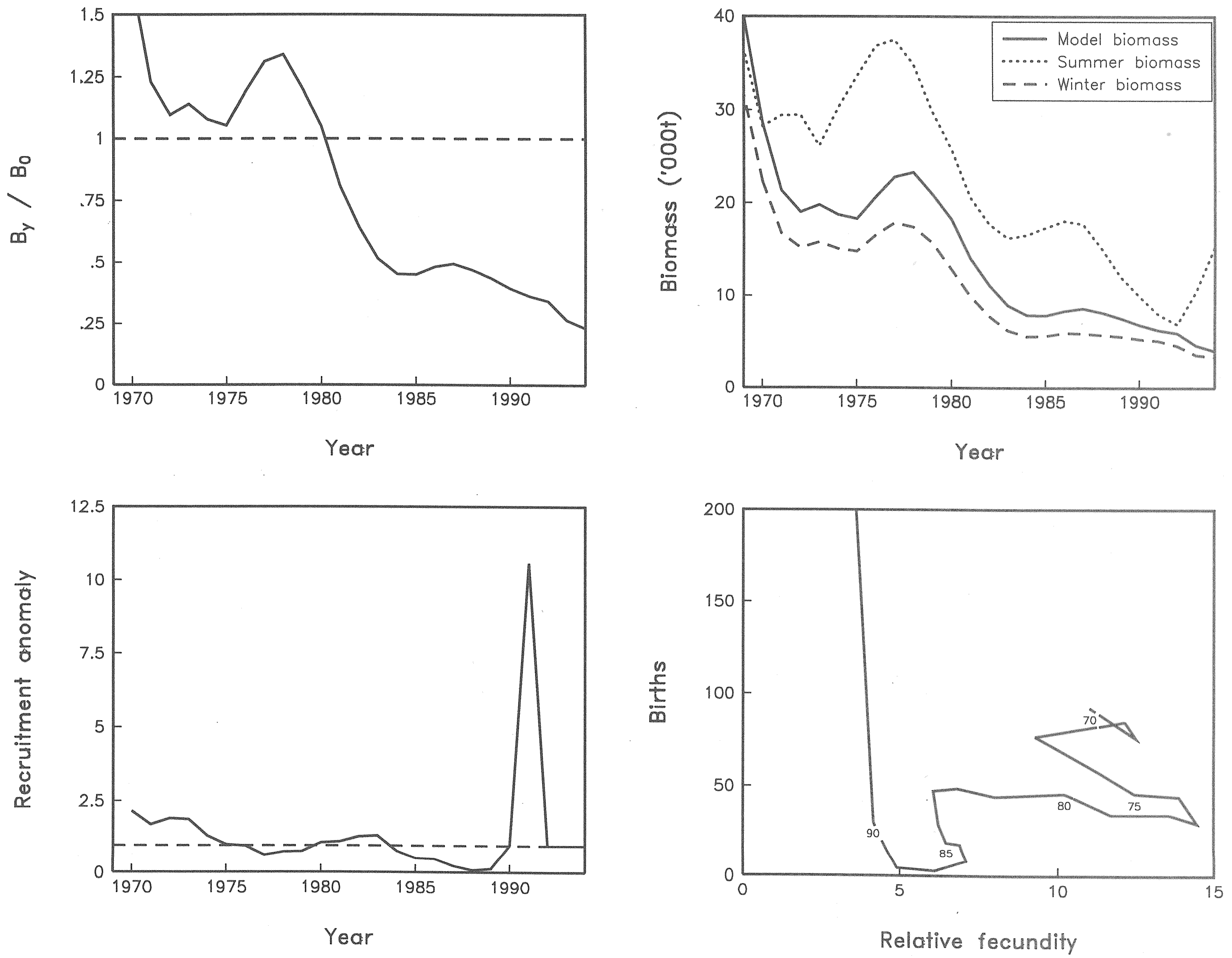


Figure 4(g)

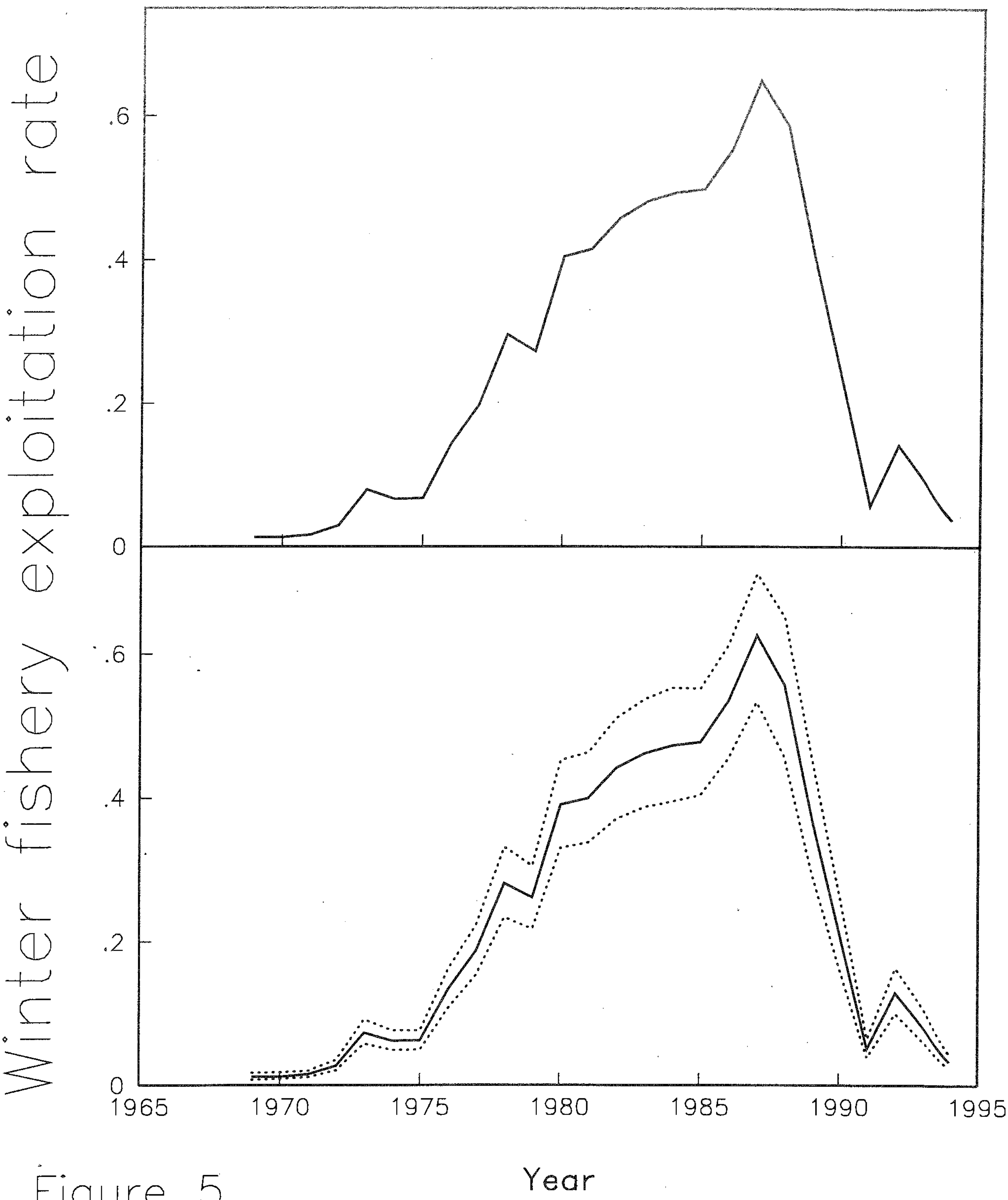

Winter fishery exploitation rate
.6
.4
.2
0
1965
1970
1975
1980
1985
1990
1995
Year

Figure 5

Base-case

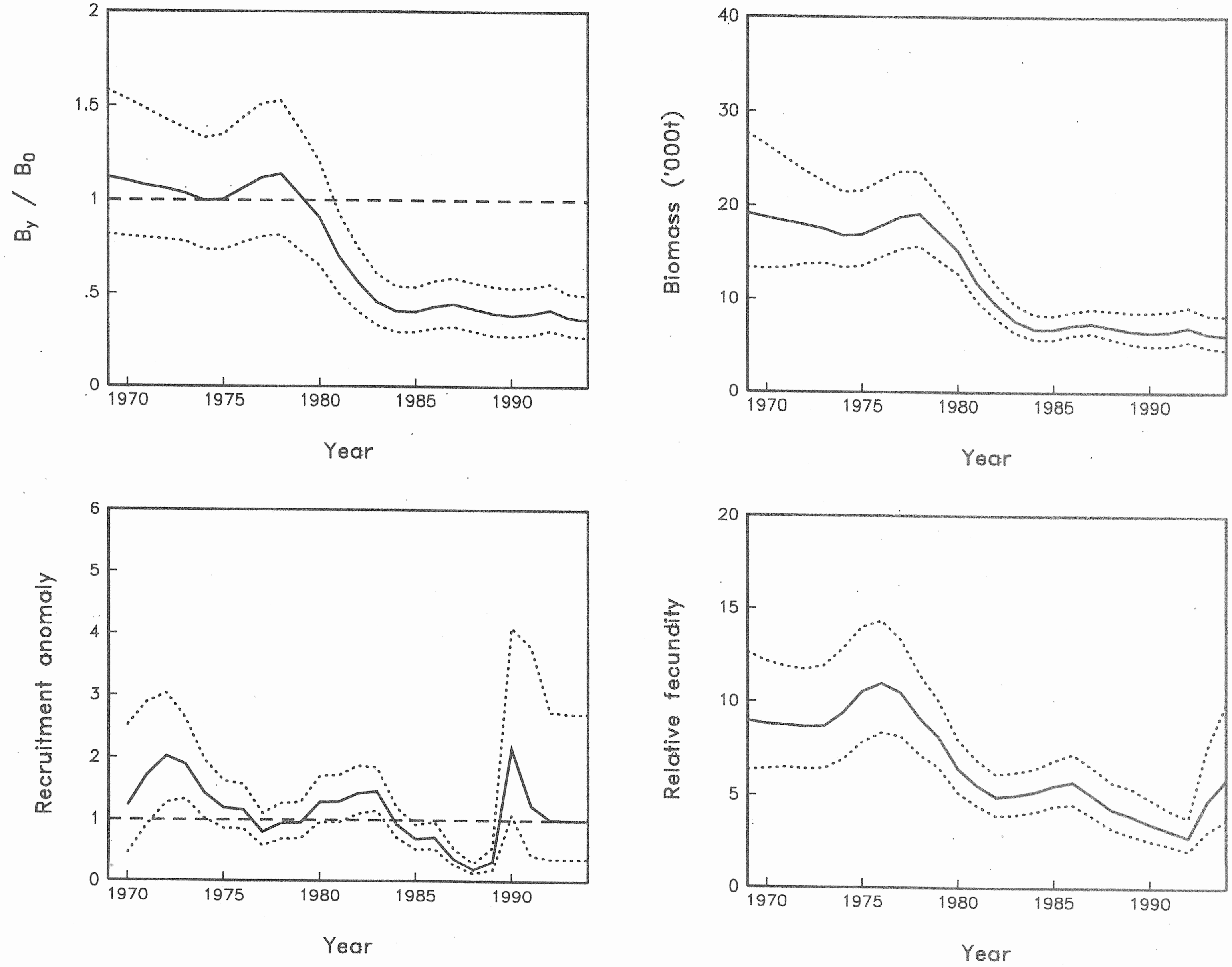


Figure 6(a)

No age/length data

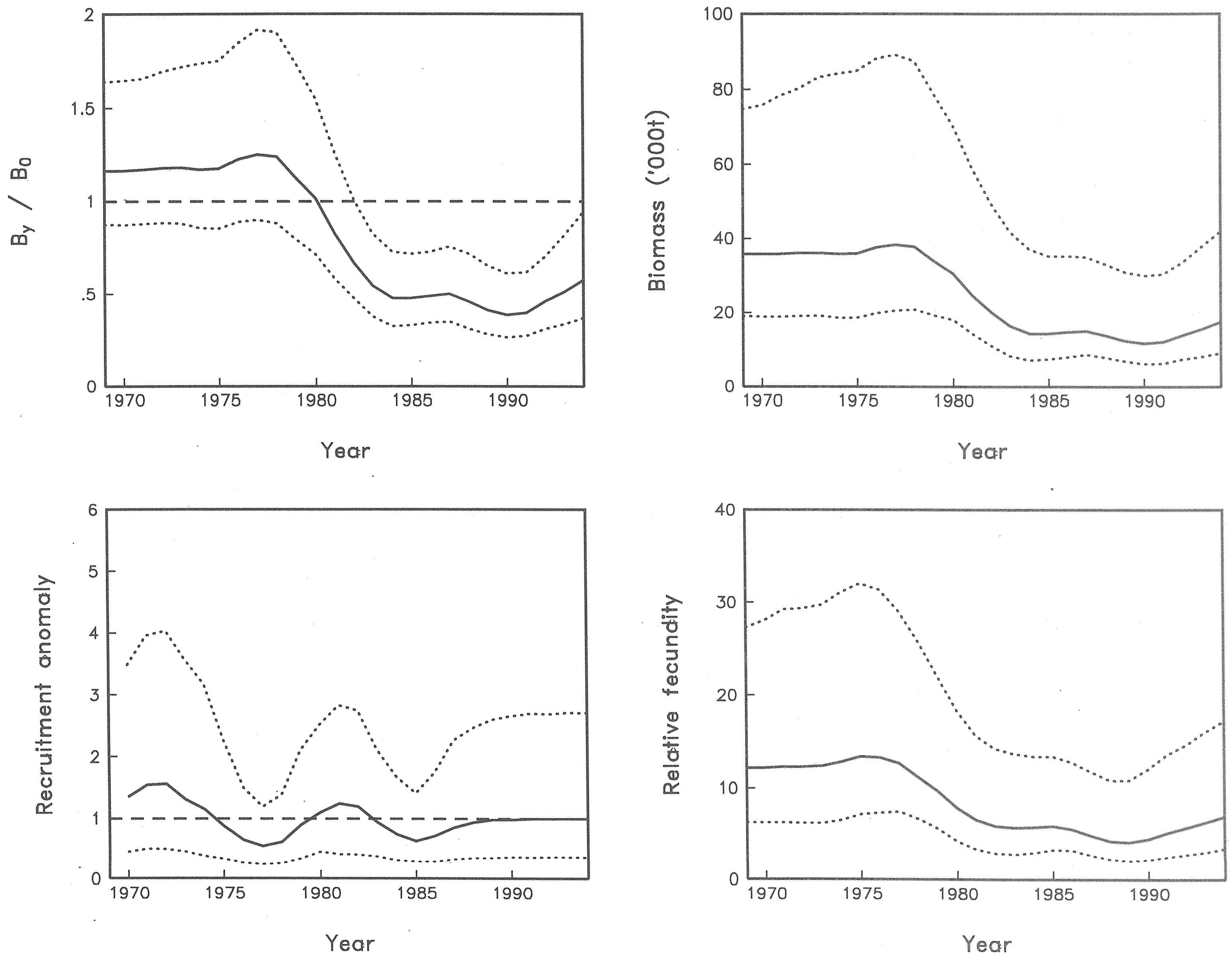


Figure 6(b)

No 1994 data

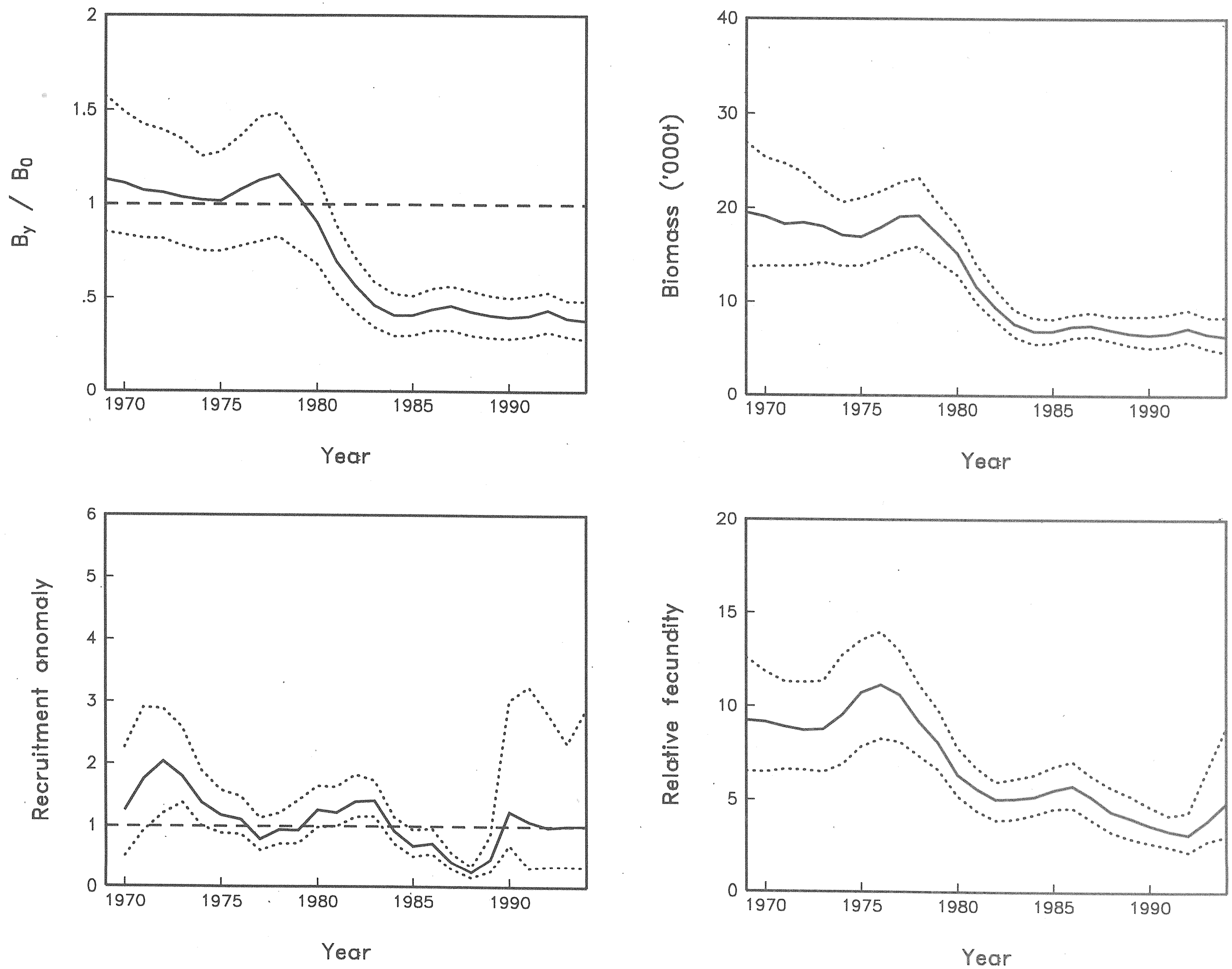


Figure 6(c)

With correlation

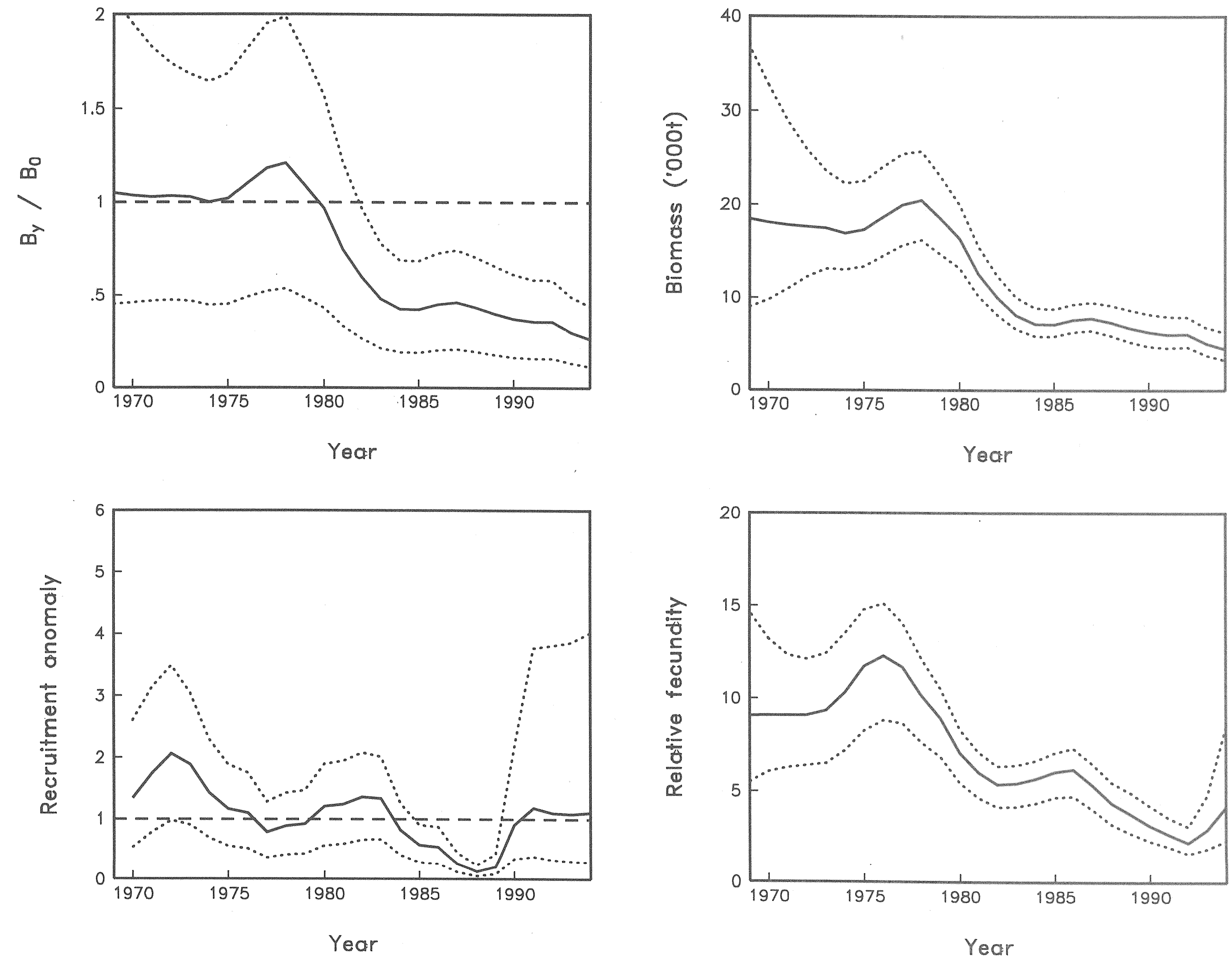


Figure 6(d)

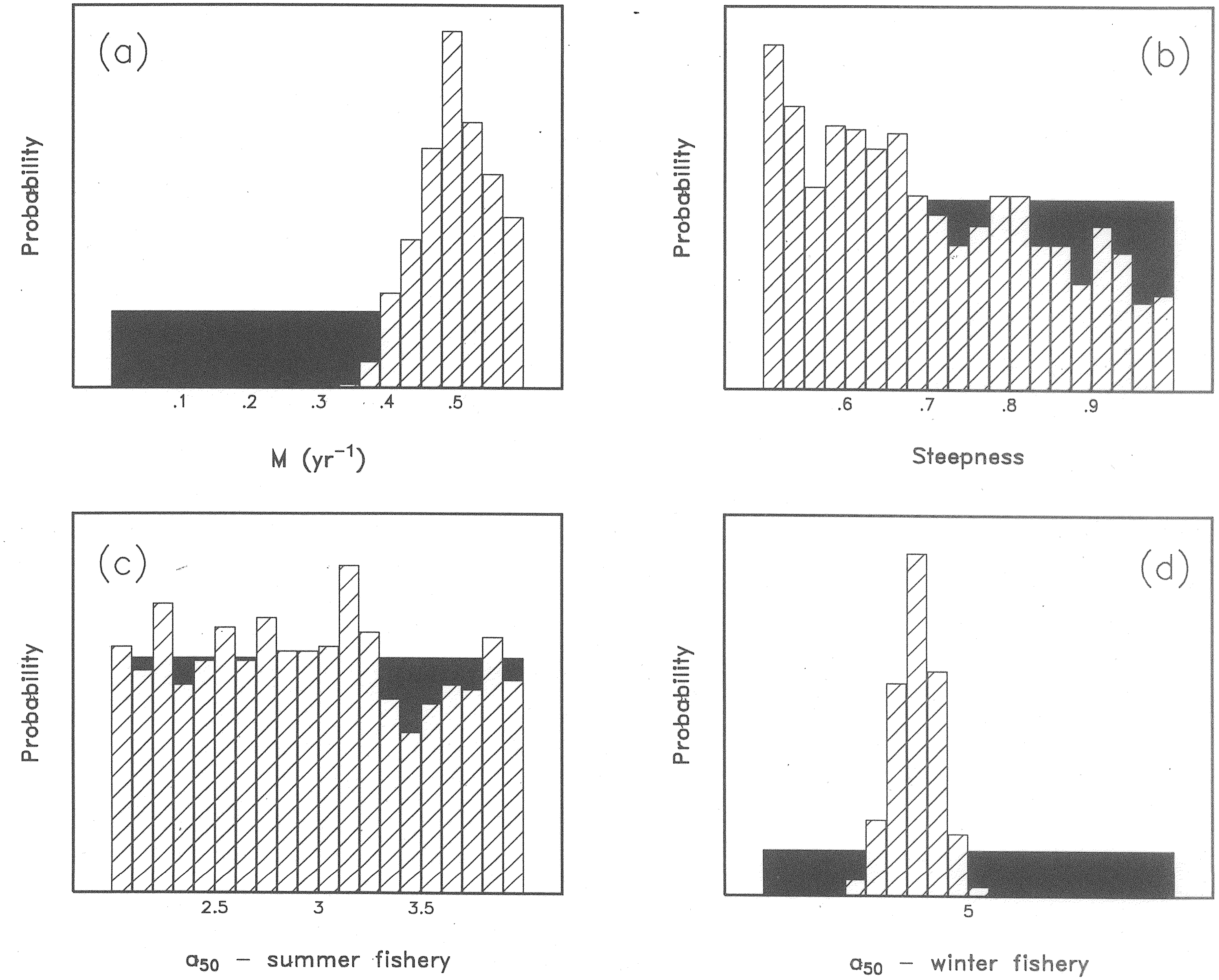

(a)
Probability
.1
.2
.3
.4
.5
M (yr⁻¹)
(b)
Probability
.6
.7
.8
.9
Steepness
(c)
Probability
2.5
3
3.5
a50 – summer fishery
(d)
Probability
5
a50 – winter fishery

Figure 7

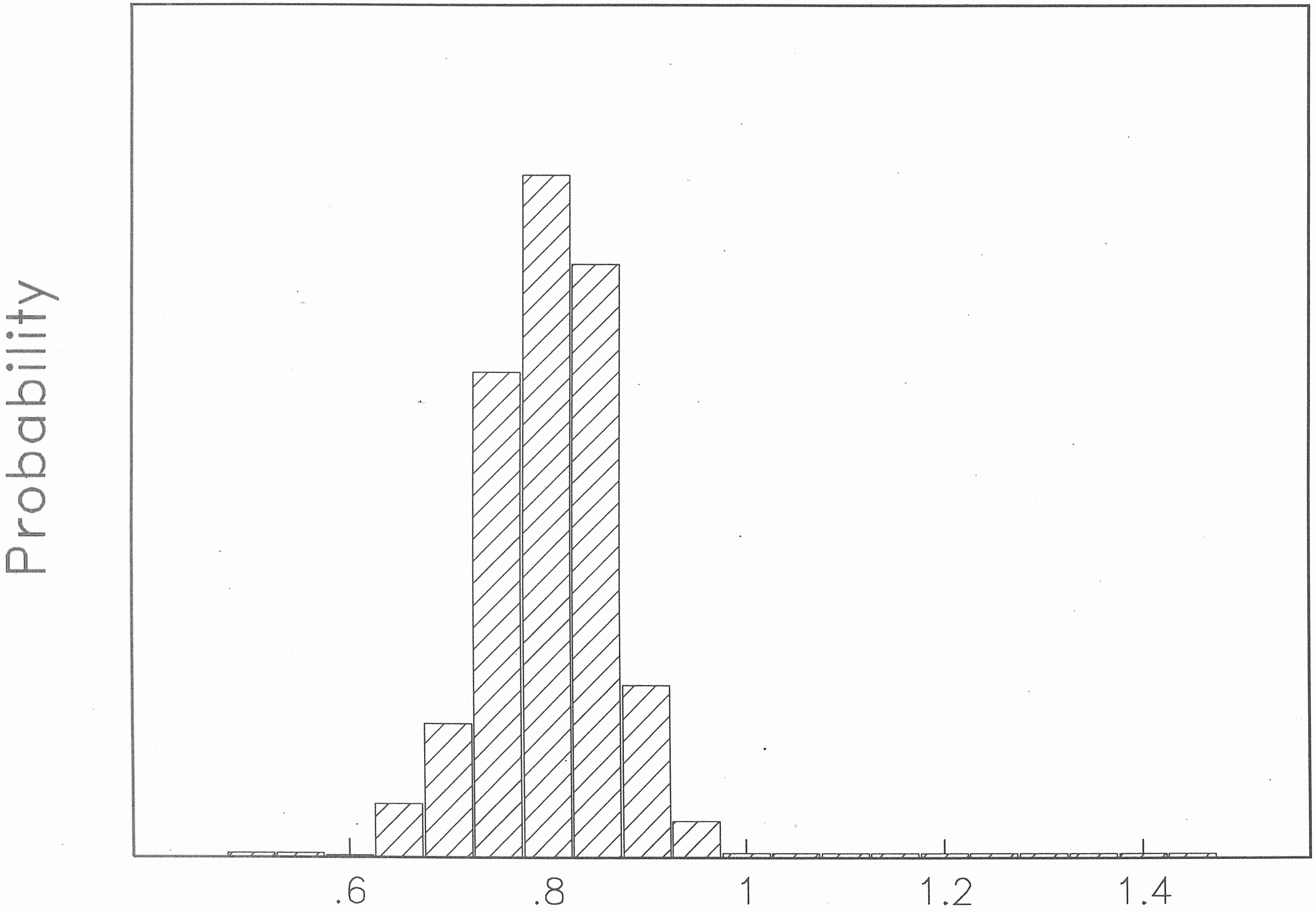


Figure 8

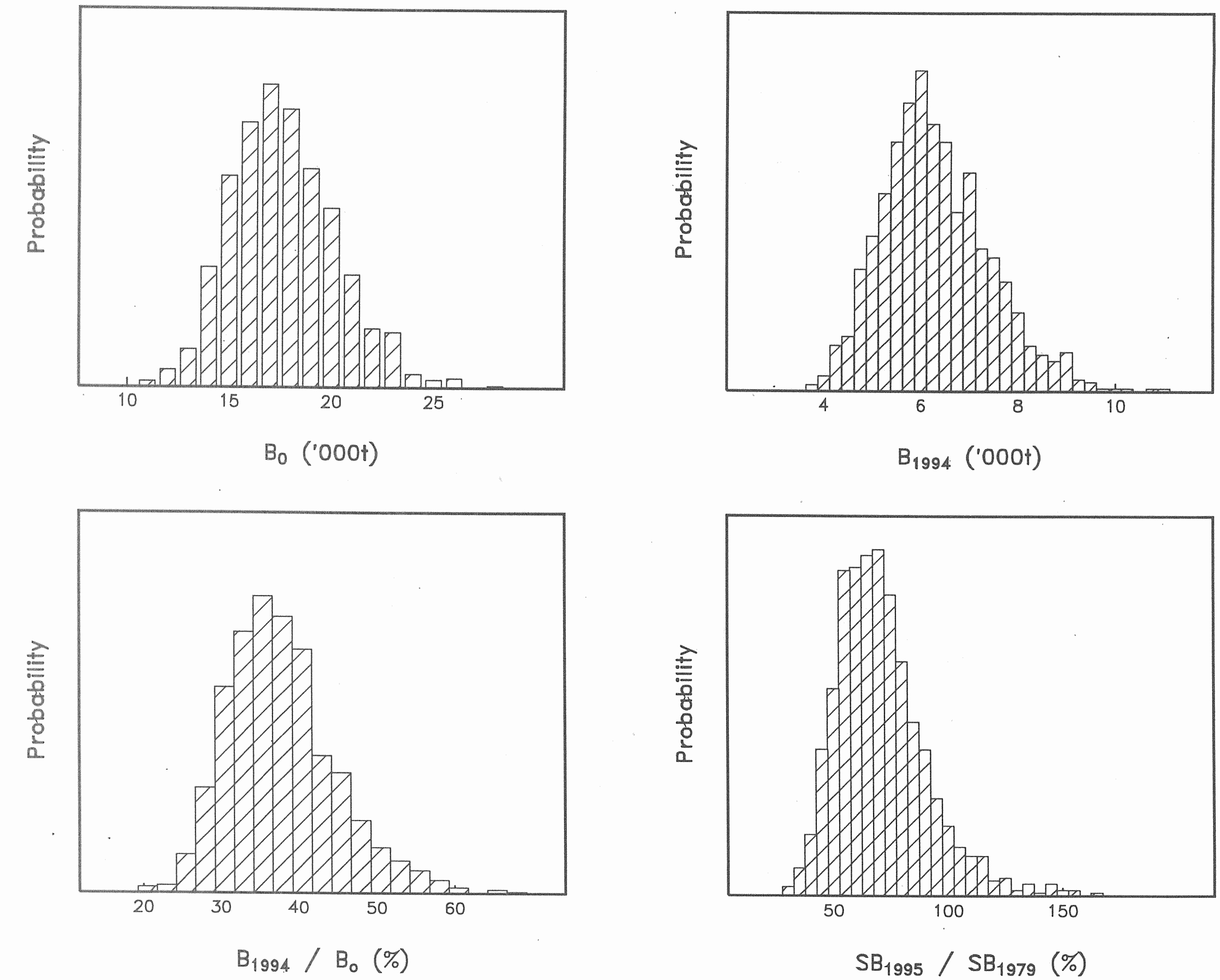

Probability
10
15
20
25
B0 ('000t)
Probability
4
6
8
10
B1994 ('000t)
Probability
20
30
40
50
60
B1994 / Bo (%)
Probability
50
100
150
SB1995 / SB1979 (%)

Figure 9

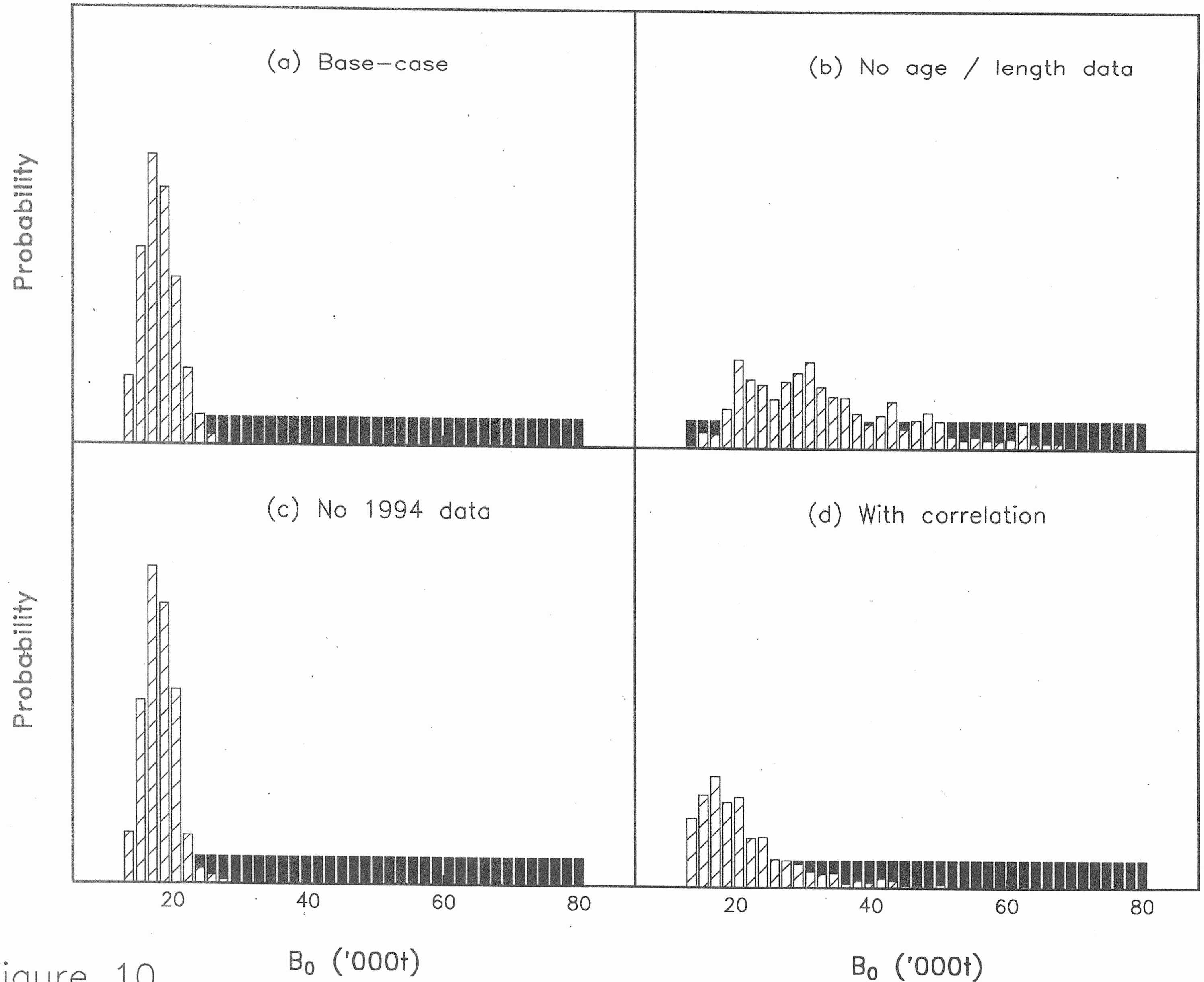
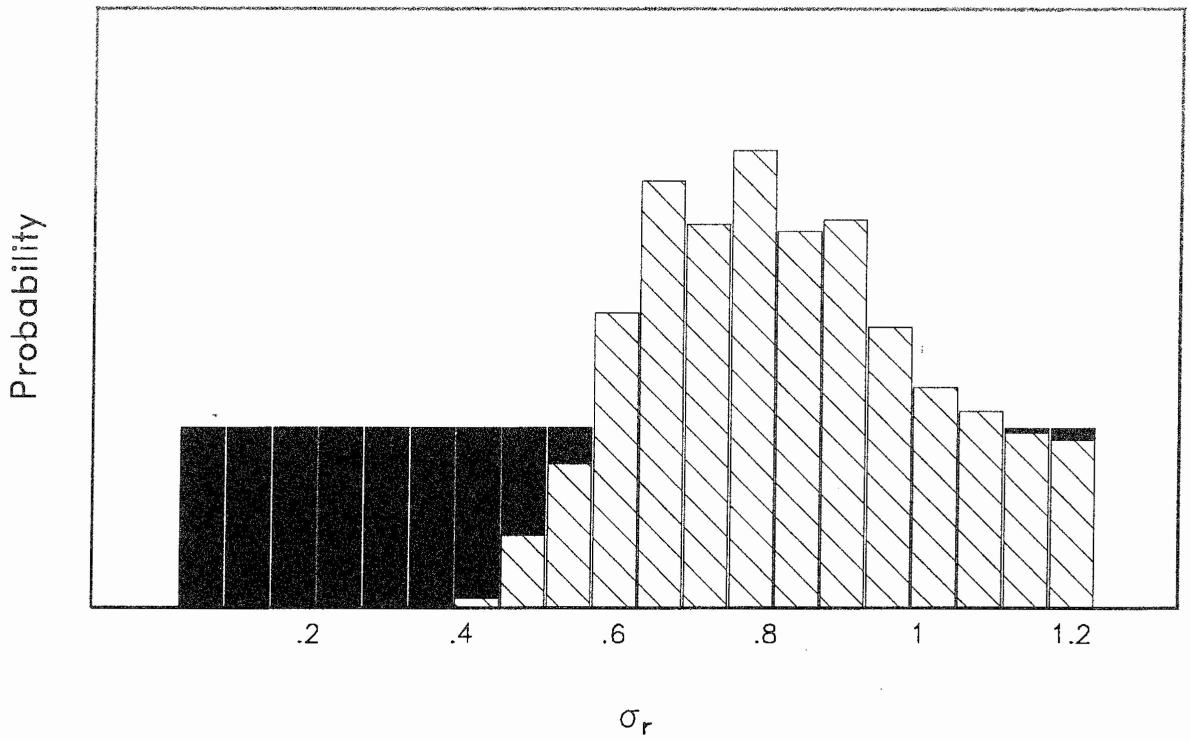

(a) Base-case
(b) No age / length data
(c) No 1994 data
(d) With correlation
Probability
Probability
20
40
60
80
20
40
60
80
B_0 ('000t)
B_0 ('000t)

Figure 10



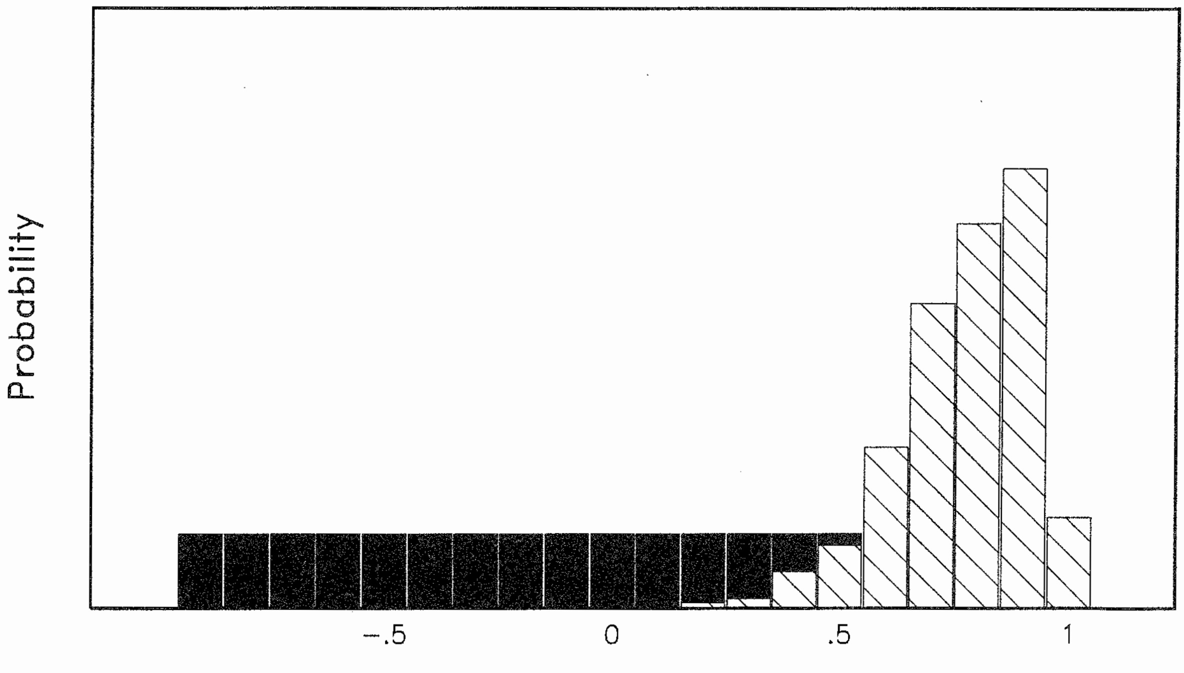


Figure 11

CHAPTER TWO

PRELIMINARY ASSESSMENT OF EASTERN GEMFISH (REXEA SOLANDRI) USING STOCK SYNTHESIS

PRELIMINARY ASSESSMENT OF EASTERN GEMFISH (*REXEA SOLANDRI*) USING STOCK SYNTHESIS

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ABSTRACT

The trawl fishery for gemfish off southeast Australia has declined from being one of the most economically valuable components of this multispecies fishery in the 1980s to a bycatch-only fishery in the 1990s with a zero total allowable catch. A stock synthesis assessment of the eastern gemfish stock is detailed that uses a two-sex, two-fishery, single area population model directly fitted to catch-at-age , catch at length, catch biomass and effort data. Sensitivity analyses are provided of the emphasis given to each source of data and limited model assumptions. The assessment confirms earlier cohort analyses (Allen 1989, Rowling 1994) that show a biomass decline and a series of poor recruitments in the late 1980s. The degree of the decline and absolute amount of current fishable biomass are dependent on the emphasis given to the age and length composition data relative to that given to the catch and effort data. Changing fishing and management practises in recent years have changed the selectivity of the fishery and this has compromised the value of catch and effort data as indicator of stock abundance for gemfish. The sensitivity of this assessment to these compromised data is a major cause for concern. A concerted effort is required to develop an unbiased and agreed-upon set of catch and effort data for this fishery and/or to investigate the feasibility of an independent biomass (and age structure) estimate.

1. INTRODUCTION

Gemfish (*Rexea solandri*) were one of the more economically valuable components of the trawl fishery off eastern Victoria and New South Wales in the 1970s and 1980s. A declining biomass and a series of poor recruitments in the late 1980s led to reduced catches and finally the total allowable catch (TAC) was reduced to zero.

Gemfish had been caught for many years before the directed trawl fishery developed. They were very common on the continental shelf off southern Tasmania in the late nineteenth century where they were taken by handlining at quite shallow depths. In one year they entered the mouth of the Derwent River "in such vast numbers that they were stranded by tons on the long sandy beaches" (Johnston 1883). However, by 1910 gemfish had become very rare in this area (McCulloch 1915, in Blackburn 1979) and are not caught off Tasmania in any numbers today. Trawling on the continental shelf off New South Wales and Victoria began in 1915, and would have caught gemfish. But gemfish (recorded as hake) were not identified in catch records until the 1950s, when approximately 125 tonnes per year are recorded as being sold on the Sydney fish market (Blackburn 1979).

Catches remained at or below this level until 1969 when the directed trawl fishery expanded to the continental slope, targeting winter aggregations of gemfish during their spawning migration onto the slope. Catches rose rapidly in the 1970s and peaked at an estimated 5100 tonnes in 1980. Catches varied between 2800 and 4200 tonnes until 1988, when a total allowable catch of 3000 tonnes was imposed in an attempt to stabilise catches (Rowling 1994). The TAC was not reached in 1989 and the first signs of poor recruitment appeared (a lack of small fish in commercial catches). Continued poor recruitments let to a reduction in TACs over the next four years with a zero TAC imposed in 1993. Bycatches of gemfish in the summer shelf fishery and in a winter continental slope fishery for mirror dory continue at several hundred tonnes per year.

The biology and fishery of the gemfish have been studied (e.g. Rowling 1990, 1994). Assessments of gemfish in the Southeast Fishery (SEF) have been done by Allen (1989, 1992, 1994), using cohort analysis tuned in the final years to effort. The analysis has explored many aspects of gemfish biology and documented the declining biomass and recruitment failures of the late 1980s. The reduction in TACs since 1990 led to a reduction in the amount and quality of catch and effort data for this fishery, and raised concerns about the comparability of 1990s data with those from earlier periods. This paper updates earlier assessments and evaluates the effect of different data sources on current biomass estimates.

2. METHODS

The data available on the gemfish fishery direct the choice of a suitable assessment technique. Allen (1989) developed a two-sex cohort analysis assessment to account for the different growth rates of male and female gemfish and the different ages at which they are first selected by the fishery. A two-sex model is used here for the same reasons.

The age and length composition of gemfish catches have not been collected consistently. Age compositions of the catches are available for even years between 1980 and 1990; no age composition data are available prior to 1980. However, length compositions of the winter catch have been collected for all years since 1976. These length composition data were used by Allen (1989) who substituted an age-length key from the nearest year to estimate (via a simplex algorithm) the age composition of catches in years with no age composition data. This estimation is necessary for the cohort analysis used, which estimates numbers-at-age in each year by back calculation of catch-at-age in each year and natural mortality.

However, estimating age compositions for one year using an age-length key from a different year is biased when the age composition is different in the two years (Kimura 1977). Age compositions of gemfish catches have indeed changed in recent years due to the biomass decline and recruitment failures, so age composition data estimated from substituted age-length keys may be biased. Therefore a statistical catch-at-age model was used in this assessment that requires no substitution of missing age-length keys.

Statistical catch-at-age models generate an underlying model of the population and fit this model to all available data to estimate the unknown parameters. Such models can account explicitly for the errors associated with age determination, and can incorporate other information. These models can be used to examine the goodness of fit between estimated and observed data to highlight inconsistencies in the available data and to determine the sensitivity of assessment results to the weighting placed on alternative data sets. Examples are CAGEAN (Deriso et al. 1985) and Stock synthesis (Methot 1990). CAGEAN assumes a lognormal error distribution for the catch-at-age data and fits the model to data using a least squares approach. Stock synthesis assumes a multinomial error distribution and uses a maximum likelihood fit. Punt (1995) describes a Bayesian and maximum likelihood assessment for gemfish.

Stock synthesis was used in this assessment, because it can specify an underlying population model that is sex-specific, incorporates different fisheries and different selectivity periods, and fits directly to age and/or length data, accounting for associated error. Flexible model specification in Stock synthesis enables the investigation of biological and environmental hypotheses to explain observed trends in a population.

Several features that need to be considered in an assessment of gemfish are:

- gemfish have different size/age compositions for males and females;
- there are two fisheries for the gemfish – a directed winter trawl fishery targeted at the older spawning fish, and a summer trawl fishery on the periphery of the distribution, where non-spawning gemfish (mostly males) are caught as bycatch;
- the gear used by the directed winter trawl fishery shifted from special large gemfish nets (trawled slowly so that the gemfish would almost swim into the mouth opening) to standard demersal trawls towed at normal towing speeds (approximately four knots). The shift in gear started in 1988 and was essentially complete by 1989 (Peter Bell, personal communication);
- individual transferable quotas (ITQs) were introduced for gemfish in 1989 and this has changed targeting, retention and reporting;
- average growth of gemfish has changed since the beginning of the fishery due to earlier capture of faster growing fish (Rowling and Reid 1992);
- gemfish may now be maturing at a younger age than previously;
- the strength of gemfish recruitment may be linked with cyclical environmental phenomena, such as westerly winds (Thresher 1994).

Some of these features have been accounted for in previous assessments, but many have not. In particular, the impacts of two (or more) periods of the fishery have not been examined; length data have not been used directly in the analyses; and errors in ageing have not been included in the analysis. These factors are evaluated in this assessment.

2.1 STOCK SYNTHESIS

Stock synthesis is a catch-at-age analysis designed to incorporate other information (Methot 1990). The model simultaneously fits to catch biomass; age-length composition and effort from multiple fisheries; and abundance and age composition from multiple surveys. The likelihood function between observed data and the model's expected values is specified to represent the steps (and errors) associated with each step in the data collection; thus the fit to catch biomass and to catch age composition are separate steps. This helps the incorporation of variability in the ageing process and correctly identifies the different leveld of confidence placed in catch biomass data and catch age composition. The model can use length frequency data and/or age composition data as the input for analysis, and can handle missing years in these data (reverting to a stock reduction analysis in the extreme where no size or age data are available).

Biological features and selectivity of the fisheries and surveys can be described as sex independent or sex-specific. The model accommodates ageing imprecision, ageing bias, and conversion of length-to-age information by incorporation of transition matrices which generate the expected distribution of the observed age class given the model's estimate of the sampled, true age composition. Deviations are expressed in terms of log-likelihood, and the model parameter values that provide best fit to the observed data are estimated by numerical maximisation of the composite log-likelihood function. Log-likelihoods for each data type can be scaled with an emphasis factor representing the confidence in those data. Adjustment of emphasis factors is a useful technique to determine the effect that each data set has on the model solution. Within each dataset, residuals from a model fit are examined to detect trends in the data that are not accounted for by the current model.

The strength of this approach is that it explicitly models both the dynamics of the population and the processes by which the population and its fishery are observed (Methot 1990). It attempts to build an assessment framework that is able to ascertain and account for biases caused by trends in biological and/or fishery parameters (for example trends in selectivity of the fishery), without adding excess model parameters. The stock synthesis model can be adjusted to accommodate patterns in the sampling process, and residual error can be distributed among all kinds of data. The resulting level of residual error should be consistent with any measurements of the variability of these data. As the model is tuned to one type of data the implications for the fits to other data are easily observed.

More complicated models, such as stock synthesis used here, may not always provide significantly better fit to the data than a simpler model, but they do enable exploration of alternative plausible explanations for the data.

2.2 DATA

CATCH DATA

Catch data for the trawl fishery are provided in Tables 1 to 3. They are divided into the directed winter fishery on the slope for spawning run fish and the non-directed summer shelf fishery. The two fisheries have quite different catch age compositions and the summer shelf fishery has a notable lack of larger female fish.

Best estimates of catch data account for assumed discards, which are assumed to be negligible in the winter fishery until 1993 and to have the same size composition as the landed catch, although fish less than 40 cm would have been discarded completely (Rowling, pers. comm.). Discards in the summer catch may have been more significant especially after the introduction of quota management in 1989.

There are some catch data available for even earlier years. Blackburn (1979) summarises catches of gemfish received from steam trawlers at the Sydney fish market from 1953 to 1956 (Table 2). These gemfish were measured, and Blackburn (1979) presents aggregated length frequency distributions for 11,263 gemfish taken from 209 samples spread fairly evenly between the period December 1946 and April 1956.

Blackburn (1979) also provides data taken from the logbooks of Red Funnel steam trawlers that provide information on the distribution of gemfish catches (Table 3). These data have been reanalysed by Klaer (1995).

CATCH AND EFFORT DATA

Catch and effort data are available from two sources: historic catch data from fisheries cooperative records (1969-1986) and more recent data from the quota monitoring database (1989-1991) and SEF logbook (1986 to 1993). The 1992 and 1993 data are considered unreliable because of the absence of a targeted fishery in these years. The catch and effort data were reanalysed by Rowling (pers. comm.) and now show similar trends to the historic data for overlapping years (Table 4, Figure 1). The two series are not independent, being derived from the same vessels. In the years since 1989 there were major changes in the gemfish fishery: introduction of quotas in 1989; declining catches since 1987; changes in the size composition of the landed catch; and the changeover from special gemfish nets to standard trawl nets by 1989. Thus the overall measure of catch per unit effort (CPUE) must be considered a poor indicator of abundance for this population until further analyses are completed. Ongoing analyses of the data on a finer spatial scale by Kevin Rowling (Fisheries Research Institute, New South Wales Fisheries) may account for changes in fishing practices.

There are some data available from the summer fishery (Table 5), from the SEF logbooks. Their usefulness is limited since the summer fishery is a non-targeted fishery that samples only a portion of the distribution; only smaller fish are caught. These data are not used in this assessment. However, comparison with catch and effort (and length) data from Red Funnel trawler catches in the 1950s might improve understanding of changes in the fishery since the directed winter fishery began.

GROWTH

Growth in length of gemfish was fitted to the von Bertalanffy growth curve by Rowling and Reid (1992) for gemfish (including juveniles) in the years 1980-1986 (Table 6). This aggregate curve was used in this assessment. The same authors observed a change in the von Bertalanffy parameters fitted to data from different years (Table 7), and concluded that fishing affects the size distribution of gemfish in the catches.

Length and weight parameters are taken from Rowling (in Allen 1989). The same parameters are assumed to apply to males and females (Table 8).

NATURAL MORTALITY

There are no independent estimates of natural mortality for gemfish. Allen (1989) provides natural mortality schedules (M) and availability to the fishery (q) for male and female gemfish based on biological observations and the overall fit to his cohort analysis (Table 9).

Sex-specific natural mortality estimates for this assessment will be two parameters estimated in the catch-at-age analysis. For simplicity, it will be assumed that natural mortality is constant with age: trends in natural mortality are confounded with trends in selectivity, for which there is no independent information.

SELECTIVITY OF THE FISHERY

There is no independent information on the selectivity of the winter or summer fisheries, and no independent surveys that describe the age or length composition of the available population. The selectivity of each fishery will be estimated in the catch-at-age analysis.

Selectivity of the fisheries is modelled with a double logistic curve. Both sexes share the same ascending logistic selectivity function but have separate descending selectivity functions. There is no direct age-specific selectivity. The selectivity function requires nine parameters for each fishery. In the base run for the winter fishery, the selectivity is constrained to be asymptotic. The shape of the selectivity curve for the summer fishery is chosen by the model.

Younger fish have been appearing in the winter fishery in recent years. Some of these younger fish are mature, apparently at an earlier age than in previous years. This suggests that there may have been a recent change in selectivity in the winter fishery, due either to the change from custom gemfish trawls to more standard trawls in 1989, or to a change in fish behaviour associated with an earlier age of maturity.

The possibility that selectivity of the winter fishery has changed since 1989 will be tested by estimating the ascending limb of the selectivity curve independently for the periods before and after 1989. There may be insufficient recent data to obtain a satisfactory answer.

LENGTH AND AGE COMPOSITION OF COMMERCIAL CATCHES

Age and length data are available for most years for the summer and winter fisheries. Age data are used in the years for which they were collected, otherwise length data are used directly.

Age-length keys for even years from 1980 to 1990 were obtained by Rowling (NSW Fisheries, unpublished data). Age-length keys from 1991 to 1993 were obtained by the Central Ageing Facility (CAF). There was a good correspondence between ages of otoliths read by a CAF reader (Morison) and Rowling (Rowling 1992). Overall the agreement between readers was 55% and agreement within +/- 1 year was 90% (Table 10).

In a second comparison of 400 otoliths read by two readers at the CAF, the following data were reported (Morison 1992):

Average percent error (Beamish & Fournier 1981)	11.8
Percent agreement between readers within 2 years	87.2
Percent agreement between readers within 3 years	96.4

Morison (1992) also noted that the average percent error for 50 otoliths read by two CAF readers and a reader from another laboratory was 11.5.

Age reading errors for this assessment were derived from the percent agreement on ages from the same otoliths read by two independent readers (Rowling 1992). There was 55% agreement at minimum and maximum ages read and no discernible trend with age. The level of variance that would produce a 55% agreement in ages (taking into account the probability that both readers got the correct age, both were off by one year in the same direction, and both were off by two years in the same direction) was computed in synthesis. The probability that both agree and were off by more than two years is considered negligible.

Age composition for the winter fishery was determined by multiplying the annual age-length key by the length frequencies sampled for the commercial catch (Table 11). Age-length keys and length frequencies were collected separately for all species after 1980. An average age-length key was used to estimate rare lengths that did not appear in a particular annual age-length key.

Variation in length-at-age was determined as the coefficient of variation for the minimum and maximum ages (Table 12). Coefficients of variation were 6.6% and 4.6% on average for age 3 and 9 males, and 5.0% and 4.4% on average for age 4 and 11 females respectively.

Length data collected from the Sydney fish market (Rowling unpublished data) were used with as little interpolation or aggregation as possible. Length data were used directly in the model for years where no age-length key was available and converted to age composition data for years when an age-length key was available. These data show the cumulative take of larger fish by the fishery between 1982 and 1987, followed by a series of poor recruitments that cause the observed lack of fish from 55 to 75 cm long by 1993 (Figs 2 and 3).

STOCK AND RECRUITMENT

Fecundity-at-age was derived from Rowling (unpublished data, Table 13). The trend in fecundity with age or size was well described by assuming a constant number of eggs per kilogram. Therefore female spawning biomass was a reasonable proxy for fecundity (numbers of eggs produced). Female spawning biomass was defined as female biomass times the maturity-at-age.

A logistic function was used to describe maturity-at-age for females. It was assumed that percent maturation follows percent availability to the winter fishery. The age of 50% maturity was set at 5 yr with a slope of 0.253 (Table 14).. These values were used here, but it is noted that in recent years the age and length of first maturity may have dropped (Rowling, pers. comm.). In 1993 there were reports of 2- and 3-year-old fish running ripe (even 2-year-old females) whereas in prior years 4-year-old fish were the youngest observed to be running ripe. No change in age of maturity was represented in the model used in this assessment.

A Beverton and Holt-type stock and recruitment relationship was fitted to the year class strengths predicted by the model and residuals were computed. A negligible weight was given to the stock and recruitment relationship so it had a negligible effect on model fit in the assessment. The shape of the stock and recruitment relationship was specified by one parameter (A), that defines the proportion of unexploited recruitment level (f), at a proportion of the unexploited biomass (b), following Kimura (1988):

$$A = [1-(b/f)]/(1-b).$$

The base case model specified no density dependence (shape parameter of zero) in the stock and recruitment relationship, making recruitment directly proportional to spawning biomass. The effect of including density dependence was examined in the sensitivity analyses by setting the shape parameter at 0.75, which equates to a curve having 80% of recruitment to unexploited biomass when stock size has been reduced to 50% of unexploited biomass. Lastly, the shape parameter that best fists the data for the base case assessment was estimated.

DEFINITION OF PREFISHERY BIOMASS

It has been estimated that the targeted gemfish fishery started in 1969 with annual catches of approximately 200 t (see above). Catch and effort data are not considered a reasonable estimate of abundance until 1973: the years before 1973 are considered to be part of a developing fishery, where catch per unit effort would represent the learning curve of the fishers rather than the relative abundance of gemfish.

Available information from the Red Funnel steam trawler catches sold at Sydney market indicates the annual catch from1952 to 1956 was 125 t (Tables 2 and 3). These catches would have been taken from the shelf and would be better represented by the selectivity for the summer fishery than the winter fishery. Overall the historic catch level for the summer fishery appears to be in the order of 125 t per year. This is higher than the best estimates of summer fishery catches for the period 1969 until 1977.

ENVIRONMENTAL INFLUENCE

It has been noted by Thresher (1994) that westerly winds have a high correlation with estimated year class strength for several SEF fish species, including gemfish. An index of the strength of westerly winds was included in the data to test its impact on stock and recruitment relationships (Table 15).

2.3 MODEL SPECIFICATION

DEFAULT ERROR VALUES FOR LIKELIHOOD COMPUTATION

The aggregate maximum likelihood value determines the best fit of the model to the data. The error level specified for each data set determines the emphasis given to it in determining the best model fit. Theoretically, the error values associated with each dataset are known and thus the emphasis given to each dataset is objective. Practically, error values are estimated and the emphasis given to each data set is subjective.

The synthesis model has an explicit "likelihood" emphasis value to test the sensitivity of the assessment to different datasets. Unity is the default value, 0.001 reduces the influence of the dataset or function to a negligible level, and values in the range 0.1 to 10 were used to test the sensitivity for this assessment.

ACCOUNTING FOR AGE COMPOSITION VARIABILITY

Stock synthesis follows a similar approach to that of Fournier and Archibald (1982), where the level of fishing mortality is calculated so that the estimated catch biomass matches the observed catch biomass exactly. The pattern of selectivity at age is then sought which will maximise the log-likelihood of the observed catch proportion-at-age. This likelihood is calculated under the assumption that the observed catch proportion-at-age behaves as if it were a single sample drawn from a multinomial distribution defined by the model's estimate of proportion-at-age. [1]

Estimated multinomial error level is dependent on the sample size. If sample sizes were specified as those actually measured the precision would be greater than appears reasonable because the model ignores process error would therefore be forced to match the estimated age/length composition very closely. Fournier and Archibald (1982) recommended that the effective sample size be specified as no greater than 400. Effective sample size was set at 200 in this assessment for winter age and length data. Because the effective CV for a proportion is:

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[1] Note the difference from CAGEAN which assumes a lognormal error distribution. In CAGEAN, the model searches for the level of fishing mortality and the pattern of selectivity-at-age that minimises the sum of squared deviations. The important distinction between the multinomial and lognormal models is that the multinomial model treats the deviation between, for example, observed = 0.3 and estimated = 0.2 as larger and more important than the deviation between 0.03 and 0.02, while the lognormal model treats these as equivalent deviations.

$$CV = s/p = \mathrm{sqrt}\,[\,(1-p) / (pN)\,]$$

this is equivalent to setting the CV equal to 21% for a proportion of 0.1. The sample size for summer data was set at 100, equivalent to a CV of 30%.

DISCOUNT FACTOR FOR PLUS GROUP

A plus group is specified in the assessment model for ages greater than 15 years. The plus group accumulates the small (less than 0.001 of any year's population) number of these fish so that they can be included as a single group in computations, saving computation time. Fishing mortality is not estimated within the model for this plus group, instead a discount factor is specified. This factor represents the level of fishing mortality for these older age classes. In this assessment it was set at 0.45, similar to natural mortality.

NUMBER OF PARAMETERS ESTIMATED

There were 45 parameters estimated in the base case assessment. These 45 parameters comprised two for natural mortality of male and females, 16 for selectivity of the summer and winter fishery, one to estimate the level of recruitment for the virgin biomass, and 26 for yearclass strength (1968-1993).

2.4 BASE CASE AND SENSITIVITY TO DATA AND ASSUMPTIONS

The following run of stock synthesis was chosen as the base case following discussions with Kevin Rowling, André Punt and fishers (each run is uniquely identified by a parameter file, Pxx):

Base case (P12)

Age composition	Winter only
Length composition	Winter for years with no age data
Age/size in ML estimator	Ages ≥5 and lengths ≥64 cm

Selectivity	Winter – asymptotic one time period
	Summer – domed one time period
CPUE	Winter only
Environmental variables	None
Growth	Constant
Stock and recruitment	Beverton and Holt – negligible emphasis
	50% of unexploited recruitment at 50% unexploited biomass.

The following changes to the base case were made to examine the sensitivity of the results to the data included in the model and some of the model assumptions (see Tables 18 to 21).

<u>Ages≥ 4 and lengths ≥ 54 cm (P22)</u>

Age/size in ML estimator	Ages ≥ 4 and lengths ≥54 cm

<u>All ages and lengths (P11)</u>

Age/size in ML estimator	Ages ≥2 and lengths ≥35 cm

<u>No winter length data (P13)</u>

Length Composition	Winter – none
	Summer – none

<u>No age or length data (P14)</u>

Age composition	None
Length composition	None
Age/size in ML estimator	None

Include summer length data (P15)

Length composition:	Winter – years with no age data
	Summer – all available data
Age/size in ML estimator	Ages ≥5 and lengths ≥64 cm

Emphasis on winter CPUE * 0.1 (P16)

CPUE	Winter CPUE only
	Emphasis reduced to 0.1

Free origin for von Bertalanffy growth curves (P18)

Growth	von Bertalanffy growth parameters for slope and maximum length fixed; origin fitted by model

Two selectivity periods for winter fishery (P19)

Selectivity	Winter – asymptotic two time-periods 1969-1988 and 1989-1994. Ascending slope and ascending inflection point only vary between the two periods
	Summer – domed one time period

Increase emphasis on spawner-recruit relationship (P21)

Stock and recruitment	Beverton and Holt – Emphasis 0.1 that of other data in base case.

Further sensitivity analyses were performed to determine the effects of changing the relative emphasis placed on the age and length versus the CPUE data:

Emphasis on winter CPUE * 0.5 (P17)

CPUE	Winter CPUE only
	Emphasis reduced to 0.5

Emphasis on winter CPUE * 10 (P26)

CPUE	Winter CPUE only
	Emphasis increased to 10

Sample size 50 (P26)

Age composition	Sample size for winter age and length data reduced to 50; 5 for summer length data.

Further sensitivity analyses were performed to determine the effects of changing parameters of the stock and recruitment relationship:

Reduce CV on stock and recruitment (P27)

Stock and recruitment	Coefficient of variation of fitted recruitment around stock and recruitment relationship reduced to 0.3.

Density-dependent stock and recruitment (P28)

Stock and recruitment	Make fitted stock and recruitment density dependent, such that recruitment is 80% of unexploited when biomass is 50% of unexploited.

Free density-dependent recruitment (P30)

Stock and recruitment	Set density dependence of stock and recruitment to be the best fit to the data.

3. RESULTS

3.1 BASE CASE

FIT TO CATCH AND EFFORT DATA

The model was fitted to winter CPUE data from 1973 to 1991 only. These data are shown as solid squares in the Figures. Earlier CPUE data for the winter fishery and for the summer fishery were not fitted by the model. These data are shown as open diamonds. The model fit is shown as a solid line (Figure 4).

Fit to the winter CPUE appears good. Winter CPUE data before 1973 do not resemble later data and presumably reflect a learning stage for the fishery.

Summer CPUE data were not fitted by the model. They show a more rapid decline from 1986 to 1992 than fitted by the model. The summer CPUE data are not considered a good indicator of relative abundance because the summer fishery selects a biased portion of the total biomass.

SELECTIVITIES

Selectivity in the length-based version of stock synthesis used here is limited to assuming the same ascending selectivity curve for males and females. In the winter fishery, where selectivity is forced to be asymptotic, this results in identical selection curves by size (Fig. 5). Because female gemfish grow faster than males, this selectivity curve forces an earlier recruitment of females to the winter fishery (by age) than males.

In the summer fishery where the selectivity curve is not forced to be asymptotic, selectivity for males is estimated as asymptotic, while selectivity for females is estimated as domed.

FIT TO AGE AND LENGTH DATA

The estimated proportion of numbers-at-age and the observed proportions for males or females are similar. There is some variability in the fit and one consistent trend: a tendency to overestimate the number of five-year-old female fish and underestimate the number of five-year-old male fish (Figure 6).

Estimated proportions of numbers at length are given for all years for which no age composition data were available (Figure 7). Estimated proportions at length match observed proportions at length fairly well for the combined sex data from 1975 to 1979. There is a consistent bias to the estimated numbers at length for the separate sex data from 1981 to 1994, with the estimated modal length being larger than the observed modal length for males, and marginally less for females.

The observed bias in the fit to age and length data for smaller fish is caused by the single ascending selectivity curve for males and females that leads the model to fit a value somewhere in between the males and female observations. The single ascending selectivity limb also causes a poor fit to the smaller lengths in 1994, where the estimated proportion of fish at lengths of 60 to 70 cm is greater than observed for females, but less than observed for males.

BIOMASSES

The biomass of male and female gemfish available to the winter fishery (total biomass multiplied by the computed selectivity of the fishery) declined from 24.5 thousand tonnes in 1969 to 3.1 thousand tonnes in 1994, or 13% of the 1969 biomass (Figure 8). Biomass available to the summer fishery declined from 3.0 thousand tonnes in 1969 to 0.4 thousand tonnes in 1994, a decline to 12% of the 1969 biomass (Figure 9).

RECRUITMENT

When the winter fishery started there were several years of relatively large recruitments (Figures 10 to 12). As the biomass dropped in the late 1970s recruitment was reduced. Recruitment stayed at a similar level in the early 1980s despite continuing decline in biomass; recruitments in the early 1980s were larger than expected from the fitted stock and recruitment relationship. In the late 1980s, recruitments were much lower than expected and biomass has continued to decline in the 1990s. This period of low recruitments coincided with a period of reduced westerly winds.

The model does not identify the 1990 recruitment as being abnormally large because the bias caused by a common ascending selectivity limb for males and females causes the recent large recruitments to be spread over the 1990, 1991 and 1992 year classes. This bias disappears as the fish become more available to the fishery, as shown by including the 1995 length composition data, when the 1990 year class stands out as the largest (see sensitivity analyses).

3.2 SENSITIVITY ANALYSES

GENERAL

Total winter biomass (biomass of all fish aged five years and older) is estimated at 3.3 thousand tonnes in the base case with negligible coefficient of variation (Table 16). This result is sensitive to the degree of emphasis put on the CPUE data relative to the age and length data. Model runs with no age or length data or with a reduced CPUE emphasis indicate a higher current biomass.

The assessment is robust to including ages younger that five-year old and to removing length composition data for the winter catches.

There is little change in the assessment caused by specifying a second selectivity period from 1989, but this may change as more data become available that represent this second period.

Current biomass increases as emphasis on a spawner-recruit relationship is increased. Increasing emphasis on the spawner-recruit relationship reduces the size of the negative recruitment residuals in the late 1980s.

RELATIVE EMPHASIS ON AGE-LENGTH OR CPUE DATA

As the emphasis on the CPUE data declines relative to the emphasis on the age and length data, the assessment suggests a lower initial (1969) biomass and a higher current (1994) biomass (Table 19). The same trend is evident for the female spawning biomass (with the exception of the assessment with no age or length data, where current female spawning biomass does not decline as much as in the baseline assessment). This range of assessments indicates that the currently available winter biomass may vary etween 2 and 28 thousand tonnes; depending on the relative emphasis put on the data sets.

Table 20 shows the effect of emphasising different data sets on the fit to those data sets. Coefficients of variation for the age and length data are a fixed input parameter equalling 0.21 for the winter age and length data (CV for a proportion of 0.1 with a sample size of 200) in all runs except for the run a reduced sample size. The coefficients of variation for the CPUE data vary from 0.05 to 0.78 depending on the emphasis given to the CPUE data relative to the age and length data.

It is important to recognise that these coefficients represent the estimated level of precision of the data; they do not account for any bias due to selective sampling of the commercial catch (age and length data) or due to changes in the fishing behaviour of the fleet (CPUE data).

RECRUITMENT

Emphasis on the stock and recruitment relationship is set very low (0.001) so changes to the stock and recruitment relationship do not have an appreciable effect on the assessment (Table 21). However, if the emphasis on fitting the data to the stock and recruitment data is increased to 0.1 (one-tenth the emphasis on CPUE, age and length data), 1994 available biomass and female spawning biomass become double those of the base case. This is primarily due to increased emphasis on the stock and recruitment relationship reducing the magnitude of recruitment anomalies, including the series of negative anomalies in the late 1980s.

When density dependence of stock and recruitment is fitted by the model, density dependence is estimated very low at 0.25; recruitment will be 57% of the unexploited level when biomass is 50% of the unexploited level (Figure 13).

4. DISCUSSION

The gemfish fishery has a good time series of data in comparison to most Australian fisheries. There is a longer 'continuous' series of catch-at-age data than for any other south east fishery quota species, and the dramatic changes observed in the length frequency composition provide good contrast in the data against which to test assessment models.

These data are sufficient on their own to demonstrate the series of poor recruitments in the late 1980s. The gemfish biomass was already declining by this time due to fishing, and the combination of poor recruitment and extensive fishing resulted in the directed fishery being closed in 1993.

Biological questions to be answered now are: why did the poor recruitments occur?; to what extent was fishing responsible for the biomass decline?; and what is the current biomass? An answer to the first and second questions is needed to help determine management strategies that might reduce the risk of a similar series of poor recruitments in the future. An answer to the third question is needed to determine the potential impact of current bycatch levels on the diminished stock and to determine when the directed fishery can be resumed.

This assessment provides some information on the first two questions, confirming the conclusion of earlier assessments that recruitment in the late 1980s was reduced because of a combination of reduced biomass and unusually poor recruitment. There is a correlation between recruitment anomalies and the number of days of zonal westerlies per year, suggesting that an environmental factor(s) independent of the fishery may be involved. Historic data show that in the last century the gemfish distribution was different from that at the beginning of the directed fishery in 1969. Data from the early part of this century show that the southern distribution was already reduced. The condition of the gemfish stock in 1969 is unclear. It may have already been smaller than previously.

The small level of density dependence in the stock and recruitment relationship fit to the base case assessment suggests that at the start of the fishery when biomasses were the high (at least for the time period covered by this assessment), the biomass was not high enough to generate density dependent recruitment. This suggests either that the biomass at the start of the fishery was already reduced to a level where density dependent recruitment processeswere reduced, or that recruitment in gemfish is controlled by density independent processes. Examples of density dependent processes that could regulate recruitment are environmental factors and generalist predators.

The apparent environmental influence on the gemfish stock raises concerns. Not only does it make it difficult to separate the impact of fishing on the stock, it also casts some doubt on the consistency of CPUE as an indicator of abundance. It is already suspected that changes in fishing practices since the late 1980s will have affected the most recent data points. If the spatial distribution of gemfish changes appreciably from year to year, such that it would impact fishers' catches, then this casts further doubt on the use of CPUE as a relative index of abundance. Further analysis of the catch and effort data is required on a finer spatial scale than available for this assessment. Such an analysis should determine the degree of confidence that can be placed in these data, and might also be useful in providing a catch and effort series that could be reproduced in the present, perhaps based on one or two consistent vessels and skippers.

This assessment is, in general, fairly insensitive to changes in data sets used and model assumptions, but it is sensitive to the emphasis put on the CPUE data. An improved understanding of the CPUE data is required before an assessment of gemfish can be considered reliable.

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Table 1. Best estimates of gemfish catches (from Chesson 1995).

	Catches of gemfish from trawlers (tonnes)			
	Winter directed fishery		Summer bycatch fishery	
Year	Recorded	Best estimate	Recorded	Best estimate
1969	-	200	-	20
1970	-	200	-	30
1971	230	230	-	40
1972	414	420	57	60
1973	1110	1110	12	20
1974	883	900	12	20
1975	901	920	31	40
1976	2085	2100	34	40
1977	3093	3100	166	170
1978	4678	4700	447	450
1979	3876	3900	458	460
1980	5069	5100	436	440
1981	4087	4100	182	190
1982	3569	3600	264	270
1983	3100	3100	305	305
1984	2800	2800	300	300
1985	2900	2900	205	205
1986	3450	3450	356	130
1987	4200	4200	75	80
1988	3500	3500	160	175
1989	2300	2200	104	175
1990	1200	1200	45	80
1991	300	300	0	50
1992	700	790	0	30
1993	–	450	–	70
1994		175		25

Early catch data for the winter fishery are derived from fisheries cooperative data (1972-1982) or are assumed (1969-1971). Later data are from the Southeast Fishery logbooks. 1993 data are from quota monitoring reports.

Table 2. **Steam trawler-caught gemfish sold at Sydney Fish Market (Blackburn 1979).**

	Recorded catch ('000 lb)				
	1953	1954	1955	1956	Total
No. Boats	10	9	5	4	
January	31	22	7	22	82
February	42	35	19	19	115
March	55	32	45	21	153
April	7	29	50	9	95
May	6	45	15	4	70
June	4	25	12	7	48
July	6	11	7	9	33
August	5	13	3	10	31
September	12	31	30	14	87
October	16	39	9	15	79
November	27	25	17	22	91
December	102	35	35	41	213
Total	313	342	249	193	1,097

Table 3. Red Funnel trawler-caught gemfish 1952-1957 (Blackburn 1979).

	Catch (baskets: 1 basket = 70lb)				
	Babel Is.	Victoria	NSW(S)	NSW (N)	Total
January	464	151	33	*	648
February	461	136	120	*	717
March	363	100	42	0	505
April	44	131	202	*	377
May	0	75	196	0	271
June	*	7	93	0	100
July	0	52	16	0	68
August	0	56	56	0	112
September	27	275	69	0	371
October	121	353	176	0	650
November	91	233	175	0	499
December	29	1,027	258	*	1,314
Total	1,600	2,596	1,436	0	5,632

* denotes no fishing

Table 4. Catch and effort data for the winter trawl fishery (Chesson 1995 and Rowling, unpublished data).

	Fishery coop records (standard fleet)				SEF logbook records CPUE		
Year	Number of vessels	Catch (t)	Effort (days)	CPUE (kg/day)	All data (a) (kg/hr)	Standard data (b) (kg/hr)	Rowling's analysis (c) (kg/hr)
1969	3	55	119	462			
1970	3	47	151	311			
1971	3	57	83	689			
1972	daily figures not available			1214			
1973	4	299	94	3403			
1974	4	326	85	3732			
1975	4	284	100	3039			
1976	11	1006	260	3873			
1977	14	1534	413	3715			
1978	28	3817	936	4078			
1979	36	2796	901	3109			
1980	39	3852	1128	3414			
1981	36	2436	897	2716			
1982	37	1624	813	1982			
1983	47	1718	1625	1059			
1984	49	2280	2017	1131			
1985	48	2196	1607	1391			
1986	49	2260	1670	1269	610	694	279
1987				1535	950	982	358
1988					697	667	349
1989				1297	428	436	242
1990				1151	301	357	203
1991				1021	142	192	114
1992					184	162	147
1993							33

(a) 'All data' are all SEF logbook data but restricted to depths and seasons where gemfish occur.

(b) 'Standard data' are all SEF logbook data but restricted to areas and depths fished consistently in all years 1986-91. This accounts for some of the spatial expansion/contraction of the fishery.

(c) Rowling analysis concentrated on consistent gemfish vessels .

Table 5. Catch and effort data for the summer trawl fishery (Chesson 1995).

	All data			Standardised data		
	Catch t	Effort hrs	CPUE kg/hr	Catch t	Effort hrs	CPUE kg/hr
1986	149	1647	90	32	217	148
1987	102	809	126	23	114	204
1988	145	1406	103	22	161	139
1989	144	3014	48	11	222	48
1990	64	1102	58	3	105	33
1991	63	1518	42	34	308	110
1992	34	876	39	10	74	140
1993						

Table 6. **Aggregate von Bertalanffy growth parameters for gemfish 1980-1986 (Rowling and Reid 1992).**

	Linf	(SE)	K	(SE)	tzero	(SE)	n
Males	97.5	0.800	0.212	0.005	-0.54	0.050	2327
Females	109.4	0.600	0.180	0.003	-0.63	0.040	3157

Table 7. Individual von Bertalanffy growth parameters for gemfish 1980-1986 (Rowling and Reid 1992)

		Linf	(SE)	K	(SE)	tzero	(SE)	n
Males								
	1980	98.1	1.1	0.223	0.007	-0.41	0.04	602
	1982	95.2	0.9	0.230	0.006	-0.44	0.04	914
	1984	94.1	1.8	0.225	0.011	-0.49	0.06	465
	1986	89.1	1.4	0.247	0.011	-0.47	0.06	682
Females								
	1980	111.7	0.9	0.172	0.004	-0.63	0.04	883
	1982	106.0	0.8	0.197	0.004	-0.48	0.04	1123
	1984	109.7	1.2	0.182	0.005	-0.55	0.04	628
	1986	106.6	1.4	0.190	0.006	-0.54	0.05	859

Table 8. Length and weight parameters for gemfish (Rowling in Allen 1989).

	Weight/length parameters			
	a	(SE)	b	(SE)
Males	$1.43*10^{-6}$		3.39	
Females	same as males			

Table 9. Natural mortality rates used in earlier cohort analysis (Allen 1989).

	Male		Female	
Age	M	q	M	q
3	0.25	0.014	0.15	0.013
4	0.25	0.056	0.15	0.030
5	0.25	0.244	0.15	0.228
6	0.25	1	0.15	0.868
7	0.25	1	0.15	1
8	0.3	1	0.15	1
9	0.5	1	0.15	1
10	0.6	1	0.24	1
11	0.8	1	0.64	1
12	1.1	1	0.94	1

Table 10. Comparison of readings of 104 otoliths by Rowling (R) and Morison (M). (Rowling 1992)

	Males		Females		Combined	
Age	R	M	R	M	Difference	Frequency
4	1	3			-4	1
5	18	15	1	2	-3	1
6	12	9	5	5	-2	6
7	4	8	17	17	-1	21
8	1	0	16	17	0	57
9			11	18	1	14
10			10	1	2	3
11			8	5		
12			0	1		

Table 11. Age compositions derived from age length keys and length frequency composition for the winter fishery.

	Number-at-Age												
Year	1	2	3	4	5	6	7	8	9	10	11	12	n
						Males							
1980	0	0	0	75	382	440	271	125	23	3	0	0	1319
1982	0	0	8	126	309	484	171	75	31	7	2	0	1213
1984	0	6	62	290	465	321	97	26	5	0	0	0	1271
1986	0	3	40	255	453	278	105	16	7	0	0	0	1157
1988	0	10	84	218	703	345	83	8	5	0	0	0	1456
1990	0	11	34	290	330	710	409	103	42	3	0	0	1932
1991	0	16	74	532	592	292	134	177	53	15	7	0	1892
1992	0	55	18	50	153	312	304	119	79	35	0	0	1126
1993	0	75	321	83	83	133	256	145	70	9	1	0	1176
						Females							
1980	0	0	0	21	153	430	500	256	143	90	58	44	1695
1982	0	0	5	23	129	532	372	177	112	72	31	9	1462
1984	0	0	3	36	289	572	366	208	98	42	30	17	1661
1986	0	0	9	55	291	582	314	135	64	39	7	6	1503
1988	0	0	21	24	348	575	292	110	48	29	4	4	1454
1990	0	0	4	52	190	741	853	427	197	88	15	22	2590
1991	0	0	18	194	613	843	734	377	113	50	15	17	2974
1992	0	4	8	35	303	925	852	468	290	76	38	4	3003
1993	0	9	50	22	55	158	414	437	272	125	19	17	1577

Table 12. Coefficient of variation of length-at-age from age-length keys.

		Age											
Year	n	1	2	3	4	5	6	7	8	9	10	11	12
							Males						
1980	507			5.6	4.9	3.9	3.9	3.5	3.2	2.4	1.3		
1982	800			5.6	5.1	3.9	3.8	3.5	2.9	3.3	4.0	2.9	
1984	344			4.5	6.1	4.0	4.6	3.7	4.2	4.2			
1986	551		5.0	5.3	5.3	4.9	4.9	4.8	5.4				
1988	257			5.1	5.4	4.0	4.3	3.1					
1990	314			6.5	4.8	4.7	4.5	4.3	5.4	2.2			
1991	297			13.4	7.2	6.4	7.1	4.8	6.0	6.7	2.8		
1992	192				14.2	9.6	6.8	7.2	6.3	8.8	8.0		
1993	140	5.0	3.9	9.1	5.6	3.7	3.8	5.3	3.5				
							Females						
1980	771				2.9	3.8	3.5	3.3	2.7	3.0	3.7	4.0	3.8
1982	952				2.6	4.8	3.4	3.7	3.0	3.1	3.4	3.5	5.1
1984	526				3.5	4.4	4.0	4.0	3.3	3.5	4.2	2.2	4.4
1986	746				5.1	4.6	4.2	4.5	4.8	4.5	4.3	6.0	4.2
1988	305			3.5	4.4	4.5	4.2	4.7	3.2	5.0	3.4	4.4	
1990	240					2.3	2.9	3.2	4.3	4.1	3.3	3.7	
1991	462				7.5	6.7	6.1	6.1	7.0	8.1	6.9	8.6	7.7
1992	338			11.6	9.2	8.3	7.1	5.8	7.1	8.2	3.4		
1993	376		1.7	10.7		5.4	6.4	4.2	4.1	4.9	3.9	3.2	2.5

Table 13. Mean fecundity-at-age (Rowling, unpublished data).

Age	Mean length (cm)	Mean weight (kg)	Fecundity (millions) number	Fecundity (millions) per kg
4	61.0	1.61	0.7	0.43
5	71.0	2.70	1.0	0.37
6	76.0	3.40	1.3	0.38
7	81.0	4.22	1.7	0.40
8	86.0	5.17	2.0	0.39
9	90.0	6.03	2.4	0.40
10	93.0	6.74	2.7	0.40
11	97.5	7.91	3.4	0.43
12+	100.0	8.62	4.0	0.46

Table 14. **Percent of mature female fish by age .**

Age	Fraction mature (a)
1	0.000
2	0.000
3	0.001
4	0.095
5	0.552
6	0.930
7	1.000
8	1.000
9	1.000
10	1.000
11	1.000
12	1.000

(a) assumed equal to proportion selected by winter fishery as estimated by synthesis model.

Table 15. Number of days per year of strong zonal west winds (Thresher 1994).

Year	Number of days
1969	127
1970	132
1971	120
1972	95
1973	85
1974	75
1975	105
1976	68
1977	89
1978	86
1979	145
1980	149
1981	113
1982	118
1983	96
1984	110
1985	70
1986	49
1987	59
1988	34
1989	29
1990	76
1991	70
1992	54
1993	85

Table 16. Total mature (5+) winter biomass, and natural mortality for the base case assessment and the sensitivity of these values to changes in data emphasis and model assumptions.

Model Run	Code	Total biomass winter (5+)				Natural mortality	
		1969	1979	1994	94/69	Female	Male
Base case	P12	31,993	30,795	3,368	0.11	0.54	0.62
Ages ^{3}4	P22	45,209	42,292	4,391	0.10	0.57	0.63
All ages	P11	30,605	35,655	3,545	0.12	0.54	0.60
No winter length	P13	23,316	30,003	3,937	0.17	0.61	0.68
No age or length data	P14	28,947	29,065	6,647	0.23	0.54	0.63
Summer length data	P15	39,742	30,420	3,507	0.09	0.56	0.64
Include 1995 length data	P24	16,540	23,552	2,491	0.15	0.45	0.53
Red CPUE emphasis 90%	P16	22,599	26,219	31,045	1.37	0.50	0.57
Model fit to growth	P18	30,345	27,230	11,017	0.36	0.51	0.64
Two selectivity periods	P19	32,617	30,920	3,961	0.12	0.54	0.62
Domed selectivity	P23	29,249	28,954	3,177	0.11	0.51	0.59
Inc S/R emphasis	P21	39,202	32,650	8,894	0.23	0.56	0.64

Table 17. Total biomass available to the winter fishery, the female spawning biomass and the total (1+) biomass for the base case assessment, their percentages of 1969 biomass, and the sensitivity of these values to changes in data emphasis and model assumptions.

		Available winter biomass		Female spawning biomass		Total (1+) biomass	
Model Run	Code	1994	94/69	1994	94/69	1994	94/69
Base case	P12	1,329	0.13	2,023	0.12	14,863	0.22
Ages 3-4	P22	2,558	0.17	2,459	0.11	105,773	1.04
All ages	P11	1,747	0.19	2,052	0.14	107,941	1.65
No winter length	P13	1,484	0.28	2,109	0.19	21,904	0.36
No age or length data	P14	2,401	0.23	3,474	0.23	16,634	0.25
Summer length data	P15	1,374	0.11	2,087	0.11	15,031	0.17
Include 1995 length data	P24	2,697	0.18	1,656	0.18	33,471	0.33
Red CPUE emphasis 90%	P16	12,414	1.76	18,660	1.59	136,030	3.03
Model fit to growth	P18	4,290	0.47	5,454	0.47	81,669	1.32
Two selectivity periods	P19	1,477	0.14	2,356	0.14	20,119	0.29
Domed selectivity	P23	3,033	0.13	1,937	0.13	13,053	0.21
Inc S/R emphasis	P21	3,284	0.27	4,974	0.26	35,737	0.40

Table 18. Maximum likelihood estimates for the fit of the base case assessment to data on: winter age composition, winter length composition, summer length composition, winter CPUE, summer CPUE, average stock and recruitment, and the variation of stock and recruitment; and the sensitivity of these values to changes in data emphasis and model assumptions.

Model Run	Code	Maximum likelihood estimate						
		Winter age	Winter length	Summer length	Winter CPUE	Summer CPUE	S/R 1	S/R 2
Base case	P12	-167	-218	-881	23		-25	-507
Ages≥4	P22	-296	-271	-755	25		-35	-852
All ages	P11	-366	-332	-13412	27	4	-39	-997
No winter length	P13	-152	-410	-822	24	5	-10	-122
No age or length data	P14	-373	-937	-406	46	7	-17	-294
Summer length data	P15	-192	-231	-144	19	7	-29	-622
Include 1995 length data	P24	-167	-217	-1045	25	4	-21	-383
Red CPUE emphasis 90%	P16	-167	-210	-739	-4	-1	-39	-928
Model fit to growth	P18	-80	-175	-607	12	0	-15	-237
Two selectivity periods	P19	-165	-221	-715	23	4	-23	-466
Domed selectivity	P23	-167	-217	-928	24	4	-27	-565
Inc S/R emphasis	P21	-170	-222	-709	-17	-6	-6	-51

Table 19. Sensitivity of assessment to changes in emphasis on age/length and CPUE data for the winter fishery.

Run	Code	Available biomass winter			Female spawning biomass			
		69	94	94/69	69	79	94	94/79
Base case	P12	24,513	3,100	13	16,266	14,654	2,023	14
No age or length data	P14	25,451	2,055	8	15,018	15,507	3,474	22
CPUE emphasis *10	P26	25,695	2,231	9	17,119	16,644	1,467	9
Sample size 50	P25	26,717	2,916	11	17,389	16,759	1,881	11
CPUE emphasis * 0.5	P17	22,632	11,454	51	15,229	13,680	7,498	55
CPUE emphasis * 0.1	P16	16,405	28,421	173	11,739	12,313	18,660	152

Table 20. Sensitivity of fit to data to changes in emphasis on age/length and CPUE data for the winter fishery.

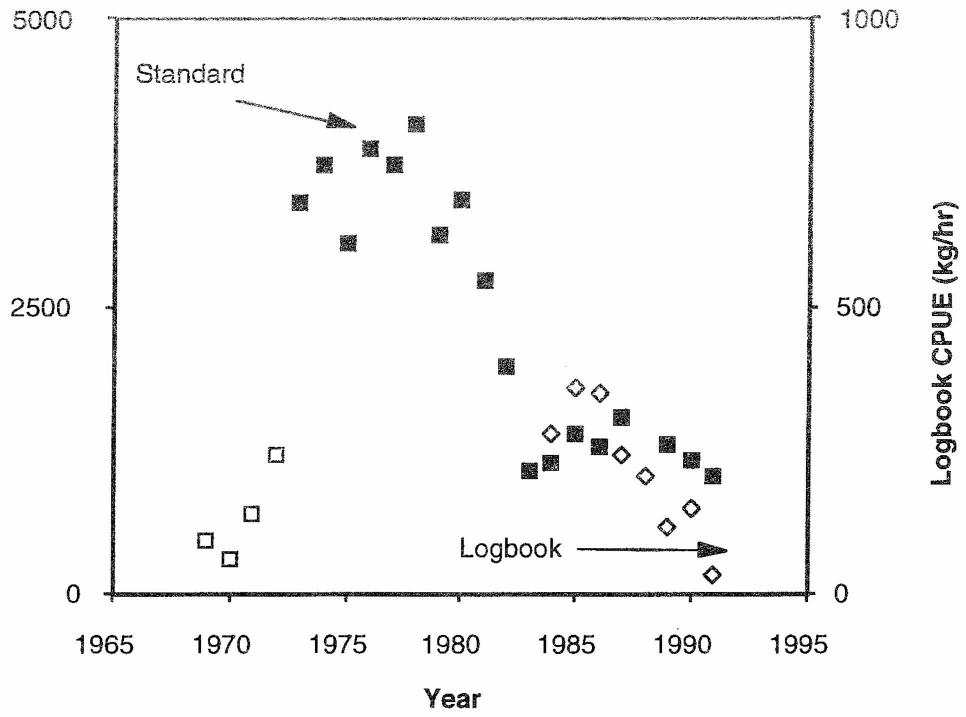
Run	Code	Likelihood contribution of data				
		Winter			Summer	
		age	length	CPUE	length	CPUE
Base case	P12	-167	-218	23	-881	4
No age or length data (a)	P14	-373	-937	46	-406	7
CPUE emphasis *10	P26	-176	-255	33	-769	6
Sample size 50	P25	-42	-58	28	-181	5
CPUE emphasis * 0.5	P17	-169	-211	5	-535	1
CPUE emphasis * 0.1	P16	-167	-210	-4	-739	-1

(a) the contribution of age and length data to the log (likelihood) for 'No age or length data' occurs because these data have not been removed, but their emphasis in the maximum log (likelihood) has been reduced to 0.001.

Table 21. Sensitivity of assessment to changes in the stock and recruitment relationship.

Run	Code	Available biomass winter			Female spawning biomass			
		69	94	94/69	69	79	94	94/79
Base case	P12	24,513	3,100	13	16,266	14,654	2,023	14
Inc S/R emphasis	P21	27,901	7,448	27	19,264	15,273	4,974	33
Reduce CV on S/R 0.3	P27	27,815	3,616	13	18,446	15,653	2,403	15
Density dependent S/R	P28	24,729	3,462	14	16,541	15,049	2,229	15
Free density dependence	P30	23,658	3,381	14	15,341	14,206	2,158	15

Figure 1. Standardised CPUE series and SEF logbook data (from Rowling, pers. comm.)[2]



2 In the figures presented in this document, points represent observed data, lines (when shown) represent the fit of the model to these data. Open data points represent observed data not fit by the model.

Figure 2. Length composition of the winter trawl fishery for three years (Rowling, unpublished data).

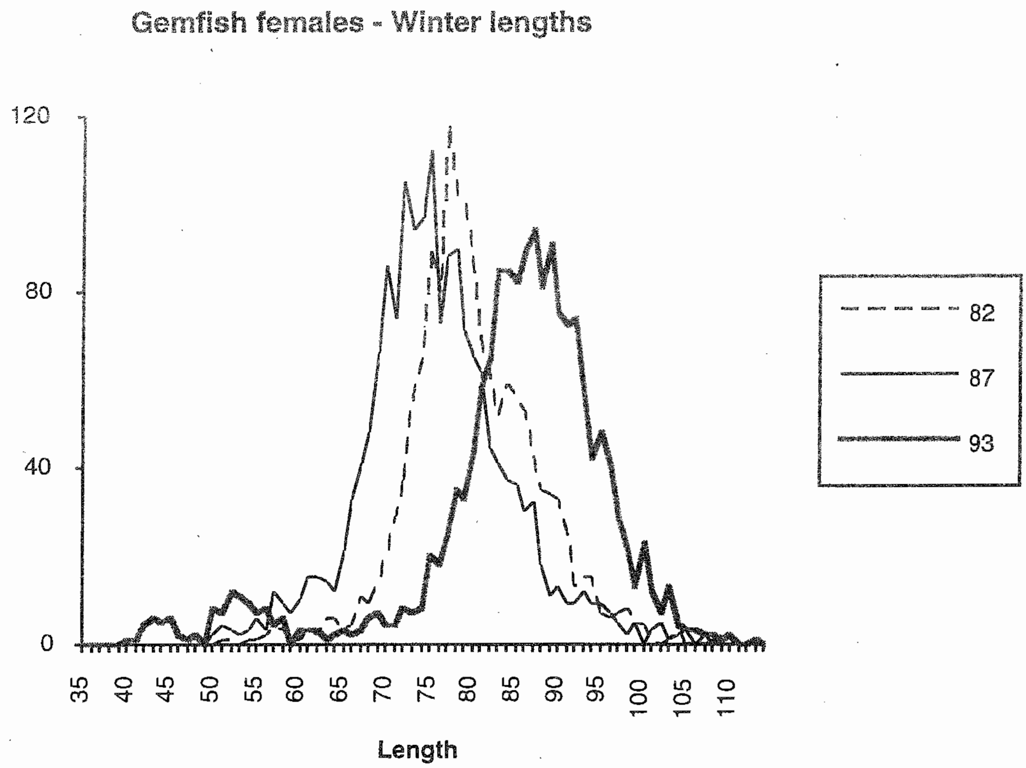


Figure 3. Length composition data for three years of the summer trawl fishery (Rowling, unpublished data).

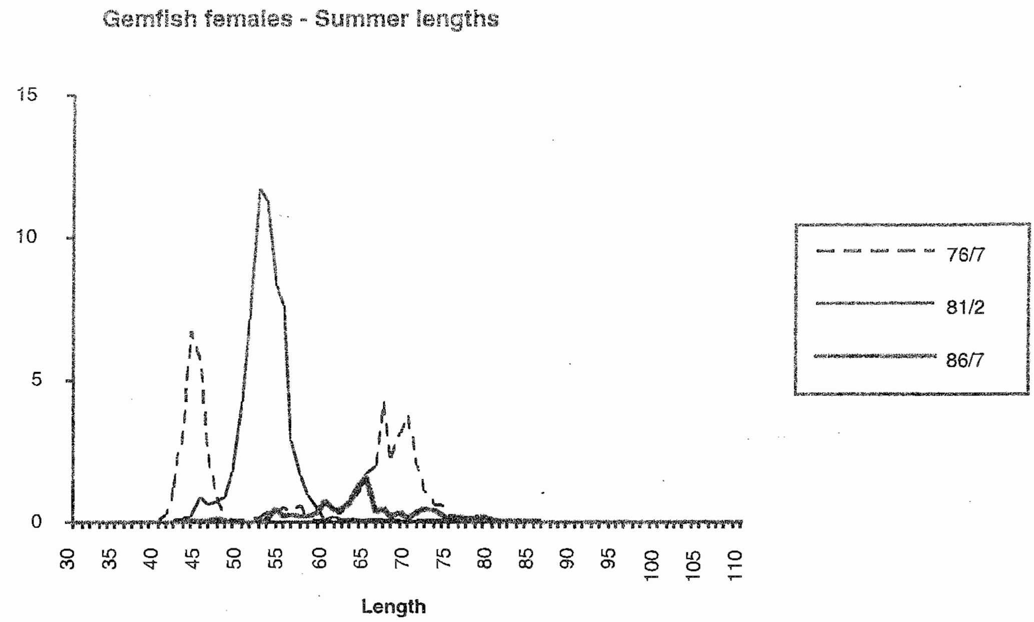


Figure 4. Fit to catch and effort data.

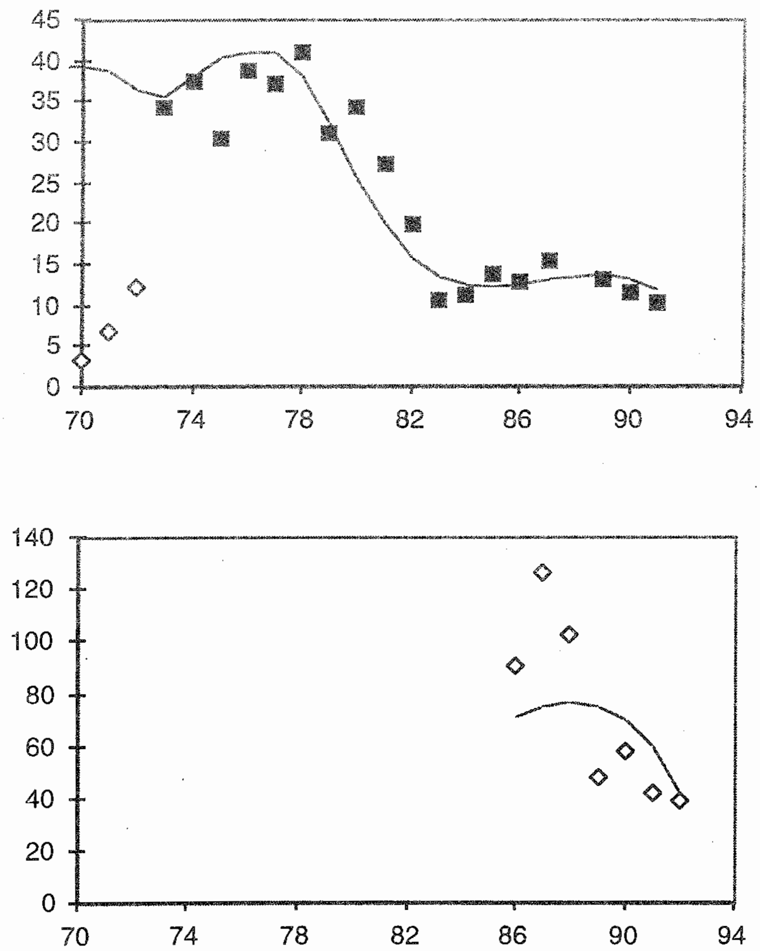


Figure 5. Selectivity of the winter and summer fishery by size and age for females (solid line) and males (dashed line).

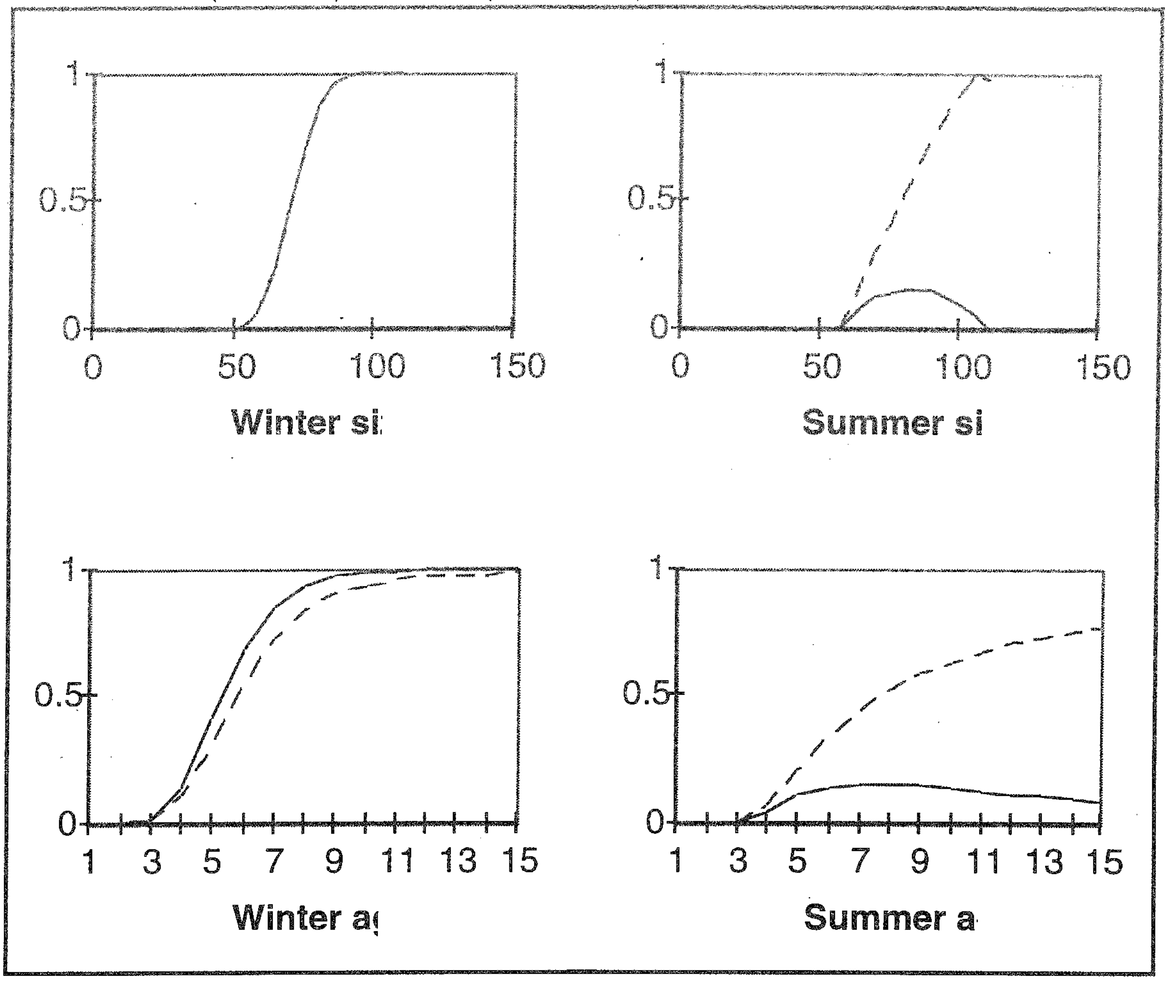


Figure 6. Fit to age composition data for the winter fishery. Solid points are the observed age composition; the line is the model fit.

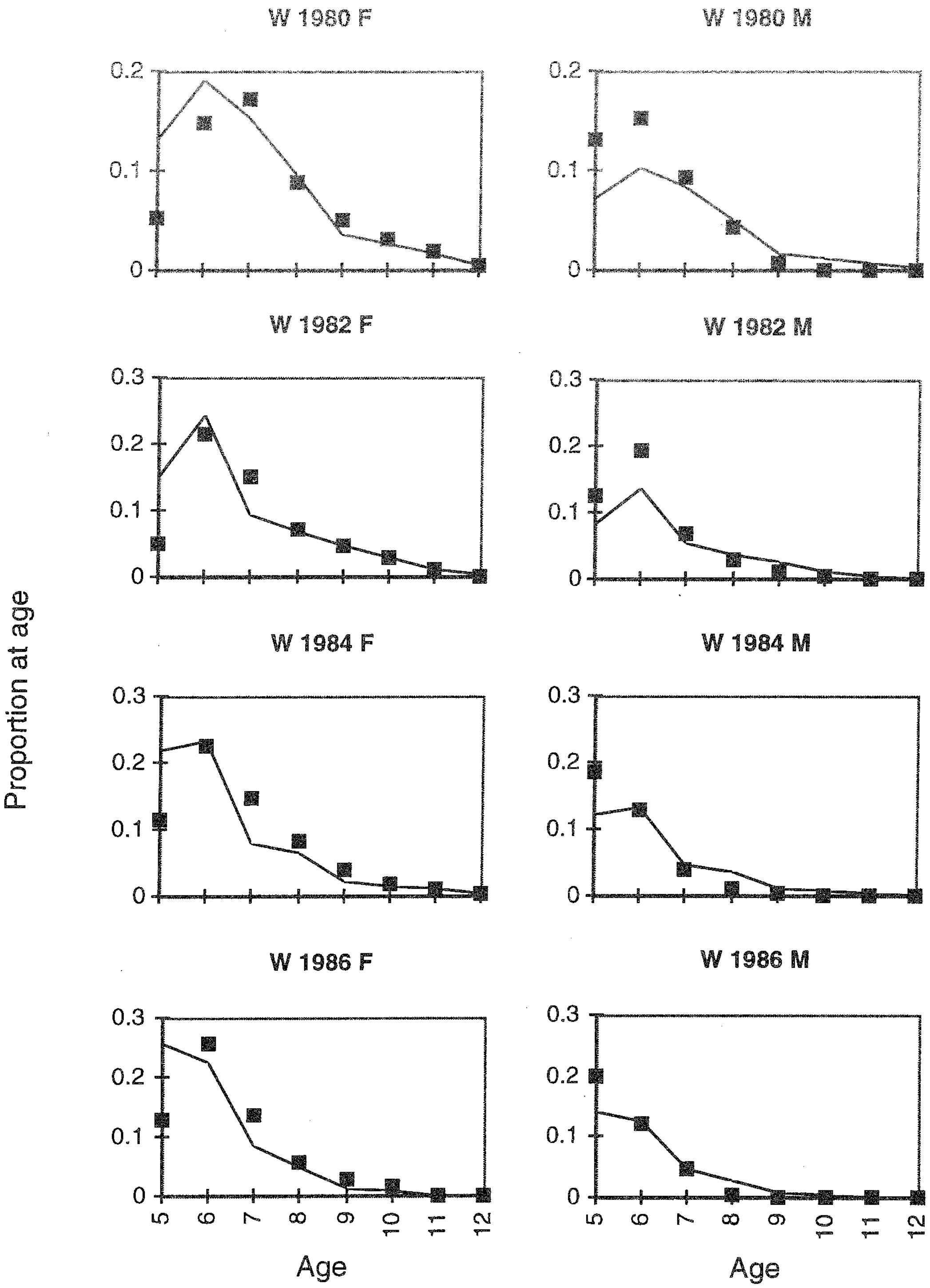


Figure 6. Continued

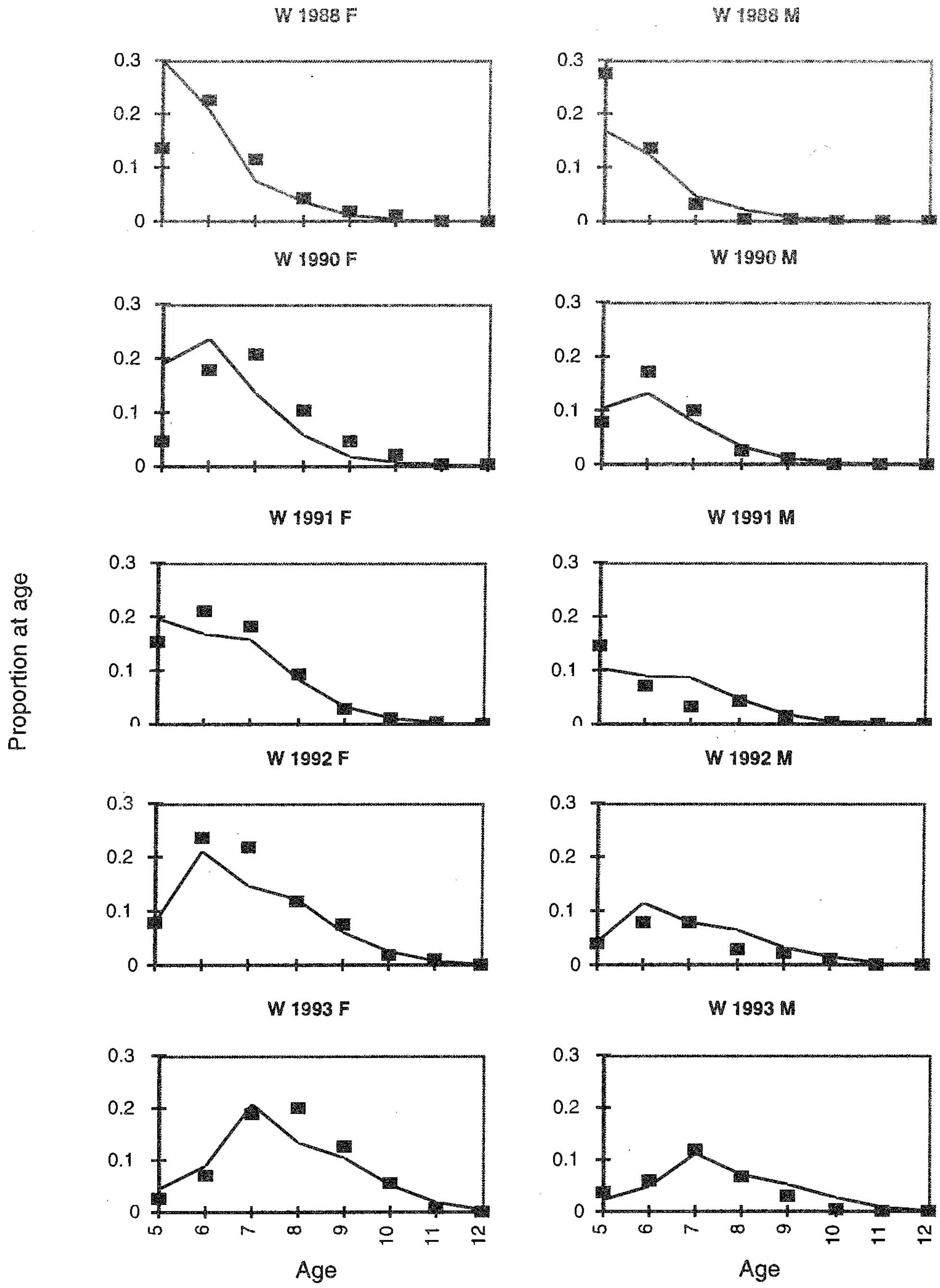


Figure 7. Fit to winter length data. Solid points are the observed age composition.

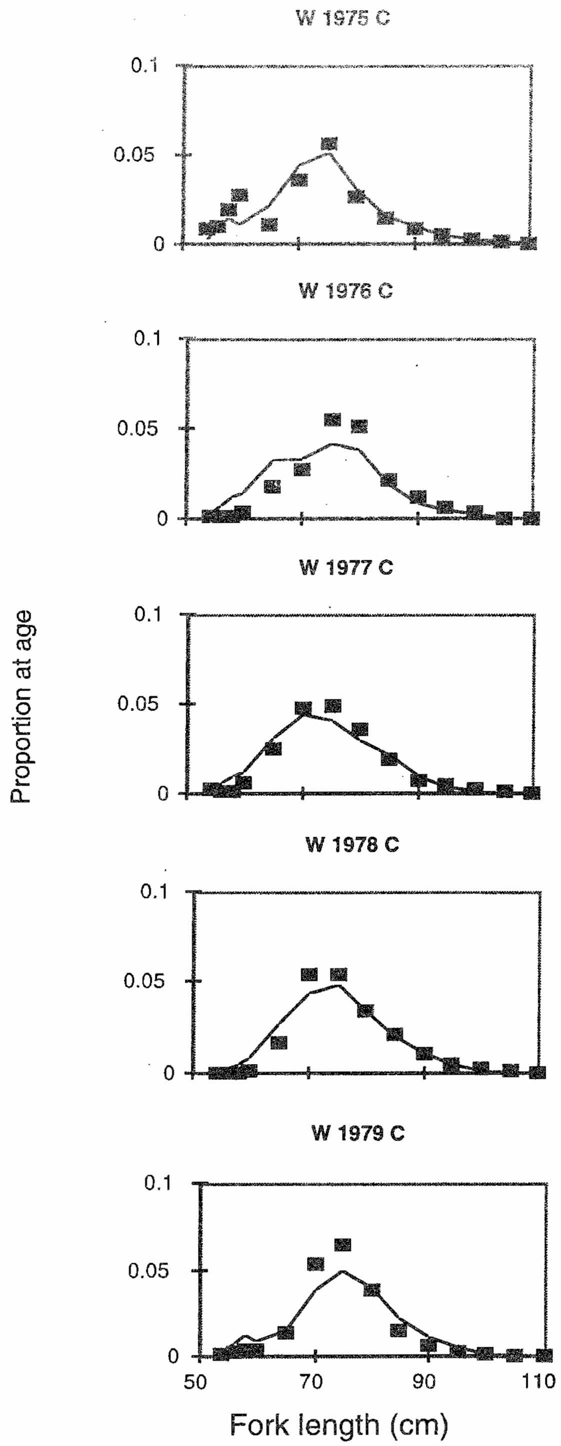


Figure 7. Continued

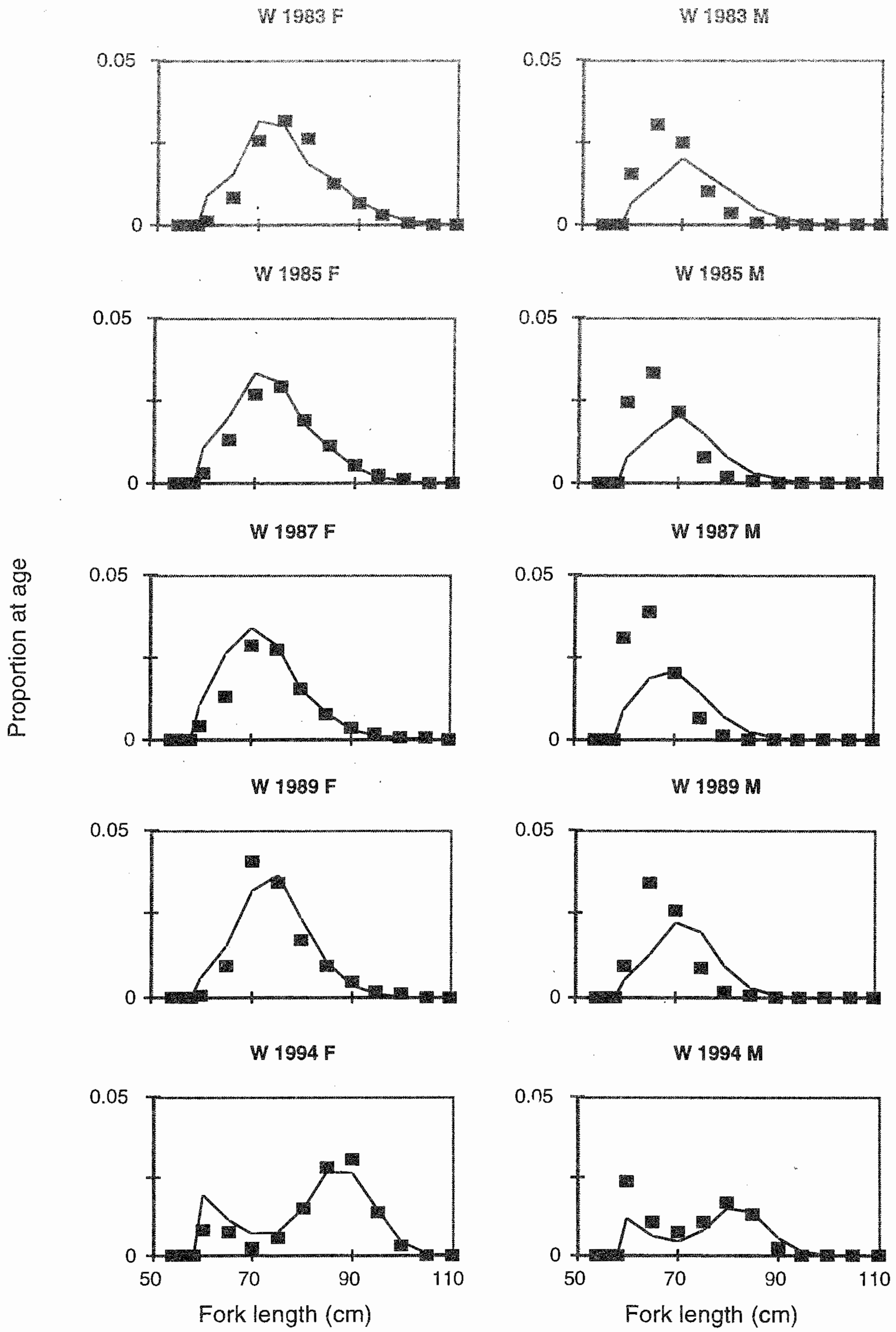


Figure 8. Available biomass in the winter fishery.

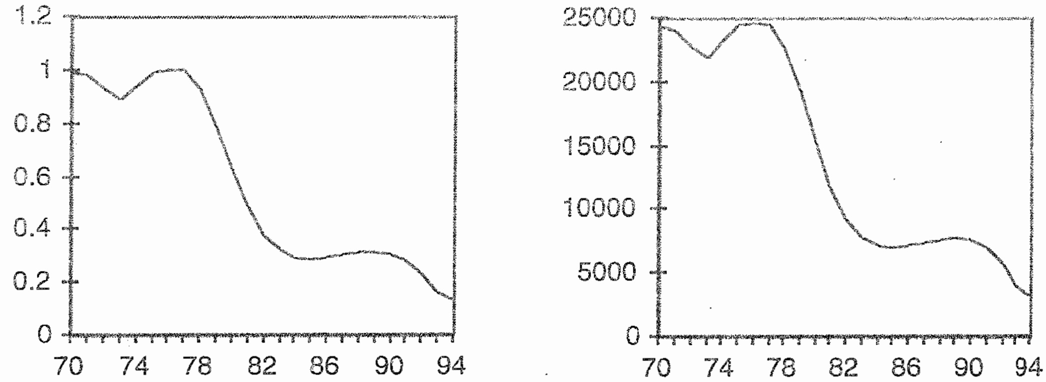


Figure 9. Available biomass in the summer fishery

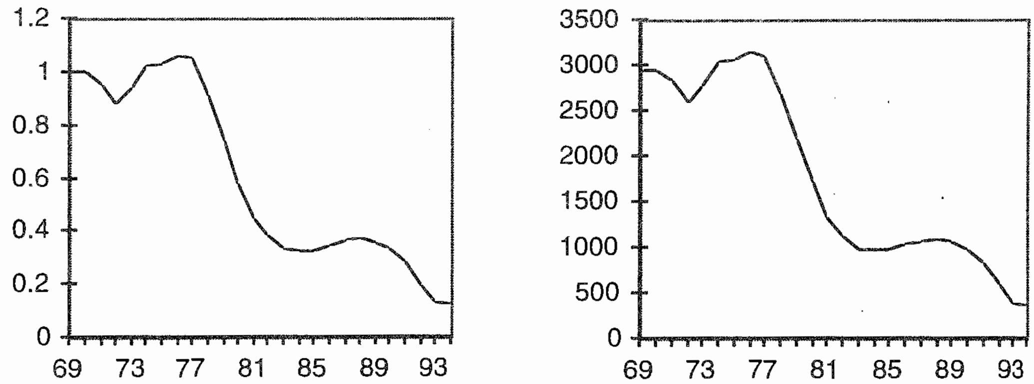


Figure 10. Relationship between female spawning biomass and number of recruits at age 1.

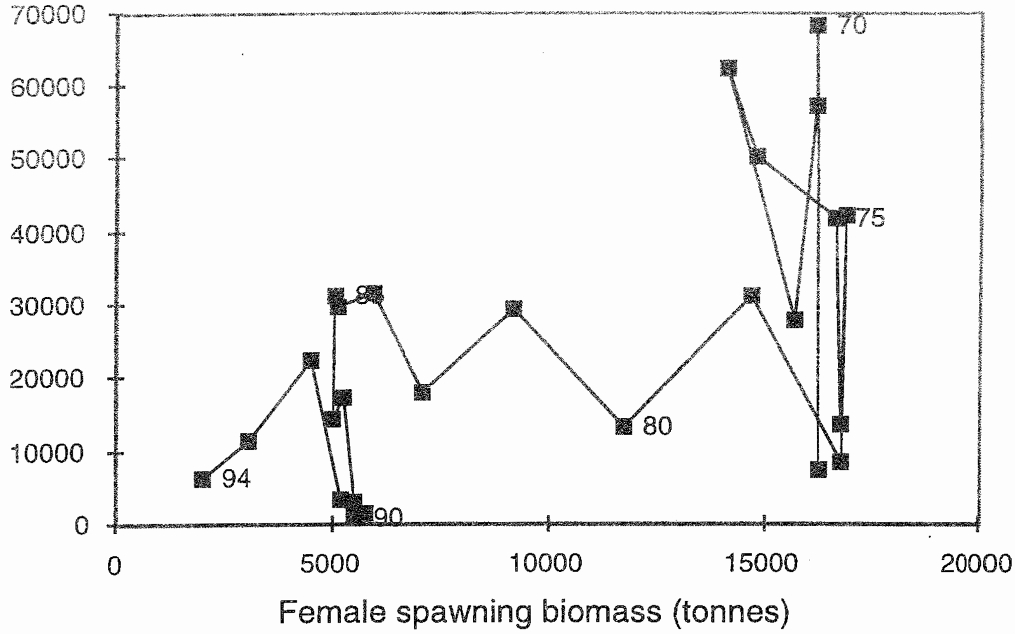


Figure 11. **Observed minus expected recruitment and number of days per year of strong zonal west winds (from Thresher 1994).**

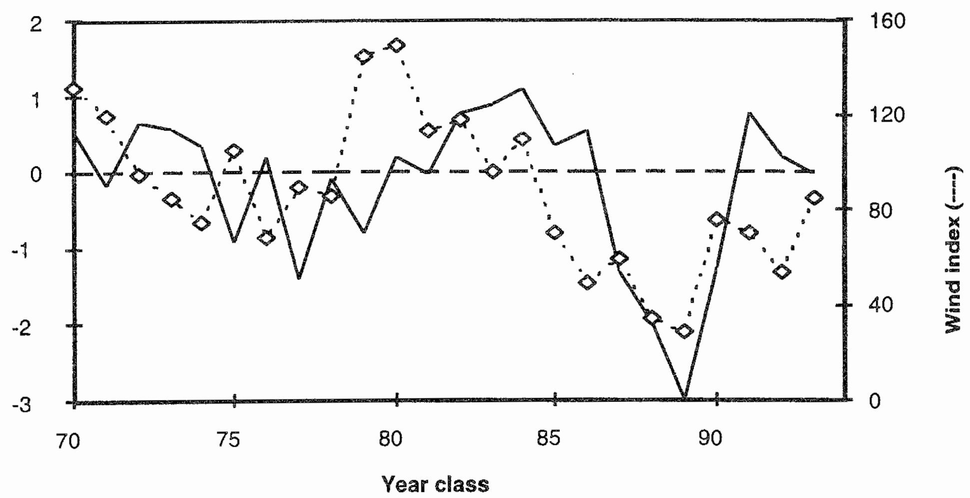


Figure 12. Estimated recruitment and recruitment expected from the fitted stock and recruitment relationship.

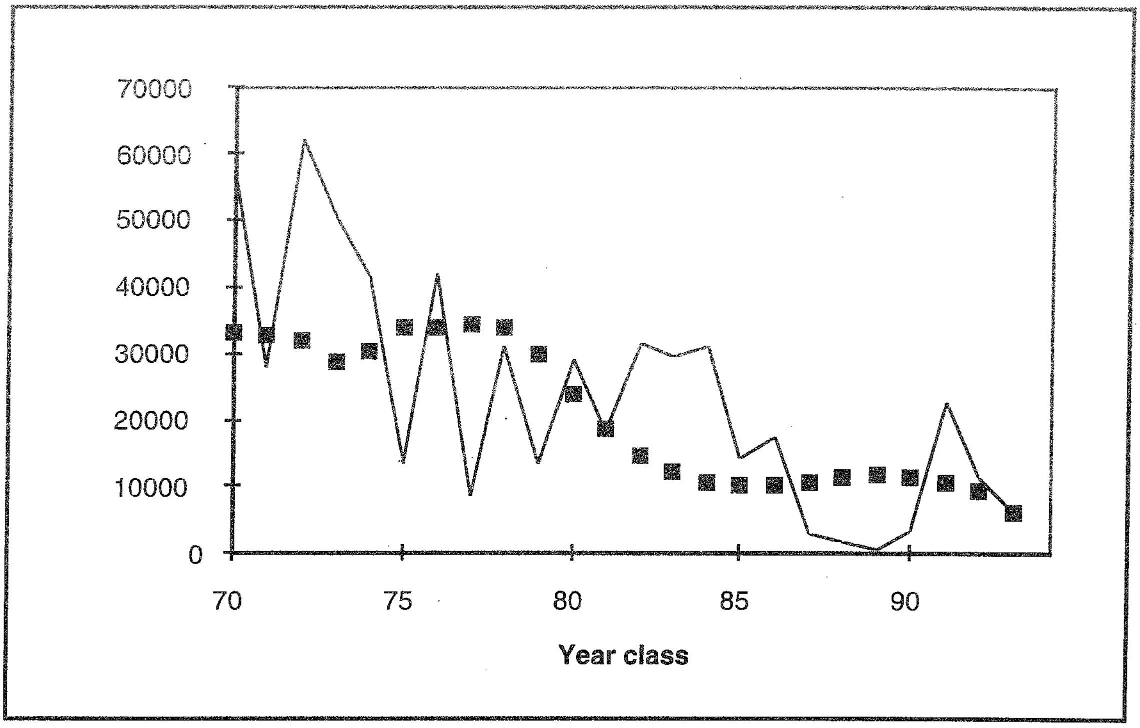
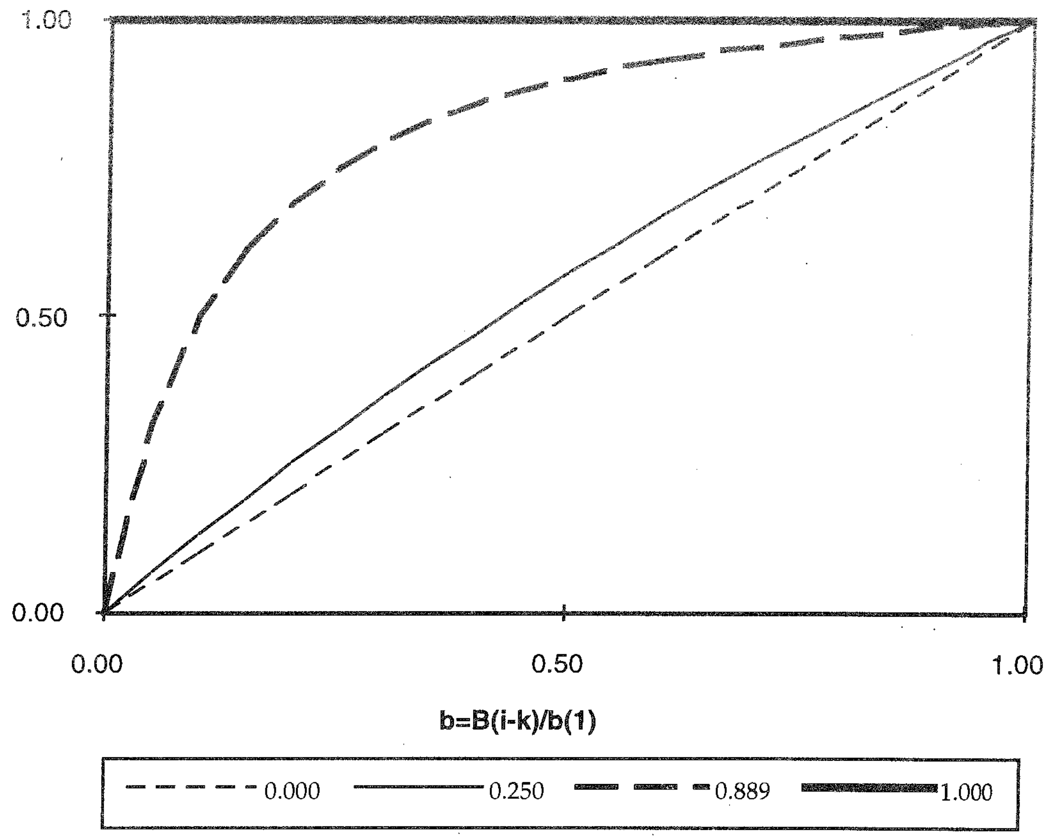


Figure 13. Shape of Beverton and Holt stock and recruitment relationship for several values of the density dependence (or shape) parameter, including 0.250 as estimated in this assessment.



CHAPTER THREE

EVALUATION OF HARVEST STRATEGIES FOR EASTERN GEMFISH (REXEA SOLANDRI) USING MONTE CARLO SIMULATION

EVALUATION OF HARVEST STRATEGIES FOR EASTERN GEMFISH (*REXEA SOLANDRI*) USING MONTE CARLO SIMULATION

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ABSTRACT

The performances of a range of harvest strategies for eastern gemfish are evaluated using Monte Carlo simulation. The fishery is simulated from 1995 to 2020 using an "operating model" to represent the future dynamics of the stock and to generate future data. The evaluation of each harvest strategy involves simulating the future of the fishery 100 times, using different parameter values and initial conditions for the operating model. The 100 sets of parameter values and initial conditions are drawn at random from the posterior distribution calculated by Punt (1995). The harvest strategies are evaluated using a range of performance indices related to management objectives. Each harvest strategy determines the catch to be taken in each year. $F_{0.n}$ feedback harvest strategies rely on an annual stock assessment for the fishery using a Laurec-Shepherd *ad hoc* tuned VPA. The $F_{0.n}$ harvest strategies are compared with constant catch strategies and the sensitivities to future recruitment scenarios are investigated. The $F_{0.4}$ and the constant 1000 t harvest strategies come closest to meeting the current management objective of achieving 40% of the 1979 spawning potential for the stock.

1. INTRODUCTION

Gemfish (*Rexea solandri*) are caught off south-eastern Australia, mainly by trawling. The eastern stock has been fished off New South Wales since the 1920s. A winter spawning-run fishery developed in the late 1960s and became an important component of the south-east trawl fishery during the 1970s and 1980s. Catches peaked at about 5000 t in 1980, declining to 3000 – 4000 t before a 3000 t total allowable catch (TAC) was implemented in 1988. TACs were successively reduced to 1750 t in 1990, 500 t in 1991 and 200 t in 1992, due mainly to evidence of a substantial decline in recruitment (Rowling, 1994). There has been a zero TAC since 1993, with trip limits to minimize by-catch.

The first quantitative stock assessment for eastern gemfish was by Allen (1989). Subsequent assessments are reviewed in Chesson (in press). The most recent assessments are described in Bax (1995) and Punt (1995), the latter including a Bayesian stock assessment. All assessments agree that there was a substantial reduction in the size of the stock during the early 1980s and a major decline in recruitment in the mid to late 1980s. The causes of the decline in recruitment remain uncertain, although there is speculation that environmental influences may have contributed (Thresher, 1994).

The immediate management objective for eastern gemfish is to rebuild the stock to a level at which targeted commercial fishing can recommence (Chesson, in press). The performance indicator which has been set by the Australian Fisheries Management Authority (AFMA) is "that the spawning biomass of eastern gemfish (estimated in 1990 to be about 20 – 25% of the 1979 level) is increasing toward the target of 40% of B_{1979}". This statement provides a target reference point for the fishery, although it leaves unanswered a number of important questions (such as the definition of "spawning biomass", an acceptable time frame for recovery, and how to deal with uncertainty in the assessment of stock status).

This paper examines several potential future harvest strategies for eastern gemfish, and examines their performance in relation to a range of management objectives (including the management target defined by AFMA). The analysis depends crucially on the Bayesian stock assessment of eastern gemfish described by Punt (1995). The results described in this paper are tentative (because this assessment has yet to be subject to peer review), and do not reflect an agreed outcome of AFMA's formal stock assessment process. The main purpose of the analyses presented in this paper is to illustrate a method which may be used to evaluate the performance of harvest strategies for specific stocks. The results are presented quantitatively, but should be interpreted qualitatively.

2. METHODS

2.1 OVERVIEW

The performances of a range of harvest strategies for eastern gemfish are evaluated using Monte Carlo simulation. This involves simulating the fishery from 1995 to 2020 using an "operating model" to represent the future dynamics of the stock and to generate future catch-at-age and catch-rate data. The harvest strategy determines the catch to be taken in each year. Some strategies, called feedback harvest strategies, rely on an annual stock assessment for the fishery. These stock assessments use both the historical data from the real fishery, together with the simulated future data. The evaluation of each harvest strategy involves simulating the future of the fishery 100 times, using different values for the parameters of the model, starting (1995) abundances, and future fluctuations in recruitment. A range of performance indices related to management objectives is calculated for each simulation. The whole process is designed to explore, as realistically as possible, the consequences of future management of the fishery.

2.2 THE OPERATING MODEL

The model used to simulate the future dynamics of the stock is virtually identical to that described in Punt (1995). It is age- and sex-structured and takes account of a summer and a winter fishery in each year. For most of the analyses, the number of births in each year is related to the total egg production by a Beverton-Holt stock-recruitment relationship. Sources of recruitment variability other than egg production are described in Section 2.5 below. The sex- and age-specific selectivity pattern is described by a logistic function and, for the summer fishery, selectivity declines with age for older animals. The detailed specifications of the operating model are given in Appendix A.

The parameter values and initial conditions for the set of 100 simulations are sampled at random and with replacement from the posterior distribution computed using the Bayesian stock assessment method described in Punt (1995). The "with correlation" variant of the assessment is used, which allows for *a priori* correlation among the recruitment anomalies. The parameters which vary across the set of simulations include the initial (1995) age distribution, the parameters of the stock-recruitment relationship (including the variance of and auto-correlation between recruitment anomalies), selectivity and natural mortality. The marginal distributions of some of the quantities which determine the state of the resource at the start of 1995 are shown in Figure 1. Thus, each simulation has a different starting point and a different set of dynamics determined by its parameters. However, all are "constrained" by the Bayesian gemfish assessment.

2.3 MANAGEMENT STRATEGIES

Two types of harvest strategy are condsidered. The first of these is an $F_{0.n}$ strategy which attempts to maintain a constant rate of fishing mortality (see Appendix B). The second is a constant catch strategy.

For the $F_{0.n}$ strategies, further constraints are placed on the way in which the quota may vary from one year to the next (see Appendix B). The quota is constrained not to vary up or down by more than a certain percentage each year, and can also be set between specified lower and upper limits. It is also possible to set a threshold below which the quota can be increased by more than the specified percentage limit. This latter feature of the strategy allows for more rapid development of the fishery from low levels of quota.

The software which has been developed for these analyses also evaluates other types of harvest strategies, such as constant escapement. Results for such strategies are not reported here.

2.4 THE STOCK ASSESSMENT MODEL

The $F_{0.n}$ harvest strategies require estimates of fishing mortalities-at-age and numbers-at-age at the start of the year for which a quota is needed. These are calculated using an *ad hoc* tuned VPA estimator (see Appendix C). The data needed to apply this estimator are time series of relative abundance (in this case, catch-rates) and catch-at-age. In the first year of each simulation, these data consist of the historical data from the gemfish fishery up to 1994. Adapt VPA (Gavaris 1988; Powers and Restrepo 1992) is used for estimation in the first year as there is no estimate of catch-rate for 1994 – the *ad hoc* tuned VPA estimator requires a catch-rate for the most recent year so cannot be applied to calculate a quota for 1995. In subsequent years, the historical data are supplemented by simulated data from the operating model, with noise added to model the effect of measurement errors. Because catch-at-age data are not available for gemfish for all years up to 1994, the posterior mean values of these, computed using the "with correlation" variant of the Bayesian estimates of Punt (1995), are used for the missing years. The natural mortality rate assumed when conducting assessments is the average of the values for each of the simulated populations.

2.5 RECRUITMENT SCENARIOS

There is general agreement that the eastern stock of gemfish suffered a major decline in recruitment from the mid to the late 1980s (Rowling, 1994). There is some suspicion that this decline may not have been due solely to overfishing. Thresher (1994) has postulated that an environmental factor may be driving an approximate ten year cycle in recruitment for a number of fish species in eastern Australia. Punt (1995) fitted a model which allowed for autocorrelated recruitment anomalies and found substantial positive correlation between anomalies. His results also seem to indicate a long-term cycle in recruitment, with an apparent cycle length of about ten years.

There is now some evidence for a recovery in recruitment since the very low levels of the mid to late 1980s. The 1990 year-class appears to have been much stronger than the preceeding year classes, althhough it's absolute strength is still uncertain as this year-class is yet to be fully recruited into the fishery.

The rate at which the stock recovers from the low recruitments of the late 1980s will be sensitive to the assumptions made about recent and future recruitment. The longer-term performance of harvest strategies is also likely to be sensitive to the assumption about future recruitment. For this reason, four future recruitment scenarios are explored in the analyses. The base case analysis assumes that recruitment is autocorrelated, with the correlation coefficient for each simulated population determined from the "with correlation" Bayesian analysis of Punt (1995). Note that the "with correlation" analysis of Punt is relatively pessimistic about the strength of the 1990 recruitment.

The other three recruitment scenarios are random variation about the deterministic component of the stock recruitment relationship, future recruitments chosen at random from historical recruitments between 1985 and 1989 (the period of poor recruitments), and cyclic recruitment with a ten year period. Each of the recruitment scenarios is specified in more detail in Appendix A.

2.6 PERFORMANCE INDICES

The harvest strategies are evaluated with respect to a series of performance criteria relating to biomass depletion, egg production, catch, and variations in catch from year to year. The specific performance indices used are:

1)	Final biomass / B_0[1]	(winter exploitable biomass in 2020 / virgin biomass)
2)	Lowest biomass / B_0	(lowest depletion over the period 1995 to 2020)
3)	Average catch	(from 1995 to 2020)
4)	Continuing catch	(average catch from 2016 to 2020)
5)	Catch variability	(average absolute change in catch as percentage of average catch)
6)	Prob($B_{fin} < 0.2\ B_0$)	(B_{fin} is winter exploitable biomass in 2020)
7)	Prob($B_{low} < 0.2\ B_0$)	(B_{low} is lowest biomass from 1995 to 2020)
8)	Prob($B_{fin} > B_{MSY}$)	(B_{MSY} is biomass at which sustainable yield is maximized)
9)	Prob($B_{fin} > B_{0.1}$)	($B_{0.1}$ is biomass under the $F_{0.1}$ strategy)
10)	Prob($E_{fin} > 0.4\ E_{79}$)	(E is egg production)

Performance indices 1 to 5 are expressed as medians over the 100 simulations in the tables of results, and plotted as 5th, 50th and 95th percentiles in the figures.

2.7 BASE CASE AND SENSITIVITY TESTS

The base case harvest strategy is an $F_{0.1}$ strategy as defined in Appendix B. The base case harvest strategy also incorporates the following constraints on the annual quota:

- maximum % decrease in quota, p = 50%
- maximum % increase in quota, q = 50%
- threshold for quota increase constraint, H = 1000 t
- minimum quota, A = 500 t
- maximum quota, B = 5000 t

Other features of the base case evaluation include:

- the recruitment anomalies are autocorrelated

[1] B_0 in this paper refers to the exploitable biomass available to the winter fishery in the absence of exploitation.

- the observation error *CV* for future catch-rates, $\sigma_q = 0.15$
- the observation error *CV* for the summer catch-at-age data , $\sigma_c^1 = 0.4$
- the observation error *CV* for the winter catch-at-age data, $\sigma_c^2 = 0.15$

The base case harvest strategy is compared with other $F_{0.n}$ strategies, including $F_{0.2}$, $F_{0.4}$ and F_{MSY}. The latter corresponds to selecting the quota using the fishing mortality rate which maximizes the yield *v.* F curve (i.e. $F_{0.0}$). The base case strategy is also compared with four constant catch strategies: C = 0, 1000, 2000 and 3000 t. Sensitivity to the future recruitment scenarios described in Section 2.5 is explored for the base case harvest strategy only. Finally, the base case results are compared with those for a harvest strategy that has no constraints on quota (except minimum quota), management using perfect information about fishing mortality-at-age and numbers-at-age, and an operating model that uses higher *CV*s on future observations (0.25 on catch-rate, 0.6 on summer catch-at-age, and 0.25 on winter catch-at-age).

3. RESULTS

3.1 BASE CASE RESULTS

The results for the base case harvest strategy and operating model are given in Table 1 and Figure 2. Figure 2 shows the trajectories from 1995 to 2020 for eight performance indices. Under the modified $F_{0.1}$ harvest strategy there is a strong recovery in the stock from 1995 to 1999. This is due to a the model predicting several strong year-classes (1990 –1992) entering the fishery together with low catches during these years. The latter is determined by initial underestimates of true stock size and the constraints placed on rapid increases in TAC. Catches mimic biomass trends and reach a peak in 2002, by which time stock size is already declining again. Catches and stock size both decline over the remaining period to 2010 after which there is some evidence that the decline has stopped. The estimation of biomass improves over time. After initial under-estimation, the estimation improves by 2002 to give results close to, although consistently slightly lower than, the true value. The median continuing catch under the base case strategy (a measure of "sustainable yield" for the strategy) is approximately 1450 t, although this measure is very sensitive to the parameters of the true population (Table 1).

The change in catch from one year to the next is very high during the period of increasing catches, but rapidly stabilizes to a situation in which catches change on average by 25% from one year to the next. Although this is well within the constraints imposed as part of the base case harvest strategy (±50%), it still represents a large average change in quota from one year to the next, and may be larger than is deemed acceptable by industry. This level of catch variability is, however, typical of harvest strategies based on VPAs, and is one of the reasons production model-based harvest strategies are preferred for management of the hake *Merluccus* spp resources off South Africa (Payne and Punt, 1995).

The base case strategy does not perform very satisfactorily in relation to AFMA's target of achieving 40% of the 1979 spawning potential. Although the initial stock recovery puts the spawning potential above this target, the median is below the target from 2004 (Figure 2), and the probability that the spawning potential is above the target in 2020 is only 22% (Table 1).

The other performance indices reflect the trends in stock size over the period of the simulations. It is interesting to note that the base case strategy does not achieve its own target of stabilizing the stock at $B_{0.1}$, but instead stabilizes the biomass somewhat below this.

3.2 COMPARISON OF $F_{0.N}$ STRATEGIES

The performances of the four $F_{0.n}$ strategies are compared in Table 2 and Figure 3. Figure 3a shows the distributions of several summary measures for each strategy, while Figure 3b shows time trajectories of median values of key performance indices (cf. Figure 2). The results are as one would expect – higher fishing mortality rates result in slightly higher catches at the expense of lower stock sizes. The variation in average and continuing catch is also higher at higher exploitation rates.

None of the $F_{0.n}$ strategies evaluated here achieve the long-term target of 40% of 1979 egg production, although the $F_{0.4}$ strategy comes close (Figure 3b). The $F_{0.2}$ strategy comes closest to stabilizing the resource at the $F_{0.1}$ target of $B_{0.1}$, and the F_{MSY} strategy leaves the resource below B_{MSY} in over 50 % of the simulations.

3.3 CONSTANT CATCH STRATEGIES

The performances of the constant catch strategies are compared with those of the base case harvest strategy in Table 3 and Figure 4. Again, the tradeoff between catch and stock size is quite clear. The performance of the base case strategy is closest to that of the 2000 t constant catch strategy, but there are some interesting differences. Both inter-annual changes in catch and the average catch achieved are much less variable for the constant catch strategy. However, this is achieved at the expense of much more variance in biomass, including increased probabilities of very low stock sizes. There is no annual assessment associated with the constant catch strategies, and therefore no opportunity to adjust catches in the face of clear evidence of overfishing. The 1000 t constant catch strategy comes closest to achieving AFMA's spawning potential target, but the median average catch is only half that of the more flexible base case strategy.

3.4 SENSITIVITY TO FUTURE RECRUITMENT

The base case simulation trials assume autocorrelation between successive recruitment anomalies for both past and future recruitments. The results in Table 4 and Figure 5 assess the performance of the base case harvest strategy (i.e. $F_{0.1}$ with the quota constraints listed in section 2.7) for alternative assumptions about future recruiment.

In general the results are not particularly sensitive to the assumptions about recruitment. The low recruitment scenario does result in lower catches and lower stock size and performs very poorly with regard to AFMA's spawning potential target. For the "sine recruitment" scenario (which represents the ten year environmental cycle hypothesis) the strategy does meet AFMA's target, but only because the peak in the cycle occurs at the end of the projection period.

3.5 OTHER SENSITIVITY TESTS

Sensitivity to other features for the base case harvest strategy are shown in Table 5 and Figure 6. In general, performance is not sensitive to the scenarios examined here. In particular, the increase in the variability on future observations of catch rate and catch-at-age data has very little effect on performance of the base case harvest strategy, although performance is degraded slightly.

The most notable differences are evident in Figure 6b. Both removal of the catch constraints and provision of perfect information result in much more rapid increases in catch from 1995 to 1999, and a resulting lower increase in biomass over the initial period. Not surprisingly, removing the catch constraints results in higher variability in catch from year to year.

4. DISCUSSION

This paper has illustrated an approach for evaluating future harvest strategies for a fishery resource given uncertainty about current status and productivity. The fishery for eastern gemfish has been used to illustrate the approach, and the stock assessment used for projecting the consequences of future management has been the "with correlation" variant of the Bayesian analysis of Punt (1995). A range of performance indices has been calculated for each strategy.

The results for a subset of harvest strategies and performance indices are summarized in Table 6 to illustrate the tradeoffs between several management objectives. Median continuing yield can be regarded as a measure of the longer-term sustainable yield under the harvest strategy. Median catch variability is a measure of how much catches change from one year to the next. Also shown in Table 6 are measures of how well each strategy performs relative to two possible biological reference points. The first reference point measures egg production (or spawning potential) in relation to the base year of 1979, with an implied target of 40% of the 1979 level. The second measures how well the strategy stabilizes the biomass at $B_{0.1}$, analagous to the $F_{0.1}$ biological reference point which is widely used in fisheries management (Smith et al., 1993).

The results in Table 6 show a clear tradeoff between the level of catch and ability to satisfy the biological targets. In general, the higher the catch, the lower the chance of satisfying the target. The only exception is that the 3000 t constant catch strategy actually has a lower continuing catch than the 2000 t constant catch strategy, but also has a lower probability of meeting the biological targets. This is because the 3000 t strategy results in very severe declines in stock size well before the end of the projection period in a significant proportion of the simulations. The realised continuing catch is only about 56% of the nominal target catch, and it is doubful that even this level of continuing catch is sustainable. Clearly, these results suggest that a constant 3000 t catch exceeds the maximum sustainable yield for this stock.

The preceding discussion deals with two possible management objectives (maximizing catch while achieving biological targets), but what about the third general class of management objective of minimizing year-to-year variation in catch? The results for the $F_{0.4}$ and constant 1000 t strategies provide a comparison where the continuing catch is very similar (1060 and 1000 t respectively). They achieve very similar outcomes for the biological targets, but differ dramatically in catch variability. The constant catch strategy will clearly be preferable, presuming that a general aim of industry will be to minimize year-to-year variations in catch, and assuming no other constraints or considerations (such as additional importance to worst-case scenarios). What is not clear, however, is whether a constant catch strategy, which achieves the same median catch as a feedback harvest strategy, can perform as well or better against other performance criteria as median catch increases. The results in Table 6 do not allow an answer to this question.

Overall, the analyses in this paper suggest that the stock of eastern gemfish is in a recovery phase, and that catches in the order of 1000 to 1300 t may be sustainable on an annual basis. These conclusions depend on the results of the Bayesian analyses in Punt (1995) and, as discussed in that paper, may be overly optimistic, particularly if catch rates in the fishery decline less rapidly than stock abundance.

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FIGURE CAPTIONS

Figure 1: Distributions of parameter values and initial conditions used in the 100 Monte Carlo simulations. Results are shown for (a) virgin exploitable biomass B_0, (b) 1994 exploitable biomass B_{1994}, (c) B_{1994}/B_0, (d) egg production in 1995 divided by that in 1979.

Figure 2: Median, 5th and 95th percentile trajectories from 1995 to 2020 for eight performance measures for the base case harvest strategy and base case operating model.

Figure 3: Performance outcomes for four $F_{0.n}$ harvest strategies. (a) Median, 5th and 95th percentiles for five performance measures and probabilities of achieving four biological reference points, and (b) median trajectories from 1995 to 2020 for eight performance measures.

Figure 4: As for Figure 3, comparing four constant catch strategies with the base case strategy.

Figure 5: As for Figure 3, comparing four future recruitment scenarios (see section 2.5).

Figure 6: As for Figure 3, comparing the base case harvest strategy with the same strategy but with: no constraints on change in quota; perfect information on numbers-at-age and fishing mortality-at-age; and increased *CVs* on future observations of catch rate and catch-at-age.

TABLE 1. **BASE CASE RESULTS.**

(a) Percentiles

	Percentiles		
Performance measures	5	50	95
Final biomass/B_0	0.03	0.28	0.74
Lowest biomass/B_0	0.01	0.14	0.39
Average catch (t)	682	1930	3592
Catch variability (%)	15	26	36
Continuing catch (t)	500	1455	4554

(b) Probabilities

$P(B_{fin} < 0.2\ B_0)$	0.37
$P(B_{low} < 0.2\ B_0)$	0.68
$P(B_{fin} > B_{msy})$	0.71
$P(B_{fin} > B_{0.1})$	0.31
$P(E_{fin} > 0.4\ E_{79})$	0.22

TABLE 2. ***F* STRATEGIES.**

(a) Medians

	Strategies			
Performance measures	F_{msy}	$F_{0.1}$	$F_{0.2}$	$F_{0.4}$
Final biomass/B_0	0.11	0.28	0.34	0.43
Lowest biomass/B_0	0.05	0.14	0.21	0.29
Average catch (t)	2121	1930	1693	1302
Catch variability (%)	22	26	27	26
Continuing catch (t)	1717	1455	1330	1063

(b) Probabilities

	Strategies			
Performance measures	F_{msy}	$F_{0.1}$	$F_{0.2}$	$F_{0.4}$
$P(B_{fin} < 0.2\ B_0)$	0.78	0.37	0.28	0.15
$P(B_{low} < 0.2\ B_0)$	0.92	0.68	0.49	0.27
$P(B_{fin} > B_{msy})$	0.32	0.71	0.78	0.88
$P(B_{fin} > B_{0.1})$	0.11	0.31	0.48	0.60
$P(E_{fin} > 0.4\ E_{79})$	0.10	0.22	0.30	0.41

TABLE 3. **CATCH STRATEGIES.**

(a) Medians

	Strategies				
Performance measures	base case	C=0	C=1000	C=2000	C=3000
Final biomass/B_0	0.28	0.87	0.55	0.17	0.02
Lowest biomass/B_0	0.14	0.43	0.30	0.08	0.01
Average catch (t)	1930	0	1000	1947	2439
Catch variability (%)	26	0	3	5	10
Continuing catch (t)	1455	0	1000	1914	1708

(b) Probabilities

	Strategies				
Performance measures	base case	C=0	C=1000	C=2000	C=3000
$P(B_{fin} < 0.2\ B_0)$	0.37	0.01	0.16	0.52	0.76
$P(B_{low} < 0.2\ B_0)$	0.68	0.03	0.23	0.69	0.88
$P(B_{fin} > B_{msy})$	0.71	0.99	0.84	0.52	0.28
$P(B_{fin} > B_{0.1})$	0.31	0.96	0.63	0.37	0.16
$P(E_{fin} > 0.4\ E_{79})$	0.22	0.70	0.48	0.28	0.16

TABLE 4. **RECRUITMENT SCENARIOS.**

(a) Medians

	Scenarios			
Performance measures	base case autocorr	white noise	low 85-89	sine
Final biomass/B_0	0.28	0.28	0.20	0.34
Lowest biomass/B_0	0.14	0.16	0.08	0.13
Average catch (t)	1930	2237	1206	2138
Catch variability (%)	26	27	31	28
Continuing catch (t)	1455	1796	1172	1693

(b) Probabilities

	Scenarios			
Performance measures	base case autocorr	white noise	low 85-89	sine
$P(B_{fin} < 0.2\ B_0)$	0.37	0.33	0.51	0.14
$P(B_{low} < 0.2\ B_0)$	0.68	0.61	0.80	0.75
$P(B_{fin} > B_{msy})$	0.71	0.81	0.62	0.85
$P(B_{fin} > B_{0.1})$	0.31	0.32	0.10	0.43
$P(E_{fin} > 0.4\ E_{79})$	0.22	0.34	0.02	0.57

TABLE 5. OTHERS.

(a) Medians

	Scenarios			
Performance measures	base case	no catch constrai	base case perfect info	high cvs
Final biomass/B_0	0.28	0.29	0.28	0.23
Lowest biomass/B_0	0.14	0.14	0.17	0.13
Average catch (t)	1930	2203	2113	1889
Catch variability (%)	26	43	16	29
Continuing catch (t)	1455	1401	1586	1401

(b) Probabilities

	Scenarios			
Performance measures	base case	no catch constrai	base case perfect info	high cvs
$P(B_{fin} < 0.2\ B_0)$	0.37	0.38	0.32	0.47
$P(B_{low} < 0.2\ B_0)$	0.68	0.73	0.62	0.72
$P(B_{fin} > B_{msy})$	0.71	0.71	0.75	0.62
$P(B_{fin} > B_{0.1})$	0.31	0.31	0.34	0.26
$P(E_{fin} > 0.4\ E_{79})$	0.22	0.20	0.21	0.20

TABLE 6. COMPARISON OF SIX HARVEST STRATEGIES ACROSS FIVE PERFORMANCE STATISTICS.

Strategy	Continuing catch (t)	Average catch (t)	Catch variability (%)	$P(E_{fin}>0.4E_{79})$	$P(B_{fin}>B_{0.1})$
$F_{0.1}$ (base case)	1450	1930	26	0.22	0.31
$F_{0.2}$	1330	1693	27	0.30	0.48
$F_{0.4}$	1060	1302	26	0.41	0.60
C=1000 t	1000	1000	3	0.48	0.63
C=2000 t	1910	1947	5	0.28	0.37
C=3000 t	1710	2439	10	0.16	0.16

APPENDIX A : THE OPERATING MODEL

The model considered in this appendix is age- and sex-structured, takes account of two pulse fisheries, and assumes that the number of births is related to the total egg production of the population by means of a Beverton-Holt stock recruitment relationship.

BASIC POPULATION DYNAMICS

The resource dynamics are modelled using the equations:

$$N^s_{y+1,a} = \begin{cases} N^s_{y+1,0} & a = 0 \\ \tilde{N}^s_{y,a-1} & a = 1,\ldots,x-1 \\ \tilde{N}^s_{y,x} + \tilde{N}^s_{y,x-1} & a = x \end{cases} \qquad \text{(A.1)}$$

where $N^s_{y,a}$ is the number of fish of sex s and age a at the start of year y,

$\tilde{N}^s_{y,a}$ is the number of fish of sex s and age a at the end of year y,

$$\tilde{N}^s_{y,a} = ((N^s_{y,a}\, e^{-t_1 M^s} - C^{1,s}_{y,a})e^{-t_2 M^s} - C^{2,s}_{y,a})e^{-(1-t_1-t_2)M^s} \qquad \text{(A.2)}$$

$N^s_{y,0}$ is the number of 0-year-olds of sex s at the start of year y,

M^s is the (age-independent) rate of natural mortality on fish of sex s,

$C^{1,s}_{y,a}$ is the catch (in number) of fish of sex s and age a during the summer fishery of year y,

$C^{2,s}_{y,a}$ is the catch (in number) of fish of sex s and age a during the winter fishery of year y,

t_1 is the time between the start of the year and the mid-point of the summer fishery,

t_2 is the time between the mid-point of the summer fishery and that of the winter fishery, and

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

Births[2]

$$N^s_{y,0} = 0.5[E_{y-1} / (\alpha + \beta E_{y-1})] e^{\varepsilon'_y - \sigma_r^2/2} \qquad \text{(A.3)}$$

$$\varepsilon'_y = \rho\, \varepsilon'_{y-1} + \sqrt{(1-\rho^2)}\, \varepsilon_y$$

where E_y is total egg production at the end of year y:

$$E_y = \sum_{a=1}^{x} f_a \tilde{N}^f_{y,a} \qquad \text{(A.4)}$$

f_a is the fecundity of a female of age a,

ε'_y is the recruitment anomaly for year y,

ε_y is the recruitment residual for year y ($\varepsilon_y \sim N(0;\sigma_r^2)$),

σ_r is the standard deviation of the logarithm of the multiplicative fluctuations in births (approximately the coefficient of variation of the fluctuations in recruitment),

ρ is the parameter which determines the extent of inter-annual autocorrelation in the recruitment anomalies ($\rho = 0$ corresponds to the assumption that recruitment anomalies are temporally uncorrelated – the "white noise" assumption), and

α, β are the stock-recruitment relationship parameters.

One of the sensitivity tests involves examining the possibility that the recruitment anomaly has a deterministic sine component :

$$N^s_{y,0} = \frac{0.5E_{y-1}}{\alpha + \beta E_{y-1}} \left(1 + X \sin\left(\frac{2\pi}{Y}(y-Z)\right)\right) e^{\varepsilon'_y - \sigma_r^2/2} \qquad \text{(A.3a)}$$

where X is amplitude (0.5),

Y is period (10), and

Z is cycle adjustment (3).

[2] One of the sensitivity tests examines the scenario in which future recruitments are selected at random and with replacement from those for 1985-1989.

INITIAL CONDITIONS

The numbers-at-age at the start of 1995 are generated from the "with correlation" posterior distribution calculated by Punt (1995). The values for the stock-recruitment function parameters α and β are calculated from the values of R_0, the number of 0-year-olds at the deterministic equilibrium that corresponds to an absence of harvesting, and the "steepness" of the stock-recruit relationship (h). The "steepness" is the fraction of R_0 to be expected (in the absence of recruitment variability) when the total egg production is reduced to 20% of its pristine level (Francis, 1992), so that:

$$\alpha = \tilde{B}_0^S \frac{1-h}{4h}$$
$$\beta = \frac{5h-1}{4hR_0} \tag{A.5}$$
$$\tilde{B}_0^S = \frac{1}{2}\left\{\sum_{a=1}^{x-1} f_a e^{-(a+1)M^f} + f_x e^{-(x+1)M^f} / \{1-e^{-M^f}\}\right\}$$

The value for R_0 is calculated from the value for the virgin biomass at the start of the year, B_0 (where this biomass is defined using the selectivity pattern for the winter fishery and the mass-at-age vector for the summer fishery), using the equation:

$$R_0 = 2B_0 / \sum_s \left\{\sum_{a=1}^{x-1} w_{a-t_2}^s S_a^{2,s} e^{-aM^s} + w_{x-t_2}^s S_x^{2,s} e^{-xM^s} / \{1-e^{-M^s}\}\right\} \tag{A.6}$$

where $S_a^{2,s}$ is the selectivity of the fishing gear used during the winter fishery on fish of sex s and age a, and

w_a^s is the mass of a fish of sex s and age a during the winter fishery:

$$w_a^s = b_1^s (L_a^s)^{b_2^s} \tag{A.7}$$
$$L_a^s = L_\infty^s (1-e^{-\kappa^s(a-t_0^s)}) \tag{A.8}$$

CATCHES

The catch (in number) of fish of sex s and age a during the summer fishery in year y, $C^{1,s}_{y,a}$, is calculated from $\tilde{C}^1_y$, the catch (in mass) during the summer fishery, using the equation:

$$C^{1,s}_{y,a} = S^{1,s}_a F^1_y N^s_{y,a} e^{-t_1 M^s} \tag{A.9}$$

where $S^{1,s}_a$ is the selectivity of the gear used during the summer fishery on fish of sex s and age a, and

F^1_y is the exploitation rate on fully-selected fish during the summer fishery of year y:

$$F^1_y = \tilde{C}^1_y / \sum_s \sum_{a=0}^{x} w^s_{a-t_2} S^{1,s}_a N^s_{y,a} e^{-t_1 M^s} \tag{A.10}$$

The catch (in number) of fish of sex s and age a during the winter fishery in year y, $C^{2,s}_{y,a}$, is calculated from $\tilde{C}^2_y$, the catch (in mass) during the winter fishery, using the equation:

$$C^{2,s}_{y,a} = S^{2,s}_a F^2_y (N^s_{y,a} e^{-t_1 M^s} - C^{1,s}_{y,a}) e^{-t_2 M^s} \tag{A.11}$$

where F^2_y is the exploitation rate on fully-selected fish during the winter fishery of year y:

$$F^2_y = \tilde{C}^2_y / \sum_s \sum_{a=0}^{x} w^s_a S^{2,s}_a (N^s_{y,a} e^{-t_1 M^s} - C^{1,s}_{y,a}) e^{-t_2 M^s} \tag{A.12}$$

SELECTIVITY

The selectivity pattern (for each fishery / sex) is given by:

$$S_a = \begin{cases} \left(1+e^{-(a-a_{50})*\delta}\right)^{-1} & \text{if } a < a_{95} \\ \left(1+e^{-(a-a_{50})*\delta}\right)^{-1} e^{-\gamma(a-a_{95})} & \text{if } a \geq a_{95} \end{cases} \tag{A.13}$$

where a_{50} is the age-at-50%-selectivity,

a_{95} is the age-at-95%-selectivity,

δ is the parameter which defines the width of the selectivity ogive (calculated from the age-at-50%-selectivity and that of 95%-selectivity using the formula: $\delta = \ell n 19 / (a_{95} - a_{50})$), and

γ is a parameter which allows selectivity-at-age to drop off with age.

It is assumed that γ=0 for the winter fishery (Punt, 1995). There are thus three parameters for each sex for the summer fishery: the age-at-50%-selectivity, the age-at-95%-selectivity, and the selectivity slope parameter, and two for each sex for the winter fishery: the age-at-50%-selectivity, and the age-at-95%-selectivity.

DATA SERIES

The simulations assume that catch, catch-rate and catch-at-age data are available for all years from 1995 to the current year. The catches are assumed to be measured without error. Catchability is assumed to be lognormally distributed, i.e.:

$$E_y^2 = \frac{F_y^2}{q} e^{v_y - \sigma_q^2/2} \tag{A.14}$$

where v_y is from $N(0;\sigma_q^2)$,

E_y^2 is the effort applied by the winter fishery during year y,

q is the catchability coefficient (generated from the Bayesian posterior), and

σ_q is the standard deviation of the observation errors.

The observed catches-at-age are assumed to be log-normally distributed about their true values :

$$C_{y,a}^{f,s,obs} = \tilde{C}_{y,a}^{f,s} \frac{\tilde{C}_y^f}{\sum_s \sum_{a'} w_{a'}^{f,s} \tilde{C}_{y,a'}^{f,s}} \tag{A.15}$$

$$\tilde{C}_{y,a}^{f,s} = C_{y,a}^{f,s} e^{\phi_{y,a}^{f,s} - \sigma_{c,y,a}^{f,2}/2}$$

where $\phi_{y,a}^{f,s}$ is from $N(0;(\sigma_{c,y,a}^{f,s})^2)$, and $w_a^{f,s}$ is the mass of a fish of sex s and age a during fishery f (either w_a^s for the winter fishery or $w_{a-t_2}^s$ for the summer fishery). The second term on the right hand side of Equation (A.15) is necessary so that the relationship $C_y^f = \sum_s \sum_{a'} w_{a'}^{f,s} C_{y,a}^{f,s,obs}$ is satisfied. The variances of estimates of catch-at-age are largest for the ages which make up relatively small contributions to the catch (e.g. Baird, 1983; Gavaris and Gavaris, 1983). To mimic this, the obseravtion error standard deviation for the catch of fish of age a during year y depends on the proportion which $C_{y,a}^{f,s}$ makes up of the total catch in number of fish of sex s by fishery f during year y:

$$\sigma^{f,s}_{c,y,a} = \sigma^{f}_{c} \sqrt{\frac{\sum_{a'} C^{f,s}_{y,a'}}{C^{f,s}_{y,a}}} \tag{A.16}$$

where σ^f_c is the standard deviation of the catch-at-age for fishery f.

APPENDIX B : $F_{0.n}$ HARVEST STRATEGIES

In the estimation of the $F_{0.n}$ harvest strategy quotas, the overall calculation involves specifying the selectivity pattern, estimating $F_{0.n}$, projecting the population to the start of year t +1, and calculating the quota. This appendix also describes the constraints on inter-annual changes in quota. The $F_{0.n}$ strategies considered in this paper differ from the conventional definitions because, in addition to yield-per-recruit effects, the impact of fishing mortality on recruitment is accounted for.

ESTIMATION OF $F_{0.n}$

$F_{0.n}$ is the fishing mortality at which the slope of the yield *vs.* fishing mortality curve is $0.n$ of that at the origin:

$$\left.\frac{\partial Y}{\partial F}\right|_{F=F_{0.n}} = 0.n \left.\frac{\partial Y}{\partial F}\right|_{F=0} \tag{B.1}$$

The equilibrium yield at a particular fishing mortality F, is given by the equation

$$Y = R(F)\tilde{Y}(F) \tag{B.2}$$

where $R(F)$ is recruitment as a function of fishing mortality, and

$\tilde{Y}(F)$ is yield-per-recruit as a function of fishing mortality.

The yield-per-recruit is calculated assuming that only the winter fishery occurs :

$$\tilde{Y}(F) = \sum_{s}\sum_{a} w^s_a \, S^s_a \, F \, \tilde{N}^s_a \, e^{-(t_1+t_2)M^s} \tag{B.3}$$

where w_a^s is the mass of a fish of sex s and age a during the winter fishery (assumed to be known exactly),

S_a^s is the selectivity of the fishing gear used during the winter fishery on a fish of sex s and age a, estimated using the equation $S_a^s = \overline{q}_a^s / \overline{q}_x^s$,

M^s is the rate of natural mortality on fish of sex s

$\vec{N}_a^s$ is the number of fish of sex s and age a, assuming 1 recruit:

$$\vec{N}_a^s = \begin{cases} 0.5 & a = 0 \\ \vec{N}_{a-1}^s e^{-M^s}(1 - S_{a-1}^s F) & a = 1,\ldots,x \\ \dfrac{\vec{N}_{x-1}^s e^{-M^s}(1 - S_{x-1}^s F)}{1 - e^{-M^s}(1 - S_x^s F)} & a = x \end{cases} \tag{B.4}$$

x is the maximum age considered (plus-group)

t_1 is the time between the start of the year and the mid-point of the summer fishery, and

t_2 is the time between the mid-point of the summer fishery and that of the winter fishery

The Beverton-Holt model is assumed to govern the relationship between egg production and resultant births:

$$R(F) = \frac{E(F)}{\hat{\alpha} + \hat{\beta} E(F)} \tag{B.5}$$

where $E(F)$ is egg production :

$$E(F) = R(F)\tilde{E}(F) \tag{B.6}$$

$\tilde{E}(F)$ is egg production-per-recruit :

$$\tilde{E}(F) = \sum_{a=1}^{x} f_a \tilde{N}_a^f \qquad \text{(B.7)}$$

f_a is the fecundity of a female of age a.

The following equation relating equilibrium recruitment to the values for the stock-recruitment relationship and egg production-per-recruit can be obtained by substituting Equation (B.6) into Equation (B.5):

$$R(F) = \frac{\tilde{E}(F) - \hat{\alpha}}{\hat{\beta}\tilde{E}(F)} \qquad \text{(B.8)}$$

CALCULATION OF $F_{0.x}$ STRATEGY QUOTAS

The quota for year $t+1$ is given by:

$$Q_{t+1} = \sum_s \sum_a w_a^s S_a^s F N_{t+1,a}^s e^{-(t_1+t_2)M^s} \qquad \text{(B.9)}$$

where $N_{t+1,a}^s$ is the number of fish of sex s and age a at the start of year $t+1$:

$$N_{t+1,a}^s = \begin{cases} \tilde{N}_{t,a-1}^s & a = 1,\ldots,x-1 \\ \tilde{N}_{t,x}^s + \tilde{N}_{t,x-1}^s & a = x \end{cases} \qquad \text{(B.10)}$$

where $\tilde{N}_{t,a}^s$ is the number of fish of sex s and age a at the end of year t:

$$\tilde{N}_{t,a}^s = ((N_{t,a}^s e^{-t_1 M^s} - C_{t,a}^{1,s})e^{-t_2 M^s} - C_{t,a}^{2,s})e^{-(1-t_1-t_2)M^s} \qquad \text{(B.11)}$$

(Definitions of symbols are in Appendix A.)

CONSTRAINTS

The quota is constrained not to vary up or down by more than a certain (pre-specified) percentage from one year to the next, and to be constrained to lie between (pre-specified) lower and upper limits. It is also possible to set a threshold below which the quota can be increased by more than the pre-specified percentage limit. The rule used to constrain inter-annual variation in quotas depends on whether or not the threshold comes into play. If this threshold does not come into play (i.e. $C_t > H$ or $Q_{t+1} < H$), then the "constrained" quota is calculated using Equation (B.12). If the threshold does apply, it is calculated using Equation (B.13) instead.

$$Q'_{t+1} = \begin{cases} C_t(1-p/100) & \text{if } Q_{t+1} < C_t(1-p/100) \\ Q_{t+1} & \text{if } C_t(1-p/100) \le Q_{t+1} \le C_t(1+q/100) \\ C_t(1+q/100) & \text{if } Q_{t+1} > C_t(1+q/100) \end{cases} \tag{B.12}$$

$$Q'_{t+1} = \begin{cases} C_t(1-p/100) & \text{if } Q_{t+1} < C_t(1-p/100) \\ Q_{t+1} & \text{if } C_t(1-p/100) \le Q_{t+1} \le C_t(1+q/100) \\ \max(C_t(1+q/100), H) & \text{if } Q_{t+1} > C_t(1+q/100) \end{cases} \tag{B.13}$$

The "constrained" quota calculated using Equations (B.12) and (B.13) is then constrained to lie between the pre-specified maximum and minimum limits:

$$Q''_{t+1} = \begin{cases} A & \text{if } Q'_{t+1} < A \\ Q'_{t+1} & \text{if } A \le Q'_{t+1} \le B \\ B & \text{if } Q'_{t+1} > B \end{cases} \tag{B.14}$$

where Q_{t+1} is the quota calculated by using Equation (B.9)

Q''_{t+1} is the actual quota for year $t+1$

C_t is the catch for year t

p is the maximum percentage decrease in quota

q is the maximum percentage increase in quota

H is the threshold ($H<B$)

A is the minimum quota

B is the maximum quota

The total quota is divided between the summer and winter fisheries in proportion to the catches by the two fisheries over the years 1980 – 1985.

APPENDIX C: THE *AD HOC* TUNED VPA ESTIMATOR

(POPE AND SHEPHERD, 1985; BUTTERWORTH ET AL., 1990)

To obtain the estimates of the fishing mortality and numbers-at-age matrices required to compute quotas, the standard VPA back-calculations for each cohort, together with the selected tuning algorithms, are applied iteratively until convergence takes place.

THE VPA BACK-CALCULATIONS

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

$$N^s_{y,a} = (C^{1,s}_{y,a} + (C^{2,s}_{y,a} + N^s_{y+1,a+1}\, e^{(1-t_1-t_2)M^s})\, e^{t_2 M^s})\, e^{t_1 M^s} \qquad a < x-1 \qquad \text{(C.1)}$$

where $N^s_{y,a}$ is the number of fish of sex s and age a at the start of year y,

M^s is the (age-independent) rate of natural mortality on fish of sex s,

$C^{1,s}_{y,a}$ is the catch (in number) of fish of sex s and age a during the summer fishery of year y,

$C^{2,s}_{y,a}$ is the catch (in number) of fish of sex s and age a during the winter fishery of year y,

t_1 is the time between the start of the year and the mid-point of the summer fishery,

t_2 is the time between the mid-point of the summer fishery and that of the winter fishery, and

The fishing mortality on animals of age a and sex s by fishery f during year y, $F^{f,s}_{y,a}$ is given by:

$$F_{y,a}^{f,s} = \begin{cases} C_{y,a}^{1,s} \big/ (N_{y,a}^{s} e^{-t_1 M^s}) & \text{if } f = 1 \\ C_{y,a}^{2,s} \big/ ((N_{y,a}^{s} e^{-t_1 M^s} - C_{y,a}^{1,s}) e^{-t_2 M^s}) & \text{if } f = 2 \end{cases} \tag{C.2}$$

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

TUNING PROCEDURE

The algorithm used to tune the oldest-age terminal fishing mortalities is based on the assumption that the age-specific selectivity function is flat over the oldest $r+1$ ages (where r is taken to be 2 for the analyses of this paper). The equation specifying the fishing mortality on the plus-group as a function of those on the r younger ages is:

$$\hat{F}_{y,x}^{2,s} = \left[\prod_{a=x-r}^{x-1} F_{y,a}^{2,s} \right]^{1/r} \qquad y = 1,\ldots,t \tag{C.3}$$

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

$$\hat{F}_{t,a}^{2,s} = \overline{q_a^2}\, E_t^{2,s} \qquad a = 0,1,\ldots,x-1 \tag{C.4}$$

where $\overline{q_a^{2,s}} = \left[\prod (F_{y,a}^2 / E_y^2)\right]^{1/n_y}$

$\overline{q_a^{2,s}}$ is the catchability coefficient for age a and sex s,

E_y^2 is the effort for the winter fishery for year y, and

n_y is the number of years for which effort data are available.

ESTIMATION OF THE PARAMETERS OF THE STOCK-RECRUITMENT RELATIONSHIP

The annual recruitment (number of 0-year-olds) is assumed to be related to the total egg production by the Beverton-Holt stock-recruitment relationship:

$$\hat{N}_{y+1,0} = \frac{\alpha E_y}{\beta + E_y} \tag{C.5}$$

where E_y is the total egg production at the end of year y:

$$E_y = \sum_{a=1}^{x} f_a \, N_{y,a}^f \tag{C.6}$$

f_a is the fecundity of a female of age a, and

α,β are the parameters of the stock-recruitment relationship.

The estimates of α, β are obtained by fitting model (C.5) to the estimates of egg production and recruitment provided by the VPA:

$$\sum_{y=1}^{t-4} (\ell n(N_{y,0}^m + N_{y,0}^f) - \ell n\hat{N}_{y,0})^2 \tag{C.7}$$

The estimates of recruitment for the years *t-3*, *t-2*, *t-1* and *t* are omitted from this regression because their variance is usually very large (see, for example, Butterworth et al., 1990).

Figure 1a

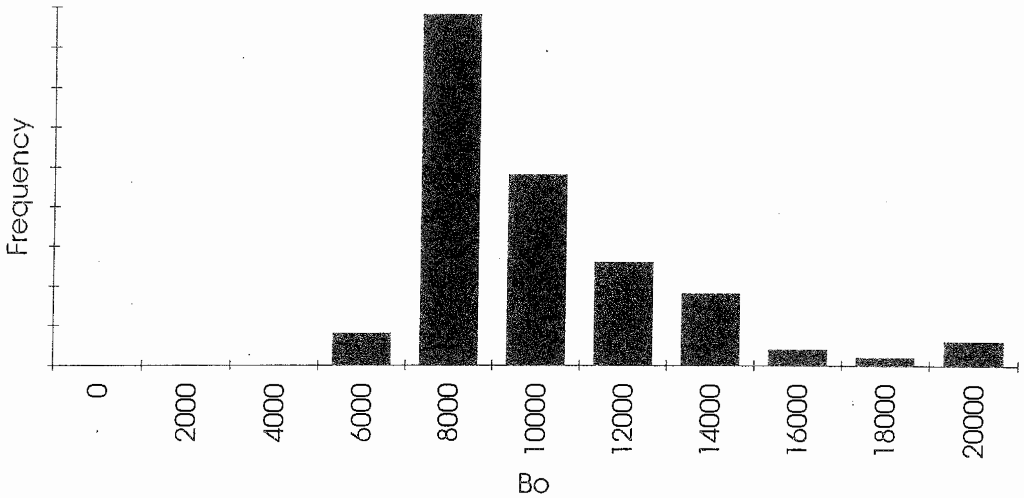

Figure 1b

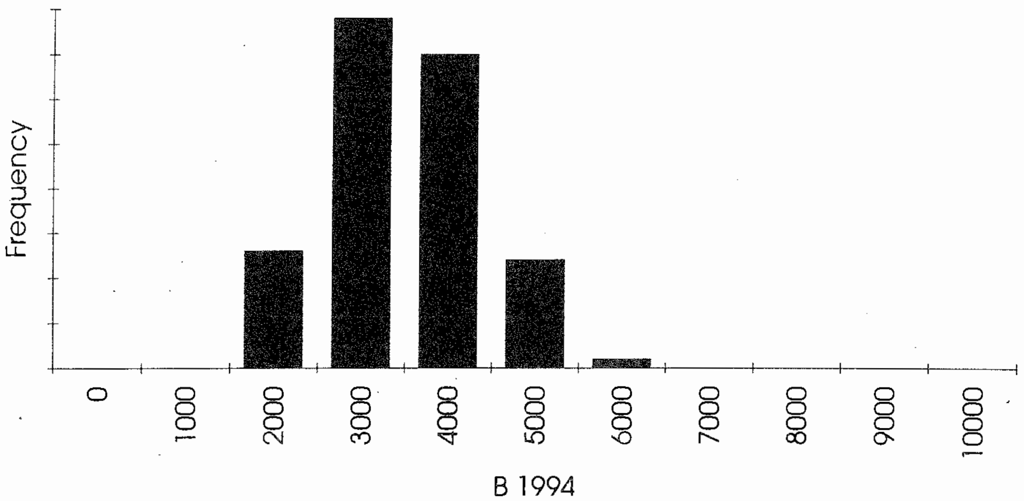

Figure 1c

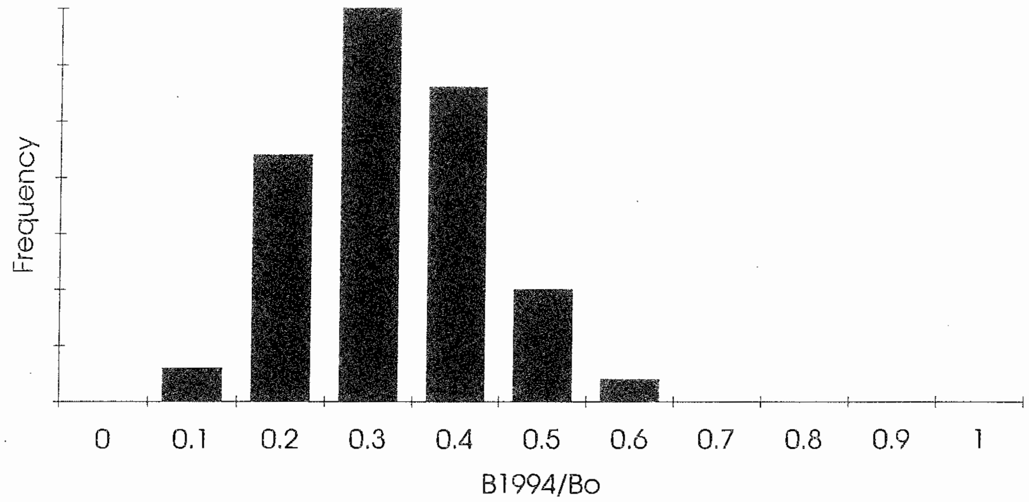

Figure 1d

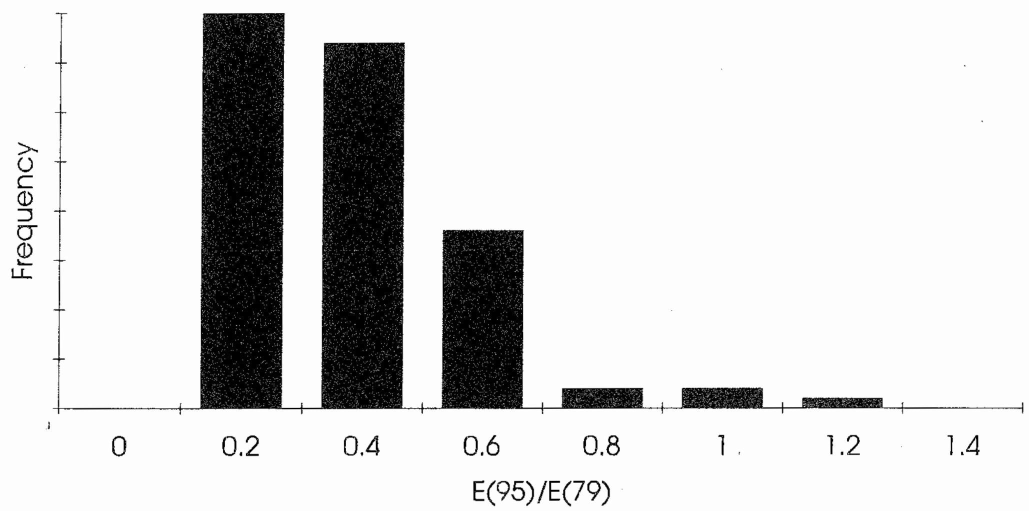

Figure 2

Median, 5th and 95th percentile trajectories for the base case

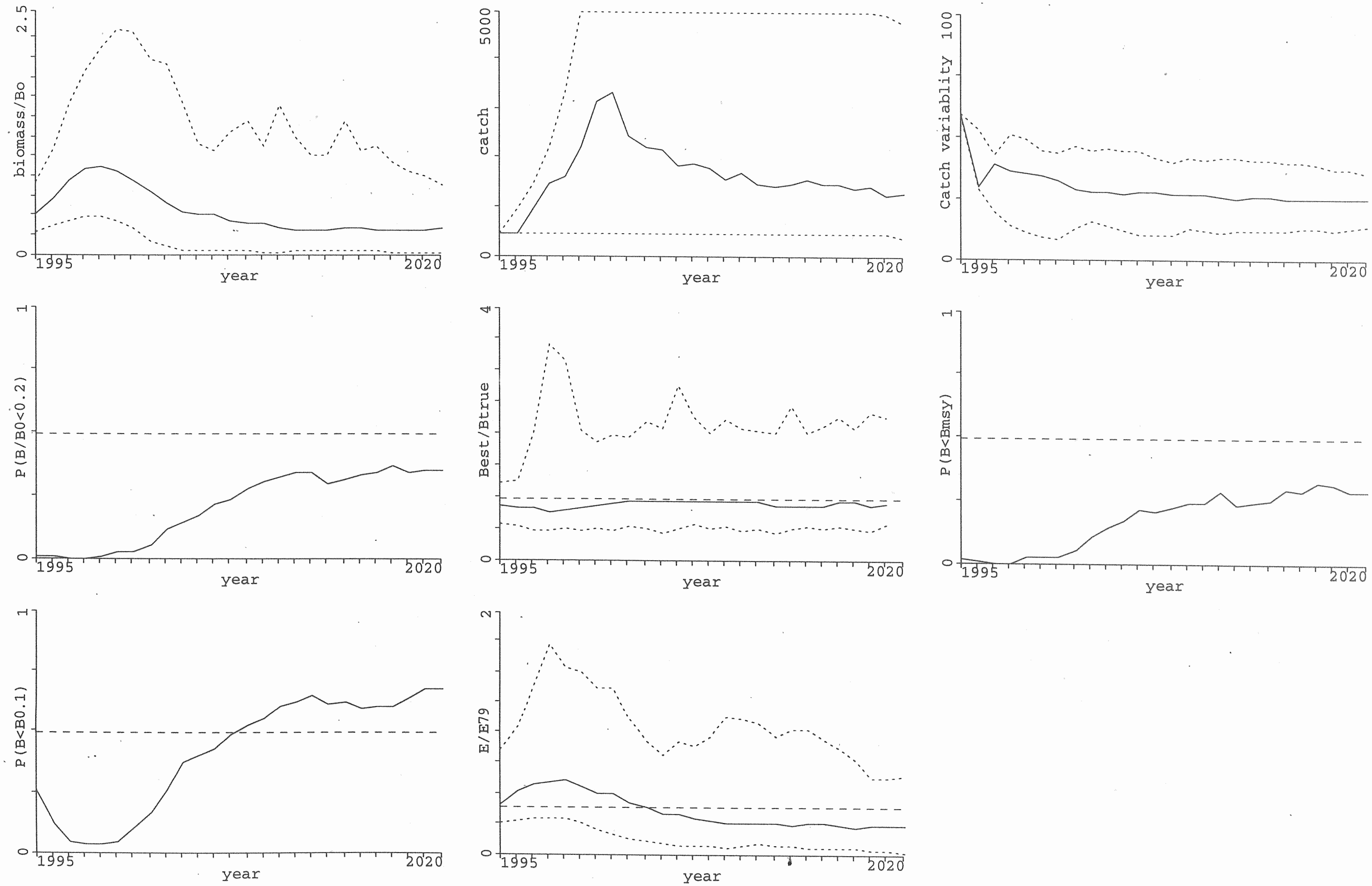

Figure 3a

Median, 5th and 95th percentiles

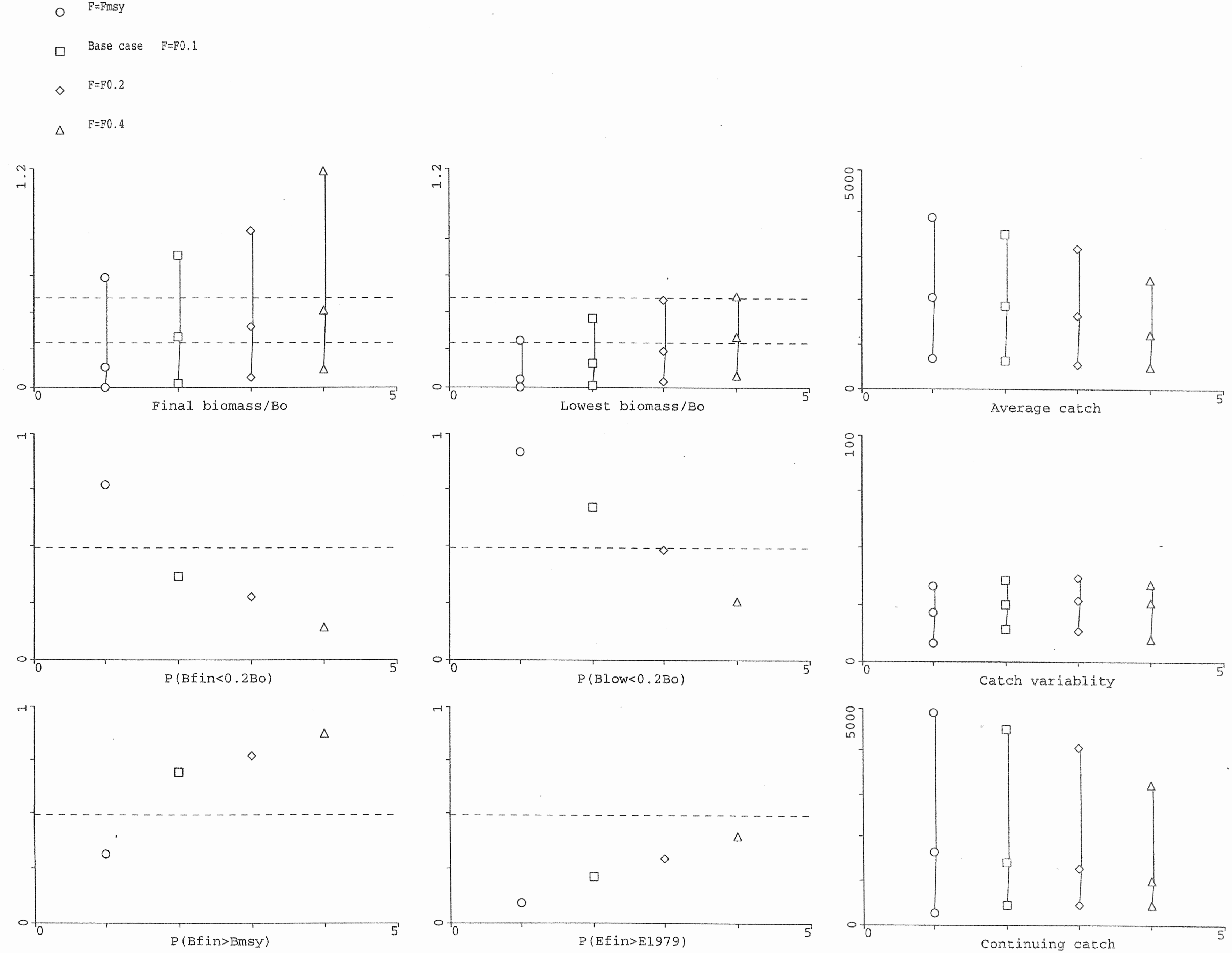

Figure 3b

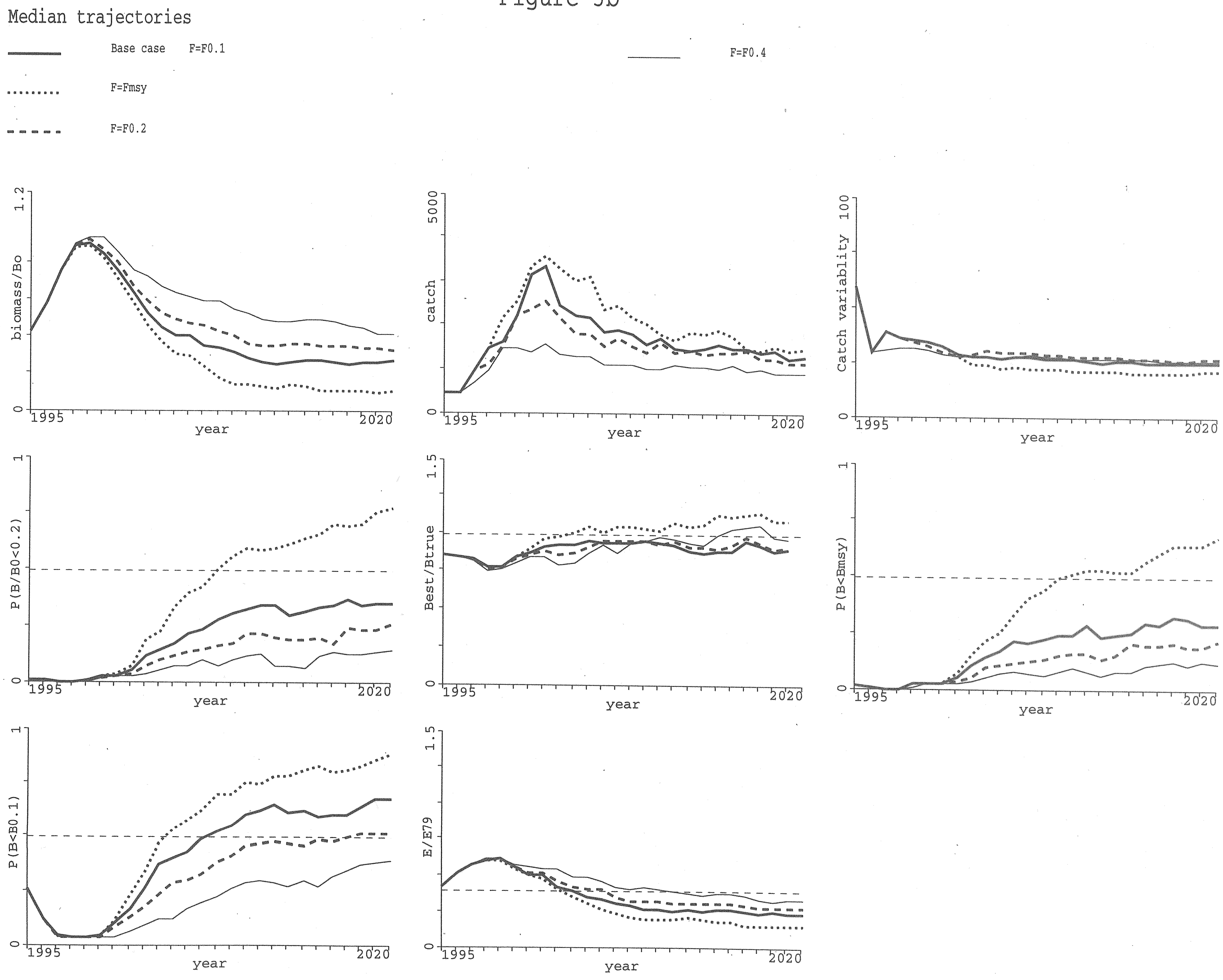
Median trajectories
Base case F=F0.1
F=Fmsy
F=F0.2
F=F0.4
biomass/Bo
catch
Catch variability
P(B/B0<0.2)
Best/Btrue
P(B<Bmsy)
P(B<B0.1)
E/E79
year
1995
2020
0
1.2
5000
100
1
1.5

Figure 4a

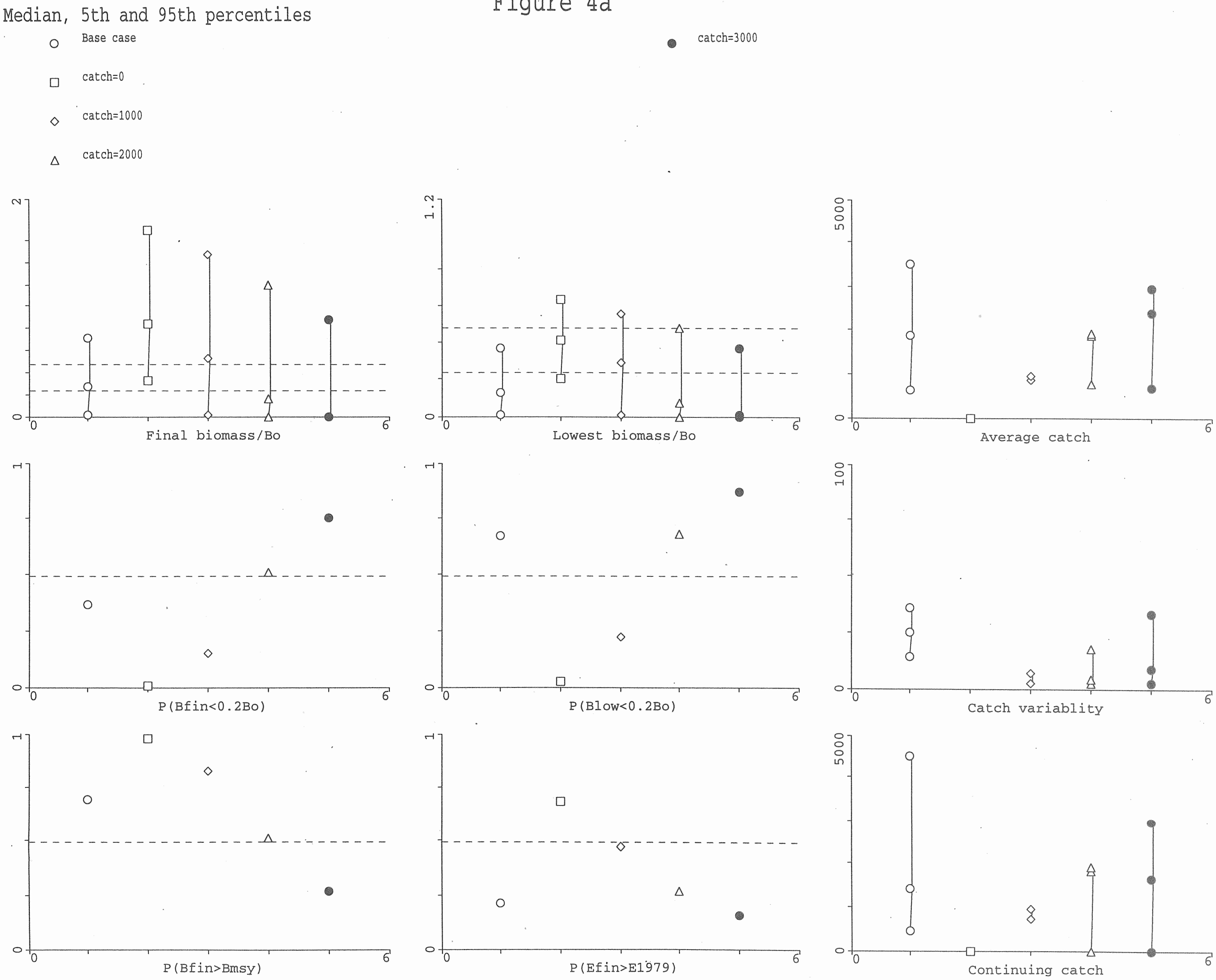
Median, 5th and 95th percentiles
Base case
catch=0
catch=1000
catch=2000
catch=3000
Final biomass/Bo
Lowest biomass/Bo
Average catch
P(Bfin<0.2Bo)
P(Blow<0.2Bo)
Catch variablity
P(Bfin>Bmsy)
P(Efin>E1979)
Continuing catch

Figure 4b

Median trajectories

Base case

catch=0

catch=1000

catch=2000

catch=3000

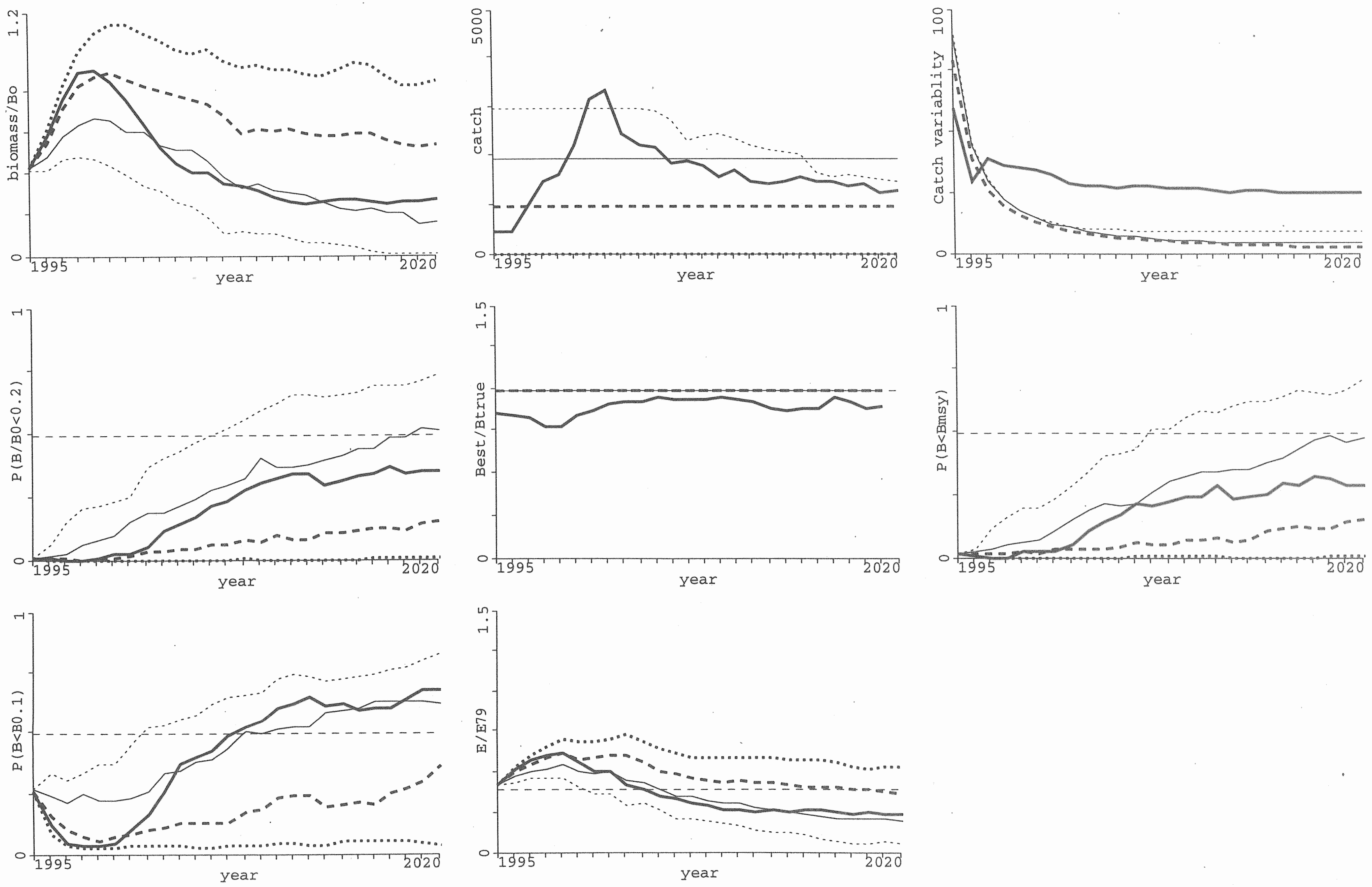

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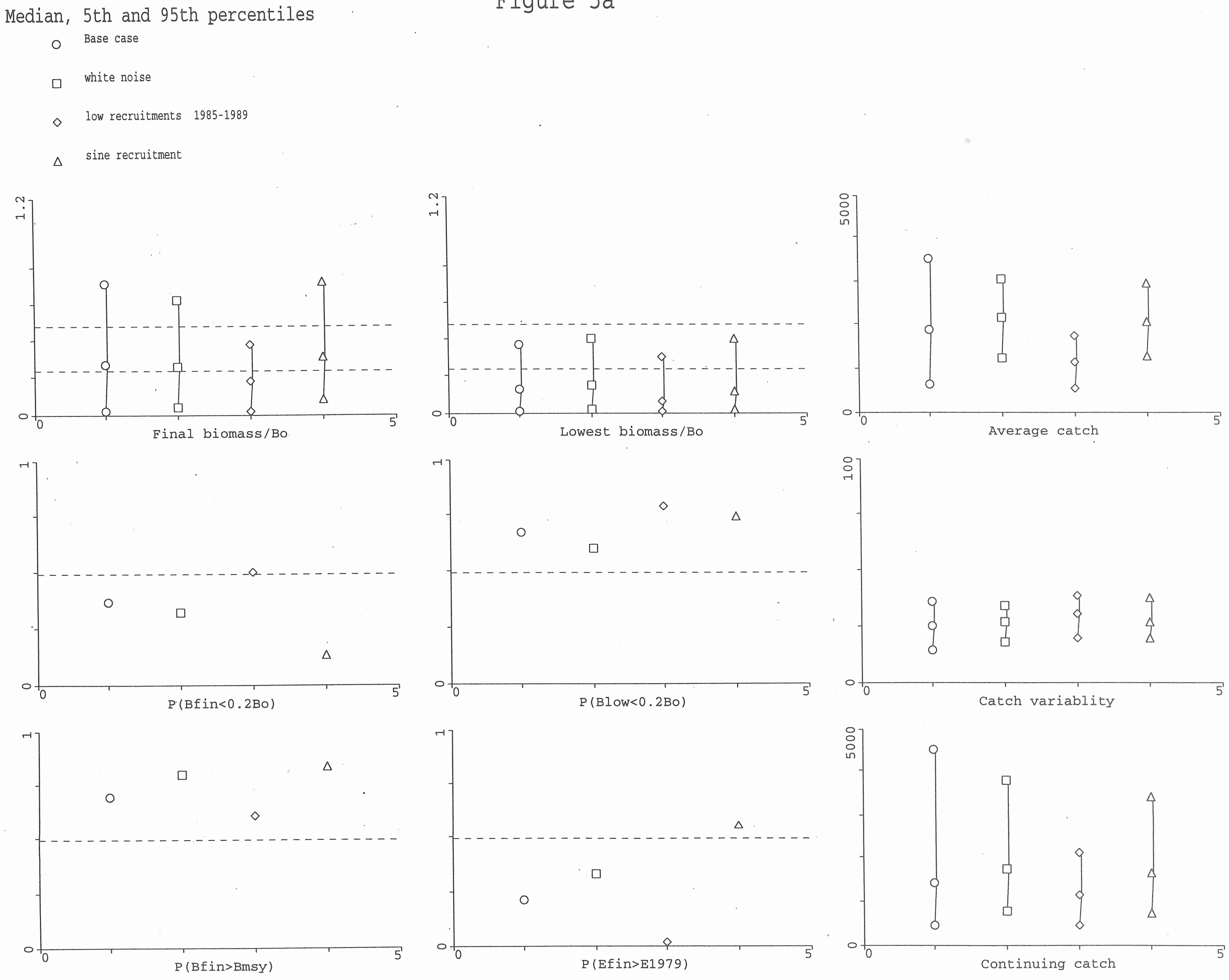
Figure 5a



Median, 5th and 95th percentiles
Base case
white noise
low recruitments 1985-1989
sine recruitment
Final biomass/Bo
Lowest biomass/Bo
Average catch
P(Bfin<0.2Bo)
P(Blow<0.2Bo)
Catch variablity
P(Bfin>Bmsy)
P(Efin>E1979)
Continuing catch

Figure 5b

Median trajectories

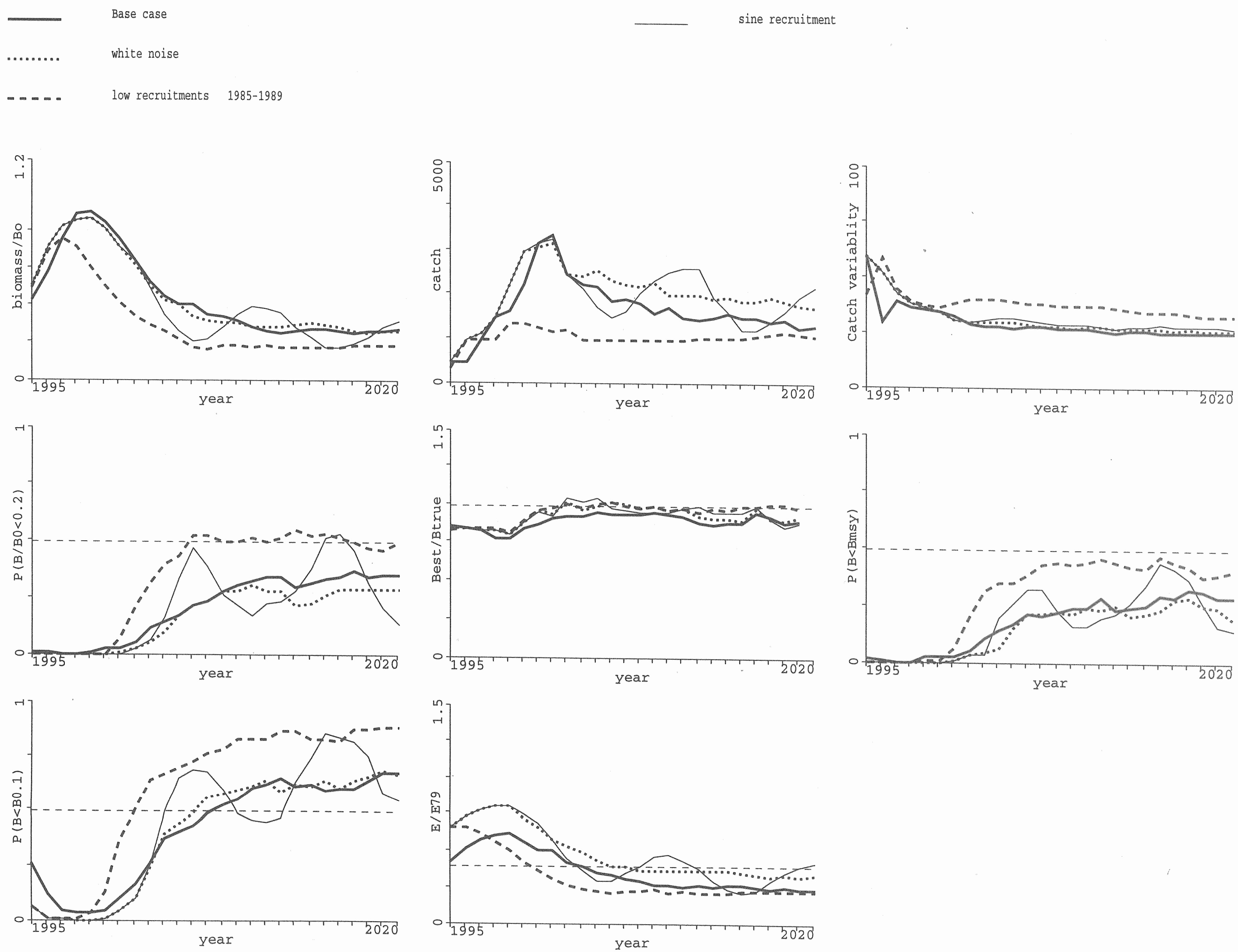


Figure 6a

Median, 5th and 95th percentiles

○ Base case

□ no catch constraints

◇ Base case perfect information

△ CPUE cv=0.25 summer catch-at-age cv=0.6 winter catch-at-age cv=0.25

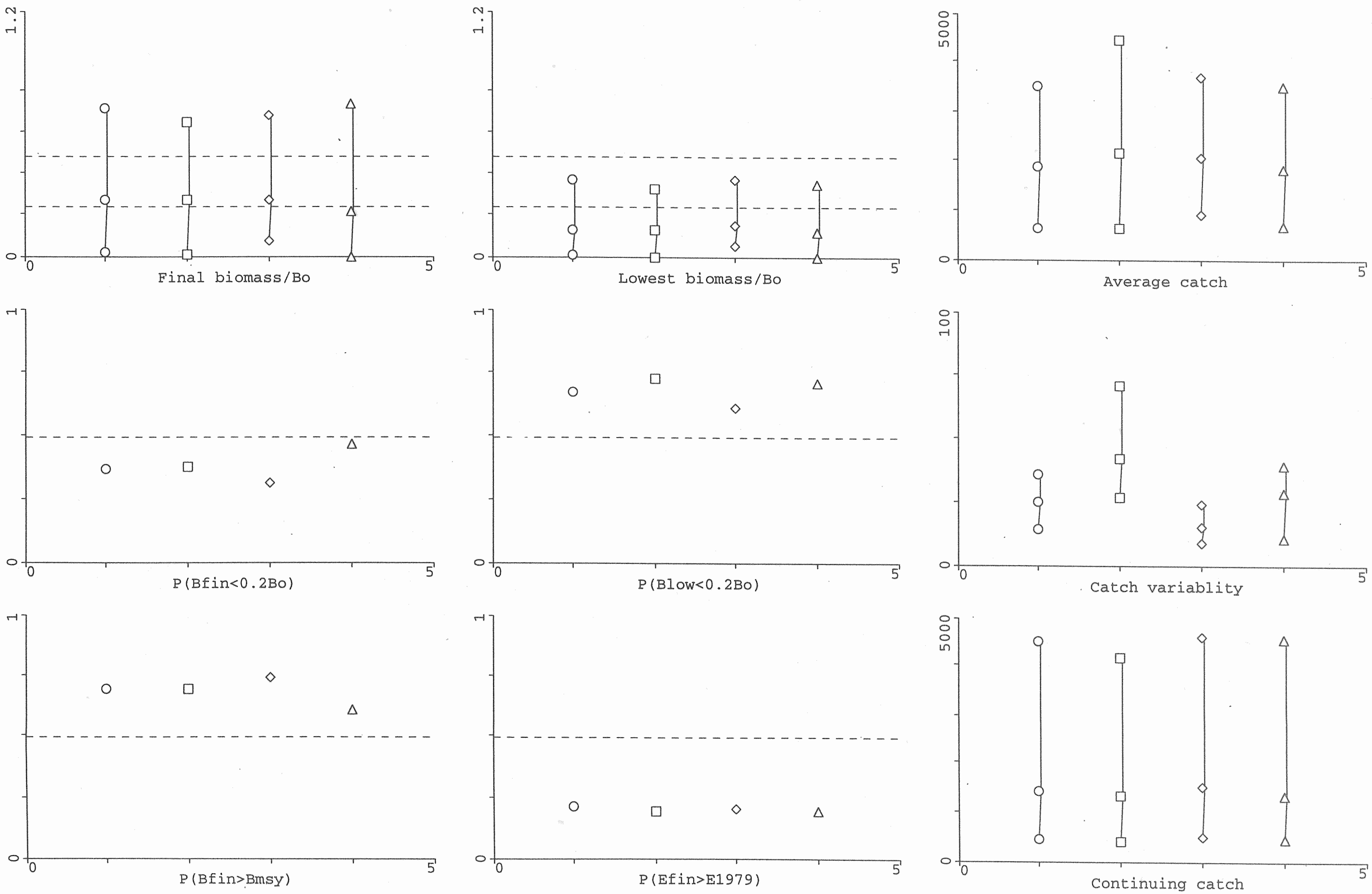
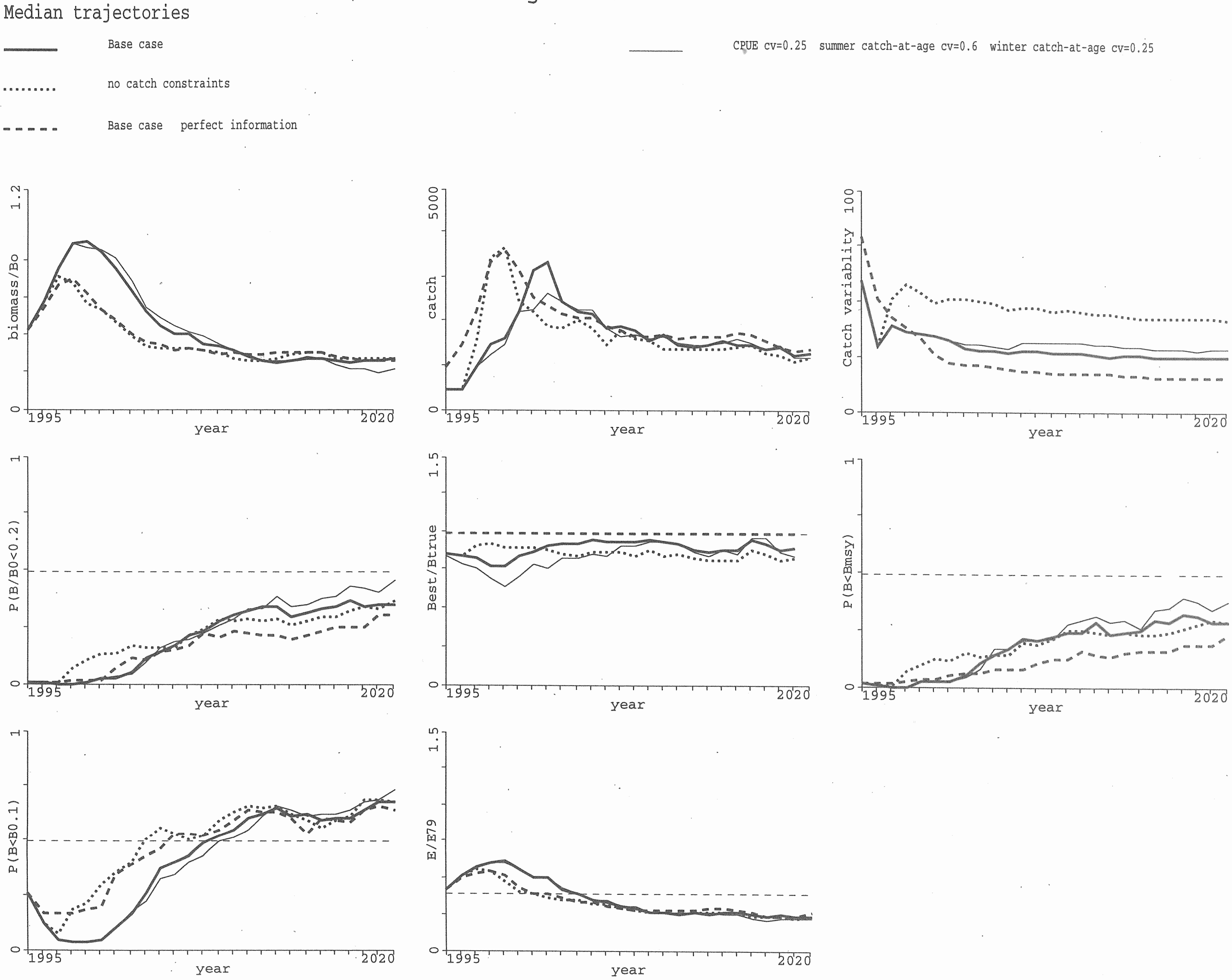


Figure 6b


Median trajectories
Base case
no catch constraints
Base case perfect information
CPUE cv=0.25 summer catch-at-age cv=0.6 winter catch-at-age cv=0.25
biomass/Bo
catch
Catch variablity
P(B/B0<0.2)
Best/Btrue
P(B<Bmsy)
P(B<B0.1)
E/E79
year
1995
2020
0
1.2
5000
100
1
1.5

APPENDIX

MANAGEMENT STRATEGY EVALUATION - COMPUTER SYSTEM

AIMS

- Development of Management Strategy Evaluation (MSE) software took place with the following goals:
- The software should run efficiently on IBM compatible PCs, and also Unix systems if necessary;
- The system should be developed in a general manner, allowing alternative species and fishery structures with a minimum of re-development;
- A modular design should be implemented to allow alternative assessment methods, operating models, management strategies etc. to be interchanged.

DEVELOPMENT ENVIRONMENT

The Management Strategy Evaluation (MSE) computer system was developed using Borland C++ version 4.02 and the C++ programming language, and runs on 386, 486 and Pentium IBM compatible PCs. This compiler version allows 32-bit DOS applications to be developed using a flat memory model which avoids memory limitations associated with normal 16-bit DOS applications. Such a system allows programmes to effectively use all memory installed in the PC.

DEVELOPMENT TOOLS

Scientific programming requires a set of tools for performing routine mathematical operations such as matrix multiplication or function minimisation, as well as utilities for graphically displaying the results from models both on-screen, and hard-copy.

Otter Research (a Canadian software company) had developed a set of C++ classes and functions which simplify the manipulation of vector and matrices which they incorporated into a set of C++ libraries called AUTODIF. Vector and matrix operations are fundamental to more complex mathematical procedures. This library was implemented, and the standards for vector and matrix processing were adopted for additional mathematical and graphics libraries.

Procedures developed in C and published in *Numerical Recipes in C* (Press, Flannery, Teukolsky and Vetterling), as well as a number of standard mathematical procedures developed by CSIRO were modified to comply with AUTODIF vector and marix processing standards and converted to C++. These provided a maths library with utilities for statistical calculations, function minimisations etc.

Over a number of years, a library of C routines was created by CSIRO and the Bureau of Resource Sciences for the production of screen graphics using Borland C compilers. This graphics library was converted to C++, and additional code was added for the production of postscript output.

DATA STRUCTURES

C++ data classes were created for the storage of various types of information used in fisheries modelling. For MSE, these classes included:

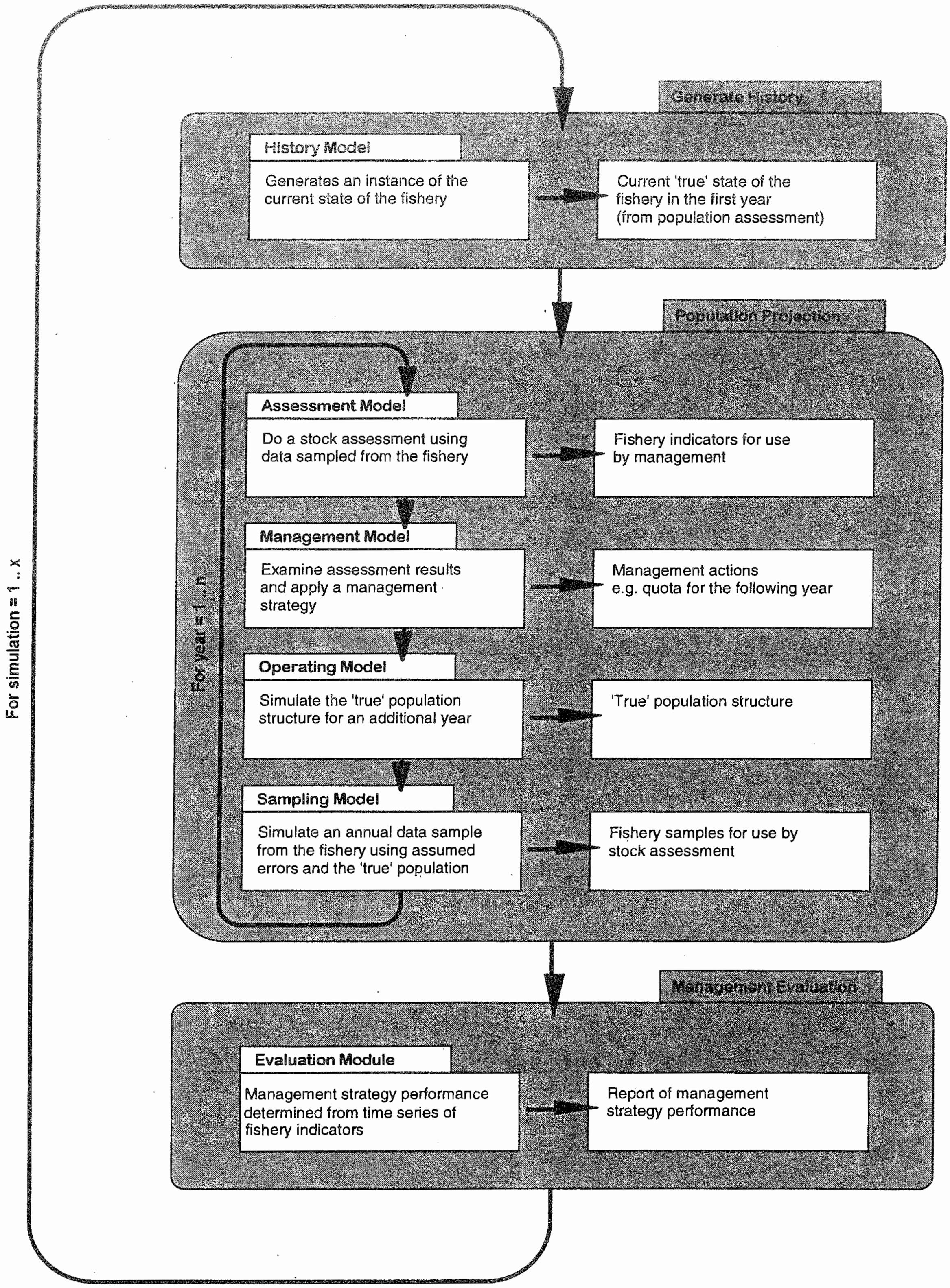
- Biological data - storage of biological information usually determined by specific research including growth parameters by sex, stock-recruitement relationship type, natural mortality rate, age specific catchabilities, fecundity, maturity ogive etc.
- Historical data - storage of historical catch, information on the number of fishing areas and seasons, annual (seasonal) fishery catch rates and catch at age by sex etc.
- Simulated population data for the operating model - storage of population numbers at age by year, total biomass and spawning biomass by sex, fishery selectivities etc.
- Additional classes were created for storage of control parameters for each module in the system. As such, the modules remain independent.

SYSTEM DESIGN

The flow-chart below describes the MSE system as developed for gemfish. Each module accepts information as parameters using C++ data structures described above. A typical run of the program may require 100 simulations, each from the years 1995 to 2020. To allow for current uncertainty in the status of the population, 100 alternative current states were created independently using methods as described in Chapter 3 of this report. This set of alternatives should capture the uncertainty existing in the most recent gemfish assessments.

A single simulation first selects at random one of these current states which the program then uses to model the 'true' population. Projections are then carried out by cycling each year through an assessment, management decisions, simulation of the next year for the 'true' population, and simulated sampling (with error). On completion of each simulation, performance statistics (e.g. the size of the spawning stock in 2020) are collected and reported.

When all simulations are complete, performance statistics are again summarised, and the results are used to judge the performance of the management strategy selected for the run. Alternative management strategies may be evaluated by carrying out additional runs. The system may likewise be used to test the performance of various assessment methods, operating models, or sampling regimes.



Generate History
History Model
Generates an instance of the current state of the fishery
Current 'true' state of the fishery in the first year (from population assessment)
Population Projection
For simulation = 1 .. x
For year = 1 .. n
Assessment Model
Do a stock assessment using data sampled from the fishery
Fishery indicators for use by management
Management Model
Examine assessment results and apply a management strategy
Management actions e.g. quota for the following year
Operating Model
Simulate the 'true' population structure for an additional year
'True' population structure
Sampling Model
Simulate an annual data sample from the fishery using assumed errors and the 'true' population
Fishery samples for use by stock assessment
Management Evaluation
Evaluation Module
Management strategy performance determined from time series of fishery indicators
Report of management strategy performance