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Analyses of Simulated Data Sets in Support of the NRC Study on Stock Assessment Methods

Edited by
Victor R. Restrepo

U.S. Department of Commerce
National Oceanic and Atmospheric Administration
National Marine Fisheries Service

NOAA Technical Memorandum NMFS-F/SPO-30
April 1998

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Introduction to the Analyses

Background

In 1995, the National Atmospheric and Oceanic Administration (NOAA) asked the National Research Council (NRC) to conduct a review of stock assessment methods used as the scientific basis for fisheries management advice. The review, carried out by a panel of scientists chosen by the NRC, was intended to document the strengths and limitations of stock assessment methods relative to the diverse data types available for assessments and to diverse fishery management systems.

As one component of their overall study, the NRC panel designed a computer-based fishery simulator and generated five 30-year realizations from it to provide data sets by which to evaluate the performance of various assessment methods when some common assumptions were not met. These data sets included apparent annual catches by number and weight and samples of their age composition for a commercial fishery and a research survey. Variations were introduced in the commercial fishery data such that the time series of catch per unit of effort were not linear indices of population size. The data sets were given to scientists expert in the application of stock assessment models. Parameter values of the model used for individual body growth and maturity schedules in the simulations were provided to the assessment scientists (see Annex). Other modeling assumptions and parameter values underlying the simulations were known only to the panel and were left for the analysts to detect from the data sets and to accommodate in their assessments. The panel later divulged some information about the simulation processes to the scientists after their initial assessments were documented. In particular, the simulated natural mortality values were disclosed. The scientists revisited the analyses to varying degrees in completing their reports.

Assessment scientists from the National Marine Fisheries Service (NMFS) cooperated in this exercise, applying a variety of methods to the simulated data. The NRC Committee suggested that this Technical Memorandum be prepared to provide additional details about the analyses that could not be provided by the NRC report and because there were innovative analyses of interest to a wider audience. This document complements the NRC panel report (NRC 1998) by providing greater detail on the analyses performed, as well as any caveats and reservations expressed by the analysts to the NRC panel.

The Analyses

This document is arranged into chapters defined by analyst(s) and assessment method, rather than by method alone, because the NMFS scientists were expressly asked by the NRC panel to work independently of each other, even when using similar methods. The scientists were to estimate from the five simulated data sets the 30-year histories of population magnitudes to the level of age composition possible by their method. In addition, the NRC panel requested a recommended allowable catch for the 31st year. Each chapter is based on the analyst's report as presented to the NRC panel in May 1996, with revisions for clarity, and with the addition or replacement, in some cases, of results from subsequent analyses that were requested by the panel. The chapters are organized, more or less, in increasing order of model complexity.

Chapter 1 presents attempts to fit a nonequilibrium, biomass-based stock production model to the data. Production models describe the population dynamics by relatively simple density-dependent equations. As a consequence, production models are most often used in situations where age-structured information is either absent or deemed unreliable. The analyses in this chapter clearly indicated that the five simulated data sets were not well suited to simple production modeling and highlighted inconsistencies between the simulated fishery-based and survey-based relative abundance data.

Chapter 2 reports assessments based on fitting the delay-difference model with some accommodation of observation and process error. Observations used include annual indices of biomass and recruitment, and random error is assumed to corrupt the biomass index but not the recruitment index. Fixed weighting of the biomass index and the delay-difference model projection of biomass presumes knowledge of the relative magnitudes of observation and process error. Delay-difference models and production models require similar types of data, but the former explicitly account for the influence of interannual recruitment fluctuations on the change in population size. The analyses estimated lower biomass levels when only simulated survey data were used to index abundance than when either fishery or fishery and survey data were included. The analyst concluded that there were inconsistencies between the various types of information provided, for example poor correlations between survey biomass and fishery landings-per-unit-effort.

Chapter 3 continues with the use of the delay-difference model for the assessments, but both the biomass and recruitment indices were assumed to be corrupted by random error. Further, an attempt was made to estimate magnitudes of observation and process errors from the biomass and recruitment indices in order to appropriately weight observations and delay-difference model projections. The analyses presented were obtained using the information regarding the value of natural mortality revealed by the panel at the May 1996 meeting. A brief report on the effect on assessments from use of incorrect values for the magnitude of natural mortality is also included. These analyses were performed separately for fishery-based and survey-based relative abundance information. The results indicated that the simulated survey data were better described by the delay-difference model than were the fishery data. Estimates of recruitment and biomass from the survey and fishery data showed varying degrees of agreement from very poor to fair, indicating general inconsistencies between both types of simulated information.

Chapter 4 presents the fitting of an age-structured model that makes no assumptions about the separability of fishing mortality into age and year components. This application is based on virtual population analysis, which assumes that the catch-at-age data are without error, and uses an observation error model for the relative abundance data. The analyses differ in approach from those in other chapters, as the work was carried out by a group of scientists in analogous fashion to a brief assessment working group meeting. The group examined the simulated data, found inconsistencies, and concluded that the simulated fishery-based indices of abundance should not be used assuming direct proportionality to stock abundance. Therefore, the scientists opted for carrying out analyses based primarily on the simulated survey abundance data.

Chapter 5 presents analyses based on an age-structured model that makes the assumption that the time series of fishing mortality can be separated into year and age effects. In contrast to the method of Chapter 4, this and the methods in subsequent chapters allow for errors in the catch-at-age data, by assuming separability in the fishing mortality matrix. Results of the analyses in Chapter 5 suggested inconsistencies between the simulated fishery-based and survey-based information in most data sets. This chapter contains summary plots by data set which provide insight into how the data sets were simulated and can be used to compare the main pieces of information inherent to the five data sets.

Chapter 6 presents an application of an age-structured model similar to that of Chapter 5, but with an added degree of complexity and flexibility. Several alternative analyses were carried out by allowing for time-varying selectivity, a nonlinear relationship between biomass and fishery-dependent indices of abundance, and a deterministic relationship between spawning stock biomass and recruitment. The results indicated that the simulated fishery-based and survey-based relative abundance data could be made compatible by allowing the fishery-dependent abundance indices to be a nonlinear function of biomass.

Chapter 7 presents analyses from another age-structured modeling approach in which several commonly made assumptions are relaxed further. The chapter combines analyses carried out in two separate stages. The first modeling efforts used simple separable models, similar to those of Chapter 5, the results of which suggested some forms of model mis-specification. In the second stage of analyses, fishery or survey catchability, fishery or survey selectivity at age, and natural mortality, were modeled as random walks constrained to relative levels of variability assumed by the analysts. The analyses were done separately using either fishery-based or both fishery and survey-based relative abundance data. Results from the more complex models estimated large changes in fishery catchability through time for most data sets. The analyses using simulated fishery data only were generally characterized by higher uncertainty and more severe retrospective patterns than when survey data were also included.

It is evident that the various participating scientists approached the exercise from different perspectives. Some relied heavily on screening the available simulated data prior to estimation (notably the analyses in Chapters 1, 4, and 5), while others relied somewhat more heavily on model output diagnostics (notably the analyses in Chapters 2, 3, and 6), or on formulating highly parameterized models that could naturally overcome data discrepancies of the types that were simulated (Chapters 6 and 7). Some analysts proceeded with the exercise emulating the sorts of group decisions that would be made by an assessment working group (Chapter 4), while others proceeded as a scientist would individually analyze a data set in a stock assessment. These and other differences in approach reflect not only the diverse nature of models used, but the diverse background of assessment scientists as well. In no case did the analysts limit themselves to the blind application of a particular model to the simulated data. In all cases, the analysts concluded that there were inconsistencies between the various types of information provided, for example poor correlations between survey biomass and fishery catch rates.

This document makes no attempt to summarize and compare the results obtained from the application of the various methods to the NRC simulated data sets. The Special Considerations section, below, presents considerations that the reader should keep in mind when attempting to draw conclusions from this exercise.

Special Considerations

The intended objective of the exercise solicited by the NRC was to examine the performance of various methods when commonly made assumptions were violated. The NRC Committee noted that the analyses of simulated data were not meant to replicate a real-world assessment situation, but rather to carry out reasonable comparisons of methods by making all analysts operate under similar constraints (NRC 1998).

A comprehensive comparison of performances by the methods is exceedingly difficult as the test data sets are subject to various assumptions that may favor one type of methodology over others. In essence, the assumptions made in simulating the data determine which model works best. For example, the comparative performances of biomass-based production models and sophisticated age-structured methods would depend on the population dynamics and variability assumed as well as the reliability of the age structure information from catches. Evidently, the simulated situations underlying the NRC data sets were generally incompatible with simple production modeling (NRC 1998, p. 146). On the other hand, data sets could have been generated in which the only reliable information would be series of total catch and effort, i.e., age of fish would not be determined accurately, and underlying population biomass dynamics could have been approximated by simple production models.

As another example, comparisons among some of the age-structured approaches would depend on the validity of the separability assumption. The underlying fish capture processes in the NRC simulation model apparently followed relatively constant selectivity patterns during blocks of years in the simulated time horizon. The methods that assume separability (Chapters 5-7) were able to easily accommodate additional complexity, e.g., errors on estimated catch or trends in catchability, partly because this assumption reduces the number of parameters (stock sizes and fishing mortalities) that must be estimated, thus providing the flexibility to estimate other parameters (e.g., those related to trends). In contrast, the approach of Chapter 4 essentially assumes infinite variability in selectivity over time, at the expense of relying on the assumption that the catches are exact. Results from comparing age-structured approaches may have differed if the simulated data been generated with more variable selectivity.

An additional reason for differing performance between age-structured approaches lies in an ageing error matrix provided with the simulated data sets (the matrix gave the probability that fish of true age i were actually assigned age j in the "observed" data).

Such information is easily accommodated in separable (forward calculation) models such as those of Chapters 5-7, but not in VPA-based (backward calculation) models such as that of Chapter 4. Other approaches for presenting ageing error information to the analysts may have resulted in different performance of the various models.

Comparison of performances by the methods presented in the following chapters requires circumspection because the applications comprise five data sets that were generated with a particular set of assumptions. The NRC Committee noted that, because each data set was a single realization of a stochastic process, the possibility of atypical (extreme) situations could not be eliminated (NRC 1998, p. 87). The authors believe that generalizations about the performance by any particular method based on these results are unwarranted.

Finally, the interplay between methods, stock assessments, and the management context to be addressed — which is of utmost relevance in real applications — was not and probably could not be incorporated into the NRC simulation exercise. Typically, considerable feedback occurs between assessment methods used, types of data collected, and management objectives. Assessments of any stock rely on the statistical model used and available data, as well as on the specialists' knowledge about the species biology and of the fishery. Indeed, many methods are developed or "tailored" around particular assessment applications by taking biological and fishery characteristics, and the available data types, into consideration. Additionally, the efficacy of an assessment is largely a function of whether it is useful for a management decision. As such, evaluation of precision and bias of a particular assessment is often dependent on the management context. For these reasons, the usefulness of a modeling method cannot be comprehensively evaluated based on the results of limited simulation-estimation exercises.

Conclusion

The NRC Committee recommended that assessment methods and management strategies be evaluated together because of the feedback that can occur between the two (NRC 1998, Chapter 4). While such an important endeavor was beyond the objectives of the overall NRC study, the authors believe that this exercise provided a useful basis for comparing the ability of different assessment methods to reconstruct historical abundance from common data sets. The experience gained from this exercise should thus be valuable in formulating more complex experiments involving closed-loop policies.

Acknowledgment

Christopher Legault and John Witzig provided helpful comments on an early draft of this Technical Memorandum. Rick Deriso and two anonymous members of the NRC Committee also provided helpful suggestions for improving this introductory section.

Reference

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Annex

Excerpts of the letter sent by the NRC Committee on Fish Stock Assessment Methods to the scientists who participated in the analysis of simulated data sets.

Dear Analysts:

[...]

Attached please find an Excel spreadsheet that contains data sets from 5 age-structured populations. Each data set contains statistics from the fishery: reported catch and effort and age composition. A survey was conducted and summarized as a relative index along with survey age composition; a constant survey fishing effort is expended each year. Simple random samples of age composition were taken from the catch (n=500) and from the survey (n=200). Ageing error is present and the ageing error generation process is given to you. Further details about the data and the population are given below

We would like you to analyze each data set in three ways if you can: [A]: using CPUE as the only measure of relative abundance; [B]: using only survey information; [C]: using both CPUE and survey information.

This will allow us to address the question of whether surveys are important. We can label the analyses as 1[A], 1[B], 1[C], 2[A],..., 5[C]. IT IS CRITICAL THAT THE [A] AND [B] ANALYSES BE DONE FIRST AND ARE INDEPENDENT OF THE [C] ANALYSES. (i.e. Do not revise the [A] and [B] analyses based on what you come up with in the [C] analyses.)

As time permits, we would also like to get retrospective analyses of each data set and analysis. Ideally, we would like to get 15 retrospectives per analysis (i.e. years 1-16, . .. years 1-30). These analyses should be done independently (i.e. Please do not use results from years 1-30 to initialize the parameters for the retrospective analyses.). We realize this may be optimistic, but given your time constraints we would like to have at least 5 retrospective analyses for each for the May meeting and more if you can do it.

We would like the results summarized as follows: summarized estimates of model parameters and model structure, estimated exploitable, mature, and total biomasses over time, average fishing mortality and exploitation rate over time, estimated recruitment (youngest age used) if part of the model, and selectivity by age (and possibly year) for the fishery and survey. You are welcome to estimate a TAC or ABC; however if you do so, please tell us what approach you will use. As a default, we recommend F40% be calculated for comparison where F40% refers to the F that reduces spawning biomass per recruit to 40% of the unfished level.

Other model features:

1. Data from the fishery occurs over 30 years, t=1,...,30. Age 15 represents a plus group but fish older than 15 are uncommon.

2. Natural mortality is unknown, may not be constant, but is in line with species with similar longevity.

3. Growth: Mean weight at age follows an allometric von Bertalanffy curve W(a) = Wm [1 - exp(-k(a - t0))]^b. The parameters are Wm=5000 g, k=0.3/yr, b=3, and t0=0 yr.

4. The maturity relationship is a logistic-shaped function m(a)=1/[1+exp(-b(a-a5)]. The b parameter is constant over the 5 data sets and equal to 1.65/yr. The a5 parameter is the age at 50% maturity and varies among data sets:a5=(7,8,9,8,7) for data sets (1,2,3,4,5), respectively. Both the growth and maturity relationships are based on true age.

5. The generation of recruitment is unknown to you.

6. Aging error was generated with 0 bias at age 1 which increases linearly to -1 at age 15. The variation in ageing error was ~N(0,s^2), with a linear increase from s = 0 for age 1 and s = 2 for age 15. The ageing error matrix consisting on probabilities pij of age j being recorded given true age i is constant among data sets and given on the spreadsheet.

7. For Set 3, a different vessel was used in years t= 16 to 30, which may or may not have altered survey catchability.

8. Catch Equation: Fishing occurs continuously throughout the year.

9. Reported yield in biomass is determined from landing reports, not as the sum of catch-age times weight-age. Reported catch in numbers is also not affected by age composition. Reported total annual catch and total yield are measured with a small amount of error relative to other sources of variation, although there could be additional unreported catches (yield).

[...]

NRC Committee on Fish Stock Assessment Methods

CHAPTER 1.

Results from Fitting a Stock-production Model to the NRC Simulated Data Sets

Michael H. Prager

National Marine Fisheries Service, Southwest Fisheries Science Center, 3150 Paradise Drive, Tiburon, California 94920. Mike.Prager@noaa.gov

Introduction

National Marine Fisheries Service scientists cooperated with the NRC Committee on Stock Assessment Methods in an exercise of analyzing five simulated data sets with several stock assessment models. The analyses in this chapter correspond to simple stock production modeling which, by its nature, ignores the large amount of age-specific information that was provided with the simulated data sets.

Modeling Methods

For these analyses, a consistent model and fitting procedure (essentially as described in Prager 1994) were used on each simulated data set. The assessment model was a continuous-time, logistic, single-species stock-production model, not using the equilibrium assumption. Fitting used an observation-error estimator conditioned on yield; the loss function was the sum of squared residuals in the logarithm of CPUE. The model and fitting procedure are implemented in a computer program (ASPIC; Prager 1995) that was used for this work. In estimation, wide constraints were put on model parameters (e.g., $0.05 < r < 6.0$, where r is the intrinsic rate of increase)[1]; estimates at a constraint were considered to indicate estimation failure, probably caused by data-model mismatch.

As requested, three model fits were made for each simulated data set. The first fit used only data from the simulated commercial fishery: yield (total landings in weight) and CPUE (yield divided by nominal effort). The second fit used the same yield data but replaced the CPUE with the simulated survey index of abundance. The third fit used the same yield data and used both CPUE and survey indices of abundance, with equal statistical weighting. In some cases, an alternative to the third fit was also made. The alternative fit either used iteratively reweighted least squares or was based on a combined abundance index computed as the first principal component of the two indices (in log transformation and re-exponentiated).

The results given below are the estimates of maximum sustainable yield, the fishing mortality rate in the final year relative to F_{MSY}, and stock biomass at the end of the

1

The range of r given implies that the optimum instantaneous rate of fishing mortality, F, lies between 0.025 and 3.0. This is believed to be a sufficiently wide range not to bias estimation for a species with the given life history (in particular, age structure and growth rate).

final year relative to B_{MSY}. These three benchmarks are labeled "MSY," "Rel F," and "Rel B." In the author's opinion, the most useful of these for management is the relative fishing mortality rate. As a general principle, estimates of relative quantities (F or B) that are far from unity (perhaps above 1.7 or below 0.6) should be considered semi-quantitative or qualitative.

Accompanying the results for each fit is an expression of the analyst's confidence in them, on a scale ranging from "none" through "high." For reasons explained in the next section, the highest confidence obtained in this study was "moderate," and that was rare. Lack of confidence was generally due to one or more of the following: poor convergence properties in fitting, one or more estimates at a constraint, stock size estimated far from its optimum through the entire time series, apparent incongruity between the stock's dynamics and those of a simple production model, lack of robustness of the results (e.g., to changes in statistical weighting), or conflicting trends in the two abundance indices. Confidence as reported is in the numerical estimates; in general, confidence in the estimated qualitative situation would be higher. For example, it is possible to have little confidence in estimates of the amount of overfishing, while having substantial confidence in the estimate that a stock is severely overfished.

General Comments on Data and Results

The simulated data sets do not seem well suited to simple production modeling, and confidence in the quantitative validity of most of the results obtained is low. Noisy data, poorly correlated CPUE and survey indices, and relatively constant effort levels all probably contribute to this situation. Without knowing the underlying population model and conducting simulations, it is impossible to say to what degree age-structure effects also contribute.

The apparently high fishing mortality rates and the extensive age-structured data available suggest that these fisheries are better suited to analysis by cohort-based methods (e.g., virtual population analysis). This suggestion is strengthened by several sets of simulated data in which apparently constant fishing effort leads to a population increase and then a decrease —such a scenario is incompatible with the assumptions underlying simple production models. This suggests either environmental forcing of recruitment, nonconstant catchability, or both.

The effort series from the five simulated data sets are similar, and can be characterized as constant effort with a large random noise component and in some data sets one or two remarkable outliers. The yield series are also very noisy; besides effort changes, this could be caused by age-structured effects, patchiness, or similar factors. Gear changes or learning behavior on the part of the fisherman would seem more likely to induce a trend than random noise.

In all five data sets, the survey index and the CPUE appear to be related nonlinearly, with a power function being a reasonable approximation. If the survey represents relative abundance more or less accurately, the nonlinear relationship could result from density-dependent catchability in the fishery. Some CPUE series (e.g., data set 1) also appeared censored, as might result from under-reporting of zero catches or a "steaming time" component in the nominal effort (Fig. 1). Because of time limitations, no attempt was made to overcome (or even fully characterize) such anomalies in the data, to explore the age-structured data for information possibly useful in improving the age-aggregated data, nor to extend the model to suit these data (e.g., attempt estimation of density-dependent catchability). In a real fishery in which such extensive data were available, it seems likely that one could construct better indices of aggregated abundance. Given suitable stock biology, these might provide improved production-model estimates.

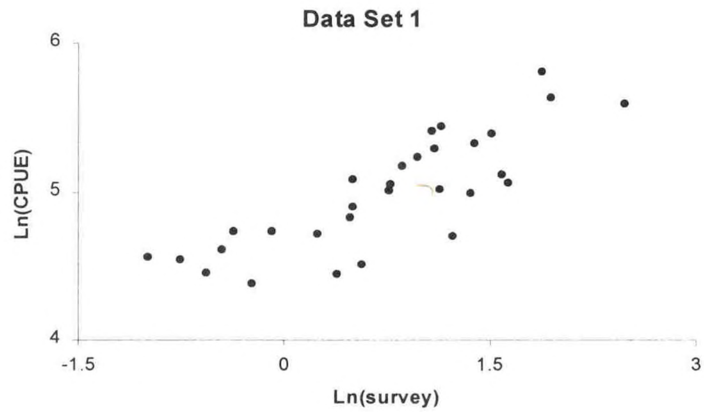

Figure 1. Plot of log CPUE vs. log survey index for data set 1. Flattening of the data towards left of frame suggests censoring of low-CPUE trips.

In many cases, the production-modeling results could provide at least qualitative guidance about management: an indication of the direction in which *F* might be manipulated to obtain better yields from the fishery, and perhaps a semi-quantitative idea of the amount of change needed. Such guidance might be suited to an adaptive management framework.

At least three of the five series exhibit substantial, monotonic, 30-year downward trends in CPUE. No mathematical model is needed to suggest that fishing mortality rates are too high in such fisheries.

Summary table of data quality (age-aggregated data)

Data set	Constant and noisy effort?	Noisy yield data?	Probable one-way trip?	r(CPUE, survey) [1]	CPUE-survey coefficient[2]
1	Y	Y	Y	0.63	0.37
2	Y	Y	Y	0.68	0.35
3	Y	Y	Y	0.47	0.22
4	Y	Y	N	0.67	0.42
5	Y	Y	?	0.81	0.64

[1] Pearson correlation coefficient between nominal CPUE and survey index.

[2] Coefficient of a linear regression of log CPUE on log (survey index). A value near unity would suggest a linear relationship between the two.

Results

General

Results are presented as a short table for each data set, followed by notes. All fits were based on the reported total yield in weight. The fits labeled "a" used the nominal CPUE as an index of abundance; the fits labeled "b" used the survey index; and the fits labeled "c" or "c1" used both indices, with equal statistical weighting. In some cases, an alternative fit was made using both indices; such fits are labeled "c2," and the method of computation is explained with the results.

Data set 1

Fit	Confidence in estimates	Estimates (if any)	Comments on modeling exercise
a	Low	MSY = 580 Rel F = 1.6 Rel B = 0.18	Poor convergence.
b	Low	MSY = 90 Rel F = 13 Rel B = 0.11	Stock being fished out.
c1	Low to none	MSY = 300 Rel F = 2.2 Rel B = 0.23	Poor convergence.
c2	None	r < 0.05	Fit used iterative reweighting. Implausible result (*r* at constraint).

- The CPUE data may be censored, as might result from underreporting of zero catches (Fig. 1).

- In fit (b), the best statistical fit is one in which the stock is estimated to have little potential growth rate and is being fished out (estimated $r = 0.06$).

- In fit (c2), the sensitivity of results to the choice of statistical weighting contributes to reduced confidence in the results of fit (c1).

Data set 2

Fit	Confidence in estimates	Estimates (if any)	Comments on modeling exercise
a	Low to none	MSY = 995 Rel F = 1.9 Rel B = 0.07	Poor convergence. Biomass estimates very low throughout.
b	None	r < 0.05	Implausible result.
c1	Low	MSY = 218 Rel F = 2.7 Rel B = 0.21	Poor convergence.
c2	None	r < 0.05	Combined index of CPUE and survey for fitting. Implausible result.

- The steadily declining abundance over three decades suggests that management is needed.

- The results in (c1) are suspect because they include the survey index, which in (b) appears unsuitable for this type of modeling.

Data set 3

- No plausible estimates could be obtained from these data, as the production model was unable to reconcile the constant (if noisy) effort with the initial population growth and later decline. This could occur in a stock in which recruitment is driven primarily by external factors (e.g., ocean conditions), or could be evidence of density-dependent catchability of both the survey and the fishery.

- To explain the observed data, one could postulate that ocean conditions changed around year 15 of this data set. Model fits were made based only on data from years 16 through 30. Using the CPUE index, the stock was estimated to have little or no reproductive potential (an implausible result). Using the survey index, the current (year-30) F was estimated at about 8 times the optimum. Using both indices, the multiple was estimated at 2.5. Confidence in all these estimates is low.

- It was given that survey catchability may have changed in year 15. A simple linear model with two time periods and CPUE as a predictor did not detect such a change.

- The correlation between CPUE and survey indices was particularly low in this set ($r = 0.47$), and the survey data appeared especially noisy.

Data set 4

Fit	Confidence in estimates	Estimates (if any)	Comments on modeling exercise
a	Very low	MSY = 2470 Rel F = 1.6 Rel B = 0.03	Population estimated as severely depressed throughout. Lack of contrast decreases confidence in estimates.
b	Low to moderate	MSY = 300 Rel F = 3.4 Rel B = 0.11	Population estimated as below optimum since about year 15.
c1	Low to moderate	MSY = 430 Rel F = 1.7 Rel B = 0.17	Population estimated as below optimum since about year 10.
c2	Low to moderate	MSY = 480 Rel F = 1.5 Rel B = 0.18	Population estimated as below optimum since about year 6. Fit uses iterative reweighting.

- The similarity of results in runs (b), (c1), and (c2) is somewhat encouraging. The estimates of relative F are similar from (a), (c1), and (c2), and within a factor of 2 of the estimate from (b). This suggests some robustness to the estimates.

Data set 5

Fit	Confidence in estimates	Estimates (if any)	Comments on modeling exercise
a1	Low	MSY = 635 Rel F = 0.51 Rel B = 1.4	Uses all data
a2	None	N/A	Omits first point. MSY at constraint. Estimates not considered valid.
b1	None	N/A	Uses all data. Model unable to reconcile yield history with initial population growth and later decline
b2	None	N/A	Omits first data point. Results as in b1.
c	N/A	N/A	Survey and CPUE show conflicting trends in last 10 years. Modeling not attempted

- The first year's data appear anomalous (extremely high catch and nominal effort), so run (a2) was undertaken without this point. It resulted in an invalid estimates; MSY was at its upper constraint, about 10 times the average recorded catch.

- The CPUE and survey indices conflict during the last 10 years or so. The CPUE series implies an increasing biomass, while the survey index implies a decreasing one. For that reason, a model incorporating both indices was not fit.

- If the survey describes the true pattern of abundance, it is incompatible with production-model dynamics.

Acknowledgment

Members of the scientific staff of the Tiburon Laboratory, Southwest Fisheries Science Center, NMFS, provided helpful comments.

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CHAPTER 2.

Results from Fitting Biomass and Recruitment Indices for the NRC Data Sets to the Deriso Delay-difference Biomass Equation

Jeffrey T. Fujioka

National Marine Fisheries Service, Alaska Fisheries Science Center, 11305 Glacier Highway, Juneau, Alaska 99801. Jeff.Fujioka@noaa.gov

Introduction

National Marine Fisheries Service stock assessment scientists were asked to participate in an exercise of fitting models they use in their assessments to blind data sets provided by the NRC Committee on Fish Stock Assessment Methods. The data sets provided consisted of survey indices of numbers and weight, age composition of survey and fishery catch, total catch in number and weight, annual fishery effort values, and a growth in weight function. Data this complete and of this quality and consistency is ideally suited to age-structured models, but is seldom, if ever, available in stocks managed by the North Pacific Fishery Management Council (NPFMC). These simulated data, which have apparently consistent abundance trends, provide us with the means to use the model to solve for absolute biomass, unlike the NPFMC situation, where even in powerful age-structured models, area-swept biomass estimates are routinely accepted as the absolute biomass. The delay-difference equation model which has also been used for NPFMC stocks, does not require detailed data and cannot take full advantage of the detailed data provided here. Nevertheless, given a recruitment index extracted from the data, the delay-difference equation model can also be used to solve for an absolute biomass estimate, and should provide for an interesting comparison.

Model Description

The model used is the Schnute (1985) form of the Deriso (1980) delay-difference equation,

$$B_{t+1} = (1 + \rho)\, s_t B_t - \rho\, s_t s_{t-1} B_{t-1} - \rho\, \omega\, s_t R_t \qquad (1)$$

where B and R denote exploitable biomass and recruitment, and the s are annual survival rates. The growth parameters ρ and ω were externally estimated from a non-linear least squares fit to the NRC weight at age values, where $w_{i+1} = w_i + \rho\,(w_i - w_{i-1})$ and $\omega = w_{T-1}/w_T$, and T is the age of recruitment. Natural mortality rates, M, for each data set (Table 1) was obtained from M. Sigler's (Chapter 5, this volume) determination utilizing the Alverson and Carney (1975) approach. Knife-edged age of recruitment, T, was assumed to be 4 years of age for data sets 1-4, and 5 years of age for data set 5.

Data Utilization

The analyses were carried out for different cases, depending on whether fishery data, survey data, or both, were used to index relative biomass. In this paper, "case A" denotes fishery data only, "case B" denotes survey data only, and "case C" denotes the use of both data types.

The fishery index of exploitable biomass used was:

$$\mathrm{CPUE}_t = (\text{total yield in year } t)/(\text{effort in year } t), \tag{2}$$

and the survey index of exploitable biomass (relative population weight, RPW) was:

$$\mathrm{RPW}_t = \left(\sum n_{i,t}\ w_{i\ (i=1\text{ to }15)} / \sum n_{i,t}\ w_{i(i=1\text{ to }15)}\right) \cdot (\text{ survey index weight for year } t), \tag{3}$$

where $n_{i,t}$ is the survey number index for age i and year t. An index of recruitment biomass for year t was obtained from the survey data as

$$r_t = n_{T-1,t-1} \cdot w_{T-1}\ . \tag{4}$$

Parameters

Two to four parameters are estimated by the model, depending on the case. Parameter λ_f relates the fishery CPUE to absolute biomass and is estimated when fishery data are used:

$$B_{f,t} = \mathrm{CPUE}_t \cdot \lambda_f \cdot \exp(\varepsilon_{f,t})\ ; \tag{5}$$

parameter λ_s relates the survey RPW to absolute biomass and is estimated in cases where survey data are used:

$$B_{s,t} = \mathrm{RPW}_t \cdot \lambda_s \cdot \exp(\varepsilon_{s,t})\ ; \tag{6}$$

parameter λ_r relates the recruitment index to a recruitment biomass and is estimated in all cases as:

$$R_t = r_t \cdot \lambda_r\ . \tag{7}$$

Finally, parameter B_0 is the biomass before the beginning of the data series and is also estimated in all cases.

Fitting Procedure

When initial guesses are given for the four parameters above, setting $B_0 = B_{-1}$, and using the average of the R_t (t=1-30) for values of R_0, and R_1, the model in equation (1) can be used to compute a projected value for B_1. For case A (CPUE index only), an updated B^*_1 is computed as a weighted average of B_1 and $B_{f,1}$ given weighting factors for the model, Ω, and the fishery index, Ω_f:

$$B^*_t = (\Omega \cdot B_t + \Omega_f \cdot B_{f,t})/(\Omega + \Omega_f). \tag{8}$$

Similarly, for case B (survey index only), the updated B^*_1 is computed as a weighted average of B_1 and B_s, where Ω_s is the weight given to the survey index:

$$B^*_t = (\Omega \cdot B_t + \Omega_s \cdot B_{s,t})/(\Omega + \Omega_s). \tag{9}$$

For case C (using both survey and CPUE data), the updated B^*_1 would be similar:

$$B^*_t = (\Omega \cdot B_t + \Omega_s \cdot B_{s,t} + \Omega_f \cdot B_{f,t})/(\Omega + \Omega_s + \Omega_f)\ . \tag{10}$$

In this exercise, the weights used for Ω , Ω_s , and Ω_f were set to 2, 1, and 1 respectively. Values for B_o, B^*_1, R_1, and R_2 are then used in (1) to compute B_2. This procedure is repeated until B^*_{30} is computed, using equations [(8), (9), or (10)] and (1). Thus:

$$B_{t+1} = (1 + \rho)\, s_t\, B^*_t\ -\ \rho\, s_t\, s_{t-1}\, B^*_{t-1}\ -\ \rho\, \omega\, s_t\, R_t.$$

Parameter estimation is made assuming measurement errors as suggested by equations (5) and (6). For case A, the sum of squared deviations (SS) from the fishery index biomass estimate is computed as

$$SS_f\ =\ \Sigma\, (\ln(B_t) - \ln(B_{f,t}))^2, \tag{11}$$

and, for case B, the sum of squared deviations from the survey index biomass is given by

$$SS_s\ =\ \Sigma\, (\ln(B_t) - \ln(B_{s,t}))^2. \tag{12}$$

For case C, this application uses both (11) and (12), with equal weight. Microsoft Excel™ Solver is used to find the parameters that provide the least-squares fit.

Results and Discussion

Table 1 provides estimates of model parameters for each data set and case. Figures 1 to 5 show annual estimates of exploitable biomass, B^*, as well as the annual fishery or survey index biomass ($B_{f,t}$, and $B_{s,t}$), and annual recruitment, R_t (values from case C). Data set 3 had an additional parameter, a fishing power correction for the survey vessel used for years 16 to 30 (see Table 1). The same correction was assumed to apply to the survey index of exploitable biomass as well as the recruitment index.

Table 1. Parameter values assumed estimated for the various fits. See text for description of the symbols. FPC = fishing power correction estimated for years 16-30 in data set 3. n/a= not applicable.

Data set	Case	M	r	ω	λ_r	λ_s	λ_f	B_0	FPC
1		0.251	0.783	0.374					
	A				2021	n/a	20776	5967	n/a
	B				1210	720	n/a	6545	n/a
	C				1177	965	11543	5542	n/a
2		0.251	0.783	0.374					
	A				1804	n/a	36994	5649	n/a
	B				667	398	n/a	2476	n/a
	C				700	475	11180	2233	n/a

Table 1 (cont.)

Data set	Case	M	r	ω	λ_r	λ_s	λ_f	B_0	FPC
3		0.169	0.783	0.374					
	A				1472	n/a	74618	13609	1.248
	B				692	467	n/a	4295	1.315
	C				785	913	37403	8327	0.997
4		0.201	0.783	0.374					
	A				1161	n/a	25964	6167	n/a
	B				1033	858	n/a	10886	n/a
	C				837	943	15889	7335	n/a
5		0.191	0.783	0.671					
	A				2544	n/a	75240	7025	n/a
	B				725	575	n/a	1264	n/a
	C				1008	1109	24779	2309	n/a

All cases and sets converged to solutions. Case A always estimated the highest values of exploitable biomass, case B estimated the lowest, and results for case C generally fell in between, but often close to case B. The result that case A estimates higher biomass values is expected, given that, for fixed catch removals, fishery CPUEs in these data sets indicated lesser rates of decrease than did the survey indices of abundance. Case 3A estimated biomass values considerably higher than did cases B or C, due likely to the low rate of decrease indicated by the fishery CPUE (NOTE: the table and plotted values for 3A were not the least squares estimates, which would have dominated the plot scale. The sum of squares did not vary much (5%) over a two-fold increase of biomass, indicating lack of precision in the biomass estimate for case 3A).

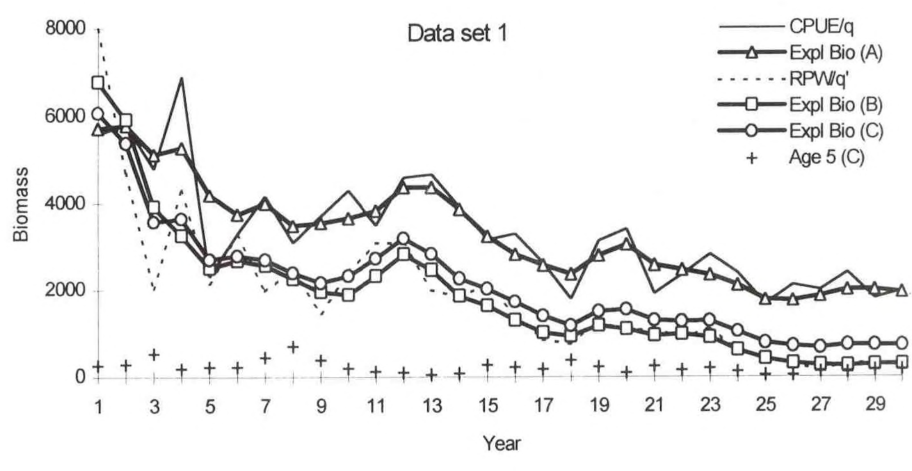

Figure 1. Annual estimates of exploitable biomass for data set 1 using fishery data (A), survey data (B), or both (C). Also shown are the fishery CPUE (solid line) and survey index (dashed line), raised to the absolute magnitude of biomass. "Age 5" corresponds to the associated recruitment estimates for case C.

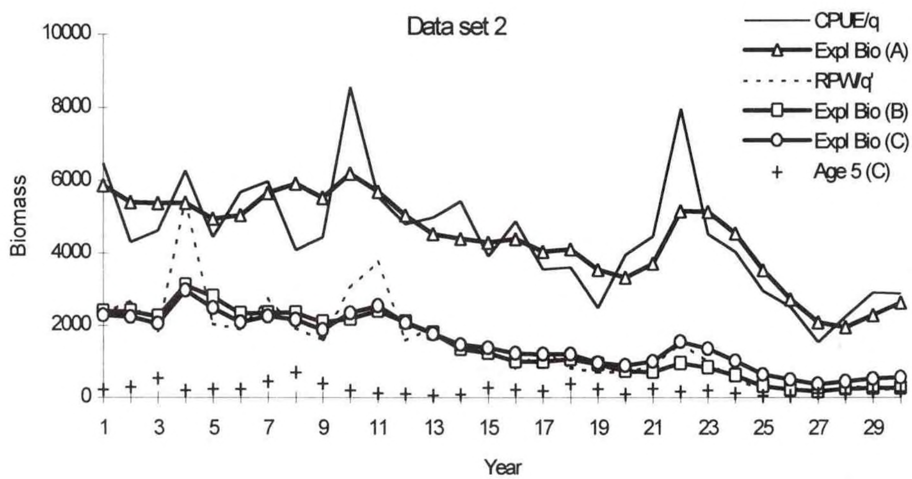

Figure 2. Annual estimates of exploitable biomass for data set 2. Lines and symbols are as in explained in the caption for Figure 1.

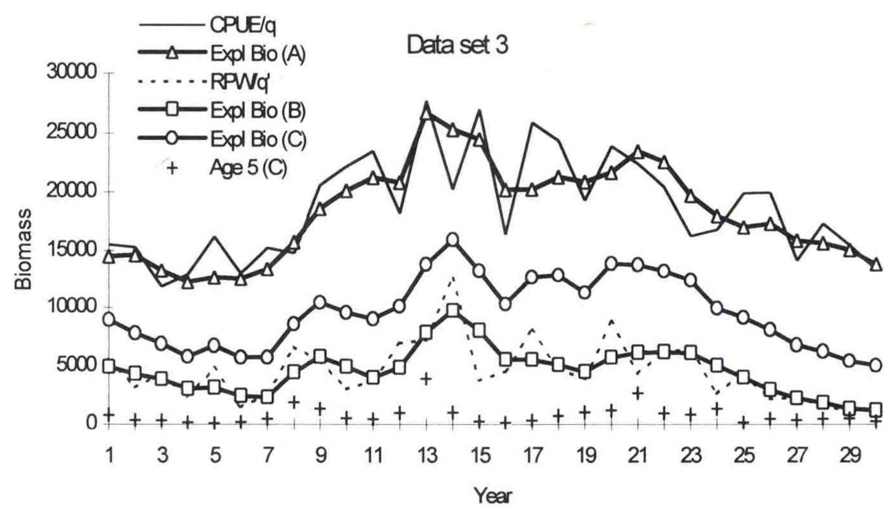

Figure 3. Annual estimates of exploitable biomass for data set 3. Lines and symbols are as in explained in the caption for Figure 1.

Case 1B, and to some extent cases 2B and 4B, estimated extremely low levels of exploitable biomass near the end of the time series, with biomass values approaching the reported catch in magnitude, leading to extremely high fishing rates. This result is due to the extreme relative decrease indicated by the survey index having to be explained by the catch and natural mortality. Fishing mortality rates as high as 2.3 per year were obtained which, if accurate, would indicate that the fishermen were extremely efficient or the fish were extremely vulnerable. More likely, there is some inconsistency between the various types of information used here. Perhaps the assumed value of M was too low. Generally, the survey would be assumed to give the most reliable index of abundance. However, it is possible that this simulated survey was not designed for this simulated stock, and only indexed it in marginal habitat. A marginal habitat may be deserted rapidly as preferred habitat becomes available, exaggerating the perceived rate of population decline. Assurance of a proper survey index that is proportional to abundance would lessen this uncertainty.

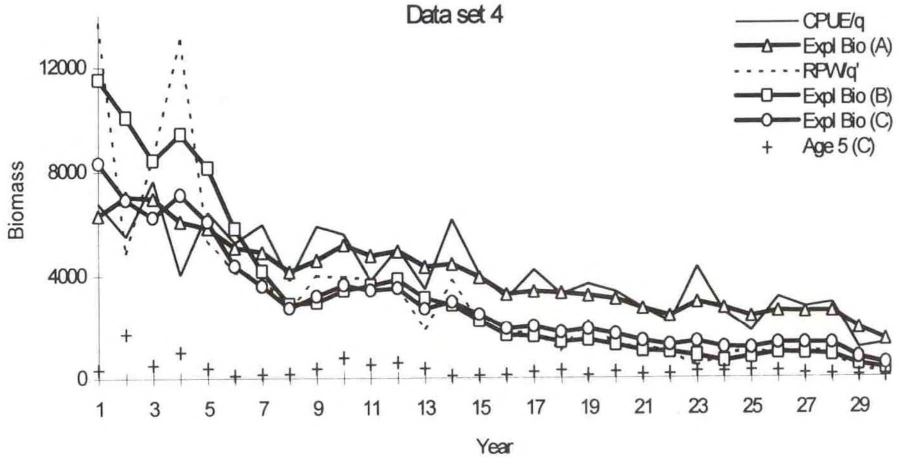

Figure 4. Annual estimates of exploitable biomass for data set 4. Lines and symbols are as in explained in the caption for Figure 1.

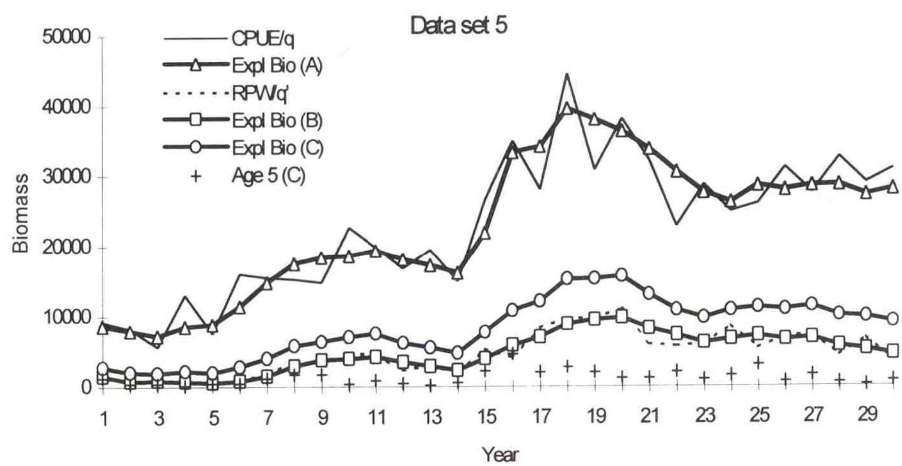

Figure 5. Annual estimates of exploitable biomass for data set 5. Lines and symbols are as in explained in the caption for Figure 1.

Concluding Remarks

Any comparison of the results between models and modelers in this exercise would need to take into account the differences in assumptions made. The degree of fluctuations in estimated biomass is influenced by arbitrary decisions, such as the weight given to the CPUE and survey index trends relative to other information. For example, the assumption that there was no error in the recruitment indices used in this analysis would force the model to respond to over- or under-estimates of relative recruitment. Apparent lags in trends and modes might be explained by the assumption of age at recruitment in the delay-difference model being different from that assumed in other models.

Because of the completeness and apparent consistency of the simulated data sets, this exercise was simple and straightforward. While a number of other analyses, alternative approaches or model elaboration might have been explored, the time devoted to this exercise was limited. Nor were further analyses necessary to demonstrate a most important point, that of the value of a reliable index of abundance. Whether one analysis or the other was able to reproduce the "true" biomass by guessing all the right assumptions made by the NRC simulations seems irrelevant, although it is obvious that age-structured models should be able to make the most of the data provided in this exercise. In real applied stock assessment situations, shortcomings in knowledge and data are usually more critical than the choice of model. Since we never know if we have modeled the population correctly when making quota recommendations, choosing harvest strategies or control rules that deal with the uncertainty and avoid overfishing may be more important.

Additional Analyses

The NRC panel requested additional computations to (a) obtain new estimates using the correct average value of M in the simulated data, and (b) compute total allowable catches (TACs) based on a strategy to harvest at a rate that would maintain equilibrium spawning biomass per recruit at 40% of its unfished level ($F_{40\%}$). The requested TAC computations are given for cases A and B in Table 2. Additionally, case B using data set 5 was fitted again using the correct value of M. The resulting TAC estimates are also given in Table 2. The relevance of any comparison between models and modelers in this additional exercise is not clear.

Table 2. Estimates of final year projected TACs based on $F_{40\%}$. $U_{40\%}$ is the exploitation rate corresponding to $F_{40\%}$. TACs result from applying $U_{40\%}$ to the projected biomass for year 31 (B_{31}) or to the updated biomass estimate for year 30 (B^*_{30}).

	Data set					
Parameter	**1**	**2**	**3**	**4**	**5**	**5[1]**
M	0.251	0.251	0.169	0.201	0.191	0.225
Recruitment age[2]	4	4	4	4	5	5
ρ^2	0.783	0.783	0.783	0.783	0.783	0.783
ω^2	0.374	0.374	0.374	0.374	0.671	0.671
Maturity age (50%)	7	8	9	8	7	7
Maturity b parameter	1.65	1.65	1.65	1.65	1.65	1.65
[3]$F_{40\%}$	0.148	0.128	0.094	0.115	0.152	0.170

Table 2 (cont.)

Parameter	1	2	Data set 3	4	5	5[1]
$U_{40\%}$	0.122	0.107	0.083	0.099	0.129	0.140
Case A (fishery data)						
B_{31}	1688	2479	12469	1184	26497	n/a
$B_{31} \cdot U_{40\%}$	206	264	1031	117	3409	n/a
B^*_{30}	1946	2639	13877	1428	28092	n/a
[4]$B^*_{30} \cdot U_{40\%}$	237	281	1147	141	3615	n/a
Case B (survey data)						
B_{31}	172	153	910	289	3739	2822
$B_{31} \cdot U_{40\%}$	21	16	75	29	481	396
B^*_{30}	294	269	1187	328	4609	3911
[4]$B^*_{30} \cdot U_{40\%}$	36	29	98	32	593	549

[1] For case 5B, the estimate of $F_{40\%}$ and the model fit was repeated using $M = 0.225$, the "true" average M in the simulated data.

[2] Knife-edge recruitment is as assumed in the initial report. A Brody growth equation which approximates the given growth curve was used to be compatible with the growth assumed in the delay equation.

[3] $F_{40\%}$ was estimated for each data set based on the values of natural mortality rate as used in the initial report, not the true M underlying the simulated data.

[4] Because the projected biomass for year 31 in some data sets is highly sensitive to the particular recruitment predictor used, a TAC value is also provided by applying $F_{40\%}$ to the more stable updated biomass B^*_{30}.

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CHAPTER 3.

Kalman Filtering of Biomass and Recruitment Indices from NRC Data Sets by Means of the Deriso Equation

Jerome J. Pella

National Marine Fisheries Service, Alaska Fisheries Science Center, 11305 Glacier Highway, Juneau, Alaska 99801. Jerry.Pella@noaa.gov

Introduction

The goal of this study was to use the Deriso (1980) equation which describes fish stock biomass dynamics to infer the histories of five simulated populations from their survey and fishery data. The advantage of the Deriso equation to age-structured modeling is its freedom from age composition information of catches and exploited stock. Therefore, most age composition information of fishery and survey catches included with the NRC data sets was not used under the pretense that they were either unavailable or very untrustworthy. However, the Deriso equation explicitly identifies recruitments as well as biomass of the exploited portion of the stock, and annual measures or indices of relative magnitudes of both variables were assumed available. The rationale justifying a recruitment index was that some success in ageing of the youngest individuals commonly can be had either from examination of length-frequency distributions or features on hard parts even though older individuals may be very difficult to age on a routine basis.

Magnitudes of apparent changes in relative stock size induced by the simulated catches and recruitments potentially provided insight into the stock size and dynamics underlying the simulations. However, apparent changes in stock biomass indicated by the biomass indices and recruitment indices were probably produced both by actual changes as well as random measurement errors. To aid in inferring stock biomass dynamics, the two causes of apparent changes in biomass and recruitment were explicitly included in the statistical modeling of the observations.

The assessment of stock biomass and recruitment dynamics from the simulated time series of catches and indices comprised two related problems: (1) estimation of parameters of the biomass dynamics and recruitment models (process models) and of the corresponding index models (measurement models) and (2) estimation of absolute (instead of relative) recruitment and biomass time series conditioned on the estimated parameter values. A Kalman filter was the statistical tool used for both estimation problems. The notation and detailed description of the general filter can be found in Harvey (1990) or Pella (1993).

Methods

Time series of simulated catches and indices of relative stock biomass and recruitment were treated as if obtained under circumstances to be described even though the actual circumstances underlying the simulations were known to differ substantially in many regards. The assumptions used for mathematical convenience in the analysis were as follows: (1) biomass was indexed annually after recruitment was complete and before fishing began; (2) annual catch was removed from the stock at a point in time; (3) recruitment to the fishery was knife-edge; (4) catch information was assumed to be accurate, but the information on relative stock biomass and recruitment contained random measurement errors; and (5) stock biomass dynamics was described by Deriso's equation and recruitments were a random walk.

Schnute's (1985) form of Deriso's equation was used as the basis of the Kalman filter. The equation used was

$$B_t = s_{t-1}B_{t-1} + \rho s_{t-1}B_{t-1} - \rho s_{t-1}s_{t-2}B_{t-2} - s_{t-1}\rho w_{k-1}R_{t-1} + w_k R_t$$
$$= g_t(B_{t-2}, B_{t-1}, R_{t-1}) + w_k R_t \ , \qquad (1)$$

where

$$s_t = s_m(1-h_t),\ h_t = C_t/B_t,\ \text{and}\ \ s_m = \exp(-M) \qquad t=3,\ldots,T_{\max} \qquad (2)$$

and,

B_t is biomass of the stock including new recruits at the beginning of year t,
R_t is the number of new recruits added to the stock at the beginning of year t,
M is the annual instantaneous natural mortality rate,
s_t is the annual total survival rate from natural mortality and fishing during year t,
h_t is the harvest rate applied after recruitment and biomass indexing are complete,
C_t is the catch in year t, and
w_k is the weight of k year-old individual fish (at which age all become fully recruited to the fishery and before which age all are unavailable to the fishery).

The function $g_t(B_{t-2}, B_{t-1}, R_{t-1})$ is included for later reference and its definition is evident from equation (1). In order that $[B_3, B_4, \ldots B_{Tmax}]$ could be computed from (1) and (2), values had to be specified for model parameters M, w_{k-1}, w_k, ρ; for initial biomass, recruitment, and harvest rates or catches, $[B_1, B_2, R_2$; and h_1, h_2, or $C_1, C_2]$; for subsequent annual recruitments, $[R_3, R_4, \ldots, R_{Tmax}]$; and for annual harvest rates, $[h_3, h_4, \ldots, h_{Tmax-1}]$ or corresponding catches, $[C_3, C_4, \ldots, C_{Tmax-1}]$. The Deriso equation at (1) is deterministic and later a random additive error is appended to accommodate biomass variation about the model projections. The error in projected B_t is assumed to be normal with mean of zero and standard deviation proportional to B_{t-1}. The constant of proportionality for biomass projection error, σ_B, is called the Deriso model coefficient of variation.

Equation (1) was used to infer underlying biomass and recruitment time series from the indices and catches by means of the Kalman filter. The analysis depended on the assumption that the expected values of the biomass (y_{1t}) and recruitment indices (y_{2t}), $\{y_t=(y_{1t}, y_{2t})', t=1,2,\ldots,T_{max}\}$, were proportional to the unobserved biomass and recruitment series and varied from this relationship due to additive sampling error. Specifically, the measurement equation providing the assumed relationship between the indices and their parameters was

$$\begin{aligned} y_{1t} &= \lambda_B B_t + \epsilon_{1t} \\ y_{2t} &= \lambda_R R_{t+1} + \epsilon_{2t} \ , \end{aligned} \tag{3}$$

where λ_B and λ_R were constants (they are called the biomass and recruitment catchability coefficients and their inverses are the biomass and recruitment index multipliers), and ϵ_{1t} and ϵ_{2t} were measurement errors.

The measurement errors, $[\epsilon_t = (\epsilon_{1t}, \epsilon_{2t})', t = 1, \ldots, T_{max}]$, were assumed to be bivariate normally distributed, uncorrelated in time, and their covariance matrices at given time were assumed to equal

$$\boldsymbol{H}_t = \begin{bmatrix} \sigma^2_{\epsilon(1t)} & \gamma \sigma_{\epsilon(1t)} \sigma_{\epsilon(2t)} \\ \gamma \sigma_{\epsilon(1t)} \sigma_{\epsilon(2t)} & \sigma^2_{\epsilon(2t)} \end{bmatrix}, \tag{4}$$

with standard errors assumed to be directly proportional to expected values of the indices, y_t, i.e.,

$$\begin{aligned} \sigma_{\epsilon(1t)} &= \sigma_M \lambda_B B_t \\ \sigma_{\epsilon(2t)} &= \sigma_M \lambda_R R_t \ . \end{aligned} \tag{5}$$

The parameter, σ_M, will be called the coefficient of variation for measurements. The covariance parameter, γ, was included to accommodate the common sample origins (fishery or survey catches) of the two indices.

To implement the Kalman filter, a model for the recruitments was required. The probability model chosen was a random walk of normal independent errors with standard error proportional to recruitment such that

$$R_t = R_{t-1} + \eta_t, \tag{6}$$

where R_t is the number of recruits in year t, and η_t is normally distributed with mean of zero and standard error of $\sigma_{\eta(t)} = \sigma_R R_{t-1}$. The parameter, σ_R, will be called the recruitment walk coefficient of variation.

An approximate linear state space form (Harvey 1990, sec. 3.1) of Deriso's model at (1)and (2) and recruitment process (6) could be written as the state transition equation,

$$\alpha_t=\begin{pmatrix} B_{t-1}\\ B_t\\ R_t\\ R_{t+1}\end{pmatrix} \simeq \begin{bmatrix} 0 & 1 & 0 & 0\\ \dfrac{\partial g_t}{\partial B_{t-2}} & \dfrac{\partial g_t}{\partial B_{t-1}} & \dfrac{\partial g_t}{\partial R_{t-1}} & w_k\\ 0 & 0 & 0 & 1\\ 0 & 0 & 0 & 1\end{bmatrix}\begin{pmatrix} B_{t-2}\\ B_{t-1}\\ R_{t-1}\\ R_t\end{pmatrix}+$$

$$\begin{pmatrix} 0\\ g_t(\hat{b}_{t-2},\hat{b}_{t-1},\hat{r}_{t-1})-\dfrac{\partial g_t}{\partial B_{t-2}}\hat{b}_{t-2}-\dfrac{\partial g_t}{\partial B_{t-1}}\hat{b}_{t-1}-\dfrac{\partial g_t}{\partial R_{t-1}}\hat{r}_{t-1}\\ 0\\ 0\end{pmatrix}+$$

$$\begin{bmatrix} 0 & 0 & 0 & 0\\ 0 & \sigma_B B_{t-1} & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & \sigma_R R_t\end{bmatrix}\begin{pmatrix} 0\\ \eta_{2t}\\ 0\\ \eta_{4t}\end{pmatrix}$$

$$=\hat{\boldsymbol{T}}_t\alpha_{t-1}+\hat{\boldsymbol{h}}_t+\boldsymbol{Q}\eta_t\ , \tag{7}$$

where $\hat{b}_{t-2}$, $\hat{b}_{t-1}$, and $\hat{r}_{t-1}$ are the conditional means of B_{t-2}, B_{t-1}, and R_{t-1} as computed by an approximate Kalman filter to be described, the derivatives of the function g_t are evaluated at these conditional means, η_{2t} and $\eta_{4,t}$ are standard normal random variables with means of zero and unit variances, and $\hat{\boldsymbol{T}}_t$, α_t, $\hat{\boldsymbol{h}}_t$, $\boldsymbol{Q}_t$, and η_t have definitions evident from details provided in (7).

In developing (7), the nonlinear Deriso equation was linearly approximated around the computed conditional means of B_{t-2}, B_{t-1}, and R_{t-1}, using a first order Taylor's series (Harvey 1990, sec. 3.7.2).

The biomass and recruitment indices are related to the state vector, α_t, through the measurement equation,

$$y_t=\boldsymbol{Z}\alpha_t+\epsilon_t\ ,\text{where}\ \ \boldsymbol{Z}=\begin{pmatrix} 0 & \lambda_B & 0 & 0\\ 0 & 0 & 0 & \lambda_R\end{pmatrix}. \tag{8}$$

A Kalman filter (Harvey 1990, sec. 3.7.2) for the linear state space model at (7) consisted of forecast and update equations for the state vector, $\alpha_t'=(B_{t-1},B_t,R_t,R_{t+1})$, at any year t. A forecast of α_t, $\mathbf{a}_{t|t-1}$, was made before the survey index at year t is available; the forecast depended on the biomass and recruitment indices from preceding years, $\boldsymbol{y}_1$, $\boldsymbol{y}_2,\ldots\boldsymbol{y}_{t-1}$, and knowledge of parameters for the Deriso, recruitment, and index equations, *viz.*, M, w_{k-1}, w_k, ρ, σ_B, σ_M, σ_R, γ, λ_B, and λ_R. (Although many of these parameters were unknown, the Kalman filter provided a means by which to estimate the parameters as described later.) After the biomass and future recruitment were indexed in year t, the forecast was updated to $\mathbf{a}_t$. The forecasts and updates were the computed conditional means of the state vector $\boldsymbol{\alpha}_t$ given the available indices and model parameters, and their corresponding covariance matrices are denoted as $\boldsymbol{P}_{t|t-1}$ and $\boldsymbol{P}_t$, respectively.

To begin the Kalman filtering process, the updated state mean and covariance matrix at year 2 was estimated using the first two years' biomass and recruitment indices, $\boldsymbol{y}_1=(y_{11},y_{21})'$ and $\boldsymbol{y}_2=(y_{12},y_{22})'$, as

$$\boldsymbol{a}_2=\boldsymbol{\alpha}_1=\begin{pmatrix}\hat{b}_1\\ \hat{b}_2\\ \hat{r}_1\\ \hat{r}_2\end{pmatrix}=\begin{pmatrix}\dfrac{y_{11}}{\lambda_B}\\ \dfrac{y_{12}}{\lambda_B}\\ \dfrac{y_{21}}{\lambda_R}\\ \dfrac{y_{22}}{\lambda_R}\end{pmatrix} \tag{9}$$

with covariance matrix given by

$$\boldsymbol{P}_2=\begin{bmatrix}\left(\dfrac{\sigma_M y_{11}}{\lambda_B}\right)^2 & 0 & \gamma\sigma_M^2\left(\dfrac{y_{11}}{\lambda_B}\right)\left(\dfrac{y_{21}}{\lambda_R}\right) & 0\\ 0 & \left(\dfrac{\sigma_M y_{12}}{\lambda_B}\right)^2 & 0 & \gamma\sigma_M^2\left(\dfrac{y_{12}}{\lambda_B}\right)\left(\dfrac{y_{22}}{\lambda_R}\right)\\ - & 0 & \left(\dfrac{\sigma_M y_{21}}{\lambda_R}\right)^2 & 0\\ 0 & - & 0 & \left(\dfrac{\sigma_M y_{22}}{\lambda_R}\right)^2\end{bmatrix}. \tag{10}$$

This specification was equivalent to using a diffuse prior to describe large uncertainty in the initial state (Harvey 1990, sec. 3.3.4).

After the mean and covariance for the initial state vector were available, forecasts and updates of the state vector in subsequent years were computed serially. Given $\boldsymbol{a}_{t-1}=(a_{1,t-1}\ a_{2,t-1},a_{3,t-1},a_{4,t-1})'$, the state forecast equation was

$$\boldsymbol{a}_{t|t-1}=\begin{pmatrix} a_{2,t-1} \\ g_t(a_{1,t-1},a_{2,t-1},a_{3,t-1})+w_k a_{4,t-1} \\ a_{4,t-1} \\ a_{4,t-1} \end{pmatrix}= \tag{11}$$

$$\begin{pmatrix} \hat{b}_{t-1} \\ g_t(\hat{b}_{t-2},\hat{b}_{t-1},\hat{r}_{t-1})+w_k \hat{r}_t \\ \hat{r}_t \\ \hat{r}_t \end{pmatrix}, \tag{12}$$

with covariance matrix

$$\boldsymbol{P}_{t|t-1}=\hat{\boldsymbol{T}}_t\boldsymbol{P}_{t-1}\hat{\boldsymbol{T}}_t'+\boldsymbol{QQ}' \ . \tag{13}$$

The state updating equation was

$$\boldsymbol{a}_t=\boldsymbol{a}_{t|t-1}+\boldsymbol{P}_{t|t-1}\boldsymbol{Z}'\boldsymbol{F}_t^{-1}(y_t-\boldsymbol{Za}_{t|t-1}) \ , \tag{14}$$

where

$$\boldsymbol{F}_t=\boldsymbol{ZP}_{t|t-1}\boldsymbol{Z}'+\boldsymbol{H}_t \ , \tag{15}$$

was the variance of the forecast error vector, $\nu_t=\boldsymbol{y}_t-\boldsymbol{Za}_{t|t-1}$, in year t.

The covariance matrix of the state update, $\boldsymbol{a}_{t-1}$, was

$$\boldsymbol{P}_t=\boldsymbol{P}_{t|t-1}-\boldsymbol{P}_{t|t-1}z'\boldsymbol{F}_t^{-1}z\boldsymbol{P}_{t|t-1} \ . \tag{16}$$

Parameter values of models were estimated through the support function, or logarithm of the likelihood function. The support function viewed the survey index and catch information as fixed and the vector of unknown parameters, say ψ = $(\lambda_B,\lambda_R,\sigma_B,\sigma_M,\sigma_R,\gamma)'$, as variable. For any choice of values for the components of ψ, the value of the support function was (Harvey, 1990; sec. 3.4)

$$logL(\psi) = -T_{\max}\log\,(2\pi) - \frac{1}{2}\sum_{t=3}^{T_{\max}} \log|\boldsymbol{F}_t| - \frac{1}{2}\sum_{t=3}^{T_{\max}} \nu_t'\boldsymbol{F}_t^{-1}\nu_t\;, \tag{17}$$

where $\mathbf{F}_t$ and ν_t depended on ψ through the forecast and update equations (9)-(16). [The summations begin at t=3 to emphasize that the initial conditions, $\boldsymbol{a}_2$, at (9) and (10), resulted in residuals of zero at t=1 and t=2.] That value of ψ for which the support function was maximized was the unconditional maximum likelihood estimate (MLE) of ψ, which is commonly used to specify unknown parameter values of the Kalman filter. Another estimate for ψ, called the bound estimate (BE), was computed in two steps: first, a lower 90% confidence bound for the parameter, λ_B, was constructed at the MLE using the likelihood ratio statistic; and, second, estimation of the remaining components of ψ were conditioned on this lower bound for λ_B.

The Kalman filter updates of the state vector conditioned on the BE of ψ provided estimates of recruitments and stock biomass (the MLE of ψ was not used for this purpose because of its poor definition in many of the data sets) . The estimated magnitudes of biomass and recruitment resulting from use of the BE of ψ should be biased low. These updates used only the biomass and recruitment indices available up to the year of an update. Fixed interval smoothing (Harvey 1990, section 3.6.2) to include indices for all years in the updates preceding the final year was not performed.

The proposed measurement model posed special problems for employing the Kalman filter because the measurement equation standard deviations, [$\sigma_{\epsilon(1t)}=\sigma_M\lambda_B B_t$, $\sigma_{\epsilon(2t)}=\sigma_M\lambda_R R_t$, t=1,2,...,T_{max}], depended on unknown B_t and R_t of the state vector, $\alpha_t'=(B_{t-1},B_t,R_t,R_{t+1})$. These standard deviations would be best computed using updated estimates of B_t and R_t. However, these standard deviations were needed in $\boldsymbol{H}_t$ at (15) for use in the updating at (14), i.e., they were needed before the updated estimates of B_t and R_t become available. An expedient described by Smith and West (1983) was adopted: the one-step ahead forecasts, $a_{2,t|t-1}$ and $a_{4,t|t-1}$, of B_t and R_t, respectively, at (11) were used in place of $a_{2,t}$ and $a_{4,t}$ to compute $\boldsymbol{H}_t$ as

$$\begin{aligned}
\sigma_{\epsilon(1t)} &= \sigma_M\lambda_B a_{2,t|t-1} = \sigma_M\lambda_B[g_t(\hat{b}_{t-2},\hat{b}_{t-1},\hat{r}_{t-1}) + w_k\hat{r}_t)] \\
\sigma_{\epsilon(2t)} &= \sigma_M\lambda_R a_{4,t|t-1} = \sigma_M\lambda_R\hat{r}_t \\
& t=3,4,\ldots T_{\max}\;.
\end{aligned} \tag{18}$$

Applications

Because of the predominant influence of λ_B among parameters in estimating magnitude of a stock, the search routine for parameter estimation was written to maximize the support function with respect to λ_R, σ_B, σ_M, σ_R, and γ, for given λ_B. Therefore, detailed examination of the support function (as related to λ_B) was easy. Choices of λ_B were made to describe the support function and determine its maximum and the associated MLE for all six parameters as well as to find the BE. A FORTRAN program using the optimization subroutine MIN (Pella and Tomlinson 1969) performed the calculations.

Two analyses were performed for each simulated fishery using different data sources —fishery and survey— to index biomass of the exploited stock and recruitment numbers. Both analyses used total biomass of fishery landings (metric tons) for ages 1-15 yr to represent fishery removals, and no attempt to assess discrepancies between landings and actual removals was attempted. The biomass index of the exploited stock was computed as (1) the catch rate (tons per boat-day) of the fishery for all ages 1-15 yr or (2) the survey catch of the same ages. Recruitment was assumed complete by 4 yr, i.e., $k=4$ in Equation (1), for simulations 1 through 4, and by 5 yr for simulation 5; corresponding prerecruit ages were 3 yr and 4 yr, respectively. The recruitment index was computed as either the catch rate (numbers per boat-day) of prerecruit-age fish in the fishery, or as the catch of prerecruit-age fish (numbers) in the survey.

Actual growth in weight used in the simulations was given by $w_a = 5000(1-\exp(-0.3a))^3$, where w_a was the true mean weight (g) for individuals of age a. However, to accommodate the Deriso (1980) equation, this growth was approximated by the linear function

$$\hat{w}_a = \alpha + \rho \hat{w}_{a-1} ,$$

with the first age equal to the prerecruit age, k-1. Parameter values of $\hat{w}_{k-1}$, α, and ρ that minimized the sum of squares,

$$\sum_{a=k-1}^{15} (w_a - \hat{w}_a)^2 ,$$

were determined by a FORTRAN program using the MIN subroutine of Pella and Tomlinson (1969).

The instantaneous natural mortality rate, M, was assumed known and equal to the mean value of the simulations, 0.225 yr^{-1}. The feasibility of estimating this parameter by the Kalman filter was examined for a few of the data sets.

Results

Growth of fish

The parameter coefficients for individual fish growth produced fitted weights with generally small bias (Tables 1 and 2). Maximum discrepancy of fitted weights was about 8% of the actual weights; but discrepancies for most ages were 1% or less of actual weights. Nonrandom errors were introduced into the Kalman filter assessments from this growth approximation, but these discrepancies were probably minor compared to those from other causes.

Table 1. Parameters of the linear growth function, $\hat{w}_a = \alpha + \rho\hat{w}_{a-1}$, used for analyzing data, where k is the age of recruitment.

Data set	k	$\hat{w}_{k-1}$	α	ρ
1-4	4	961	985	0.812
5	5	1675	1041	0.798

Table 2. Actual and fitted weights (g) and corresponding errors (magnitude and percent of actual weight) for ages used in the Deriso equation, by data set.

		Data sets 1-4		Data set 5	
Age	Actual weight	Fitted weight	Error	Fitted weight	Error
3	1045	961	88 (8.4%)	-	-
4	1706	1766	-59 (3.5%)	1675	31 (1.8%)
5	2344	2419	-74 (3.2%)	2379	-35 (1.5%)
6	2908	2949	-41 (1.4%)	2941	-33 (1.1%)
7	3379	3380	-1 (~0%)	3389	-10 (0.3%)
8	3759	3729	30 (0.8%)	3747	12 (0.3%)
9	4058	4013	45 (1.1%)	4033	26 (0.6%)
10	4290	4244	46 (1.1%)	4261	29 (0.7%)
11	4467	4431	36 (0.8%)	4443	24 (0.5%)
12	4601	4583	19 (0.4%)	4588	13 (0.3%)
13	4702	4706	-4 (0.1%)	4704	-2 (~0%)
14	4778	4806	-28 (0.6%)	4797	-19 (0.4%)
15	4835	4888	-52 (1.1%)	4871	-36 (0.7%)

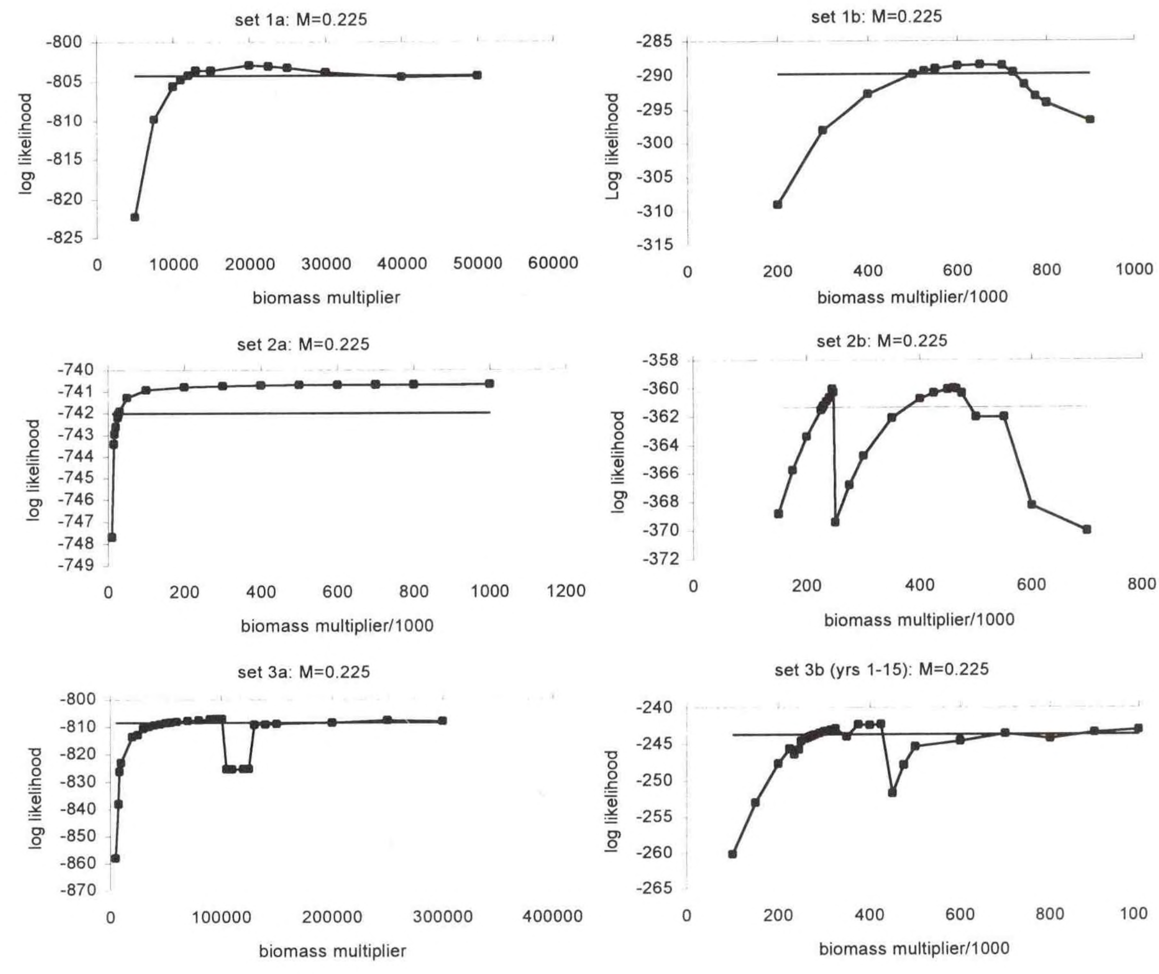
Support functions

Graphs of maxima of the support functions for specified values of the biomass multiplier invariably increased sharply with increase of biomass multiplier at its lower values (Figures 1-11). Thereafter, some flattened with poorly-defined maxima (Figures 1, 3, and 11), became erratic with multiple peaks (Figures 4, 5, and 6), and others had fairly well-defined peaks (Figures 2, 7, 8, 9, and 10). Cause of the erratic graphs has not been examined throughly, but, at the discontinuities, search by the routine MIN was probably incomplete.

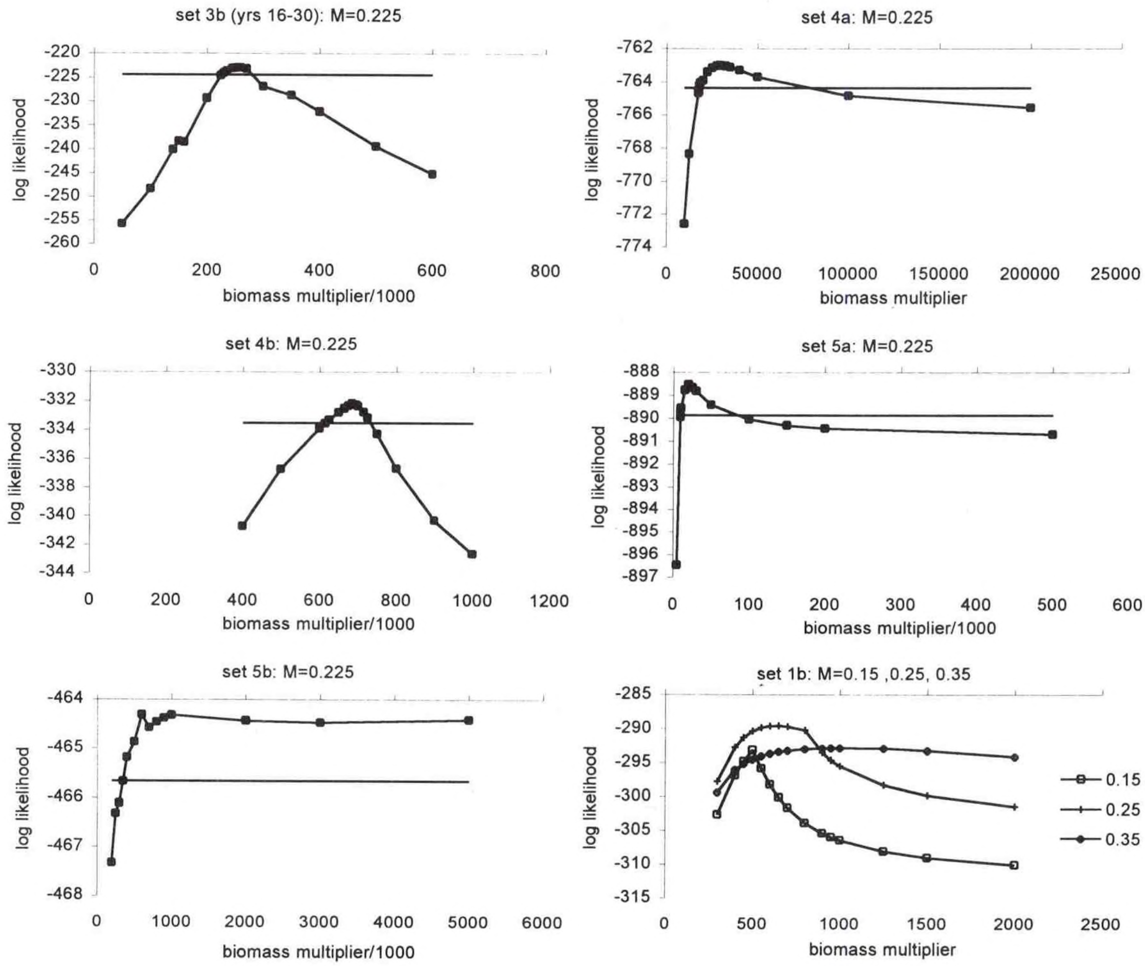
The support functions provided a graphic quantitative measure of the uncertainty in the biomass multiplier. Because the choice of an appropriate biomass multiplier was often so poorly defined at the maximum of the support function, the lower bound of a 90% confidence interval for the multiplier, an estimate with higher precision but some bias, was chosen to replace it. (In Figures 1-11, this estimate equals the smallest value of the biomass multiplier at an intersection of the horizontal reference line and the support function.) Estimates of parameter values at the maximum (MLE) and at the lower bound

(BE) (Tables 3 and 4) generally show that parameters other than the biomass and recruitment multipliers were little changed. When the support function provided good definition for the biomass multiplier, the estimate at the maximum of the support function and that of the 90% bound did not differ greatly.

The survey data were better described (σ_B was smaller) by the Deriso equation than were the fishery data. General level of variability assigned biomass and recruitment indices (σ_M) from the two sources did not differ a lot. Recruitment variation (σ_R) appeared generally greater from fishery than survey data. Estimated coefficients of variation from survey data had the following ranges among data sets: for discrepancies from the Deriso equation, 0%-6%; for measurement errors of biomass and recruitment indices, 25%-46%; and for the recruitment walk, 13%-144% (Table 3). Corresponding ranges for fishery data were 1%-21%, 17%-46%, and 69%-363% (Table 4).



Figures 1 to 6 (left to right, top to bottom): Support functions and 90% reference lines of bound estimates for biomass multipliers with $M = 0.225$ by data set (a=fishery, b=survey).



Figures 7 to 12 (left to right, top to bottom): Support functions and 90% reference lines of bound estimates for biomass multipliers with $M = 0.225$ (figs. 7-11) and with $M = 0.15$, 0.25 or 0.35 (fig. 12) by data set (a=fishery, b=survey).

Table 3. Summary of parameter estimates [maximum likelihood (MLE) and bound (BE)] from survey data sets using a Kalman filter with biomass of the exploited stock modeled by the Deriso equation and recruitment numbers modeled by a random walk.

		Multipliers[1]		Coefficient of variation (%)			Correlation
Data set	Estimator	Biomass (λ_B x 10^{-3})	Recruits (λ_R x 10^{-3})	Deriso model (σ_B X 100)	Index (σ_M X 100)	Recruit walk (σ_R X 100)	of index errors (γ X 100)
1b	MLE	675	685	0	30	46	8
	BE	500	639	0	30	43	9

Table 3 (cont.)

Data set	Estimator	Multipliers[1] Biomass (λ_B x 10^{-3})	Recruits (λ_R x 10^{-3})	Coefficient of variation (%) Deriso model (σ_B X 100)	Index (σ_M X 100)	Recruit walk (σ_R X 100)	Correlation of index errors (γ X 100)
2b	MLE[2]	245	391	0	42	13	4
	MLE[3]	460	460	0	36	69	14
	BE	228	387	0	42	13	4
3b[4]	MLE	375	616	0	40	141	20
t=1-15	BE	290	519	0	46	144	23
3b[5]	MLE	245	245	0	30	59	15
t=16-30	BE	225	225	0	30	58	15
4b	MLE	685	685	0	33	49	15
	BE	615	660	0	34	49	15
5b	MLE	600	730	6	28	80	14
	BE	350	490	5	25	79	13

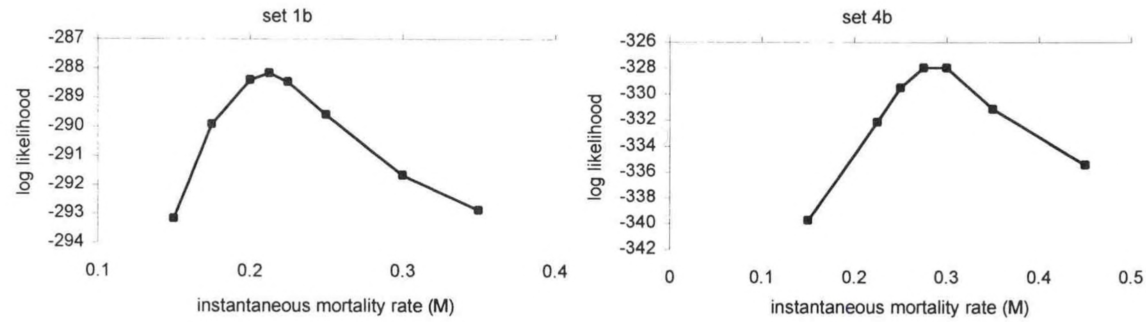
[1] Biomass index was survey catch (metric tons) of all ages, and recruitment index was survey catch (numbers) of 3 yr (sets 1b-4b) or 4 yr (set 5b) fish.
[2] MLE at first apparent local maximum;
[3] MLE at second apparent local maximum;
[4] Estimates from data of yr 1-15;
[5] Estimates from data of yr 16-30;

Table 4. Summary of parameter estimates [maximum likelihood (MLE) and bound (BE)] from fishery data sets using a Kalman filter with biomass of the exploited stock modeled by the Deriso equation and recruitment numbers modeled by a random walk.

Data set	Estimator	Multipliers[1] Biomass (λ_B x 10^{-3})	Recruits (λ_R x 10^{-3})	Coefficient of variation (%) Deriso model (σ_B X 100)	Index (σ_M X 100)	Recruit walk (σ_R X 100)	Correlation of index errors (γ X 100)
1a	MLE	18.8	18.8	12	21	148	12
	BE	12	12	14	25	153	15
2a	MLE	>10,000	>10,000	18	22	101	12
	BE	28	29.7	21	25	103	14
3a	MLE[2]	100	109	8	17	134	8
	MLE[3]	105	139	1	46	148	23
	BE	53.5	63.2	9	17	134	9
4a	MLE	29	29	12	25	69	14
	BE	17.8	17.8	14	26	73	14
5a	MLE	17.5	17.5	14	24	363	12
	BE	9.4	9.4	17	23	361	13

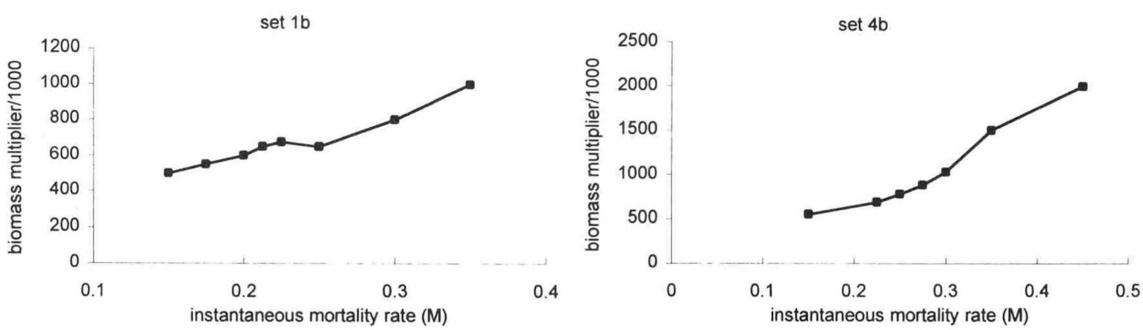
[1] Biomass index was fishery catch (metric tons) per boat-day of all ages, and recruitment index was fishery catch (numbers) per boat-day of 3 yr (sets 1a-4a) or 4 yr (set 5a) fish.
[2] At the apparent maximum of the support function;
[3] At the apparent local minimum just after the apparent maximum of the support function;

An attempt to estimate the natural mortality rate was undertaken using survey data of sets 1 and 4 and fishery data of set 4. In part, choice of these data sets was based on the apparent continuity of their support functions, indicating the search for optimizing values was fairly complete. The analysis showed the mortality parameter, M, could reasonably be estimated for survey data of set 1. Support functions were determined at selected values of M between 0.15 and 0.35 yr^{-1} (Figure 12 shows results for three choices) and the maxima of these functions showed clearly that the unconditional maximum likelihood estimate for M was between 0.200 and 0.225 yr^{-1} (Figure 13). However, the same analysis for survey data of set 4 showed the estimate of M to be in greater error, apparently between 0.275 and 0.300 yr^{-1} (Figure 14). The attempt using fishery data of set 4 was abandoned because of difficulty in finding maxima for support functions for several choices of M.



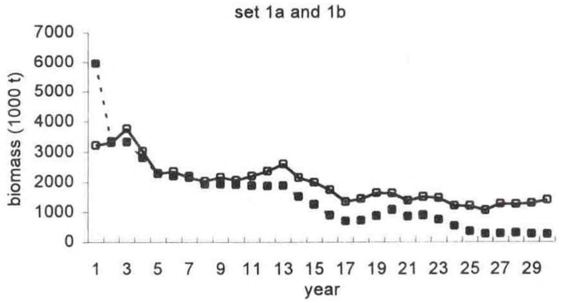
Figures 13 and 14 (left to right): Support functions for M using survey data sets 1b and 4b.

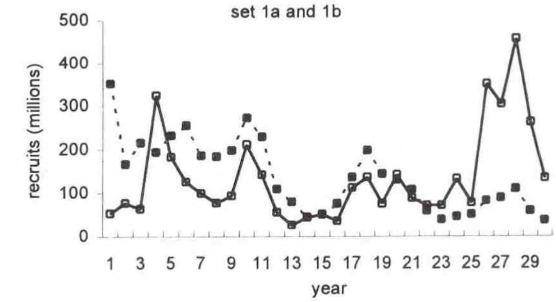
Knowledge of the natural mortality rate was critical to estimation of stock biomass in view of its effect on the estimate of the biomass multiplier. The MLE estimates of the biomass multiplier varied in a positive relation to the values of M examined (Figures 15 and 16).

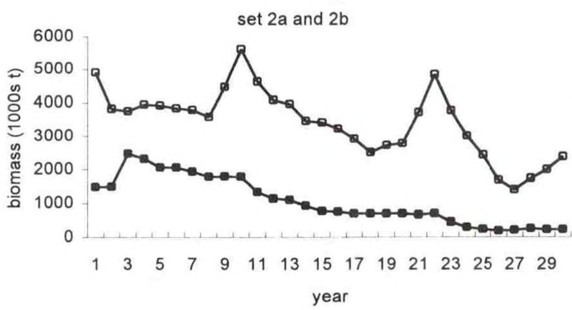


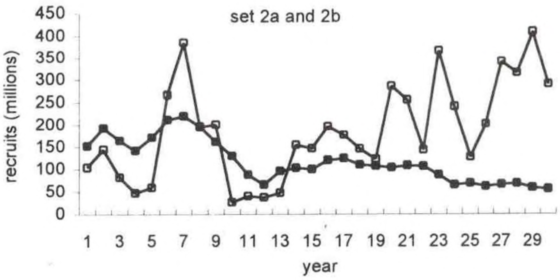
Figures 15 and 16 (left to right): Estimates of optimal biomass multipliers as a function of M for survey data sets 1b and 4b.

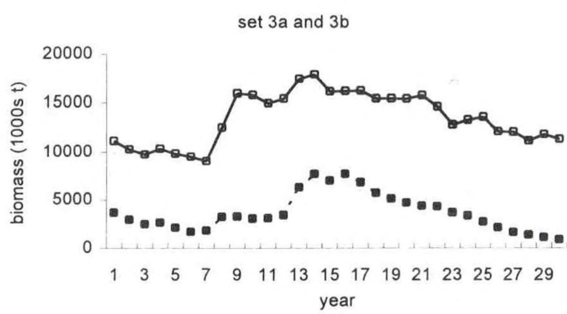
The biomass and recruitment updates from survey and fishery data (Figures 17-26) show varying degrees of agreement from very poor (Figures 19, 21, and 26) to fair (Figures 17, 23, 24, and 25). The forecast values of stock biomass in year 31 from survey and fishery data were used to compute a recommended catch (Table 5). Generally, allowable catches from fishery data greatly exceeded those from survey data because stock biomass was estimated to be much larger.

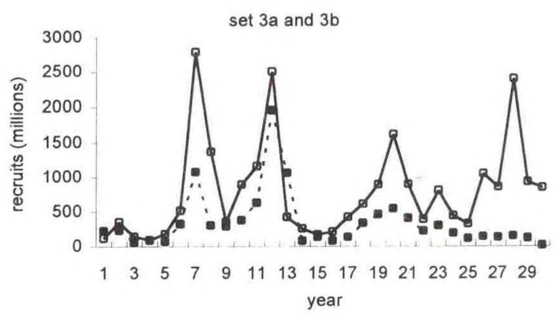


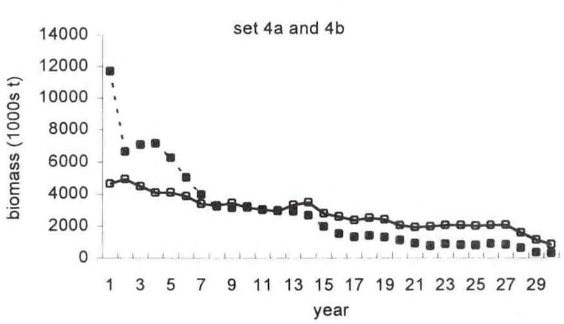


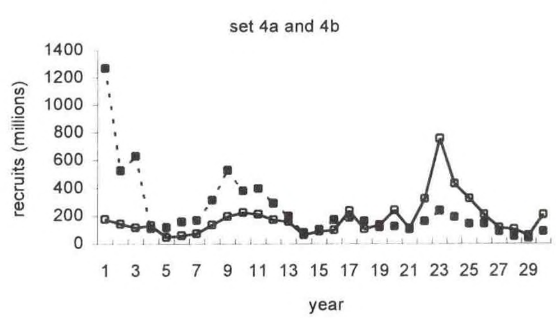




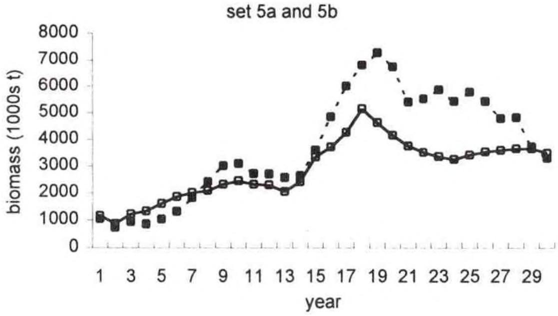


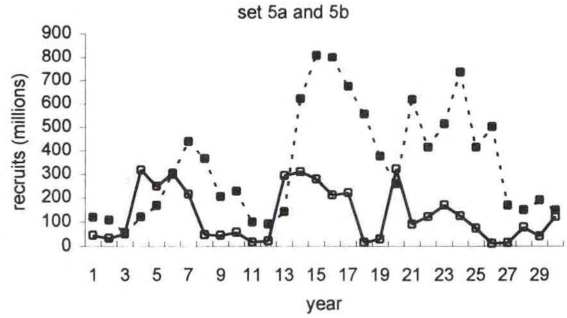






Figures 17 to 24 (left to right, top to bottom): Biomass and recruitment estimates by data set (solid symbols = survey; open symbols = fishery).





Figures 25 to 26 (left to right): Biomass and recruitment estimates by data set (solid symbols = survey; open symbols = fishery).

Table 5. Forecast biomass[1] (1000s metric tons), exploitation rate[2], and total allowable catch[3] (TAC, 1000s metric tons) for year 31.

Data set	Exploitation rate	Fishery data		Survey data	
		Biomass	TAC	Biomass	TAC
1	0.117	1,429	167	225	26
2	0.102	2,638	269	213	22
3	0.091	10,996	1,001	558	51
4	0.102	1,039	106	447	46
5	0.140	3,409	477	2,932	410

[1] The forecast used the updated state vector of year 30 from the BE.
[2] This exploitation rate would maintain the spawning stock biomass at 40% of the unfished condition if recruitment were constant. The rate was computed using knife-edge recruitment (4 yr for sets 1-4 and 5 yr for set 5) to the fishery, M=0.225, and the allometric von Bertalanffy growth curve and logistic maturity function that underlay the simulations.
[3] Product of exploitation rate and forecast biomass.

Finally, a re-examination of the support function for survey data of set 2b revealed that its apparently discontinuous behavior was probably an artifact of incomplete searching for maxima at choices for the biomass multiplier (Figure 27). The parameter γ was constrained to a value of 4% and the support function was determined again for comparison with the previous unconstrained search. Larger values occurred at some choices of the biomass multiplier, but the resulting support function was again discontinuous. Probably the erratic forms of the support functions for other data sets were produced by incomplete search. In future applications, derivatives of the support function should be computed analytically and used in a more reliable optimization algorithm.

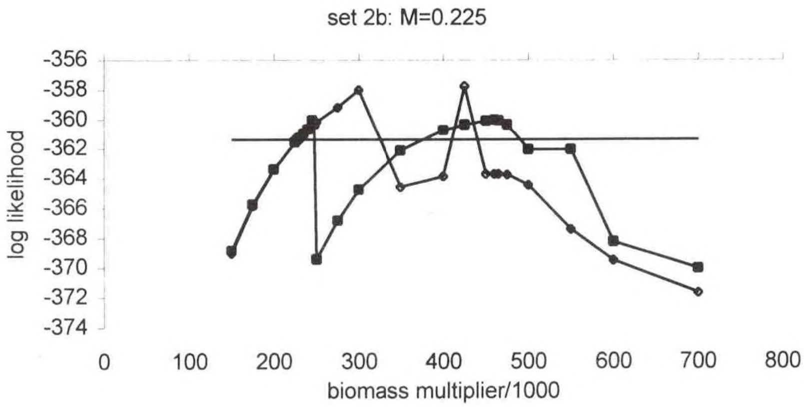


Figure 27. Support function for biomass multiplier for survey data set 2b with γ constrained (diamond symbols) and unconstrained (square symbols).

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CHAPTER 4.

Application of ADAPT to the NRC Simulated Data Sets

Ray Conser[1,5], Wendy Gabriel[2], Phil Goodyear[3], Clay Porch[3], Joseph Powers[3], Victor Restrepo[4], and Gerald Scott[3] .

[1]National Marine Fisheries Service (NMFS), Northwest Fisheries Science Center, 2030 Marine Science Drive, Newport, Oregon 97365. Ray.Conser@noaa.gov

[2]NMFS, Northeast Fisheries Science Center, 166 Water Street, Woods Hole, Massachusetts 02543.

[3]NMFS Southeast Fisheries Science Center, 75 Virginia Beach Drive, Miami, Florida 33149.

[4]University of Miami, 4600 Rickenbacker Causeway, Miami, Florida 33149.

[5]Working Group Chairman.

Introduction

In March 1996, the National Research Council (NRC), Ocean Studies Board, Committee on Fish Stock Assessment Methods requested the assistance of the National Marine Fisheries Service in evaluating the performance of several models commonly used for fish stock assessment in the United States. Using five realizations of simulated fish populations and the fisheries upon them, the NRC Committee generated from each population the kinds of data that would typically be available for stock assessment studies (e.g. catch, effort, research survey data, etc). Sources of error generally associated with fisheries data were added to the signals underlying the true population dynamics of the simulated stocks. The resulting data sets were distributed to NMFS scientists for use with various models, but the true population dynamics were not divulged.

An ad hoc working group of NMFS scientists met at the Southeast Fisheries Science Center, Miami Laboratory during 23-24 April 1996 to examine the NRC simulated data sets using the stock assessment framework generally know as ADAPT (Parrack 1986; Gavaris 1988; Conser and Powers 1990; Powers and Restrepo 1992). ADAPT is an age-structured, adaptable framework for estimating historical stock sizes of an exploited population. It is not a rigidly defined model in the mathematical sense, but rather a flexible set of modular tools designed to integrate all available data that may contain useful information on population size. It is widely used in the western Atlantic for USA and Canadian domestic assessments, as well as internationally within assessment working groups of ICCAT, NAFO, and ICES (Conser 1993).

The statistical basis of the ADAPTive approach is to minimize the discrepancy between observations of state variables and their predicted values. The observed state variables are usually (but not limited to) age-specific indices of population size, e.g. from commercial catch-effort data, research surveys, mark-recapture experiments, etc. The predicted values are a function of a vector of estimated population size (age-specific) and catchability parameters; and standard population dynamics equations (usually VPA).

Typically, the statistical comparison is done in an arithmetic or, alternatively, a logarithm scale using nonlinear least squares or weighted least squares (maximum likelihood) objective functions to minimize the discrepancies.

The terms of reference for the Working Group were:

(1) to apply the ADAPT methodology to each of the data sets provided by the NRC Committee; and

(2) to do so in a manner that resembled, as closely as possible, a typical working group stock assessment environment.

The Group recognized from the onset that Item (1), above, would be challenging during a two-day meeting, and that Item (2) was not a realistic goal for a two-day meeting. These reservations, along with other limitations and caveats, are discussed more fully in the following section.

Caveats and Limitations

The Group felt that its two-day meeting was successful and further that the working group environment provided a much more realistic assessment setting for working with the NRC simulated data sets than the environment of any individual scientist working in isolation. However, several major caveats and limitations became apparent during this exercise that should be taken fully into account when interpreting the results. The most important points are highlighted immediately below. More minor points are delineated within the discussion of the results for each data set.

<u>Time constraints</u>

Contemporary stock assessments using ADAPT (and other methods) are rarely carried out by an individual scientist working in isolation. Rather, the most common environment is that of a working group of assessment scientists consisting of anywhere from a few participants to perhaps twenty or more. The number of stocks to assess can vary from one to a dozen or more. Duration of working group meetings can vary from a few days for some domestic, single stock assessments, to nine or ten days for some international working groups.

Further, the working group environment is characterized by open discussion, considerable give and take, and iterative model-building and analyses. It is rare when initial model results are either accepted or rejected outright. Rather, they are usually taken as the first iteration. Comments of working group participants are taken into account and additional model runs are made until consensus is reached. Given the five NRC Committee simulated stocks, it was not possible for this working group to deal with them comprehensively during its two-day meeting. Many compromises were necessary to produce the results contained herein.

<u>ADAPT philosophy</u>

In choosing to utilize an ADAPT framework or not, an analyst evaluates the sources of errors in the data sets. In a typical ADAPT application, the errors (changes) in selectivity of the various fisheries participating are thought to override the measurement error in catch-at-age and that catch-at-age contains signals which are important to the dynamics. If this is not true, then the analyst would then, of course, consider other alternatives to provide management advice. The Group felt that this level of evaluation had not taken place in these applications.

Additionally, assessments using any modeling approach are linked to the management questions being addressed. Therefore, evaluation of an assessment approach depends upon the management context. It is unclear (in the data sets supplied) what that context is.

Biological and fisheries information

The amount of data and general information on the biology, ecology, and life history of the simulated stocks was meager compared to that usually available in a real assessment environment. Usually not only additional "hard" data are available but also a considerable amount of qualitative information on fisheries operations and practices are tabled by various working group members. This information (even when qualitative) can be invaluable for model-building and good group decision-making.

Nature of the effort data

Fishing effort data (or CPUE indices of abundance) are commonly used in assessments where ADAPT is the model framework of choice. In many cases, CPUE indices of abundance are used in conjunction with survey indices. However, fishery-independent surveys are not always available, and assessment results can be heavily dependent upon CPUE indices, e.g. in many tuna and swordfish assessments. In these situations, a great deal of care is taken in selecting CPUE indices that will index abundance and in assuring that proper effort-standardizing techniques have been employed. In virtually no real assessment environment within the Group's experience would nominal, unstandardized effort data (akin to the NRC-provided effort data) be acceptable for indexing abundance. It is not surprising then that, for most of the NRC data sets, the effort data was either of little value or entirely misleading (see the Utility of effort data section, below). Thus, if any conclusions based on this simulation exercise are reached regarding the general utility of effort data, it should be made clear that only nominal, unstandardized effort data were made available.

Ageing error matrix

Most of the data and biological information provided for each of the simulated populations are typical of the data that would generally be available for age-structured fish stock assessment. However, the ageing error matrix, which provides the distribution of observed ages for each true age, is not something that would typically be available in an assessment environment. This departure from realism was troubling to the Group. It is clear how one would take advantage of this information in a forward simulation modeling approach. However, it is not so straightforward to do so in a back-calculation (VPA-based) approach such as ADAPT. The Group devoted a non-insignificant amount of time (of the two-day period) attempting to incorporate the information using approaches similar to Bartoo and Parker (1983) and Goodyear (1997). However, a practical means to make use of this information was not achieved during the meeting and the Group proceeded by assuming that the provided catch-at-age matrix was indeed the true catch-at-age. The Group felt that in a real application, the research program which supplies the ageing error matrix for an ADAPT application would have structured the conditional probabilities accordingly. Any inter-method comparisons between the age-structured analyses of these simulated data should consider this potential bias due to the provision of the ageing error matrix.

Other Parameter Considerations

Natural mortality rate

After examining the catch-at-age data, growth parameters, and maturity ogive, a value of $M = 0.15$ yr^{-1} was selected for use in these analyses. However, this was further investigated by fitting the survey data to data sets 1 and 5 using a fit from a forward simulation approach ("IPA", Porch 1995). The method could be considered a hybrid of ADAPT and methods in which forward projection of the catch equation is used with a catch term in the objection function. Catches were assumed to be normally distributed with a constant coefficient of variation of 10% and separability was assumed within three blocks of years. With this additional structure, M could be estimated. In one case, M was estimated at M=0.18 and in the other M=0.13 yr^{-1}. While these estimates were not precise, they did provide support for the life history-based selection of M=0.15.

Utility of the Effort Data

It is well known that use of tuning indices that have conflicting trends can lead to erroneous assessment results and misleading management advice (e.g. see Hilborn and Walters 1992). Visual examination of the NRC-provided aggregate survey and CPUE indices (in numbers) indicated the potential for conflict in some of the data sets (particularly sets 1 through 4). For this reason, the Group decided to evaluate whether it would be sensible to include both survey and commercial CPUE information in the assessments (i.e. analysis type C). Furthermore, the available information suggested no reason to believe that the survey indices would be biased as a relative measure of abundance, while the CPUE data was suspect given the widely known concerns with nominal, unstandardized commercial effort statistics which the Group interpreted to be those CPUE data sets supplied to the Group. The Group felt that considerable effort should have been expended on evaluating and statistically standardizing the CPUE.

The Group thus decided to examine the question of constant catchability in the commercial effort data rather than using it blindly for tuning in ADAPT. Two approaches were followed.

Approach 1.

The first approach was to obtain relative age-specific catchabilities from the raw data. For any given year and age, q_{ya} was approximated by

$$q_{ya} = \frac{C_{ya} / f_y}{I_{ya}}$$

where I is the survey index of abundance, C is catch, f is effort, and a and y index age and year. For comparison, these were then re-scaled by the age-specific mean for all years (for data set 3, two means were used for years 1-15 and 16-30). Figure 1 displays the estimates so obtained for all data sets, ages 3 to 7 (other ages are not shown because the small sample sizes led to many zeros). The results suggest increases in catchability through time for data sets 1, 2, and 4. The scattered points for data sets 3 and 5 are more centered around q=1, suggesting only small or negligible trends through time. The main disadvantage of this approach is that the commercial data reflect an average annual process affected by each year's exploitation rate, while the survey data reflect the abundance at the start of the year. For this reason, Approach 2 was also used.

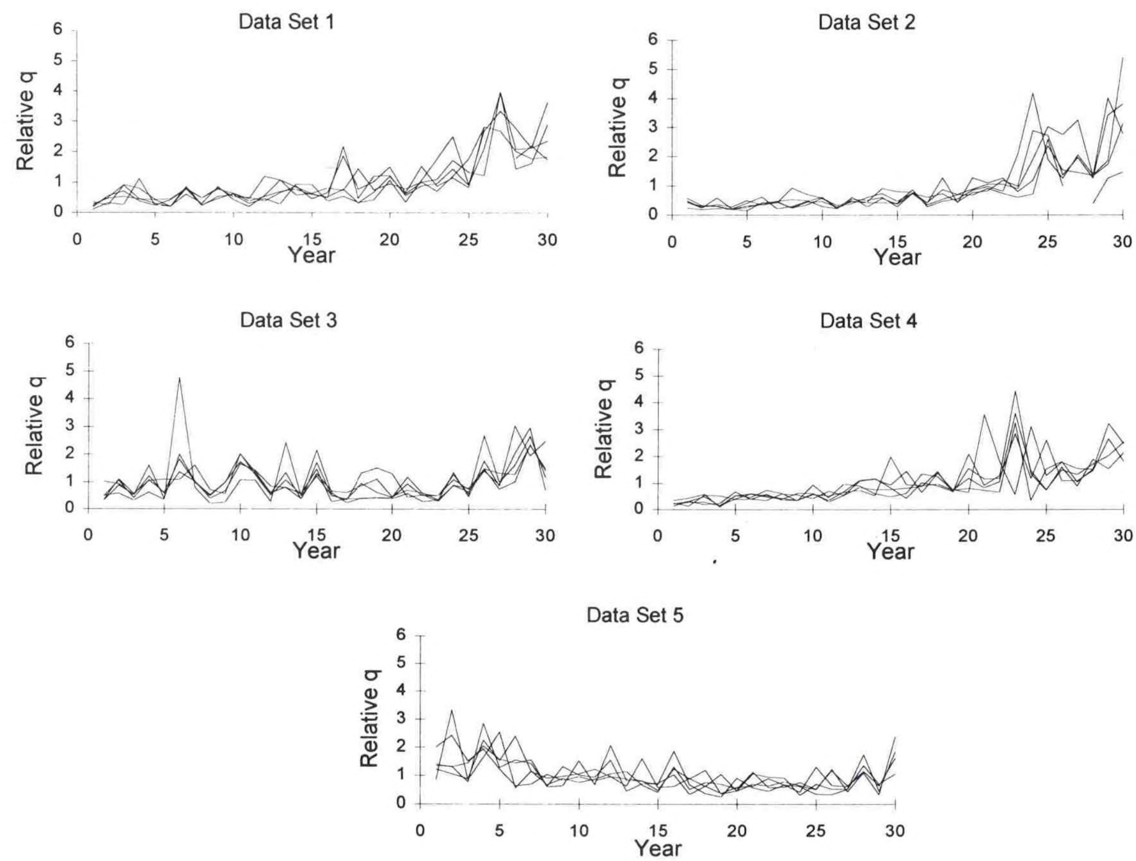

Figure 1. Estimates of age-specific (ages 3 to 7) fishery catchability (q) relative to survey ones for the simulated data sets.

Approach 2.

The second approach involved first carrying out the ADAPT analyses using the survey indices only (case B), assuming that they are unbiased. Then, based on these results, an approximate estimate of catchability trends for the commercial effort data was calculated as:

$$q_t = \frac{Y_t}{f_t B_t},$$

where B_t is the mean annual biomass from the ADAPT results, summed over all ages, and Y_t and f_t are the reported total commercial yield and effort.

The estimates of q_t (t = 1 to 27) are plotted in Figure 2. Data sets 1 through 4 show an increasing trend through time, particularly for the most recent years. Data set 5 shows no evidence of increasing catchability based on these analyses.

Based on the results above, the Group decided to carry out case C with data set 5 only. The Group could have explored other possibilities if it had more time. In particular, it may be fruitful to explore, external to the tuning process, transformations of the CPUE data that would make it consistent with the survey one. Alternatively, an approach along the lines of that proposed by Schnute and Hilborn (1993) could be explored, rather than resorting to the blind use of obviously conflicting data sets.

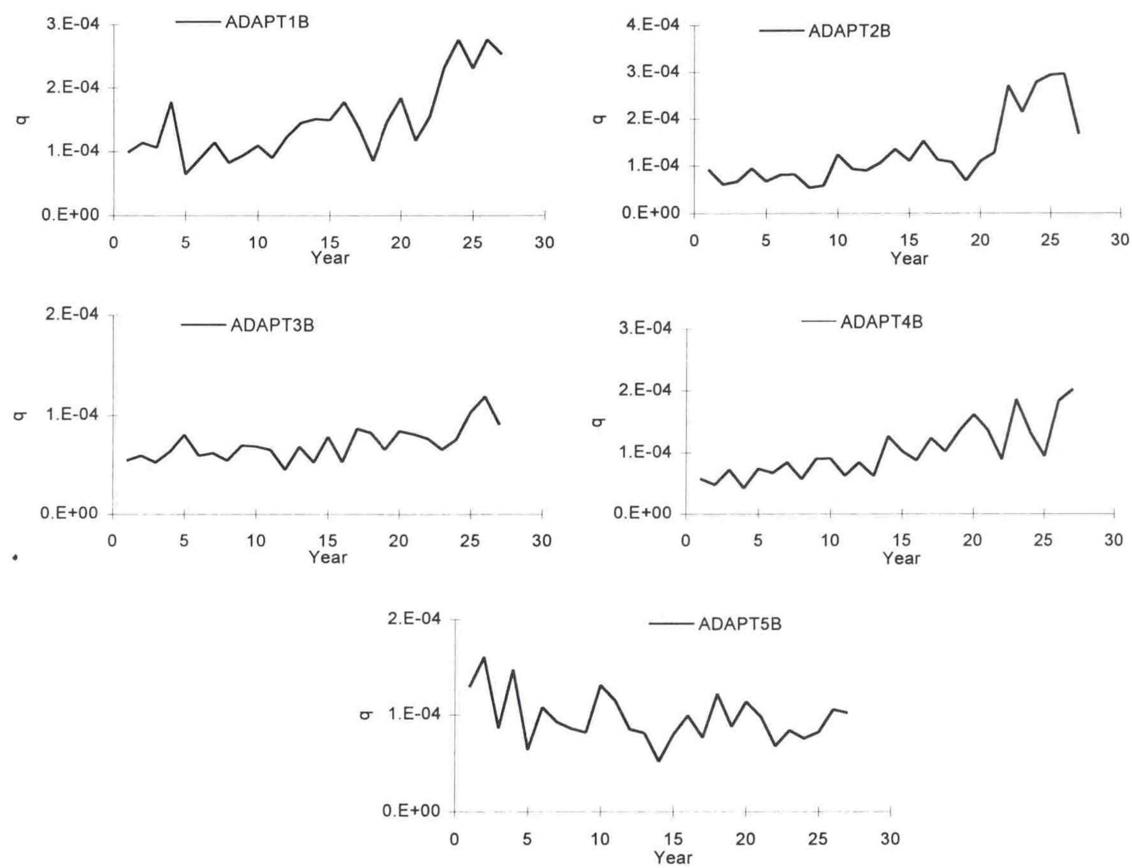

Figure 2. Estimates of catchability (q) for the fishery CPUE data as obtained from ADAPT results using survey index data only.

Applications

In all cases, except for data set 5, only survey indices were used in the model fits because (1) the CPUE data were nominal and unstandardized, and (2) comparative examination of the CPUE versus survey indices from the data and from preliminary ADAPT runs indicated that there was a trend in catchability of the effort data (Figs. 1 and 2). The information provided for the simulated data and the evidence from the preliminary analyses suggested that the CPUE data should not be used in the model fits to data sets 1 through 4.

Table 1 summarizes the model formulations and constraints used for the various runs. In all cases, age data were pooled at a plus group due to the sparsity of catches in the older age groups and to the aging error matrix. The number of stock sizes estimated directly during minimization varied depending on each data set. The selectivities for the age groups not directly estimated as parameters in the terminal year were linked to the selectivities of other age groups that were directly estimated.This linking consisted of fixing the ratios of age-specific selectivities to those computed from a separable VPA (Pope and Shepherd 1982). An additional constraint was to fix the ratio of fishing mortality rates of the plus group relative to that of the next youngest true age. This again was accomplished by using the time series of *F* ratios estimated by the separable VPA.

Table 1. Model structure used for the different ADAPT applications to the simulated data sets.

Run	Oldest age[1]	Parameters[2]	Selectivity constraints[3]
1B	8	2-6	6-8 --> 5
2B	11	2-3,7	3-4 --> 2; 5, 7-11 --> 6
3B	11	2-3,7	3-4 --> 2; 5, 7-11 --> 6
4B	11	2-5	5-11 --> 4
5B-C	11	2-9	9-11 --> 8

[1] Used as a "plus" group.
[2] Parameters estimated are stock sizes for the given ages at the start of year 31.
[3] Selectivities for given age ranges are linked directly to specified ages in year 30. For instance, 6-8 --> 5 means that the selectivities for ages 6-8 are fixed relative to the VPA-estimated selectivity for age 5.

Results of the application of ADAPT to the various data sets are shown in Figures 3 to 8. The plots present the estimated trajectories of biomass (total, exploitable and spawning), recruitment, and an overall measure of fishing mortality computed as the ratio of estimated mid-year exploitable biomass to total reported yield. These results may suffer from a retrospective pattern which could not be investigated in the allotted time. Therefore, as is common in reporting results to decision-making bodies, the final year was removed from the reporting. This is consistent with the method of the averaging of *F*s to compute benchmarks.

Estimates of abundance and fishing mortality for data set 1 are shown in Figure 3.

The results indicate some rather large *F*s and substantially declining trends in abundance, SSB, and recruitment. Estimates for data set 2 are shown in Figure 4. These results also indicate some rather large *F*s and substantially declining trends in abundance, spawning biomass (SSB), and recruitment. For both simulated stocks, it is expected that the management advice would be robust to much of the concerns with the analyses expressed above.

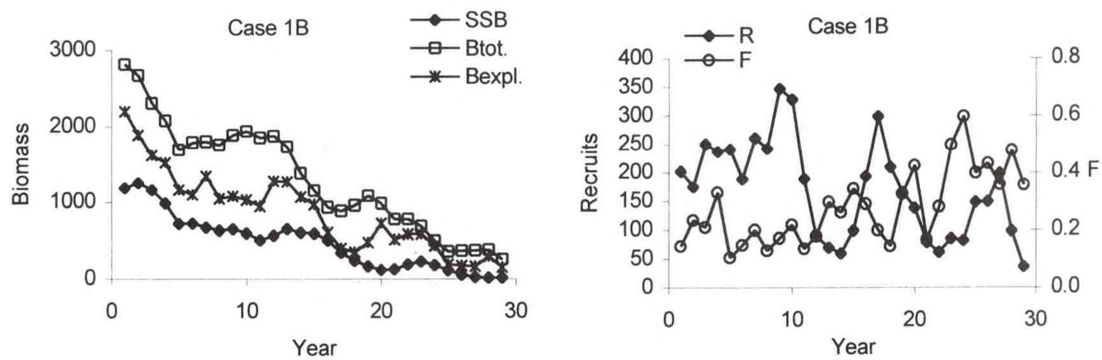

Figure 3. Estimates of biomass (SSB = spawning, Btot = total, Bexpl = exploitable), recruitment and fishing mortality (F) for case 1B.

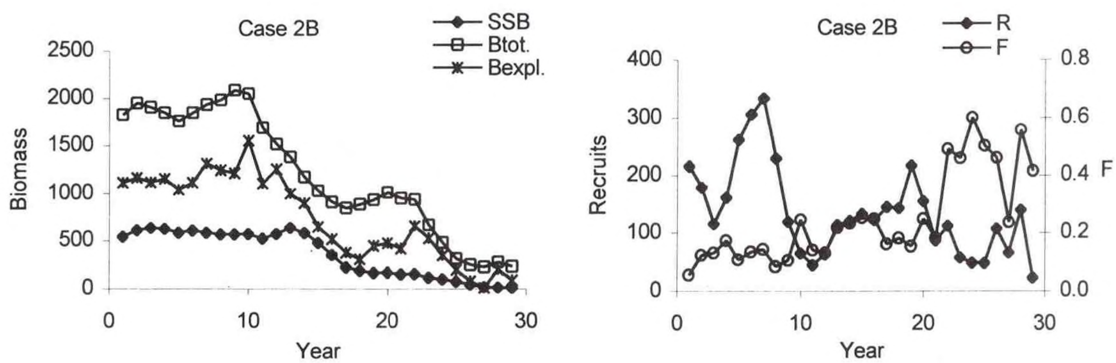

Figure 4. Estimates of biomass (SSB = spawning, Btot = total, Bexpl = exploitable), recruitment and fishing mortality (F) for case 2B.

Information provided by the NRC panel suggested that there may have been a change in survey catchability half-way through the series for data set 3. An trial ADAPT run was made using the entire 30 year survey series. Examination of residuals did not reveal a pattern consistent with an intervention event at the 15 year mark, i.e. a sudden change in survey catchability. Consequently, the entire 30 year survey series was used in final runs. The results of abundance and fishing mortality rate for data set 3 are shown in Figure 5. These results indicate some rather large *F*s and substantially declining trends in abundance in this data set in the recent years. This conclusion would not differ greatly if only the last 15 years of the survey series had been used.

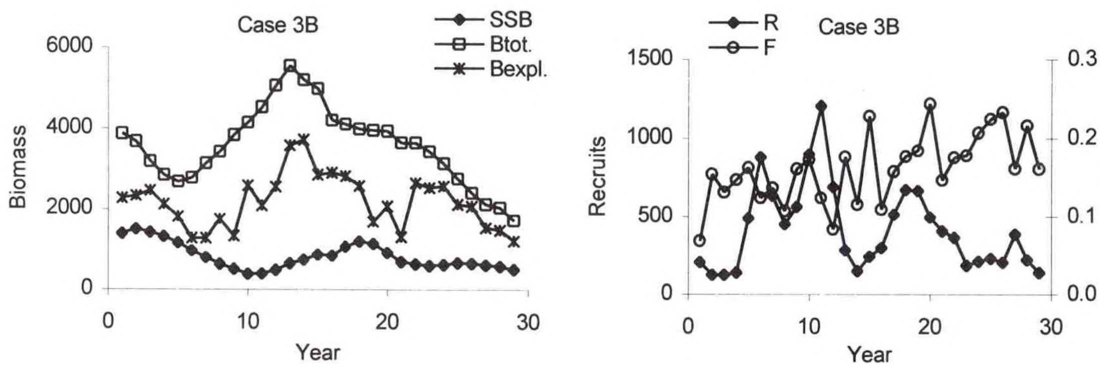

Figure 5. Estimates of biomass (SSB = spawning, Btot = total, Bexpl = exploitable), recruitment and fishing mortality (F) for case 3B.

The results for data set 4 are shown in Figure 6. They indicate some rather large *F*s and substantially declining trends in abundance and SSB, despite a strong year-class about eight years ago. Again, it is expected that the management advice for this stock would be robust to much of the concerns with the analyses expressed above.

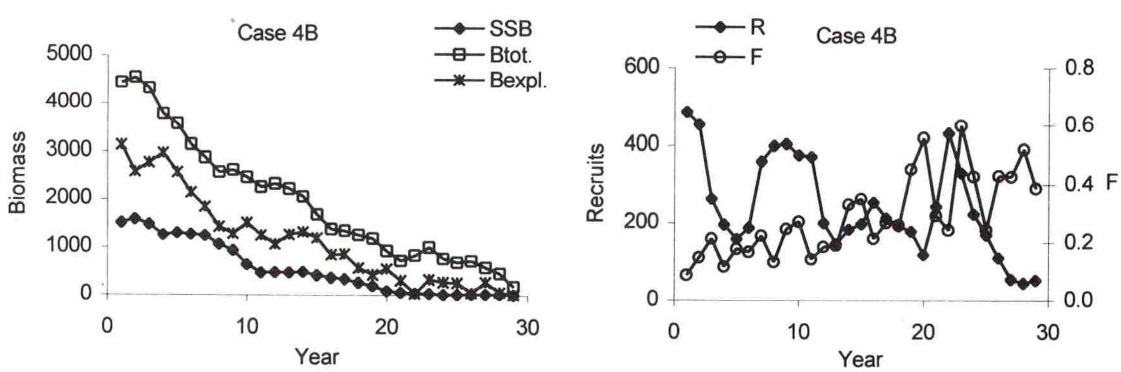

Figure 6. Estimates of biomass (SSB = spawning, Btot = total, Bexpl = exploitable), recruitment and fishing mortality (F) for case 4B.

For data set 5, both the CPUE and survey indices were used in the model fit. Although the CPUE appeared to be nominal and unstandardized, the comparative examination of the CPUE versus survey indices from the data and from preliminary ADAPT runs provided no evidence that there was a trend in catchability (Figures 1 and

2). Therefore, both types of indices were used. By doing so, parameter estimates were stabilized somewhat from those using the survey estimates alone. The results of abundance and fishing mortality rate are shown in Figure 7 for Run 5B, and in Figure 8 for Run 5C. The fishing mortality rates appear to be somewhat higher than *M*, but not greatly so. SSB is at very high level. However, recruitment in recent years appears to be small relatively to the past.

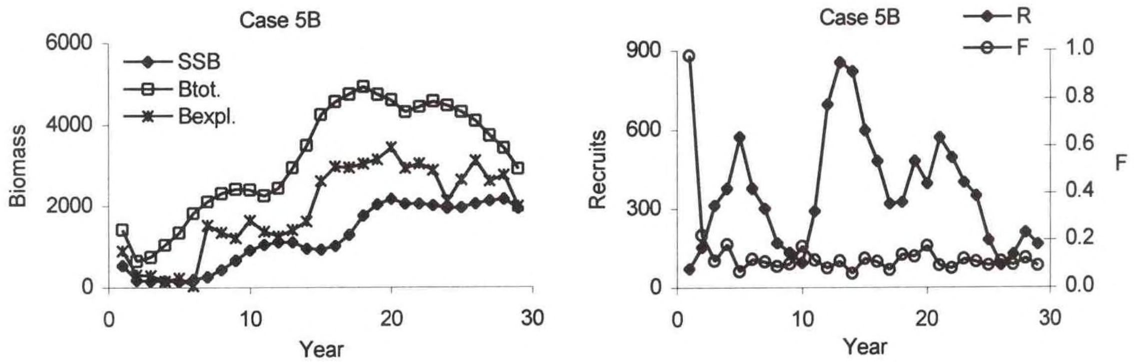

Figure 7. Estimates of biomass (SSB = spawning, Btot = total, Bexpl = exploitable), recruitment and fishing mortality (F) for case 5B.

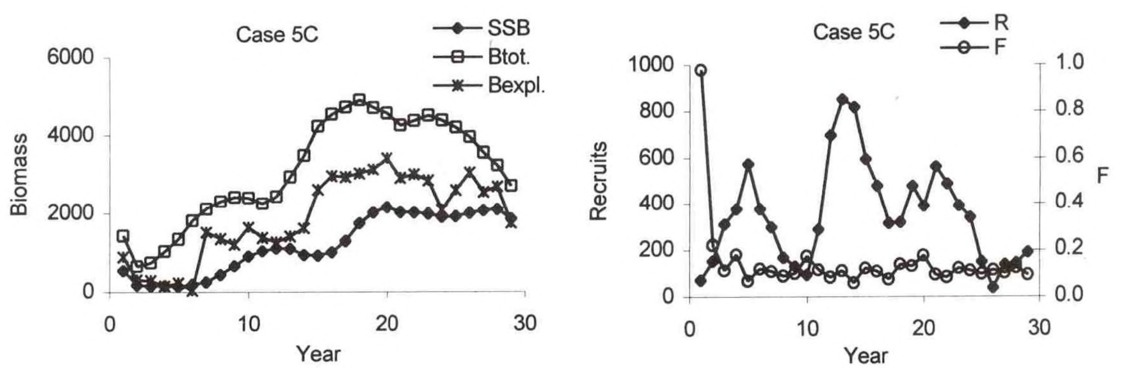

Figure 8. Estimates of biomass (SSB = spawning, Btot = total, Bexpl = exploitable), recruitment and fishing mortality (F) for case 5C.

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CHAPTER 5.

An Age-structured Analysis of NRC Simulated Data Sets

Michael Sigler

National Marine Fisheries Service, Alaska Fisheries Science Center, Auke Bay Laboratory, 11305 Glacier Highway, Juneau, Alaska 99801. Mike.Sigler@noaa.gov

Introduction

This document presents the results of applying a simple age-structured assessment model to the five simulated data sets generated by the NRC Committee on Stock Assessment Methods. The approach assumes separability of fishing mortality into an age and a year component and uses an observation error maximum likelihood estimator. To some extent, the formulation of the models and the interpretation of the results rely on a detailed examination of the simulated data sets.

Estimation Methods

The analysis generally follows the approach of Kimura (1990) for age-structured separable sequential population analysis. Let $i = 1, \ldots y$ be the year index, and $j = 1, \ldots a$ be the age index. Let

c_{ij} = the observed catch in numbers at age,
F_i = the instantaneous fishing mortality rate for fully available ages (i.e., ages for which $s_j = 1$),
s_j = the selectivity for age j fish such that the assumption of "separability" holds, i.e.,
$F_{ij} = F_i s_j$ = the instantaneous fishing mortality rate of age j fish during year i,
N_{ij} = the total number at age,
$N_{ij}^f = s_j N_{ij}$ = the fishable number at age, and

$\sum_{j=1}^{a} N_{ij}^f = N_i^f$ = the fishable number.

$U_{ij} = F_{ij} / (M + F_{ij})\ (1 - \exp(-M - F_{ij}))$ is the exploitation rate on age j fish in year i, assuming an instantaneous natural mortality rate of M. It follows that

$$N_{i+1,j+1} = N_{ij} e^{-M-F_{ij}}$$

and predicted catch would be $\hat{c}_{ij} = U_{ij} N_{ij}$. An approximation is to assume an instantaneous fishery at the mid-point of the year,

$$\hat{c}_{ij} = \mu_{ij} N_{ij} e^{-M/2} \text{ such that}$$

$$N_{i+1,j+1} = N_{ij}(1 - \mu_{ij})e^{-M} .$$

Model convergence was much faster with this approximation and resulted in only a small positive bias in exploitable biomass (Figure 1). This approximation was used to estimate population model parameters because of the large number of analyses and the limited time.

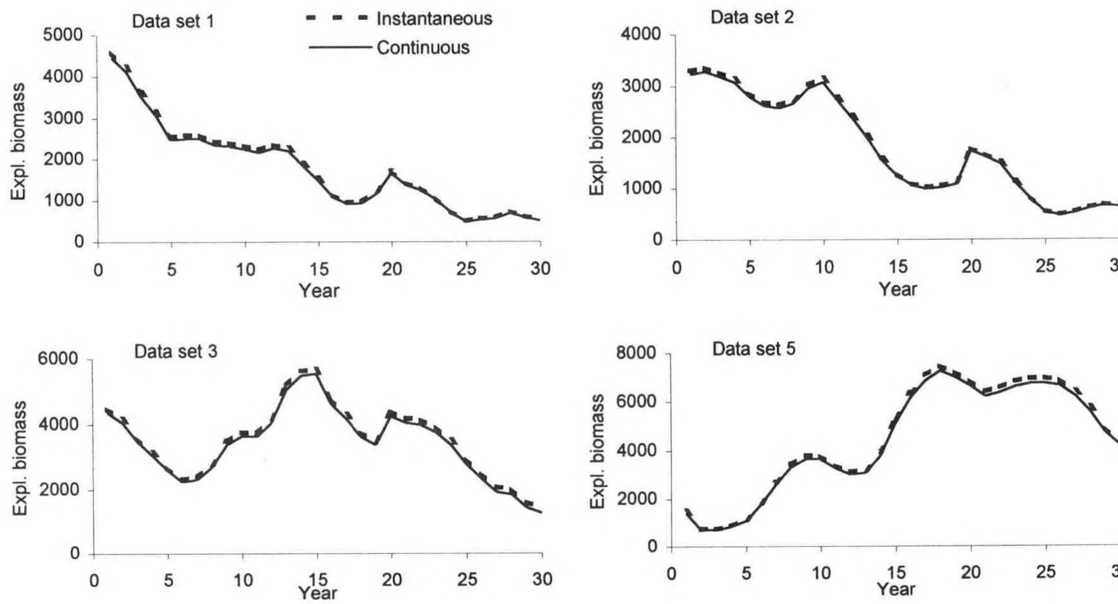


Figure 1. Annual estimates of exploitable biomass for case B analyses. The plots compare results assuming a continuous fishery and an instantaneous one at mid-year.

Selectivity is described as a function of age. The logistic function is appropriate when selectivity increases with age to an asymptote,

$$s_j = \frac{1}{1 + e^{\beta(A_{50} - j)}}$$

where A_{50} is the age where 50% of the population is vulnerable and β is the slope of the function at A_{50}. Selectivity is dome-shaped for some surveys and fisheries, where selectivity increases with age to a maximum, and then decreases for older fish. Dome-shaped selectivity can be described by the "exponential-logistic" function (Thompson 1994)

$$s_j = \left(\frac{1}{1-\gamma}\right)\left(\frac{1-\gamma}{\gamma}\right)^{\gamma}\left(\frac{e^{\beta\gamma(A_{50}-j)}}{1 + e^{\beta(A_{50}-j)}}\right) .$$

The exponential-logistic function automatically scales maximum vulnerability to 1.0 and reduces to the logistic as γ approaches zero. Note that for $\gamma > 0$, A_{50} and β lose their biological meaning (e.g., A_{50} no longer represents the age at 50% vulnerability).

Relative abundance information in the simulated data were collected annually, either by a fishery-independent survey or from the fishery. For this work, the abundance index from the fishery was computed as the number of fish (thousands) caught per boat-day. Relative abundance and age composition data are denoted as an abundance index in numbers, S_i, and proportion at age, p_{ij}. The predicted abundance index is

$$\hat{S}_i = \hat{q}\hat{N}_i^f$$

where q is catchability and quantities predicted with the model are indicated with "hats." An ageing error transition matrix was provided, where $e_{j'j}$ = the probability that a fish sampled of true age class j' would be aged as j. This information can be incorporated by transforming the predicted age data to

$$\hat{a}_{ij} = \sum_{j'} \hat{p}_{ij'} e_{j'j} .$$

Parameters can be estimated by assuming the probability distributions of the sampled abundance index and age data are known. Fournier and Archibald (1982) suggested multinomial errors for age data and log-normal errors for catch data. The log-likelihood incorporating an abundance index and age data is

$$L = \sum_{ij} n_i a_{ij} \log \frac{\hat{a}_{ij}}{a_{ij}} - \frac{1}{2\sigma^2} \sum_i (\log(S_i) - \log(\hat{q}\hat{N}_i^f))^2 \tag{1}$$

where n_i is the number of ages sampled in year i and σ^2 is the variance of the observed abundance index. Maximum likelihood estimates for the parameters can be found by maximizing L. Assuming that the annual instantaneous natural mortality rate M is known, recruitment, $N_{11}, \ldots N_{y1}$, the initial age composition, $N_{12}, \ldots N_{1a}$, and the selectivity parameters, A_{50}, β, and γ, need to be varied in order to maximize L. The other parameters, q, and the instantaneous rates of fishing mortality, $F_1 \ldots F_y$, are computed from the survey indices, catches, and the remaining parameters at the values that would maximize L. Setting $dL/d\hat{q}$ equal to zero, assuming σ^2 is known beforehand, and solving for $\hat{q}$, gives

$$\hat{q} = \exp\left[\frac{\sum_i \log \frac{S_i}{\hat{N}_i^f}}{y}\right] .$$

Thus, survey catchability can be computed from the observed abundance indices and estimated abundances. If the fishery is continuous, the $F_1, \ldots F_y$ are found by iteratively solving the catch equation for each F_i

$$c_i = \sum_j \frac{F_{ij}}{M+F_{ij}} (1 - \exp(-M - F_{ij}))\, \hat{N}_{ij} \ .$$

If an instantaneous fishery at the mid-point of the year is assumed, as was done in these analyses, then the $\{\mu_1, \ldots \mu_y\}$ are computed as

$$\hat{\mu}_i = \frac{c_i}{\hat{N}_i^f} \ .$$

Thus, the number of parameters estimated in the model is $y + a - 1$, plus the number of selectivity parameters. As noted by Kimura (1989, 1990), reliability in the estimation process is improved if the parameters are estimated in log space rather than on the original (untransformed) scale. This makes the parameters more similar in magnitude, and probably reduces parameter-effects nonlinearity (Ratkowsky 1983).

The variances of the observations can be used to weight the likelihood components if the variances are known. Methods have been suggested to compute the variance of the abundance index, σ^2 (Kimura 1989, 1990, 1991). The maximum likelihood estimate of σ^2 can be obtained by setting $dL/d\,\sigma^2 = 0$, the estimate being (Kimura 1991)

$$\hat{\sigma}^2 = \frac{\sum_i (\log \hat{S}_i - \log S_i)^2}{y} \ .$$

Substituting this equation back into equation (1), the log-likelihood becomes

$$L = \sum_{ij} n_i p_{ij} \log \frac{\hat{p}_{ij}}{p_{ij}} - \frac{y}{2} \log(2\pi\hat{\sigma}^2) + constant \ .$$

This log-likelihood is appropriate for a single abundance index and source of age data. Additional index and age data were incorporated by adding likelihood components.

The instantaneous rate of natural mortality, *M*, was estimated independently of the population model. Abundance and *M* cannot be estimated simultaneously in the population model given only an abundance index, age, and catch data. Additional information such as mark-recapture data would be necessary to estimate both abundance and *M* reliably in the population model. In this work, *M* was estimated from the age of maximum biomass, t^*, and the growth parameter, k

$$M = \frac{3k}{\exp(t^* k) - 1} \tag{2}$$

following Alverson and Carney (1975). t^* was computed for each cohort of the surveyed population, then averaged over the first several cohorts where it appeared constant. For example, t^* was averaged over cohorts spawned in years -2 to 10 for data set 1. This approach assumes that survey biomass is representative of total biomass and that the population is lightly exploited over the period M is estimated.

The data set-specific values of t^* and resulting estimates of M were:

Data set	Year classes	Average t*	M
1	-2 to 10	5.08	0.251
2	-3 to 9	5.08	0.251
3	-3 to 9	6.15	0.169
4	-3 to 5	5.67	0.201
5	-4 to 22	5.81	0.191

The following population parameters were assumed constant over the 30-year time period: M, growth rate, survey catchability (except for data set 3), and survey selectivity. Separate survey catchabilities were estimated for years 1-15 and 16-30 for data set 3 to determine if the vessel change divulged by the NRC Committee affected survey catchability. I assumed that survey catchability was constant because survey effort can be controlled in most real situations. Biologists can control survey effort by paying close attention to detail in the design, methods, and general implementation of a survey. Species-specific surveys also help ensure that relative abundance is being indexed by tailoring the survey to the target species, the terrain it inhabits, and by ensuring that the survey covers all or nearly all habitat the species inhabits.

No information such as gear type or the match-mismatch of the survey area, fishery area and area inhabited, was provided to suggest whether selectivity was asymptotic or dome-shaped, so I assumed that the simpler asymptotic model was correct. I would try estimating dome-shaped selectivity if more information was provided which indicated that such might be the case. If dome-shaped selectivity occurred, then the estimate of M by the Alverson-Carney method could be biased, because the degree of dome-shape and M are confounded (Thompson 1994).

Examination of the simulated data sets revealed that young fish were more vulnerable to the survey than they were to the fishery. Higher proportions at age for ages 1 and 2 were observed for the survey compared to the fishery for all data sets (Figure 2). For data sets 1-3, fishery selectivity appeared to change after year 19 to increase selection on younger fish. Mean weight was lower for the survey than it was for the fishery for years 1-19. However, after year 19, the two mean weights were similar, suggesting that fishery selectivity had changed at that time. Therefore, separate fishery selectivities were estimated for years 1-19 and years 20-30 for cases B and C. Separate fishery selectivities were not estimated for case A, because an analyst using fishery data alone would be unable to distinguish the selectivity change from increased recruitment until several years after selectivity change had taken place.

The survey and fishery proportions at age 15+ were compared to determine if the survey and fishery selectivities were similar for older fish (Figure 2). The similarity of the proportions imply that fishery and survey selectivity for older fish were similar. The proportion at age 15+ was usually higher for the fishery data, but this difference is small enough that it could be interpreted as being artificial, due to the survey selecting younger fish and the proportions-at-age for both data types having to sum to 1.0.

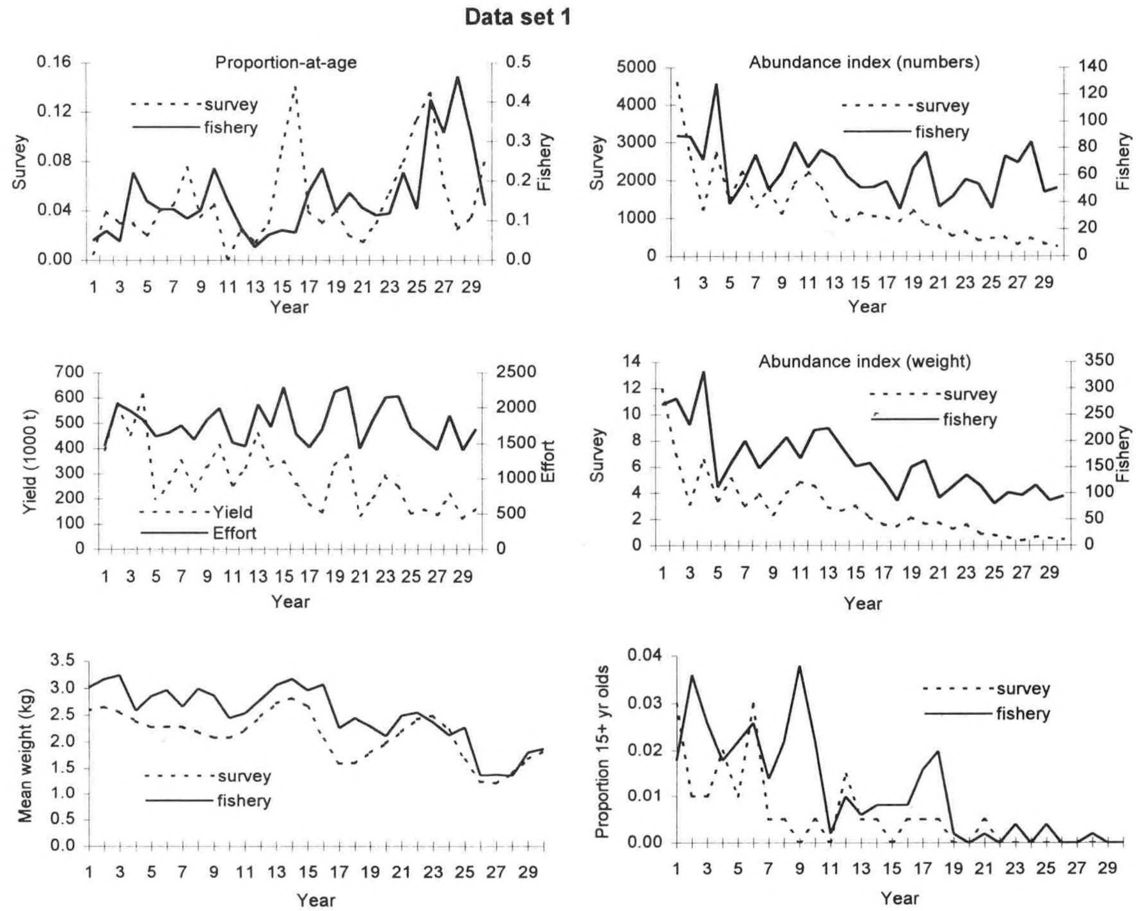
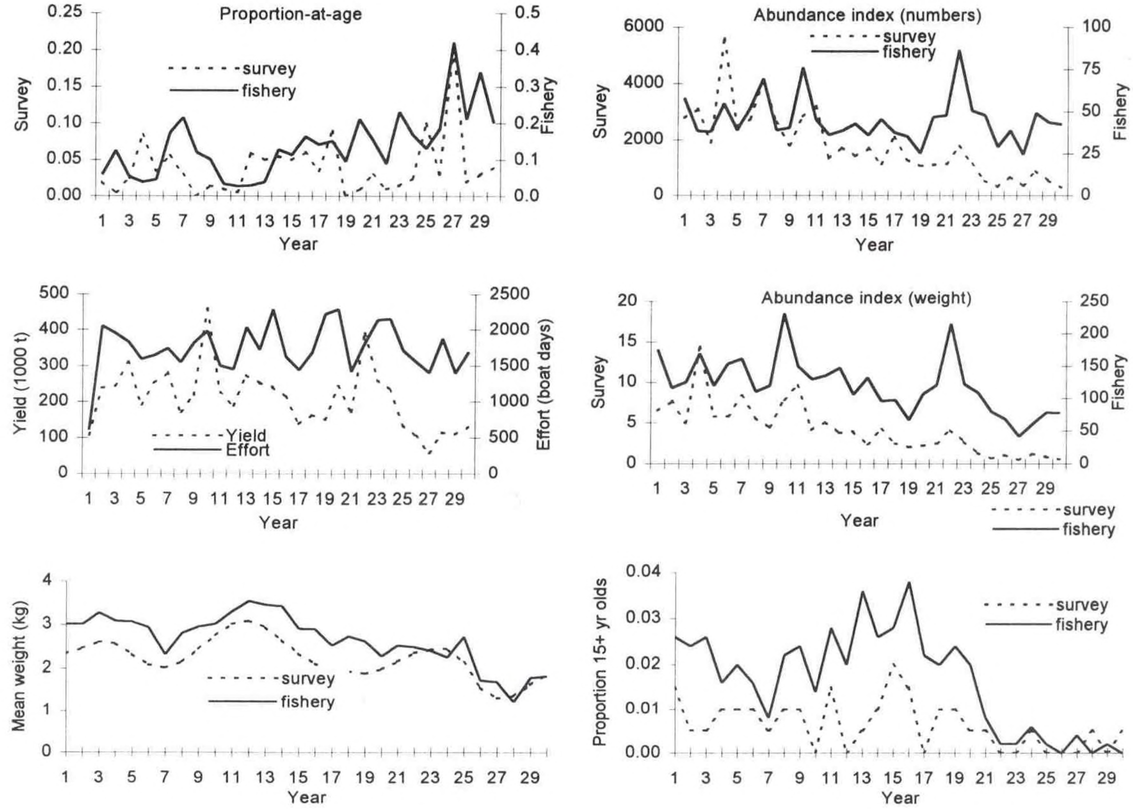


Figure 2. Summary plots of simulated NRC data. From left to right, top to bottom: Proportion at age from survey (1-yr-old) and fishery (3-yr-old); abundance index (numbers) for survey and CPUE (number per boat-day); yield (1000 t) and effort (boat-days); abundance index (weight) for survey (t) and fishery (t per boat-day); mean weight (kg) for survey and fishery; proportion at age 15+ in survey and fishery.

Data set 2



Data set 3

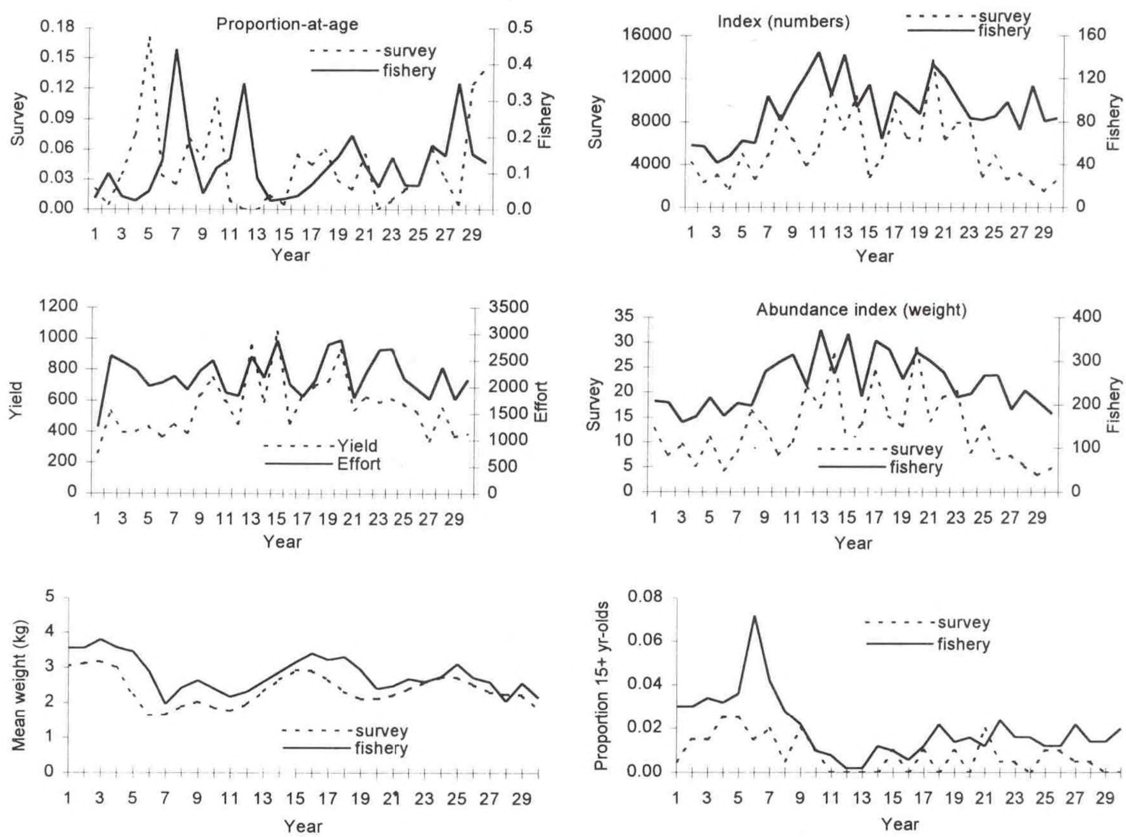
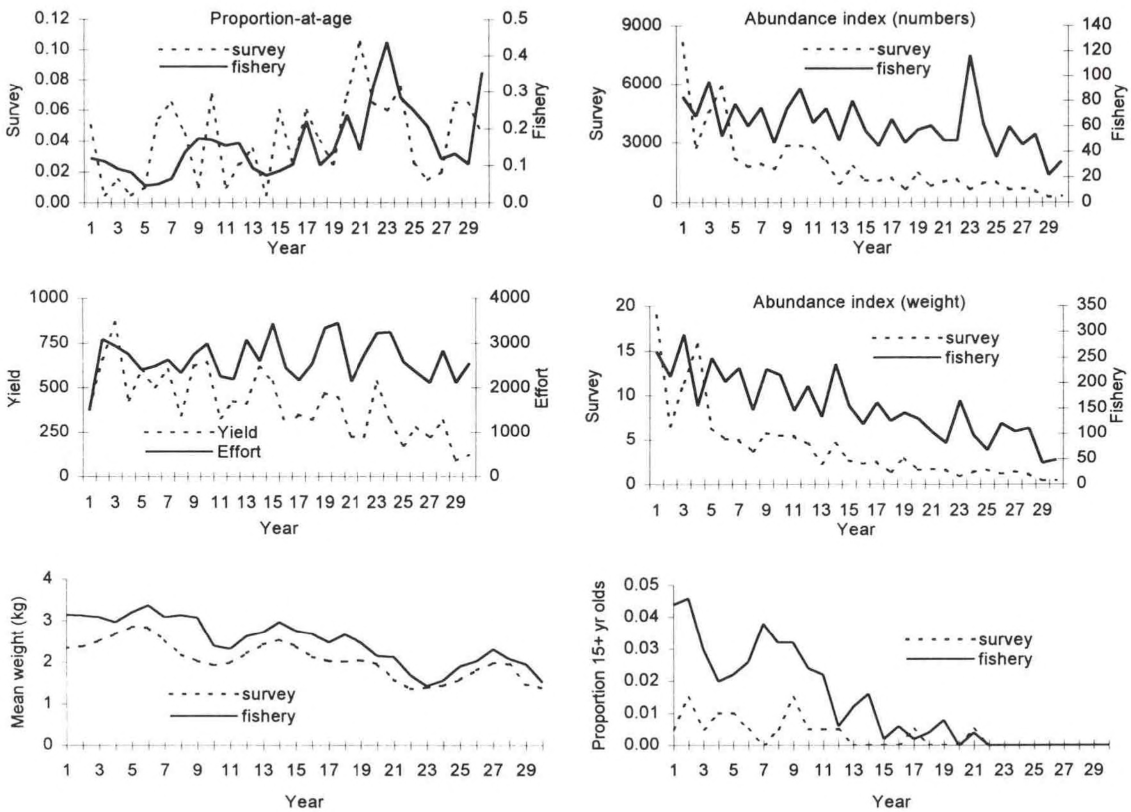


Figure 2 (cont.)

Data set 4



Data set 5

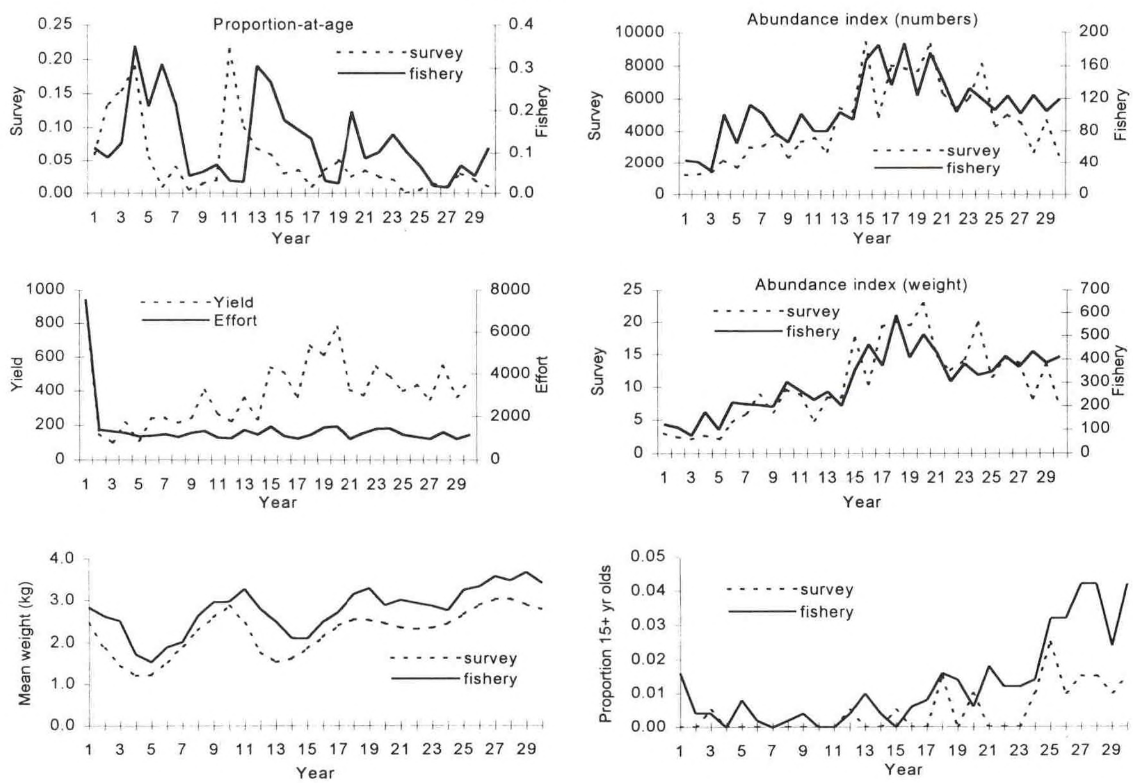


Figure 2 (cont.)

Other characteristics of the fisheries became apparent by examining the data sets (Figs. 2 and 3):

- Survey variability appeared low, medium, high, low, and medium for data sets 1-5 respectively.

- Observed proportions-at-age in the survey suggested that recruitment was autocorrelated for data sets 1-3 and 5 and random for data set 4.

- Effort varied without trend for each data set (Figure 3). The pattern, but not the scale, of annual effort was the same, implying that the same random deviates were used for all five data sets with mean (and probably variance as well) effort differing between data sets.

- The abundance trends from the fishery and survey usually did not match (Figure 2). Because survey effort normally is standardized, the likely suspect is the fishery data. Fishers may target concentrations of fish such that the fishery abundance index is not a linear function of abundance. Fishers may also become more efficient over time, regardless of abundance. In real applications, I would not use fishery catch rate as an abundance index unless its reliability could be assessed, for example by plotting catch rate and fish size by location and time. For the simulated data sets 3 and 5, the fishery and survey abundance trends were similar only for years 1-20; fishery catchability appeared to increase thereafter, when the survey index (in numbers) fell while the fishery index was stable.

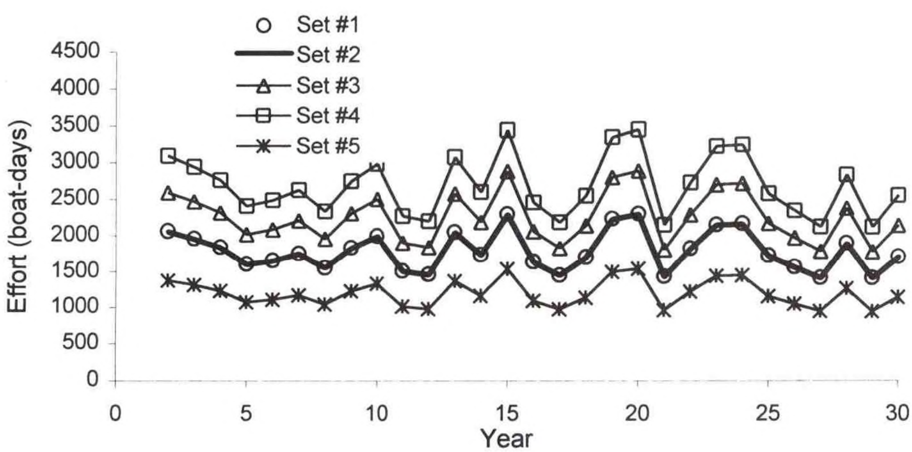


Figure 3. Annual fishery effort by simulated data set.

Results

The presentation of the cases analyzed follows the nomenclature XY, where X = 1, 2,...5 corresponds to a simulated data set and Y is either A, B or C, depending on whether relative abundance information was obtained from the simulated fishery (A), survey (B), or both (C). The following cases were modeled: cases A, B, and C assuming an instantaneous fishery at the mid-point of the year, and case B assuming a continuous fishery. The results were tabulated and presented to the NRC and only some are repeated here. Table 1 presents estimates of the parameters defining the selectivity patterns. Subsequent comments highlight results I consider important, but are not intended to be comprehensive. Only results assuming an instantaneous fishery at the mid-point of the year are discussed.

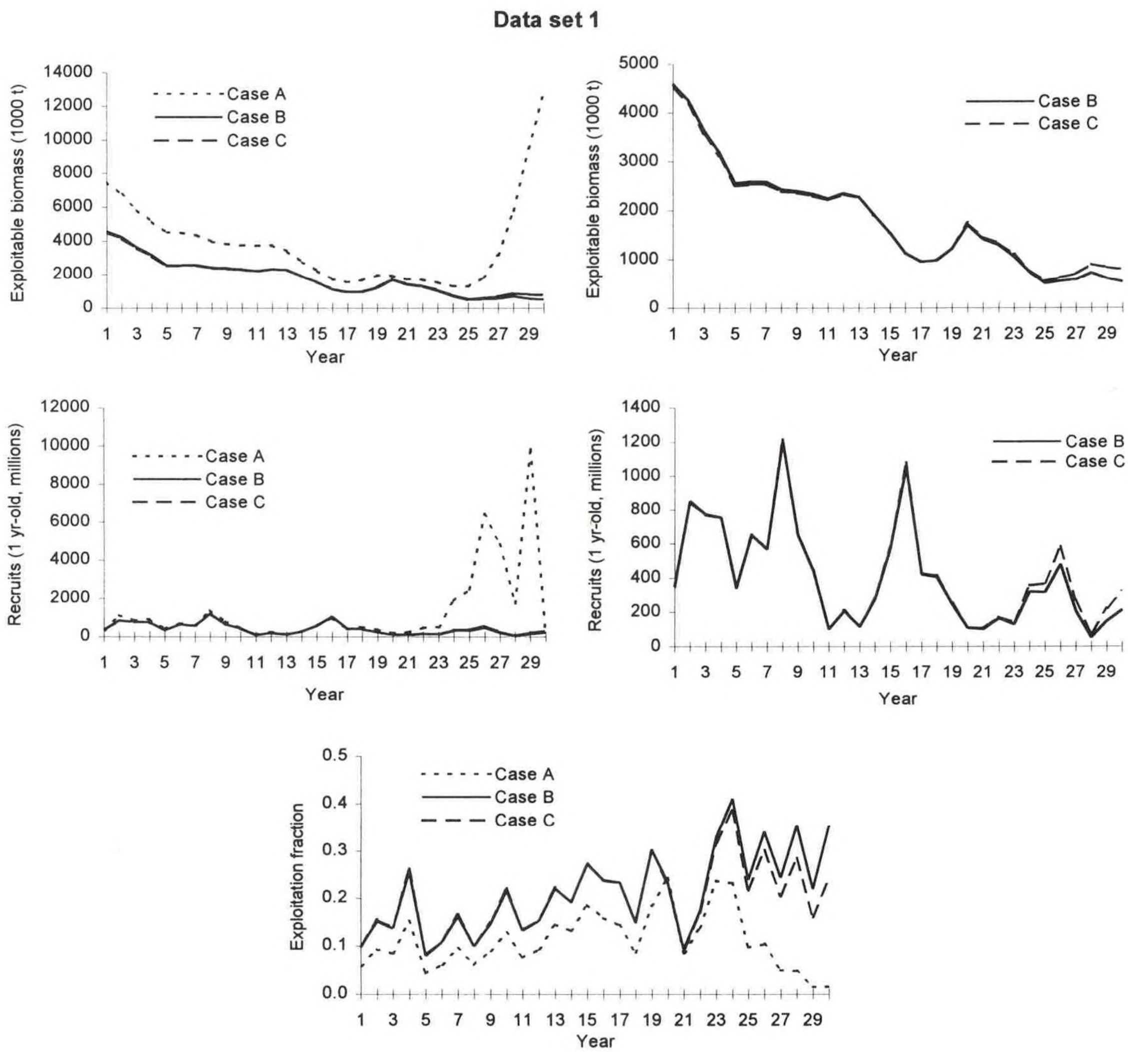
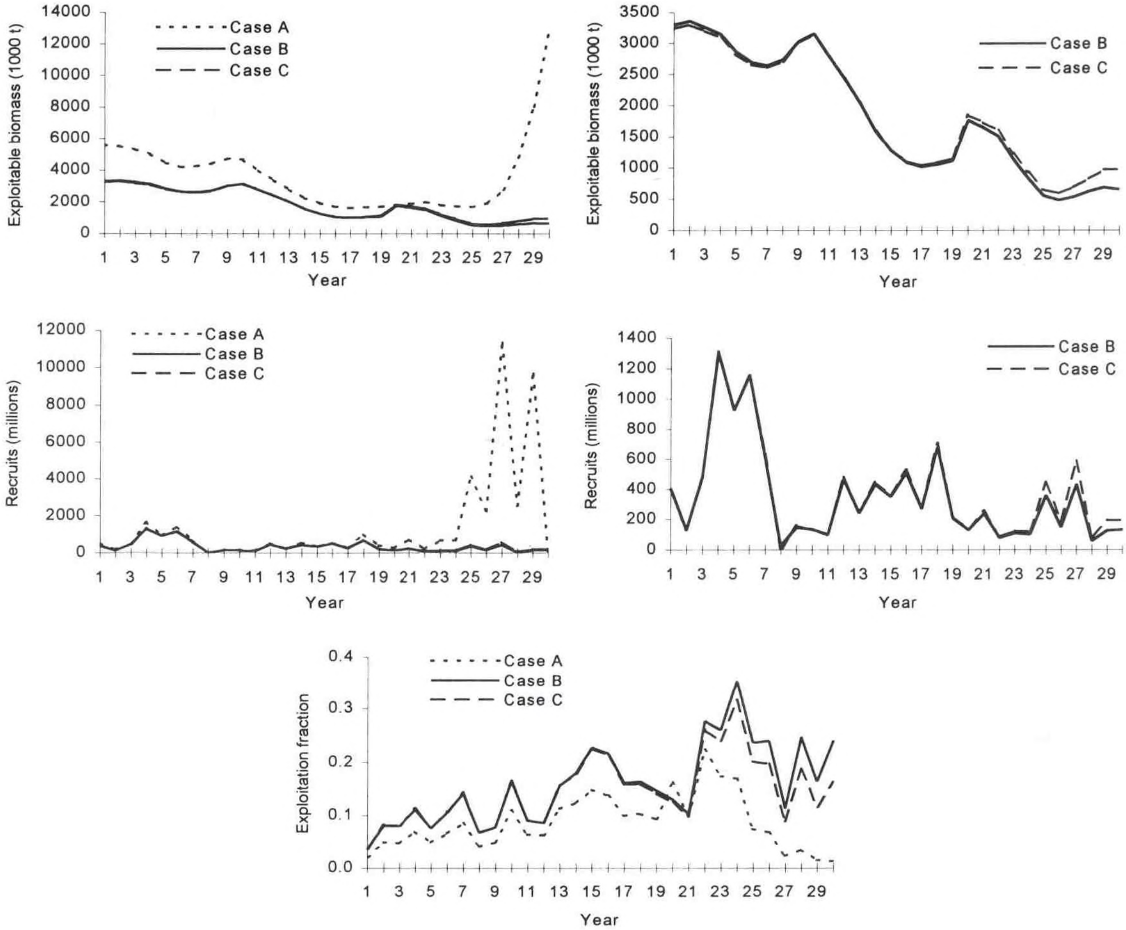


Figure 4. Estimates of exploitable biomass, recruitment, and exploitation rate by data set and case.

Data set 2



Data set 3

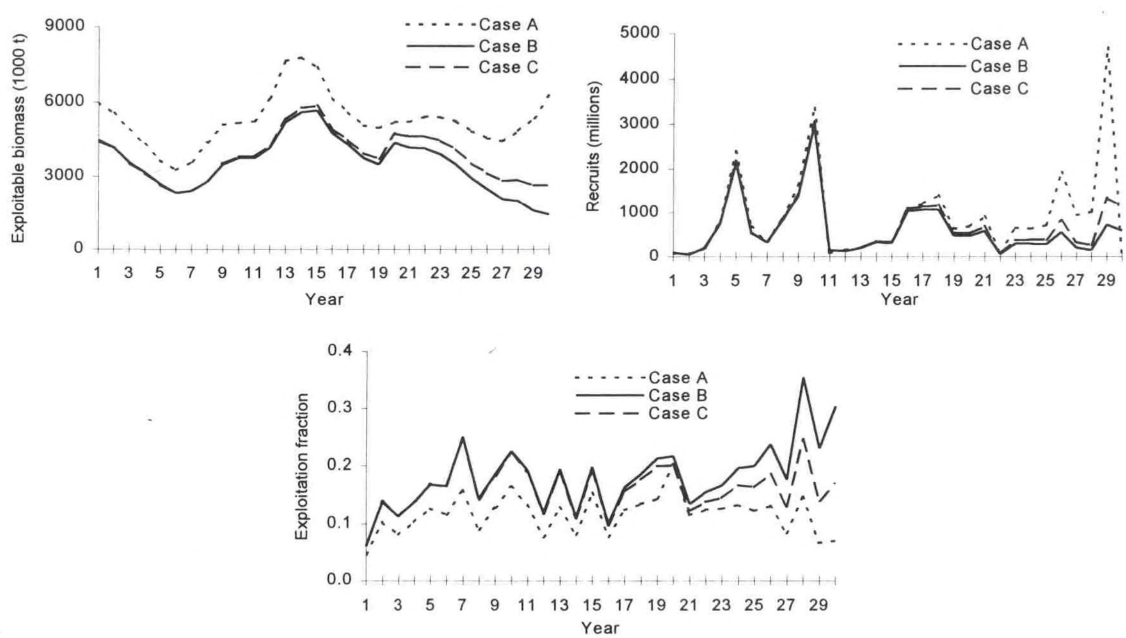


Figure 4 (cont.)

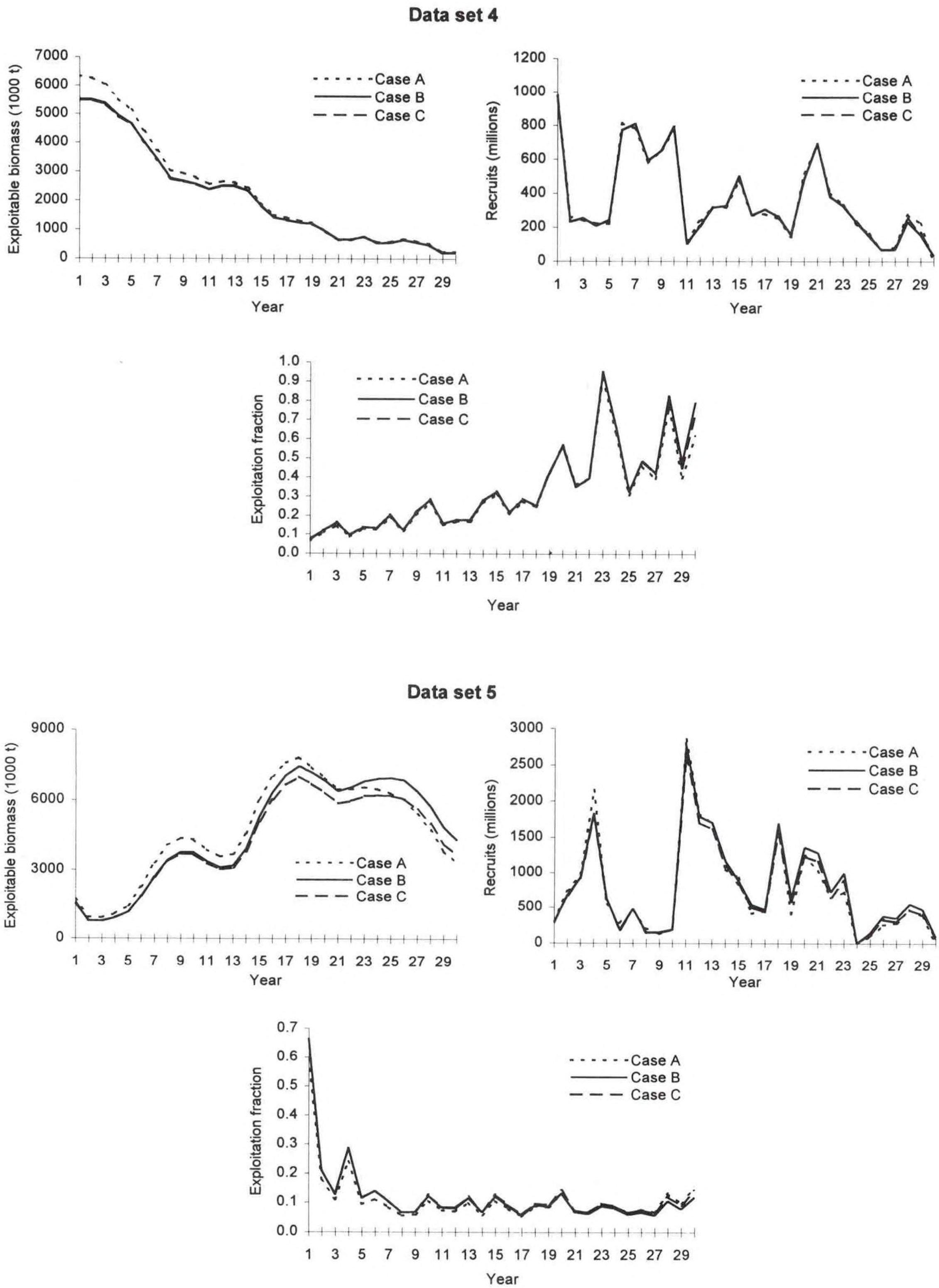


Figure 4 (cont.)

Table 1. Estimated values of age at 50% selectivity (A_{50}) and slope of selectivity function at A_{50} (β) for the fishery and survey data. Different selectivity was allowed for years 1-19, 20-30 for data sets 1-3, cases B-C.

	Fishery[1]		Fishery[2]		Survey[3]	
Case	A_{50}	β	A_{50}	β	A_{50}	β
1A	3.2	1.8	3.2	1.8		
1B	4.3	1.1	2.1	8.0	2.7	1.3
1C	4.3	1.1	2.1	8.0	2.8	1.3
2A	3.6	1.5	3.6	1.5		
2B	4.4	1.1	2.1	6.6	2.6	1.4
2C	4.4	1.1	2.1	7.0	2.6	1.4
3A	3.4	1.6	3.4	1.6		
3B	4.1	1.1	2.8	2.0	2.6	1.3
3C	4.1	1.1	2.8	2.1	2.6	1.3
4A	3.5	1.3	3.5	1.3		
4B	3.7	1.2	3.7	1.2	2.5	1.4
4C	3.7	1.2	3.7	1.2	2.5	1.4
5A	3.6	1.4	3.6	1.4		
5B	3.9	1.3	3.9	1.3	2.5	1.4
5C	3.9	1.3	3.9	1.3	2.4	1.4

[1] Years 1 to 19.
[2] Years 20 to 30.
[3] Years 1 to 30.

Data sets 1-3

Estimated exploitable biomass was larger for case A compared to cases B and C (Figure 4) for three reasons:

-1. Selection of young fish by the fishery increased starting in year 20. This change was accounted for in cases B and C but not A for reasons noted previously. By estimating separate selectivities in cases B and C, the increased proportions of young fish were interpreted as being due to increased selection of young fish. When no change in selectivity is allowed, as was the case in A, the increased proportions of young fish were interpreted as strong year classes. Consequently, larger recruitments and exploitable biomasses were estimated. To avoid this trap when using fishery data alone, the analyst must examine the spatial distribution of the fishery and fish sizes to determine why the proportion of young fish increased. Preferably, annual fishery-independent surveys should be conducted.

-2. The fishery abundance index appears less sensitive to apparent changes in abundance than the survey one. For example, the fishery abundance index decreases more slowly than does the survey abundance index. In general, a smaller change in an abundance index, given a fixed catch, implies a larger initial biomass. As a result, larger biomass values were estimated when using the fishery index alone.

-3. The fishery age compositions and the fishery abundance index are contradictory starting in year 20 if a constant fishery selectivity pattern is assumed for all 30 years: The age data imply that abundance is increasing whereas the index data (in numbers) imply that abundance remains steady. The estimated abundance trends follow the signal given by the age data because the latter comprise the most influential contribution to the likelihood. This was corroborated by noting that the fit to the fishery abundance index became poor after year 26 (Figure 5), at the expense of better fits to the age proportions. The age component was the largest part of the likelihood because multinomial sampling for age was assumed. Had there been additional sources of age sampling variability, the age component of the likelihood would have been less influential and a smaller final year biomass would have been estimated.

The estimate of survey catchability increased 45% from years 1-15 to 16-30 for data set 3. If the catchability change is not modeled, then abundance would be overestimated. A change in survey vessel should not result in such a large increase in catchability with experienced field biologists supervising vessel operations.

Abundance was increasingly difficult to estimate going from data set 1 to 2, to 3. The estimated exploitation fraction was smaller, and the abundance indices were noisier, for data set 2 than they were for set 1 (Figure 2). Estimation for data set 3 was made more difficult because the abundance indices were the most variable overall and because of the reported change in survey vessel after year 15.

<u>Data set 4</u>

Cases A-C all show that exploitable biomass is falling in agreement with the consistent signals in the fishery and survey age compositions, and the survey index (Figure 4). The fit of the fishery abundance index was again poor (Figure 5), implying that the fishery abundance index conflicted with the other information. Use of the fishery abundance index in the model results in a shallower decline in exploitable biomass. The case A results agree more with the fishery age composition data than with the fishery abundance index because the largest contribution to the likelihood is in the age components.

The historical catch for this simulated stock was not adjusted downward sufficiently to prevent the exploitation fraction from rising (Figure 4). This is interpreted as obvious mismanagement of the fishery, and no model would be necessary to conclude that the resource was being overexploited: The survey abundance index is sufficiently precise that examining the effect of catches on the index trends should be informative enough to reach the conclusion that the catches were too high. The same conclusion of mismanagement can be reached for data sets 1-2, and possibly 3.

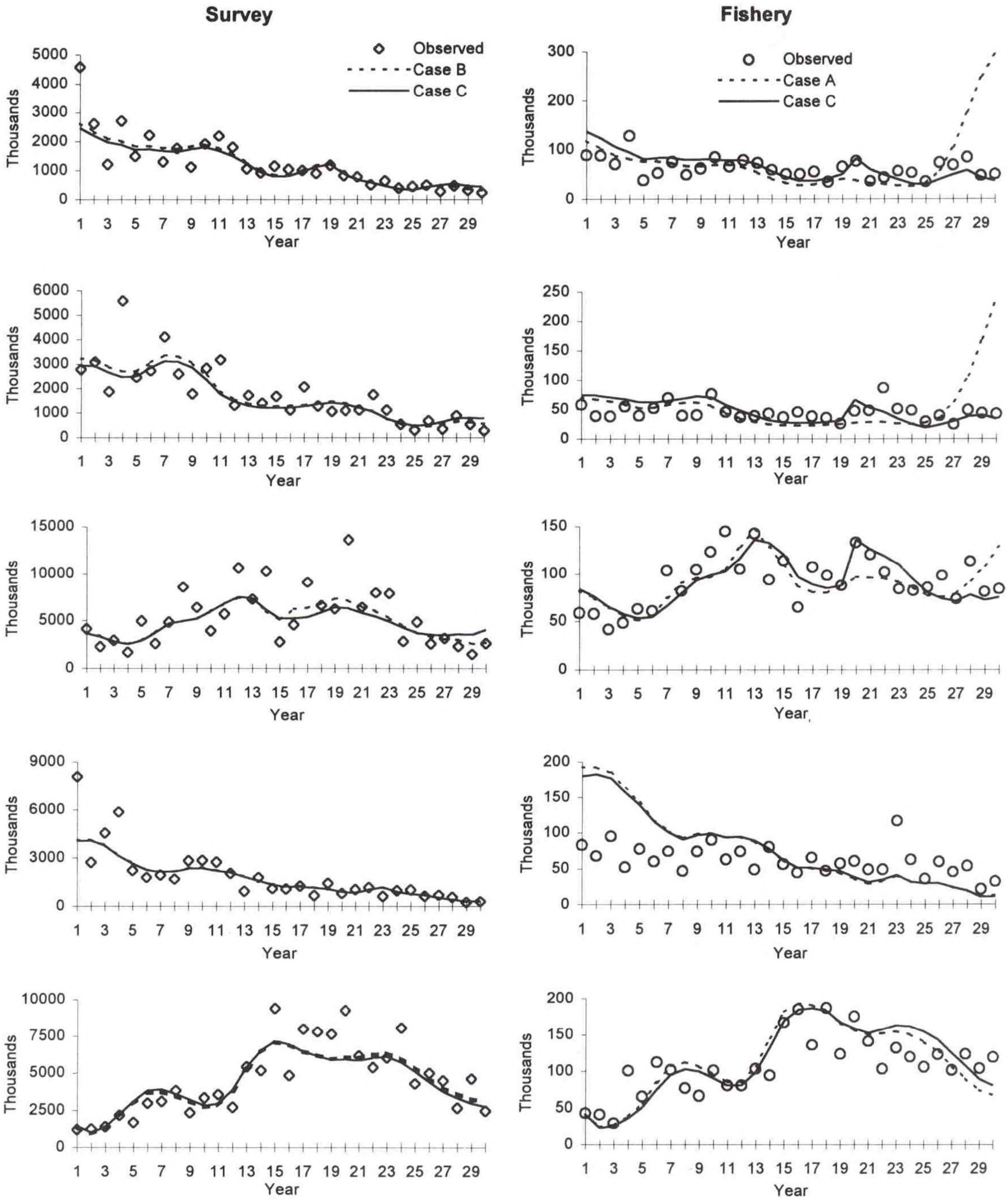


Figure 5. Annual observed and expected values of the abundance indices by data set (1 to 5, ordered from top to bottom) and case.

Data set 5

The observed fishery and survey abundance indices were generally in agreement (Figure 2). The apparent constant effort policy usually was effective at keeping the exploitation fraction constant as abundance and recruitment varied (Figure 4). Eventually, the fishery became more efficient even though the number of nominal boat-days remained steady, as indicated by a decline in the survey abundance index concurrent with a steady fishery abundance index (Figure 2).

Additional Analyses

Subsequent to the presentation of the above results to the NRC panel in May of 1996, the panel requested that additional analyses be made. Specifically, panel members provided a value of the average mortality rate underlying the simulated data, and asked for the computation of total allowable catches (TACs) under an $F_{40\%}$ strategy (one that would maintain equilibrium spawning biomass per recruit at 40% of its maximum). These additional analyses were carried out for case B with all data sets. Figure 6 shows the estimates of total biomass for two values of *M*: The "true" one of 0.225 yr^{-1}, and that which was assumed in previous analyses. The TACs corresponding to $F_{40\%}$ were (X 1000 mt): 54, 64, 150, 24, and 607 (for runs 1B to 5B) using the originally-assumed *M* values, and 43, 53, 202, 37, and 720 using the "true" *M.*

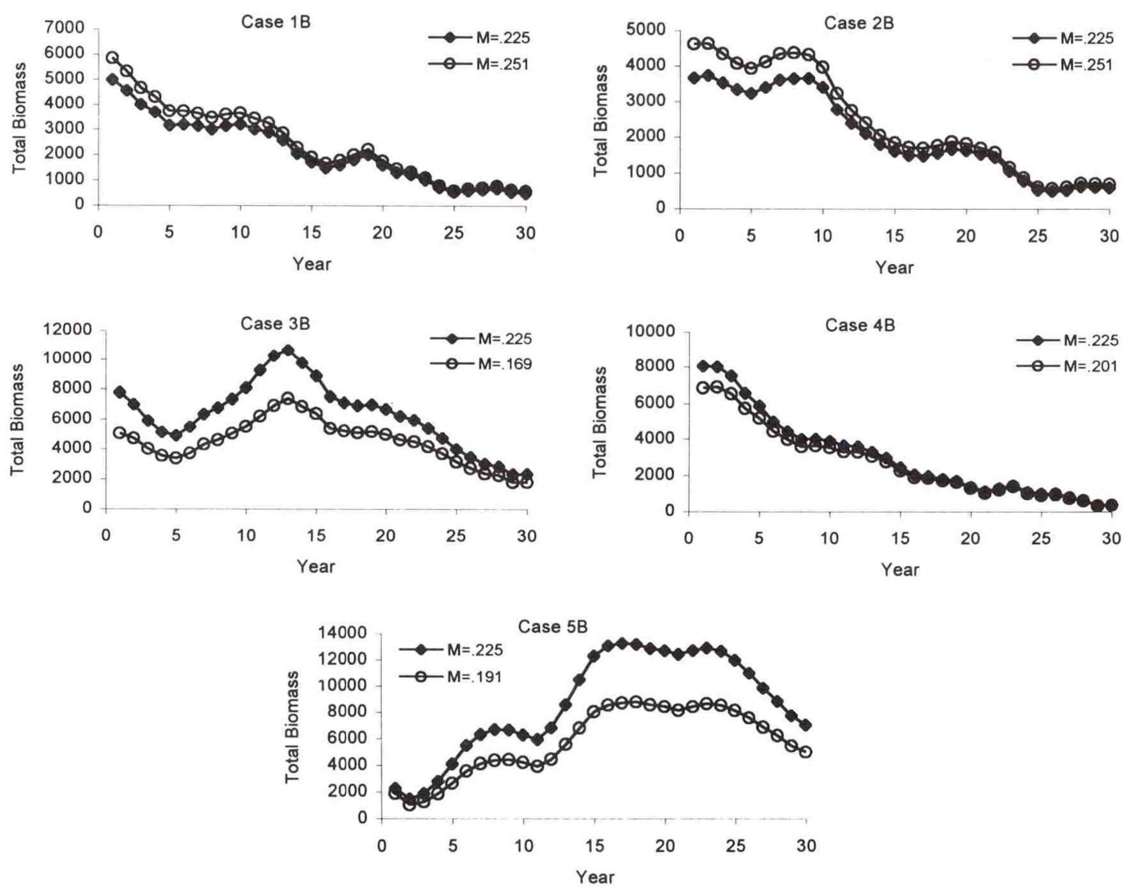


Figure 6. Estimates of total biomass (tons) by data set using survey data only. The plots compare results obtained with different assumed values of natural mortality, M.

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CHAPTER 6.

Application of Stock Synthesis to NRC Test Data Sets

Richard Methot

National Marine Fisheries Service, Northwest Fisheries Science Center, 2725 Montlake Blvd. E, Seattle, Washington 98112. Richard.Methot@noaa.gov

Introduction

In 1996, the National Research Council (NRC) panel on Stock Assessment Methods generated five simulated data sets for the purpose of testing the performance of various commonly-used stock assessment techniques. This paper presents an application of a model known as stock synthesis to the simulated data sets.

The stock synthesis model (Methot, 1989) was developed to provide a bridge between biomass-based assessment methods and full age-structured methods (Deriso, et al. 1985; Fournier and Archibald, 1982). Subsequently, synthesis evolved to a flexible tool for analysis of biomass, age-structure, and size-structure data (Methot, 1990) and has been used for many west coast and Alaska groundfish stock assessments during 1988-1997. In all configurations, synthesis maintains a full age-structured description of the population and employs conventional equations to describe the population dynamics. With an appropriate set of assumptions, the estimation process can be condensed to a few stock-recruitment parameters that mimic Stock Reduction Analysis (Kimura and Tagart, 1982). On the other extreme, inclusion of a vector of parameters to allow time-varying fishery selectivity allows synthesis to closely track fluctuations in a complete fishery catch-at-age database. In between is a simple age-structured model with constant age-specific selectivity that will be the primary focus of this exploration.

Synthesis, like most other modern assessment tools, is not a simple black-box with no flexibility in how to approach a problem. The number of possibilities that could be explored during the time devoted to this exercise was rather limited compared to the number of options available when using synthesis. In what follows, a brief overview of the synthesis model is first given to inform the reader about the basic model and some of its options. The paper then proceeds with a condensed presentation of the actual application to the NRC test data sets.

The Stock Synthesis Model

The overview of stock synthesis given here complements that in Methot (1990). Synthesis essentially consists of a forward population projection model that simulates the dynamics of a stock within a statistical estimation framework aimed at explaining, as well as possible, the observed fishery and survey data.

Basic population dynamics

The population simulation, in its simplest form, specifies the numbers-at-age in the beginning year of the simulation, the numbers of recruits in each subsequent year, and the survival rate for each cohort as it moves through the population:

a	= ages for $1 \le a \le A$,
y	= years for $1 \le y \le Y$,
j	= fisheries for $1 \le j \le J$,
M_a	= instantaneous rate of natural mortality,
$W_{y,a,j}$	= body weight at age for fishery or survey j,
$s_{a,j}$	= selectivity at age for fishery or survey j,
$f_{y,j}$	= annual fishing mortality factor for fishery j,
$F_{y,a,j} = f_{y,j}\, s_{a,j}$	= fishing mortality at age for fishery j,
$Z_{y,a} = M_a + \sum_j (F_{y,a,j})$	= total mortality rate,
$N_{y,a}$	= population numbers in year y, at age a,
$\bar{N}_{y,a} = N_{y,a}(1 - e^{-Z_{y,a}})/Z_{y,a}$	= mean numbers in year y,
$c_{y,a,j} = \bar{N}_{y,a} F_{y,a,j}$	= catch numbers for fishery j,
$C_{y,j} = \sum_a (c_{y,a,j}\, W_{y,a,j})$	= catch biomass for fishery or survey j,
$N_{y+1,a+1} = N_{y,a}\, e^{-Z_{y,a}}$	= survivors, for $a < A$, and
$N_{y+1,A} = N_{y,A-1}\, e^{-Z_{y,A-1}} + N_{y,A}\, e^{-Z_{y,A}}$	= survivors, for $a = A$.

Structural elaborations

The above equations define a situation in which both sexes are identical, mortality is continuous throughout the year, and all individuals of a given age have equal probability of surviving. Synthesis allows some relaxation of these conditions. First, the population numbers, weight-at-age, and selectivity can be sex-specific. Second, up to four time periods can be defined within a year so that certain fisheries can be restricted to the time period in which they actually occur. Third, up to three geographic areas can be created and each fishery is defined to occur in a particular area. In this situation, a fraction of the fish may be in an area that does not have high fishing mortality rates. If fish recruit into one or more areas, then age-specific migration functions move fish between areas. These elaborations to the model are not described further here.

Selectivity function

Selectivity is typically modeled in synthesis as the product of two logistic functions:

$$(1)\quad s_a = \frac{1}{(1+e^{-\alpha(a-\beta)})(1+e^{-\gamma(a-\delta)})}\,\frac{1}{\mu}$$

where α, β, γ, δ are parameters to be estimated by the model, and μ is a scaling factor such that $\max(s_a)$ is 1.0.

This four-parameter formulation allows the selectivity pattern to be dome-shaped or asymptotic on either the left or right side. The synthesis implementation allows the selectivity parameters to be time-invariant, time-invariant within defined ranges of years, year-specific, with a linear trend over a specific range of years, a function of an independent variable, or any combination of these options. Other formulations accessible in the synthesis implementation add additional parameters to define male selectivity relative to female selectivity, to have specific parameters that define selectivity at the minimum and maximum ages, and to define the specific age at which the selectivity reaches a maximum.

Recruitment and initial age composition

Synthesis includes the ability to define the initial age composition and all subsequent recruitments with many independent parameters (one for each year and for each age in the initial year), or to define all from a two-parameter stock-recruitment (S-R) function. The Beverton-Holt spawner-recruitment function is defined in synthesis according to Kimura (1988):

$$(2)\quad R_y = R_0 \frac{\dfrac{SB_{y-k}}{SB_0}}{1 - K\left(1 - \dfrac{SB_{y-k}}{SB_0}\right)}$$

where:

SB_{y-k}	= mature female biomass (or estimated total egg production),
k	= number of years between spawning and recruitment,
R_0	= initial recruitment parameter,
SB_0	= mature female biomass (or egg production) calculated from R_0 and natural mortality,
K	= parameter defining the degree of density-dependence.

All intermediate options are available so that some poorly estimable recruitments can be taken from the S-R function while others are estimated as individual parameters. When all recruitments are taken from the S-R function, synthesis essentially becomes an age-structured stock-reduction analysis (Kimura and Tagart, 1982) The manner in which the individually estimated recruitments are compared to the S-R function is described later.

The initial population age composition is defined by:

$$(3.1)\quad N_{1,a} = R_a \qquad \text{for } 1 \le a \le m,$$

$$(3.2)\quad N_{1,a} = R_0 \Pi e^{-Z_a} \qquad \text{for } m<a<A, \text{ and}$$

$$(3.3)\quad N_{1,a} = N_{1,A-1}\frac{e^{-Z_{A-1}}}{1-e^{-Z_A}} \qquad \text{for } a=A,$$

where:

R_0 and R_a	= parameters,
$Z_a = M_a + f_{0,1}s_{a,1}$,	using fishing mortality for fishery type 1,
$f_{0,1}$	= a parameter, or is set to match historical equilibrium catch level, and
m	= the last age for which an individual parameter is used, $1 \le m \le A$.

Observation process

Abundance index

Catch-per-unit-effort (CPUE) for a survey is expected to be proportional to the model's estimate of available biomass at the time of year of the survey:

$$(4)\quad \hat{G}_{y,j} = Q_j \sum\nolimits_a (\bar{N}_{y,a} s_{a,j} W_{y,a,j}) .$$

If the survey is expanded to a measurement of absolute biomass, then the constant of proportionality, Q_j, is 1.0 or some other externally derived value. Even in this case the $s_{a,j}$ still allow some ages to contribute less than fully to the survey. In most cases the survey CPUE is interpreted simply as a relative index of population biomass. In this case, the scaling factor is calculated so that the mean log deviation is zero:

$$(5)\quad Q_j = e^{[\sum_y \ln(G_{y,j}/\hat{G}_{y,j})/\sum_y 1]} ,$$

where the summation is over the years y for which CPUE observations are available.

For fishery CPUE or fishery effort, the treatment is similar to that for a survey, however it is important to consider the possibility of a non-linear relationship between the population variable and the observed index:

$$(6)\quad \hat{G}_{y,j} = Q_j(\hat{B}_{y,j})^{(1+P)} \quad = \text{the predicted value for fishery CPUE,}$$

$$(7)\quad \hat{E}_{y,j} = \frac{F_{y,j}}{\hat{G}_{y,j}} \quad = \text{the predicted value for fishery effort, } E,$$

F = the estimated fishing mortality rate for the age with selectivity equal to 1.0,

$\hat{B} = \sum_a \bar{N}_{y,a} s_{y,a,j} W_{y,a,j}$ = the estimated biomass that is selected by the fishery, and

P = a parameter that is commonly set to 0.0, but when estimated it provides for a non-linear relationship between fishery CPUE (or effort) and the biomass (or fishing mortality) available to the fishery.

Synthesis is configured to allow the user to input either fishery CPUE or fishery effort data, according to the specifications above.

Age composition

Observed fishery or survey age composition is compared to the model's estimate of catch age composition, $c_{y,i,j}$, after applying an ageing imprecision matrix to the $c_{y,a,j}$. Ageing imprecision causes strong year classes to smear into adjacent weaker year classes, and it flattens the overall vector of age composition (Tyler et al., 1989). Thus the level of ageing imprecision interacts with the variance of recruitment and with the slope of the selectivity functions. The elements of the matrix, $e_{i,a}$, define the probability that a fish sampled of true age class, a, would be aged into bin i. It is important to think of the observed "ages" simply as bins. This allows the bins to be defined in terms of nearly any transformation of age. The imprecision matrix may range from a one-to-one correspondence between a true age and a bin of measured age, to moderate imprecision in the measured age, to incorporation of bias and imprecision, and to the transformation of true ages into size bins (Methot, 1990). The level of ageing imprecision is commonly determined by the observed level of agreement between readers. When there are "age" data from multiple methods (i.e. otoliths, scales, fish length), then the simultaneous inclusion of each method's observation into synthesis assists in the cross-calibration of the methods.

Statistical model

The comparison between observed and expected values is quantified in terms of log(likelihood), λ. A separate likelihood component is defined for each data source and kind of observation. The total log-likelihood is the weighted sum of the individual components (indexed by l):

(8) $\lambda = \Sigma \omega_l L_l$

where:

λ = the total log-likelihood that will be maximized,
ω_l = a weighting factor for each likelihood component, and
L_l = the individual likelihood components, including:
- For each fishery:
  - catch,
  - effort or CPUE, and
  - age composition for each ageing method.
- For each survey:
  - total abundance, and
  - age composition for each ageing method.

Parameter penalty function for selected parameters.
Stock-recruitment:
deviations of individual years about estimated curve, and
deviations of S-R curve parameters from mean and variance of individual year estimates.

The log(likelihood) for a fishery CPUE observation or a survey abundance observation is defined as:

$$(9)\quad L_j = -0.5\,\Sigma_y\left[\left(\frac{\ln(G_{y,j}/\hat{G}_{y,j})}{\sigma_{y,j}}\right)^2 - \ln(\sigma_{y,j})\right],$$

where:

$G_{y,j}$ = observation,
$\sigma_{y,j}$ = standard error of $\ln(G_{y,j})$. It is preferable to use standard errors that are estimated from sampling statistics for each $G_{y,j}$. Alternatively, a single, fixed value of $\sigma_{y,j}$ can be used for the entire time series. Finally, synthesis can be instructed to use the root mean squared error of the model's current fit to the $G_{y,j}$ as the estimate of $\sigma_{y,j}$.

The log(likelihood) for the fit to an age composition observation from fishery or survey source *j* is defined by:

$$(10)\quad L_{y,j} = \upsilon_{y,j}\sum_i p_{y,i,j}\ln(\hat{p}_{y,i,j}),$$

where:

$\upsilon_{y,j}$ = assigned sample size for this observation (typically 200 fish, but should be scaled according to the variance of the sample according to sampling statistics),
$p_{y,i,j}$ = observed proportion in each age bin *i*, and
$\hat{p}_{y,i}$ = estimated proportion in each age bin *i*.

The likelihood components for the recruitment information is composed of two parts, either of which may be excluded from consideration by setting a nil emphasis ($\omega \sim 0$). The first of these components is for deviations between recruitment estimates for individual years and predicted values from the estimated stock-recruitment curve. Including this component in the estimation procedure tends to draw individual recruitment estimates towards the S-R curve unless there are data which indicate otherwise. It is defined as:

$$(11)\quad L_R = -0.5\,\Sigma_y\left[\left(\frac{\ln(R_y/\hat{R}_y)}{\sigma_R}\right)^2 - \ln(\sigma_R)\right],$$

where:

R_y = estimated recruitment in year *y*,

R_y = predicted recruitment in year y from the S-R relationship, and

σ_R = recruitment standard deviation (a model parameter).

The log-likelihood for the fit of the S-R curve to the estimated recruitments and for the difference between the recruitment standard deviation parameter and the standard deviation of the estimated recruitments is calculated as:

$$(12) \quad L_R = -0.5\left(\frac{(\sigma_R^{\prime} - \sigma_R)}{\sigma_R^2/r}\right)^2 - \ln(\sigma_R^2/r) - 0.5\left(\frac{D}{\sigma_R/r}\right)^2 - \ln(\sigma_R/r),$$

where:

D = sum of lognormal deviations = $\Sigma_y(\ln(R_y/\hat{R}_y))$,

r = number of estimated recruitments,

$\sigma_R^{\prime}$ = calculated root mean squared error R_y about predicted values = D/r.

Parameter priors

A Bayesian prior can be established for any parameter and entered into a log-likelihood component by:

$$(13) \quad L_l = -0.5\Sigma_b\left[\left(\frac{\ln(\theta_b/\hat{\theta}_b)}{\sigma_\theta}\right)^2\right],$$

where:

b indexes parameters for which a prior is defined,

θ_b = parameter value,

$\hat{\theta}_b$ = prior value for parameter, and

$\sigma_{\theta b}$ = standard deviation for parameter prior.

Parameter estimation

The total log(likelihood), λ, is maximized by iterative application of the inverse Hessian method. In this application, the first and second derivatives of λ with respect to each parameter, and the mixed partial derivatives for each parameter combination are approximated by recalculating λ after small tweaks to each parameter. Then the entire parameter vector is adjusted to move towards the point where all first derivatives got to zero. Parameter variances can be obtained from the inverse of the Hessian matrix.

Synthesis Model Configuration for NRC Data

Five data sets were supplied by the NRC, each containing a series of fishery CPUE and survey CPUE. These were relabeled for use in synthesis according to the following nomenclature.

Data files:

A1	data set 1.
A2	data set 2.
A3	data set 3.
A3A	data set 3, with survey time series broken into two periods at year 16.
A4	data set 4.
A5	data set 5.

(Note: For conformity with A3A, other data and parameter files have a dummy second survey defined.)

Each data set was analyzed with a hierarchy of model configurations. The simplest configurations (P01 and P02 below) ignored the age-composition data, set fishery or survey selectivity to be knife-edge at a reasonable age after inspection of the age data, used fishery effort or survey CPUE to indicate trends in fishing mortality or in population biomass, respectively, and set each year's recruitment equal to the predicted value from an estimated Beverton-Holt (B-H) stock-recruitment function (equation 2). In this configuration, the only parameters to be estimated by the model are the 2 parameters of the B-H curve and the fishing mortality rate for each year. This configuration is essentially the same as Stock Reduction Analysis (Kimura, 1982). An additional configuration that could have been included would have allowed the model to estimate annual recruitment values, but still not include the age composition data. Such a configuration would be functionally similar to a delay-difference (Deriso, 1980) class of model.

Configurations P03-P07 used the age composition data in addition to the effort and/or CPUE index. These configurations allowed estimation of the initial age composition and the recruitment in each year. Configurations that used the fishery effort as the tuning index (*-F*) did not include either the survey biomass or the survey age composition. Configurations that used the survey biomass as the tuning index (*-S*) did not include the fishery effort data, but did include the fishery age composition. The most complex configuration (P05) used both data sources (*-B*), with associated age composition data, and estimated each year's recruitment, time-varying fishery selectivity and biomass-varying fishery catchability coefficient ("bio-Q", i.e. estimating the parameter P in equation 6). The P07 configuration is more parsimonious than P05, while addressing major issues that could affect results.

Synthesis model configurations used on each data set:

Parameter file	Tune to fishery or survey	Recruitment estimates	Fishery selectivity	Fishery catchability
*-B.P01	Both	B-H	Knife-edge	constant
*-B.P02	Both	B-H	Knife-edge	bio- Q
*-B.P03	Both	each yr	constant	constant
*-B.P04	Both	each yr	each yr	constant
*-B.P05	Both	each yr	each yr	bio-Q
*-B.P06	Both	each yr	constant	bio-Q
*-B.P07	Both	each yr	two periods	bio- Q

Configurations (cont.)

Parameter file	Tune to fishery or survey	Recruitment estimates	Fishery selectivity	Fishery catchability
*-F.P01	Fishery	B-H	Knife-edge	constant
*-F.P03	Fishery	each yr	constant	constant
*-F.P06	Fishery	each yr	constant	bio-Q
*-S.P01	Survey	B-H	Knife-edge	constant
*-S.P03	Survey	each yr	constant	constant

Some particular aspects of the implementation for the NRC exercise are described below:

1. Natural mortality is set equal to 0.20 yr^{-1}. Values ranging from 0.16 to 0.25 were investigated in auxiliary runs.

2. Body weight-at-age and percent maturity-at-age are taken from the NRC data files. The weight-at-age vector applies to month 1 and is linearly interpolated to other months of the year when computing population biomass. The input weight-at-age vector is used directly for the fishery and survey. Note that this interpretation of the supplied weight-at-age vector and the seasonal growth pattern may not be optimally configured.

3. Catch biomass ($C_{y,j}$) is assumed to be known without error, and the model is configured to calculate a fishing mortality value for each year such that the model's estimate of catch biomass exactly matches the observed catch biomass. The selectivity pattern for the fishery is double logistic as in equation (1). For this investigation, the function was defined to be asymptotic so only the ascending inflection age and slope are estimated. The log-likelihood multiplier (ω) for deviations in fit to catch biomass was 1.0. The standard deviation used in calculating the likelihood of a catch deviation was set at 0.10 (note that catch deviations occur only when the fishing mortality needed to match a particular year's observed catch biomass would exceed the maximum fishing mortality, set at 2.5 in this exercise).

4. The matrix describing the probability distribution of assigned age for each true age is taken from the NRC data file. From the synthesis perspective, the ageing transition matrix defines the probability distribution of assigned ages for a fish of a given true age. Commonly this matrix is generated within synthesis from user supplied information on the degree of repeatability of age assignment between readers. Another option, which was used here, allows the user to supply synthesis with the full matrix of probability distributions. A likelihood component is defined for the third age type (biased ages) and the emphasis is set to 1.0.

5. The expected value for fishery effort data is assumed proportional to a function of the estimated fishing mortality rate (equations 6 and 7). A likelihood component is defined for the fit to the fishery effort data. The emphasis is 1.0 and the

error is taken from the RMSE of the current fit to the data (assuming lognormal error structure), i.e. we use iterative re-weighting for this likelihood component. There are two parameters. The first is mean Q and it is automatically adjusted to achieve a mean deviation of 0.0. The second parameter defines the degree to which Q varies with the level of biomass available to the fishery (equation 6). A negative value indicates that Q increases as the biomass decreases.

6. Recruitments are estimated individually for each year and compared to an estimated Beverton-Holt spawner-recruitment function, except in the simple model configurations (P01 and P02) where the recruitments are all taken directly from the estimated spawner-recruitment curve. A prior of 0.9 is set for the shape parameter, K, of the Beverton-Holt curve according to Kimura's re-parameterization (see equation 2).

7. In configurations for which the model will be estimating recruitments for each year (P03 to P07), the estimated age composition in year 1 for ages 1-15+ is calculated from the estimated "virgin" recruitment level from the estimated spawner-recruitment curve, and from a mortality level equal to natural mortality plus an estimated level of initial fishing mortality (see equation 3). The age composition for ages 1-8 is then replaced by values from individually estimated parameters. Synthesis allows none to all of these initial individual age values to be estimated. Selection of 8 ages to estimate individually was based on inspection of the data with an objective of parsimony.

8. The total log-likelihood being maximized, λ, is a weighted sum of individual log-likelihood components (L_l) as explained in the previous section (equation 8). The weighting factors (ω) took a value of 1.0 for included components and 0.0001 for components that were excluded (e.g. given a nil emphasis). Individual likelihood components were:

$l = 1 =$ Fishery catch (lognormal).
$l = 2 =$ Fishery effort (lognormal).
$l = 3 =$ Fishery age composition (multinomial).
$l = 4 =$ Survey total biomass (lognormal).
$l = 5 =$ Survey age composition (multinomial).
$l = 6 =$ Survey 2 total biomass (for years 16-30 in data set 3) (lognormal).
$l = 7 =$ Survey 2 age composition (for years 16-30 in data set 3) (multinomial).
$l = 8 =$ Parameter penalty function for selected parameters.
$l = 9 =$ Stock-recruitment: deviations of individual years about estimated curve (lognormal).
$l = 10 =$ Stock-recruitment: deviations of S-R curve parameters from mean and variance of individual year estimates.

Results

Age composition example

The model estimates a time series of population numbers-at-age (Figure 1) from which expected values for all types of samples are derived. Within each year, fishery and survey selectivity vectors are used to calculate the sample age composition for each in terms of true age. This sample age composition is then processed through the ageing transition matrix to produce the estimate of the expected age composition in terms of the ageing method being used. These steps are illustrated in Figure 2. The expected age composition is compared to the observed age composition according to a multinomial error structure.

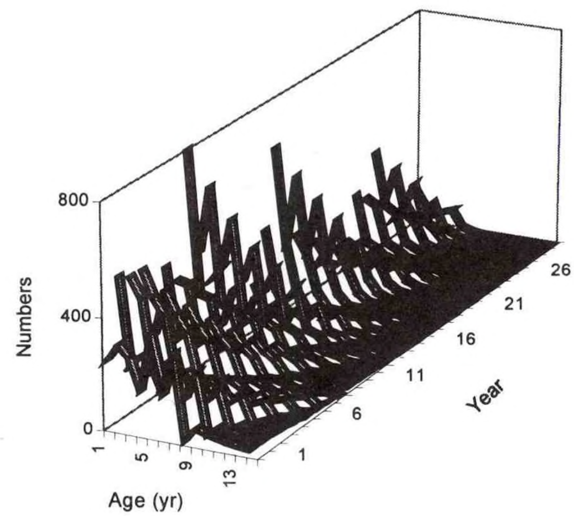


Figure 1. Estimated time series of population numbers-at-age for model run A1-B.P06.

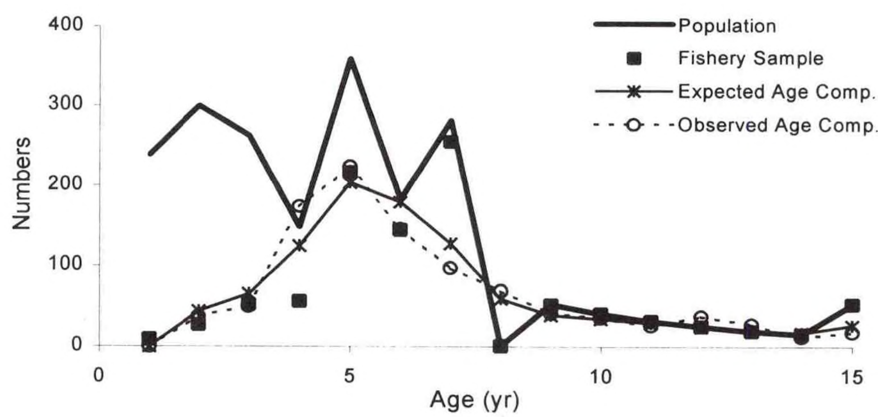


Figure 2. Population and fishery age-composition in year 1 of model run A1-B.P06. Fishery sample (squares) is derived from population estimates (thick line) by applying the estimated selectivity vector. The expected composition is derived from the sample by applying the ageing error transition matrix.

The sample sizes, υ, for the fishery age composition were 500 fish per annual observation, and the sample size was 200 for the survey age compositions. The mean squared error (MSE) of the residuals between the observed and expected proportions per age bin allow calculation of an effective sample size. The effective sample size for the fishery age composition data for run A1-B.P06 ranged from 38 to 1794 with an average of 276 (Figure 3). The effective sample size to the survey age composition data for run A1-B.P06 ranges from 96 to 1484 with an average of 311. In model run A1-B.P05, the inflection age for fishery selectivity was allowed to vary annually (except one value for last 4 years of the time series). In this case, the mean effective sample size for the fit to the fishery age composition increases to 545. This similarity between the actual and estimated effective sample sizes suggests that the model is not "over-parameterized". Rather, sufficient model structure has been provided to capture the major features of the data with a biologically realistic framework.

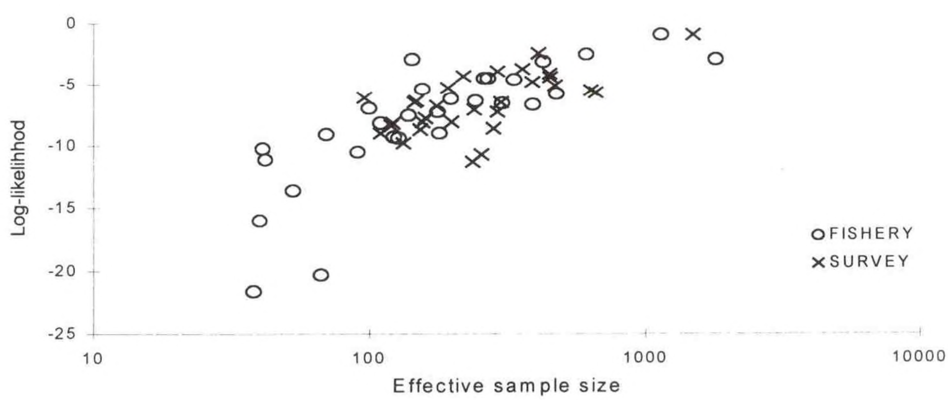


Figure 3. Relationship between multinomial log-likelihood (with N = 200 fish) and the effective N for fits to the fishery and survey age-composition for run A1-B.P06.

<u>Summary results</u>

The result of each model configuration for each data set is summarized in Tables 1-3. These tables report the log-likelihood for each component and the beginning and ending biomass values. Figures 4-9 display the fit to the fishery effort and the survey CPUE and show the resulting estimates of recruitment and spawning biomass. For clarity, only 5 of the 12 model configurations are shown in these figures.

The results from analysis of data set 1 illustrate some general patterns found in analysis of each data set. With an equilibrium recruitment model and only fishery effort data (A1-F.P01) the log-likelihood for the effort data was relatively close to the fit achieved by the best model (Table 1). However, there is a poor (but de-emphasized) fit to the fishery age composition and the survey data. With addition of the fishery age composition data and with estimation of year-specific recruitment (A1-F.P03) there is a much improved fit to the fishery age composition and a degraded fit to the effort data (Table 1). With addition of the biomass-varying fishery catchability coefficient (A1-

F.P06), the fit to both effort and age composition data improves and the estimate of ending biomass declines. The fits to survey data under equilibrium (A1-S.P01) or year-specific recruitment (A1-S.P03) had good fits to the survey CPUE, lower ending biomass than the fishery-tuned runs, and implied poor fits to the fishery effort time series. With the use of both fishery and survey data, model results tended to follow the survey data even when the bio-Q parameter was not estimated. This probably occurs because the fishery and survey age composition data are unbiased, such that they are consistent with the survey CPUE time series. With estimation of the bio-Q parameter (A1-B.P06) the model is able to simultaneously fit both the fishery effort and survey CPUE data. The most fully parameterized model (A1-B.P05) had annually varying fishery selectivity and achieved much improved fits to the fishery age-composition data. However, this improved fit was not accompanied by substantial change in the estimated population abundance. This general result held for data sets 2, 4, and 5.

Table 1. Log-likelihood values and total biomass estimates in years 1 and 30 for each model run on data sets 1 and 2. Values in parenthesis had nil weighting (ω = 0.0001) so did not affect the total log-likelihood.

		Fishery			**Survey 1**		**Survey 2**			**Recruitment**		**Biomass**	
Run name	Total *L*	Catch	Effort	Age com-position	Bio-mass	Age com-position	Bio-mass	Age com-position	Penal-ty	Each	Mo-ments	Yr 1	Yr 30
a1-B.p01	31.8	0.0	26.3	-(1371.4)	5.8	-(1072.9)	--	--	0.0	0.0	0.0	2915	871
a1-B.p02	43.0	0.0	27.2	-(1472.8)	16.1	-(1116.3)	--	--	0.0	0.0	0.0	2737	314
a1-B.p03	-402.5	0.0	-1.9	-239.4	23.9	-193.8	--	--	-0.1	-0.6	8.2	4074	544
a1-B.p04	-271.7	0.0	2.2	-134.3	25.6	-176.0	--	--	0.0	1.1	8.4	3976	421
a1-B.p05	-240.1	0.0	32.6	-132.6	26.3	-177.1	--	--	-0.1	1.1	8.4	4006	365
a1-B.p06	-369.1	0.0	30.4	-238.5	25.5	-195.5	--	--	-0.1	-0.4	8.2	4098	457
a1-B.p07	-324.1	0.0	30.7	-209.9	26.4	-181.8	--	--	0.0	0.8	8.3	3981	357
a1-F.p01	28.1	0.0	28.4	-(1366.7)	(1.9)	-(1073.8)	--	--	0.0	0.0	0.0	2942	1168
a1-F.p03	-208.7	0.0	3.6	-216.2	(10.3)	-(285.2)	--	--	-0.1	-3.8	7.9	4476	1433
a1-F.p06	-177.8	0.0	30.5	-214.9	(21.9)	-(282.0)	--	--	-0.1	-1.4	8.1	4526	636
a1-S.p01	17.1	0.0	(2.2)	-(1399.0)	17.4	-(1083.1)	--	--	0.0	0.0	0.0	2857	242
a1-s.p03	-399.5	0.0	-(3.8)	-238.5	25.6	-195.6	--	--	-0.1	-0.4	8.2	4098	447
a2-B.p01	20.7	0.0	15.5	-(1321.2)	5.9	-(1296.9)	--	--	-0.4	0.0	0.0	2551	794
a2-B.p02	39.2	0.0	23.2	-(1379.4)	16.7	-(1335.8)	--	--	-0.5	0.0	0.0	2559	213
a2-B.p03	-426.6	0.0	-2.2	-224.0	16.5	-218.5	--	--	-0.1	-7.1	7.5	2879	611
a2-B.p04	-312.9	0.0	3.1	-139.5	18.6	-198.4	--	--	0.0	-5.7	7.7	2696	432
a2-B.p05	-284.2	0.0	29.9	-137.4	19.7	-199.7	--	--	0.0	-5.6	7.7	2719	319
a2-B.p06	-394.8	0.0	28.1	-222.6	18.7	-220.5	--	--	-0.1	-7.2	7.5	2909	448
a2-B.p07	-345.1	0.0	28.9	-191.6	19.6	-204.6	--	--	0.0	-6.4	7.6	2756	313
a2-F.p01	19.5	0.0	20.2	-(1220.3)	-(2.5)	-(1260.4)	--	--	-0.4	0.0	0.0	3392	1708
a2-F.p03	-189.9	0.0	3.3	-190.9	(2.0)	-(342.3)	--	--	-0.1	-9.5	7.3	3438	2343
a2-F.p06	-163.9	0.0	27.0	-191.6	(16.1)	-(323.0)	--	--	-0.1	-6.7	7.6	3483	666
a2-S.p01	16.1	0.0	-(2.8)	-(1335.0)	16.8	-(1317.0)	--	--	-0.5	0.0	0.0	2647	202
a2-S.p03	-422.9	0.0	-(4.9)	-221.6	18.6	-221.3	--	--	-0.1	-7.2	7.5	2913	459

Equilibrium recruitment configurations

The performance of the model without estimating annual recruitment levels was mixed. For data sets 1, 2, and 4 the equilibrium recruitment result produced an ending biomass that was comparable to that produced with variable recruitment. For data set 5, the equilibrium result produced an ending biomass that was about twice that in the variable recruitment configuration. For data set 3, the equilibrium recruitment result was

Table 2. Log-likelihood values and total biomass estimates in years 1 and 30 for each model run on data sets 3 and 3A. Values in parenthesis had nil weighting so did not affect the total log-likelihood.

		Fishery			**Survey 1**		**Survey 2**			**Recruitment**		**Biomass**	
Run name	Total L	Catch	Effort	Age composition	Biomass	Age composition	Biomass	Age composition	Penalty	Each	Moments	Yr 1	Yr 30
a3-B.p02	35.3	0.0	32.7	-(1422.7)	3.0	-(1581.4)	--	--	-0.1	0.0	0.0	239345	81969
a3-B.p03	-407.0	0.0	26.9	-205.4	8.9	-230.8	--	--	0.0	-14.7	6.8	5881	5058
a3-B.p04	-337.6	0.0	27.8	-145.5	11.0	-226.7	--	--	0.0	-12.4	7.0	5608	3684
a3-B.p05	-328.2	0.0	33.0	-144.6	11.8	-224.0	--	--	0.0	-12.7	7.0	5562	2172
a3-B.p06	-397.5	0.0	31.9	-206.1	10.6	-227.5	--	--	-0.1	-14.5	6.8	5916	2893
a3-B.p07	-371.4	0.0	32.8	-184.3	11.8	-225.1	--	--	-0.1	-14.4	6.8	5652	1998
a3-F.p01	32.4	0.0	32.8	-(1412.9)	(3.1)	-(1589.8)	--	--	-0.1	0.0	0.0	259548	105702
a3-F.p03	-162.2	0.0	27.2	-181.9	(6.4)	-(314.4)	--	--	-0.1	-14.2	6.8	7095	7595
a3-F.p06	-156.9	0.0	31.1	-180.9	(8.6)	-(348.8)	--	--	-0.1	-13.8	6.9	7102	4041
a3-S.p01	2.6	0.0	(32.5)	-(1392.5)	3.0	-(1538.7)	--	--	-0.1	0.0	0.0	102474	44433
a3-S.p03	-429.5	0.0	(15.9)	-206.2	10.5	-227.7	--	--	-0.1	-14.1	6.8	5943	2691
a3A-B.p01	36.4	0.0	32.6	-(1422.2)	4.1	-(958.7)	-0.4	-615.4	-0.1	0.0	0.0	220142	70486
a3A-B.p02	36.4	0.0	32.6	-(1502.4)	4.2	-(983.1)	-0.4	-602.3	-0.1	0.0	0.0	138806	55930
a3A-B.p03	-397.6	0.0	26.4	-200.9	7.6	-107.7	1.7	-116.1	0.0	-15.3	6.7	6084	5851
a3A-B.p04	-334.3	0.0	26.5	-145.2	7.7	-106.2	4.5	-115.9	0.0	-12.6	7.0	5738	3742
a3A-B.p05	-320.7	0.0	31.8	-144.2	7.6	-105.8	10.0	-114.2	-0.1	-12.8	6.9	5797	1556
a3A-B.p06	-387.1	0.0	31.0	-204.0	7.4	-108.5	8.3	-113.7	-0.1	-14.4	6.8	6177	2277
a3A-B.p07	-364.5	0.0	32.0	-184.3	7.6	-106.2	10.1	-116.3	-0.2	-14.1	6.8	5833	1582
a3A-F.p01	32.4	0.0	32.8	-(1413.0)	(4.1)	-(960.1)	-0.3	-628.8	-0.1	0.0	0.0	309707	102987
a3A-F.p03	-162.1	0.0	27.3	-182.1	(7.6)	-(139.4)	0.6	-175.6	-0.1	-14.0	6.8	7127	7624
a3A-F.p06	-156.8	0.0	31.1	-180.9	(7.4)	-(142.7)	4.5	-202.2	-0.1	-13.7	6.9	7076	4128
a3A-S.p01	10.9	0.0	-(6.2)	-(3315.0)	2.5	-(1052.6)	9.1	-1368.2	-0.1	0.0	0.0	3370	633
a3A-S.p03	-418.3	0.0	(11.4)	-203.9	7.4	-109.2	8.3	-113.5	-0.1	-14.1	6.8	6215	2272

Table 3. Log-likelihood values and total biomass estimates in years 1 and 30 for each model run on data sets 4 and 5. Values in parenthesis had nil weighting so did not affect the total log-likelihood.

		Fishery			**Survey 1**		**Survey 2**			**Recruitment**		**Biomass**	
Run name	Total L	Catch	Effort	Age composition	Biomass	Age composition	Biomass	Age composition	Penalty	Each	Moments	Yr 1	Yr 30
a4-B.p02	40.3	0.0	29.5	-(2623.4)	11.4	-(1492.8)	--	--	-0.1	0.0	0.0	2813	288
a4-B.p03	-314.4	0.0	-5.7	-141.2	19.6	-201.6	--	--	-0.1	4.6	8.7	6152	346
a4-B.p04	-276.3	0.0	-3.5	-110.1	19.5	-195.9	--	--	-0.1	3.9	8.6	6035	374
a4-B.p05	-241.7	-0.1	30.6	-109.1	19.3	-194.5	--	--	-0.1	2.4	8.5	6096	321
a4-B.p06	-278.2	-0.6	29.7	-138.8	19.5	-202.4	--	--	-0.1	4.5	8.7	6183	301
a4-B.p07	-273.8	0.0	29.3	-139.4	19.2	-197.2	--	--	-0.1	4.3	8.7	6113	275
a4-F.p01	18.4	0.0	18.9	-(2391.7)	(4.3)	-(1387.0)	--	--	-0.1	0.0	0.0	2874	750
a4-F.p03	-119.8	0.0	-6.4	-131.3	(19.9)	-(251.2)	--	--	-0.1	8.9	9.1	6676	348
a4-F.p06	-88.3	0.0	29.0	-136.4	(19.4)	-(270.0)	--	--	-0.1	9.9	9.2	6790	283
a4-S.p01	11.9	0.0	(6.5)	-(2003.4)	12.3	-(1165.0)	--	--	-0.1	0.0	0.0	3158	242
a4-S.p03	-308.9	0.0	-(6.4)	-138.7	19.5	-204.6	--	--	-0.1	4.9	8.7	6210	315
a5-B.p01	36.5	0.0	25.1	-(1969.3)	11.8	-(1797.8)	--	--	0.0	0.0	0.0	2340	16633
a5-B.p02	38.2	0.0	25.7	-(2114.1)	12.9	-(1715.7)	--	--	-0.1	0.0	0.0	2350	8642
a5-B.p03	-361.4	0.0	19.2	-199.8	26.2	-204.2	--	--	-0.1	-11.1	7.1	1849	3739
a5-B.p04	-311.4	0.0	20.7	-151.4	26.0	-204.0	--	--	-0.1	-11.0	7.2	1864	3854
a5-B.p05	-297.2	0.0	32.9	-150.3	26.8	-204.4	--	--	-0.1	-10.6	7.2	1822	4749
a5-B.p06	-346.3	0.0	32.9	-199.0	27.2	-205.4	--	--	-0.1	-10.4	7.2	1821	4683
a5-B.p07	-346.0	0.0	32.9	-198.3	27.2	-205.7	--	--	-0.1	-10.5	7.2	1816	4664
a5-F.p01	25.1	0.0	25.5	-(1831.7)	(10.4)	-(1744.1)	--	--	0.0	0.0	0.0	4565	19032
a5-F.p03	-165.9	0.0	19.7	-181.9	(24.6)	-(282.9)	--	--	-0.1	-10.8	7.2	1954	3666
a5-F.p06	-150.8	0.0	32.8	-180.9	(27.3)	-(281.2)	--	--	-0.1	-9.8	7.3	1879	5574
a5-S.p01	12.6	0.0	(23.8)	-(2008.3)	13.1	-(1633.2)	--	--	-0.1	0.0	0.0	2081	9066
a5-S.p03	-379.1	0.0	(16.5)	-198.8	27.1	-205.1	--	--	-0.1	-10.8	7.2	1819	4330

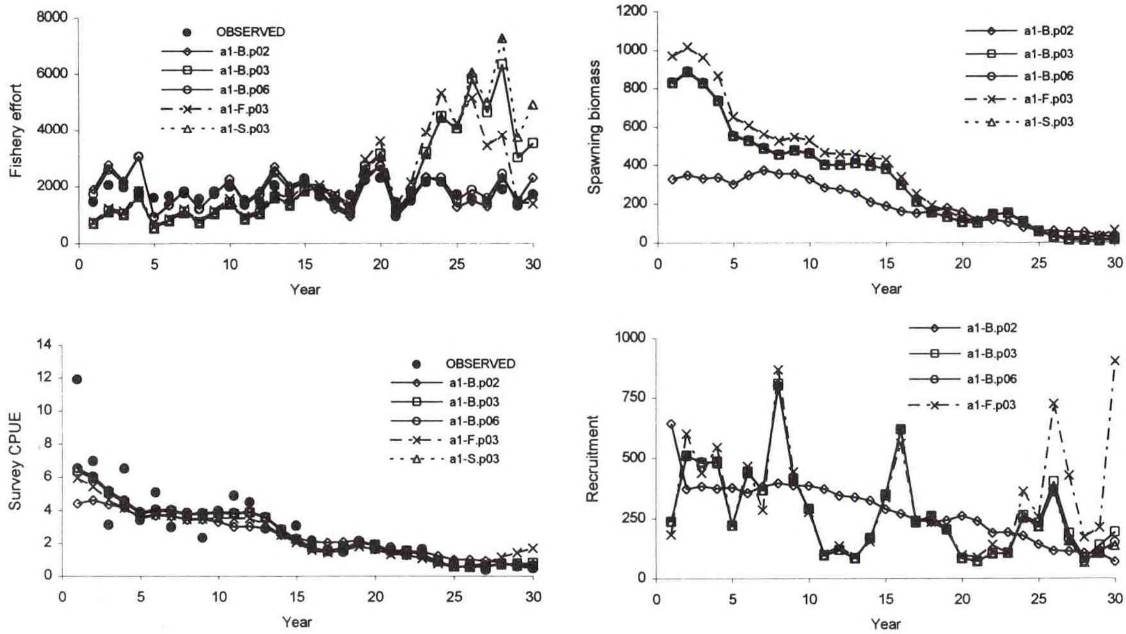


Figure 4. Fit to fishery effort and survey CPUE for 5 of 12 model configurations using data set 1. Estimated recruitment and spawning biomass are shown in right-hand panels.

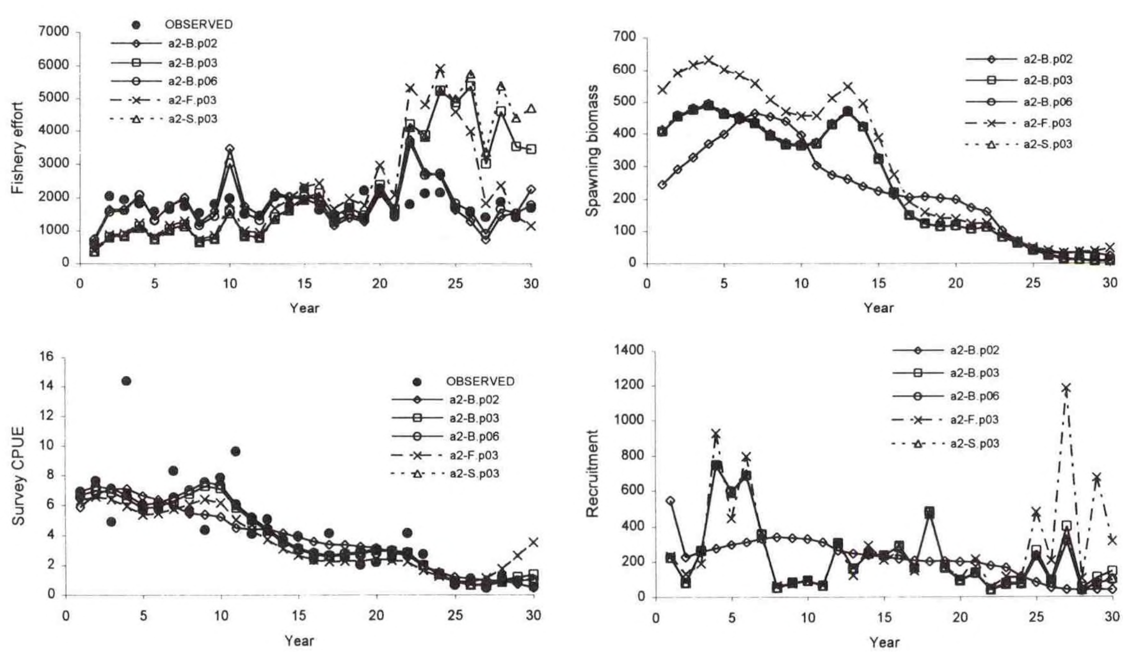


Figure 5. Fit to fishery effort and survey CPUE for 5 of 12 model configurations using data set 2. Estimated recruitment and spawning biomass are shown in right-hand panels.

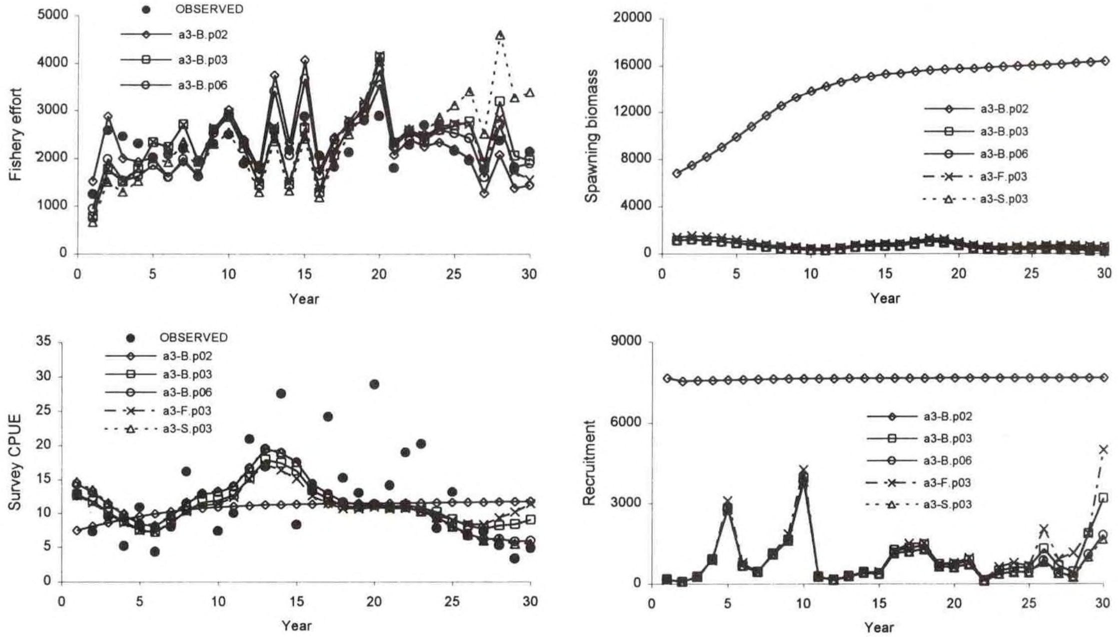


Figure 6. Fit to fishery effort and survey CPUE for 5 of 12 model configurations using data set 3. Estimated recruitment and spawning biomass are shown in right-hand panels.

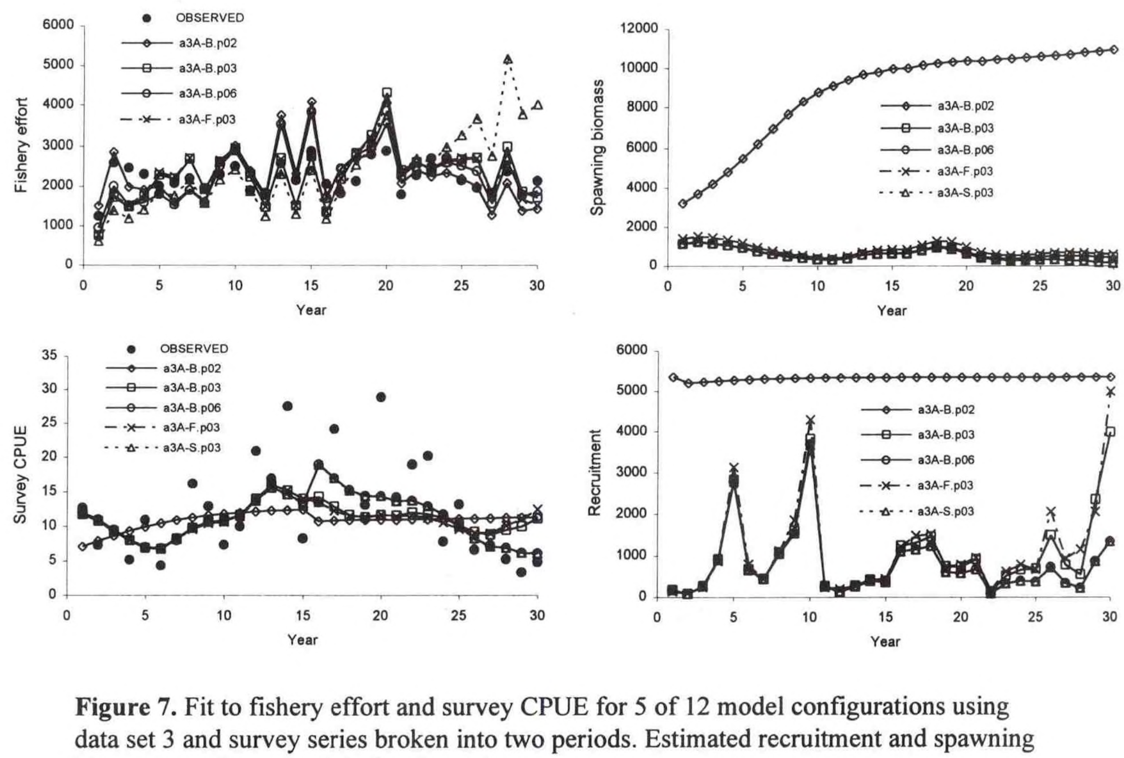


Figure 7. Fit to fishery effort and survey CPUE for 5 of 12 model configurations using data set 3 and survey series broken into two periods. Estimated recruitment and spawning biomass are shown in right-hand panels.

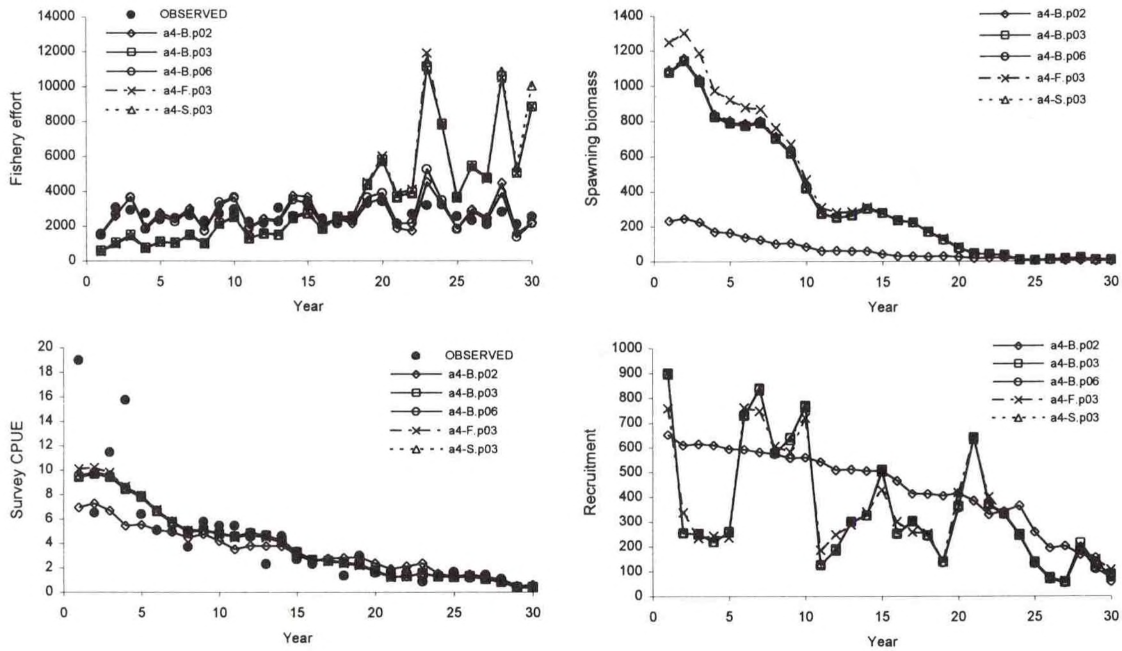


Figure 8. Fit to fishery effort and survey CPUE for 5 of 12 model configurations using data set 4. Estimated recruitment and spawning biomass are shown in right-hand panels.

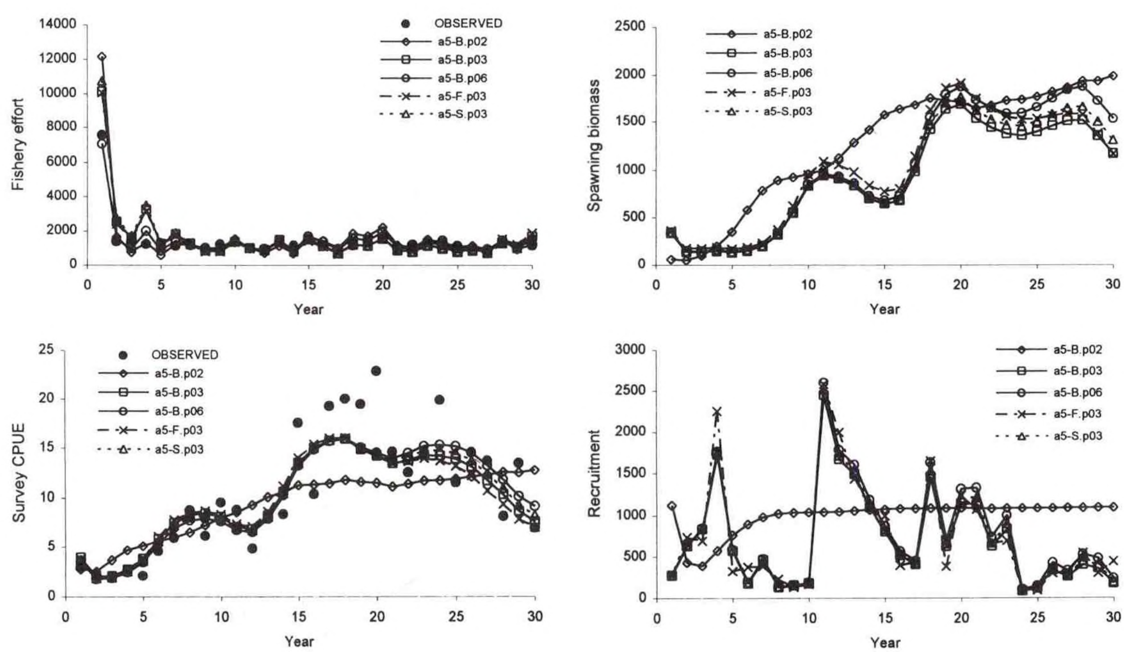


Figure 9. Fit to fishery effort and survey CPUE for 5 of 12 model configurations using data set 5. Estimated recruitment and spawning biomass are shown in right-hand panels.

more than an order of magnitude greater than the variable recruitment result. This run had a strong pattern to the residuals (Figure 6, survey CPUE) which would have been investigated with alternative parameter starting values in a real assessment situation. The results of the equilibrium run tuned only to fishery effort produced a higher ending biomass than equilibrium runs tuned to survey CPUE, and the result tuned to survey and fishery effort with bio-Q (runs *-B.P02) was nearly the same as the equilibrium run tuned only to survey CPUE (*-S.P01). Any difference in inferred population trend between the survey CPUE and the fishery effort is absorbed by the bio-Q parameter, so the result basically matches the result with the survey CPUE alone.

Time-varying selectivity

Model runs *.P05 estimated the greatest number of parameters by including year-specific age at 50% selectivity to the fishery, except for years 27-30 which have the same value (Figure 10). This addition of 26 model parameters produced improvements in the fishery log-likelihood of about 40 to 100 units (Tables 1-3). Note however that there was very little change in the estimated recruitments, primarily because of the stability of the survey age compositions. There was a tendency for the inflection to move to a lower mean age during the end of the time series. This information led to model configuration *.P07 which defined two time periods for the inflection parameter (years 1-19 and 20-30). This addition of one parameter improved the log-likelihood by 28, 31, 22, 0, 0 for data sets 1-5 respectively. With the left-shift in the fishery selectivity there was a small decrease in estimated recruitment levels at the end of the time series, and an associated decline in the estimated ending biomass.

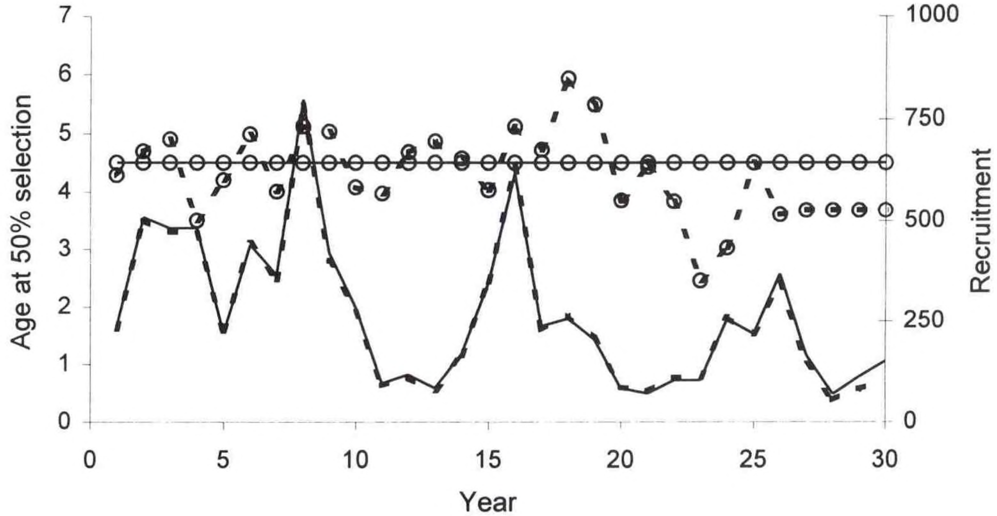


Figure 10. Fishery selectivity (open circles) and corresponding recruitment (lines without symbols) for data set 1. Solid lines: model A1-B.P06 with constant age at 50% selection. Dashed lines: model A1-B.P05 with annual fluctuation in age at 50% selection.

Catchability coefficient

In an ideal situation, the catchability coefficient (Q) for the fishery and the survey would be constant over time or would have only a random error component. In synthesis, the survey Q must be constant over time, but distinct shifts in Q can be accomodated by defining a new survey. Fishery Q can be a function of the available biomass so that fishery CPUE is a power function of available biomass. For both surveys and fisheries, care must be taken in interpreting Q when there is time-varying selectivity. Algebraically, Q is the catchability for the age that has a selectivity of 1.0. Thus, time-varying selectivity will change the effective Q for other ages, or may even change the age at which selectivity is 1.0. In data set 3A, the potential for changing survey Q was accommodated by breaking the survey into two sequential, independent surveys at year 16. When this was done, the estimate of Q was 0.0020 for survey 1 and 0.0036 for survey 2 (in run A3A-B.P06). However, selectivity at ages 2-5 decreased by about 30% for survey 2 relative to survey 1. This would moderate the change in Q for the age range that contributed much of the biomass.

Fishery Q is multiplied by available biomass raised to a power (bio-Q). Bio-Q is normally assumed to be 0.0 so that fishery Q is constant. However, the supplied data sets had sufficiently high data quality and contrast to estimate a value for bio-Q. These values were:

Data Set:	1	2	3	3A	4	5
Bio-Q:	-.68	-.70	-.73	-.81	-.64	-.39.

Retrospective analysis

A substantial retrospective pattern occurs when the model is tuned to fishery effort without accounting for changing catchability (Figure 11). When the model is tuned to survey CPUE and to fishery effort with changing catchability, the retrospective pattern effectively disappears (Figure 11 top panel).

Natural mortality

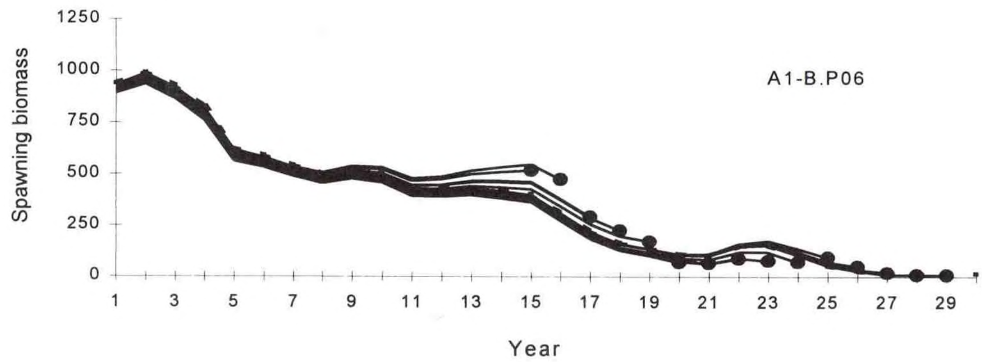
All reported model runs were conducted with natural mortality assumed to be 0.20 per year. This value was selected without significant investigation. When the model was profiled across a range of values for natural mortality with the *-B.P06 conditions, better model fits were obtained at M levels at least as low as 0.16 (Figure 12). Data set 2 had the flattest profile. When its profile was extended down to M=0.11, a slight peak at M=0.16 appeared. The absolute level of the ending biomass increased with increasing M. The estimate of natural mortality had little effect on the bio-Q parameter, but the value of the initial equilibrium fishing mortality decreased as M increased.

Final model runs

Subsequent to the May 1996 meeting, the NRC panel revealed that the actual average natural mortality rate was 0.225, and they requested additional model runs with this value. They also requested that fishery available biomass be reported and that projected catch at *F*40% be calculated. These results are reported in Table 4. Results for *M*=0.200 differ slightly from those reported in Tables 1-3. This is due to a small change in the maximum permissible level of fishing mortality, and some variability in the exact model convergence caused by the high non-linearity associated with the high fishing mortality values in these data sets.

Table 4. Summary results for runs with $M = 0.225$ and $M = 0.200$. $F_{40\%}$ is the target fishing mortality rate, and TAC is the projected catch in year 31 at $F_{40\%}$.

	Summary with M = 0.225									**Summary with M = 0.200**								
		Age 1+	Fishery		Mature						Age 1+	Fishery		Mature				
		Biomass	Biomass		Biomass			Year 31			Biomass	Biomass		Biomass			Year 31	
Run	-*L*	Yr. 30	Yr. 1	Yr. 30	Virg.	Yr. 1	Yr. 30	TAC	F40%	-*L*	Yr. 30	Yr. 1	Yr. 30	Virg.	Yr. 1	Yr. 30	TAC	F40%
A1 B P03	405.2	460	3407	288	910	930	21	39	0.17	402.4	433	3015	273	1006	823	20	34	0.16
A1 B P06	370.9	389	3418	239	917	938	17	29	0.17	369.1	362	3014	224	1014	827	16	25	0.16
A1 B P07	324.8	303	3225	247	994	907	16	20	0.15	324.0	288	2868	234	1066	807	15	18	0.14
A1 F P03	210.7	1227	4173	880	1040	1118	66	138	0.16	208.8	1257	3641	912	1224	975	69	137	0.15
A1 F P06	178.0	493	4118	336	949	1114	21	43	0.16	176.5	511	3646	358	1019	987	22	44	0.15
A1 F P07	150.1	216	3783	182	1098	1049	11	8	0.14	149.9	223	3330	188	1178	925	12	8	0.13
A1 S P03	401.3	377	3415	232	922	935	16	28	0.17	399.5	356	3014	220	996	827	15	25	0.16
A2 B P03	428.5	570	2446	333	607	490	12	44	0.14	426.5	536	2051	317	682	410	11	39	0.13
A2 B P06	395.8	425	2460	244	609	494	7	29	0.14	394.7	393	2054	227	675	412	7	25	0.13
A2 B P07	345.9	299	2180	223	626	457	7	18	0.13	345.1	277	1845	206	689	387	7	15	0.12
A2 F P03	190.7	2646	3294	1777	856	673	76	271	0.13	189.9	2337	2684	1587	955	549	68	232	0.12
A2 F P06	164.1	614	3300	397	615	676	12	52	0.13	163.4	595	2685	389	698	552	12	49	0.13
A2 F P07	138.5	202	2805	157	670	597	5	8	0.12	138.1	213	2322	166	724	495	6	9	0.12
A2 S P03	423.6	437	2470	251	600	496	8	30	0.14	422.9	412	2069	240	663	415	7	27	0.13
A3 B P03	409.9	4469	6025	3597	4608	1315	472	412	0.12	407.2	3708	5000	2988	4715	1092	392	329	0.11
A3 B P06	400.5	2548	6046	2024	5055	1329	246	219	0.12	397.6	2125	5049	1693	5032	1108	204	173	0.11
A3 B P07	373.8	2073	5544	1829	4842	1250	237	174	0.11	371.7	1715	4663	1512	4093	1042	194	135	0.11
A3 F P03	165.7	6359	7748	5486	2682	1712	655	629	0.12	161.8	5793	6442	5090	3438	1433	628	559	0.11
A3 F P06	158.6	3492	7879	2999	2103	1719	339	328	0.12	156.0	3443	6352	2975	3055	1413	345	316	0.11
A3 F P07	139.3	2543	6711	2376	2676	1518	325	219	0.11	137.5	2839	5558	2667	2690	1255	375	243	0.10
A3 S P03	432.0	2346	6108	1860	4966	1341	223	199	0.12	429.3	2024	5098	1610	5264	1123	192	163	0.11
A3A B P03	399.9	5148	6324	4136	5453	1388	520	486	0.12	398.0	4264	5226	3435	4583	1138	432	389	0.11
A3A B P06	389.1	1821	6419	1440	5164	1406	158	148	0.12	387.1	1678	5302	1330	5165	1161	146	131	0.11
A3A B P07	366.5	1325	5810	1159	4687	1304	137	99	0.11	364.6	1204	4871	1054	5000	1095	125	85	0.11
A3A F P03	165.6	6477	7753	5590	2701	1712	668	642	0.12	161.8	5771	6429	5064	3307	1429	624	556	0.11
A3A F P06	158.6	3361	7872	2884	2076	1718	324	314	0.12	156.5	3480	6324	3002	2459	1391	346	320	0.11
A3A F P07	140.4	2457	6714	2295	2731	1521	313	210	0.11	139.1	3195	5558	3000	2307	1243	424	279	0.10
A3A S P03	419.7	1850	6465	1462	5211	1417	160	151	0.12	418.1	1665	5343	1319	5293	1172	144	129	0.11
A4 B P03	316.2	167	4711	132	1051	1231	9	14	0.15	314.4	158	4085	123	1253	1078	9	12	0.14
A4 B P06	280.6	138	4741	108	1095	1232	7	10	0.15	279.0	134	4210	108	1241	1089	7	9	0.14
A4 B P07	274.7	134	4674	120	1127	1222	8	10	0.14	274.0	129	4050	114	1284	1071	8	9	0.14
A4 F P03	121.5	181	5504	159	1085	1377	11	18	0.14	118.9	172	5005	155	1206	1289	11	16	0.13
A4 F P06	84.7	122	5358	99	1147	1374	6	8	0.15	84.1	125	5201	114	1231	1304	7	9	0.13
A4 F P07	81.9	119	5333	104	1124	1362	7	7	0.14	81.4	116	4826	105	1320	1252	7	7	0.13
A4 S P03	309.7	145	4771	114	1132	1238	7	11	0.15	308.8	140	4218	113	1286	1080	7	10	0.14
A5 B P03	364.5	3954	1422	3598	2617	371	1480	434	0.17	361.3	3321	1309	3030	2566	345	1249	342	0.16
A5 B P06	348.9	5036	1392	4573	2913	366	1887	572	0.17	346.3	4192	1283	3821	2837	339	1580	447	0.16
A5 B P07	348.6	5013	1377	4576	2915	365	1884	565	0.17	346.0	4139	1272	3788	2819	340	1564	439	0.16
A5 F P03	168.2	3860	1631	3599	2725	403	1453	422	0.16	165.7	3245	1464	3033	2637	366	1227	333	0.15
A5 F P06	152.8	6507	1542	6021	3511	389	2439	759	0.17	150.1	5998	1407	5582	3591	355	2268	668	0.15
A5 F P07	151.1	5974	1485	5590	3348	379	2270	681	0.16	148.3	5737	1376	5390	3457	351	2196	627	0.15
A5 S P03	381.6	4683	1392	4258	2826	364	1756	527	0.17	379.1	3916	1284	3571	2741	339	1476	414	0.16



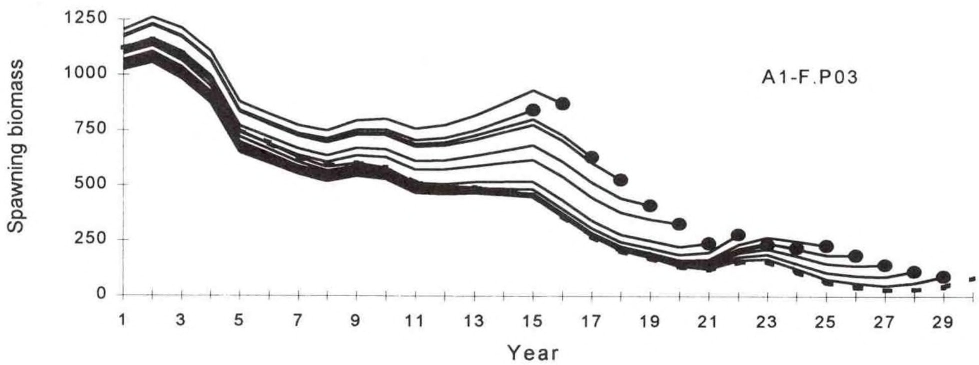


Figure 11. Retrospective estimates of spawning biomass for data set 1 using fishery effort and survey CPUE (top) or only fishery effort (bottom). A strong pattern occurred when the model was tuned only to fishery effort without accounting for changing catchability (bottom).

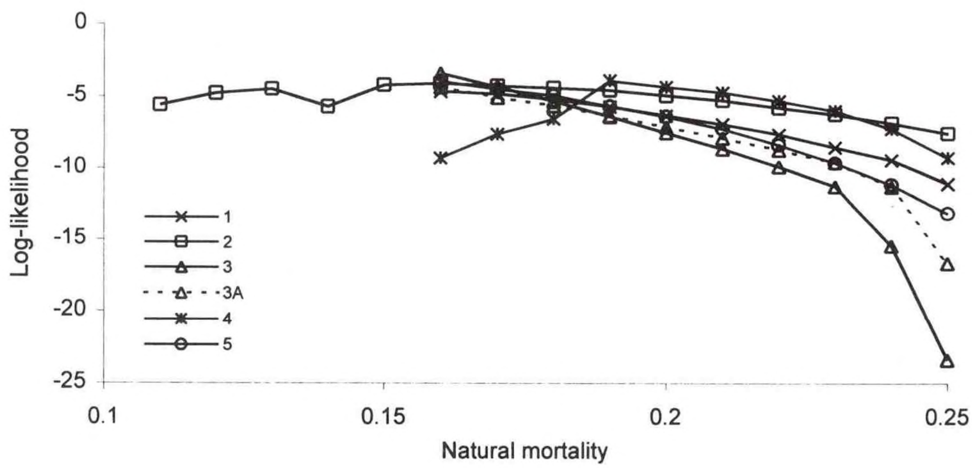


Figure 12. Log-likelihood profiles for a range of natural mortality values. A constant has been added to the log-likelihood values for each data set in order to scale the lines to similar magnitudes.

Concluding Remarks

The NRC-supplied data sets contained 30-year time series of fishery and survey data including complete age composition information, and precise information on the calibration of the age determination process. Such a comprehensive database is unprecedented for any actual application of the synthesis model. Understanding the model's performance under this data-rich situation is important, but probably not sufficient to characterize the fidelity in model performance when data are sparse, or where the biological situation is known to be complex. The importance of fully understanding the fishery and biological situation cannot be over-emphasized. Synthesis, like most other modern assessment tools, is not a simple black-box with no flexibility in how to approach a problem, but it also does not contain sufficient artificial intelligence to achieve flexibility without user-intervention. Normally an assessment scientist devotes months to understanding potential patterns and biases in the data collection process before configuring the model to account for this knowledge. Assessment issues such as natural mortality, potential for dome-shaped survey selectivity, expected changes in fishery selectivity over time, degree of calibration for the fishery logbook data deserve an in-depth investigation that cannot be accomplished by a brief perusal of a supplied data file. With the above caveats, I hope that the results of this exercise are taken simply as examples of how synthesis and other assessment tools could be used to approach a problem. A true evaluation of each model's accuracy and precision could only be obtained through an experiment with hundreds of randomly drawn realizations of such data sets.

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CHAPTER 7.

Alternative Age-structured Analyses of the NRC Simulated Stock Assessment Data

James N. Ianelli[1], and David A. Fournier[2]

[1] National Marine Fisheries Service, Alaska Fisheries Science Center, 7600 Sand Point Way NE, Seattle Washington 98115. Jim.Ianelli@noaa.gov

[2] Otter Research Ltd., PO Box 265, Station A, Nanaimo, B.C. V9R 5K9, Canada

Introduction

The following represents independent analyses of the NRC simulated data sets using a statistical age-structured model extended from Fournier and Archibald (1982). We apply Bayesian methods (Berger 1985) for a comprehensive treatment of errors in variables and underlying processes.

The purpose of this presentation is primarily to demonstrate how typical fishery data problems can be addressed in a comprehensive and formal manner. The analyses were carried out in two stages: The initial models had fairly simple specifications similar to those of Fournier and Archibald (1982) and their results were presented at the May 1996 meeting of the NRC panel. The final models were more complex in nature, allowing for temporal trends in several key parameters. In addition, the final models made use of the "true" average value of natural mortality used in simulating the data which was divulged by the NRC panel.

Methods

Population Dynamics

The model used standard population dynamics forms. We used an explicit age-structured model with the standard catch equation as the operational population dynamics model (e.g., Deriso et al. 1985, Hilborn and Walters 1992). Catch in numbers at age in year t ($C_{a,t}$) and total catch biomass (Y_t) were

$$C_{t,a} = \frac{F_{t,a}}{Z_{t,a}} (1 - e^{-Z_{t,a}}) N_{t,a} \qquad 1 \le t \le T \; 1 \le a \le A$$

$$N_{t+1,a+1} = N_{t,a} e^{-Z_{t,a}} \qquad 1 \le t \le T \; 1 \le a < A$$

$$N_{t+1,A} = N_{t,A-1} e^{-Z_{t,A-1}} + N_{t,A} e^{-Z_{t,A}} \qquad 1 \le t \le T$$

$$Z_{t,a} = F_{t,a} + M_t$$

$$C_t = \sum_{a=1}^{A} C_{t,a}$$

$$p_{t,a} = C_{t,a} / C_t$$

$$Y_t = \sum_{a=1}^{A} w_a C_{t,a}$$

$$B_t = \sum_{a=1}^{A} w_a \phi_a N_{t,a}$$

where

T	= number of years of fishing,
A	= number of age classes in the population,
$N_{t,a}$	= number of fish age a in year t,
$C_{t,a}$	= catch of age class a in year t,
$p_{t,a}$	= proportion of the total catch in year t, that is in age class a,
C_t	= total catch in year t,
w_a	= mean body weight (kg) of fish in age class a,
Y_t	= total yield biomass in year t,
B_t	= spawning biomass in year t, with ϕ provided by the NRC panel,
$F_{t,a}$	= instantaneous fishing mortality for age class a, in year t,
M_t	= instantaneous natural mortality in year t, and
$Z_{t,a}$	= instantaneous total mortality for age class a, in year t.

Model structure in the initial analyses

In the initial modeling stages, the fishing mortality rates were defined by

$$F_{t,a} = s_a q E_t e^{\varepsilon_t}, \qquad \varepsilon_t \sim N(0,\sigma_\varepsilon^2),$$

where E is fishing effort, q is a catchability coefficient, and s_a is selectivity at age. The error term, ε, can be thought of as an errors-in-variables problem where our prior information is principally that the effective effort is measured with a significant amount of error. We assumed the instantaneous natural mortality rate, M, was constant over time and equal to 0.2 year^{-1}. Selectivity was modeled as a logistic function :

$$s_a = \frac{1}{1 + e^{-\alpha(a-\beta)}},$$

where β is the inflection age for s_a, and α is the slope at the inflection. This parameterization represents a continuous function from which discrete selectivity values were selected. The computation for predicting survey numbers at age simply assumed that the survey started at the beginning of the year, prior to the fishery and removals by the survey were insignificant. Consequently, a separate selectivity curve using the same logistic form given above was estimated for the survey gear. The predicted survey numbers at age was thus given by:

$$N_{t,a}^{s} = N_{t,a} q^{s} s_a^{s}.$$

We chose not to model an underlying stock-recruitment relationship since the main goal of this exercise was to assess the current status of the stocks. If an analyses of projections been required, the Bayesian framework presented here would have been well suited to several types of appropriate stock recruitment analyses (e.g., Thompson 1992, Ianelli and Heifetz 1995). Recruitment (R_t) representing numbers of age-1 individuals was modeled as a stochastic process about a mean value (R_0):

$$N_{t,1} = R_t = R_0 e^{\delta_t}, \qquad \delta_t \sim \mathrm{N}(0, \sigma_R^2).$$

For parameter estimation, the objective function, f, was simply the product of the likelihood function and prior distributions. Initially, the negative log-likelihood function for the survey and fishery catch at age data (in numbers) is given by:

$$f = 0.5 \cdot A \cdot T \cdot \ln\left(\sum_{a,t} \frac{\left(O_{at} - \hat{C}_{at}\right)^2}{\hat{C}_{at}} \right),$$

$$\hat{C} = C \cdot E_{ageing}$$

$$E_{ageing} = \begin{pmatrix} b_{1,1} & b_{1,2} & b_{1,3} & \cdots & b_{1,15} \\ b_{2,1} & b_{2,2} & & & \\ b_{3,1} & & \ddots & & \\ \vdots & & & \ddots & \\ b_{15,2} & & & & b_{15,15} \end{pmatrix},$$

where $O_{a,t}, \hat{C}_{a,t}$ represent the observed and predicted catches. The elements $b_{i,j}$ represent ageing mis-classification proportions which were provided by the NRC panel. An identical calculation is added to f for survey numbers-at-age. For the errors in estimating effective effort, the objective function is extended by adding the term

$$f = f + \lambda_E 0.5\, T \ln\left(\sum_t \varepsilon_t^2\right).$$

Finally, a term for the variation in recruitment deviations from the mean value is added as

$$f = f + \lambda_R \left(\sum_t \delta_t^2\right).$$

The values for λ_E and λ_R were set to 0.01, thus downweighting the influence of the variation in effective effort and recruitment.

<u>Model structure in subsequent analyses</u>

The model structure in the second stage of analyses was changed in order to further relax some of the assumptions made in the initial stage, and to take into account the information provided by the NRC panel regarding the average value of natural mortality ($M = 0.225$) in the simulations. These changes consisted of

- Modeling selectivity, catchability and natural mortality as simple random walks,
- Modeling selectivity-at-age as age-specific series instead of as a 2-parameter curve,
- Using a robust likelihood for the proportions-at-age data from the fishery and survey, and
- Estimating fluctuations in natural mortality rather than forcing it to be constant.

Recruitment and fishing mortality rates were defined as before. Random walk time series processes were assumed for selectivity, catchability, and natural mortality as

$$s_{t+1,a} = s_{t,a} e^{\gamma_{t,a}}, \qquad \gamma_{t,a} \sim N(0, \sigma_s^2),$$

$$q_{t+1} = q_t e^{\psi_t}, \qquad \psi_t \sim N(0, \sigma_q^2),$$

$$M_{t+1} = M_t e^{\omega_t}, \qquad \omega_t \sim N(0, \sigma_M^2).$$

If the selectivities ($s_{t,a}$) are constant over time, then variable catchabilities (q_t) result in a decomposition of the fishing mortality rate into an age component and a year component. This assumption creates what is known as separable model, essentially the model that was assumed in the initial stages. If selectivity in fact changes over time, then the separable model can mask important changes in fish abundance. In our analyses, we constrain the variance term (σ_s^2) to allow selectivity to change slowly over time — thus improving our ability to estimate the $\gamma_{t,a}$. Also, to provide regularity in the age component, we placed a curvature penalty on the selectivity coefficients using the squared second-differences. Time series structure in catchability and selectivity was introduced by Gudmundsson (1994) for analyses of catch-at-age data. Prior assumptions about the relative variance quantities were made. For example, we assume that the variance of transient effects (e.g., σ_E^2) is large relative to permanent changes in catchability (σ_q^2). Similarly, small variance values were selected for changes in natural mortality.

The computation for predicting survey proportions at age made the same assumptions than in the initial stage model, except that the catchability and selectivity terms were modeled as random walk processes parameterized as described above for the fishery.

The objective function was similar to that in the simpler model formulations. However, with the addition of a large number of parameters in this more flexible approach, certain parameters were estimated in different stages. The ability to estimate stages is also important in using robust likelihood functions since it is often undesirable to use robust objective functions when models are far from a solution. Consequently, in the early stages of estimation we use the same negative log-likelihood function for the survey and fishery catch at age data as was used in the simpler models. As the model fit approached a solution, we invoke a robust likelihood function which fit proportions at age as (Fournier and Hampton 1996):

$$\prod_{a=1}^{A}\prod_{t=1}^{T}\left[\frac{1}{\sqrt{2\pi(\eta_{t,a}+0.1/T)}\,\tau}\exp\left(-\frac{(p_{t,a}-\hat{p}_{t,a})^2}{2(\eta_{t,a}+0.1/T)\,\tau^2}+0.01\right)\right]$$

Taking the logarithm we obtain the log-likelihood function for the age composition data:

$$-1/2\sum_{a=1}^{A}\sum_{t=1}^{T}\ln(2\pi(\eta_{t,a}+0.1/T))-\sum_{a=1}^{A}T\ln(\tau)$$

$$+\sum_{a=1}^{A}\sum_{t=1}^{T}\ln\left[\exp\left(-\frac{(p_{t,a}-\hat{p}_{t,a})^2}{2(\eta_{t,a}+0.1/T)\,\tau^2}\right)+0.01\right]$$

where $\eta_{t,a}=\hat{p}_{t,a}(1-\hat{p}_{t,a})$ and τ^2 = (sample size)$^{-1}$ give the variance for $p_{t,a}$ as

$(\eta_{t,a}+0.1/T)\tau^2$.

Completing the estimation in this fashion reduces the model sensitivity to outlier data points. The contribution to the log-likelihood function for the observed total catches is given by

$$\lambda_c\sum_t(\ln(O_t/\hat{C}_t))^2,$$

where λ_c represents prior assumptions about the accuracy of the observed catch data. Similarly, the contribution of prior distributions (in negative log-density) to the log-likelihood function include the terms

$$\lambda_\varepsilon\sum_t\varepsilon_t^2+\lambda_\gamma\sum_{t,a}\gamma_{t,a}^2+\lambda_\psi\sum_t\psi_t^2+\lambda_\omega\sum_t\omega_t^2+g(M),$$

where the size of the *λ's* represent prior assumptions about the variances of these random variables. The term *g(M)* represents the negative log-likelihood of a log-normal density with a mean 0.225 (the true average value of natural mortality in the simulated data sets) and standard deviation of 0.15. We used uninformative prior probability density functions (pdf's) for all other model parameters.

Estimation algorithm

For some of the models presented below, over 400 parameters were estimated. To easily estimate such a large number of parameters in such a non-linear model, automatic differentiation software extended from Greiwank and Corliss (1991) and developed into C++ class libraries was used. This software provided the derivative calculations needed for finding the posterior mode via a quasi-Newton function minimization routine (e.g., Press et al. 1992). The model implementation language (ADModel Builder) gave simple and rapid access to these routines and provided the ability estimate the variance-covariance matrix for all dependent and independent parameters of interest. For key quantities of interest, e.g., current stock size, the software also produces likelihood profiles which avoids the assumption that the likelihood shape is quadratic (implied when the inverse Hessian estimates are used).

Levels of analyses

With the simpler model formulations of the initial analysis stage, we performed stock assessments using fishery-dependent data, survey data, or both. For the more complex models, we performed stock assessments using either fishery data or both fishery and survey data. In addition, we carried out retrospective analyses for all cases as requested by the NRC panel, following the concepts and general methodology in Parma (1993). For brevity, not all those analyses are summarized in this report. Instead, with focus primarily on contrasting the simpler and more complex model results using both simulated fishery and survey abundance data.

Computation of quotas

The Panel requested that for benchmark purposes, the $F_{40\%}$ harvest rate be applied to make recommendations for harvests in the next year. The $F_{40\%}$ rate corresponds to the fishing mortality that will reduce the spawning biomass per recruit to 40% of its unfished level. Therefore, the key quantities involved include age-specific fishery selectivity, maturation, growth in weight, and natural mortality. As mentioned above, had time permitted, a more detailed analyses of the stock recruitment data would have been appropriate to arrive at a comprehensive analyses of harvest levels.

Results and Discussion

Time trajectories of various key population and fishery parameters in Figures 1 to 5 for the simpler (plotted in the left-hand column in the figures) and more complex (in the right-hand column) models. Relative recruitment trends were similar for both modeling approaches. However, the magnitude of recruitment differed between both modeling stages, primarily as a result of changes in the levels of natural mortality (M was fixed at 0.2 in the initial models and estimated to vary around 0.225 in the final ones). Estimated biomass and fishing mortality trends showed some differences, particularly for data set 3 (Figure 3).

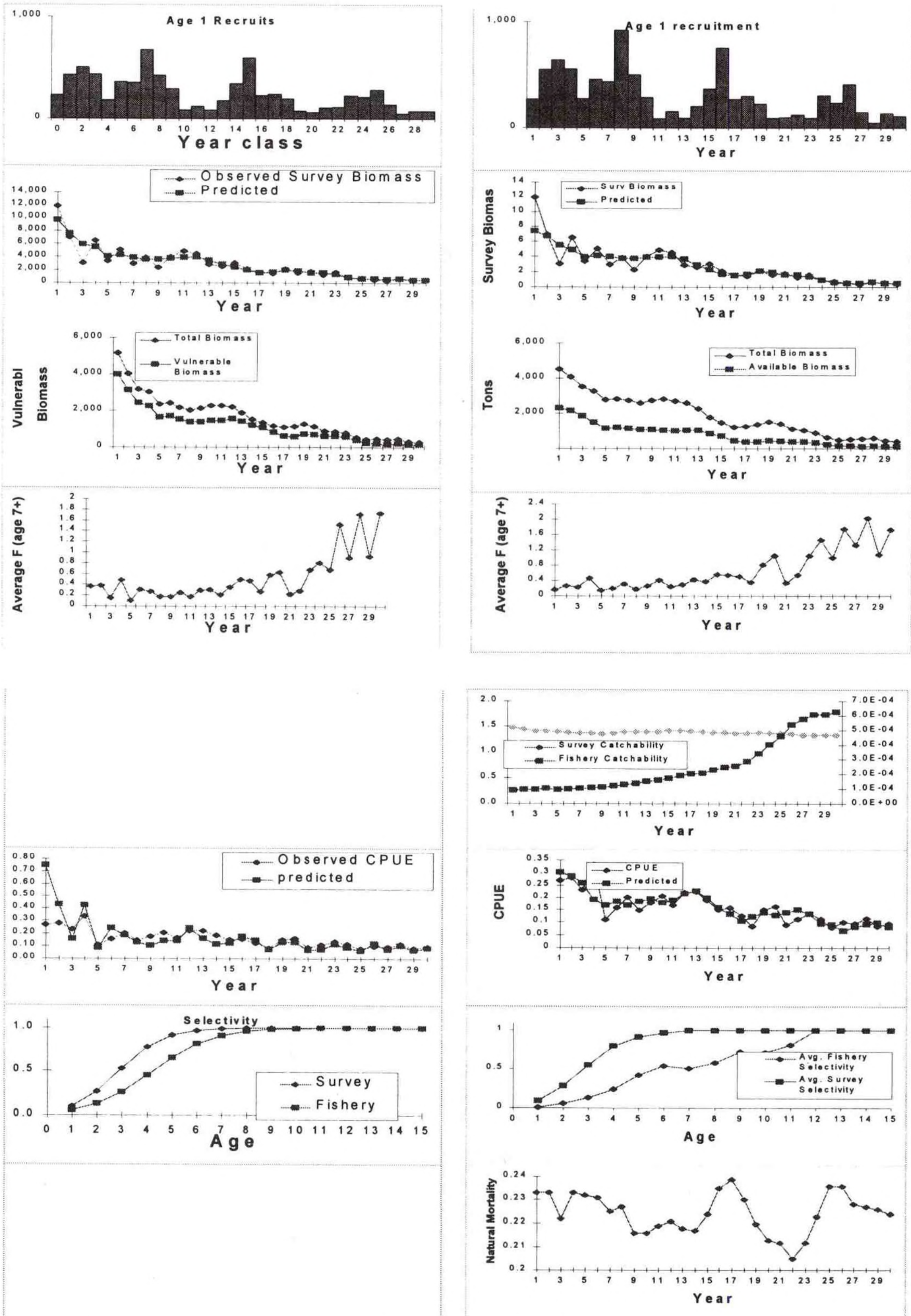

Figure 1. Analyses of data set 1 using fishery and survey data with simpler models (left) and more complex models that include random walks for some parameters (right).

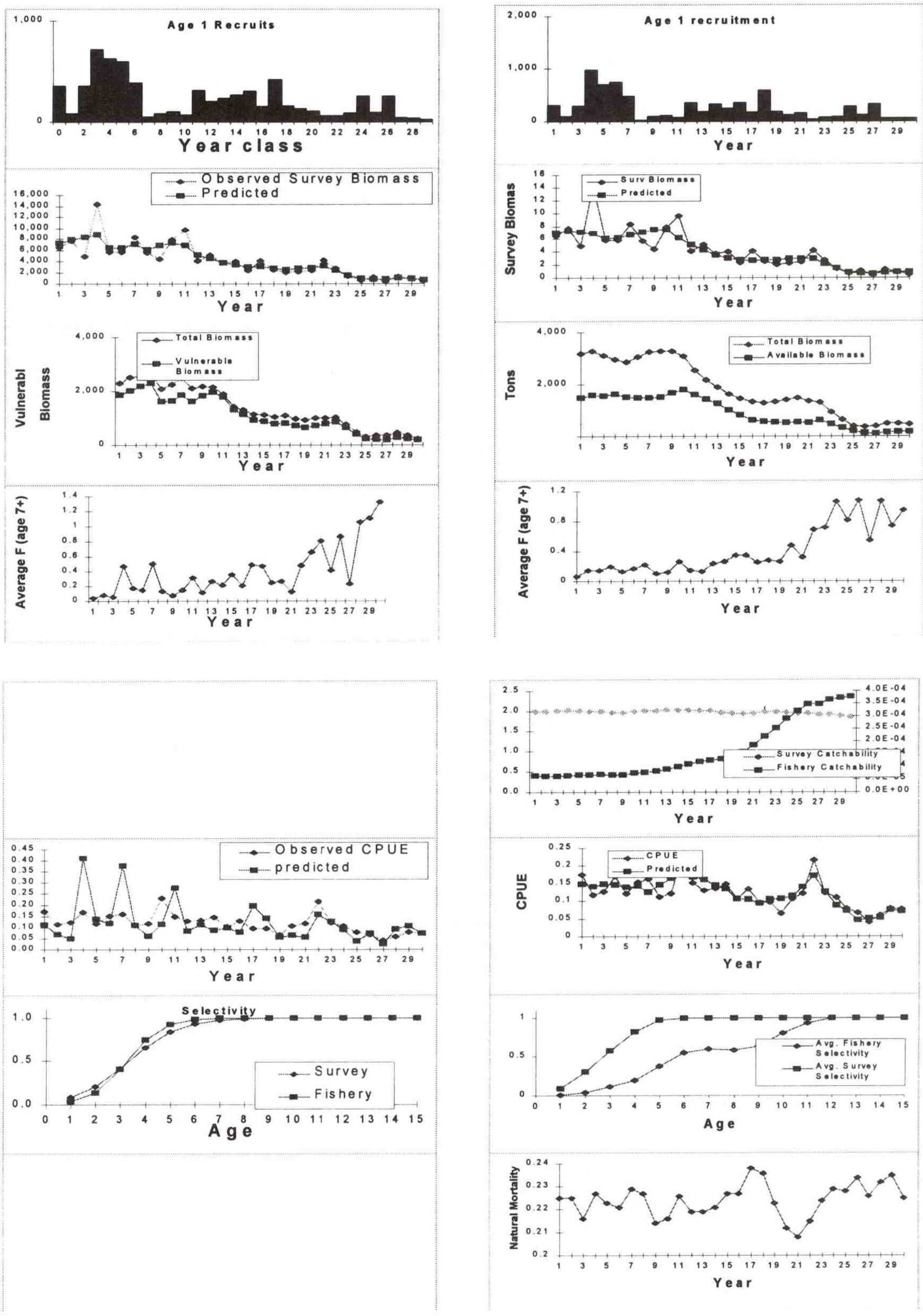

Figure 2. Analyses of data set 2 using fishery and survey data with simpler models (left) and more complex models that include random walks for some parameters (right).

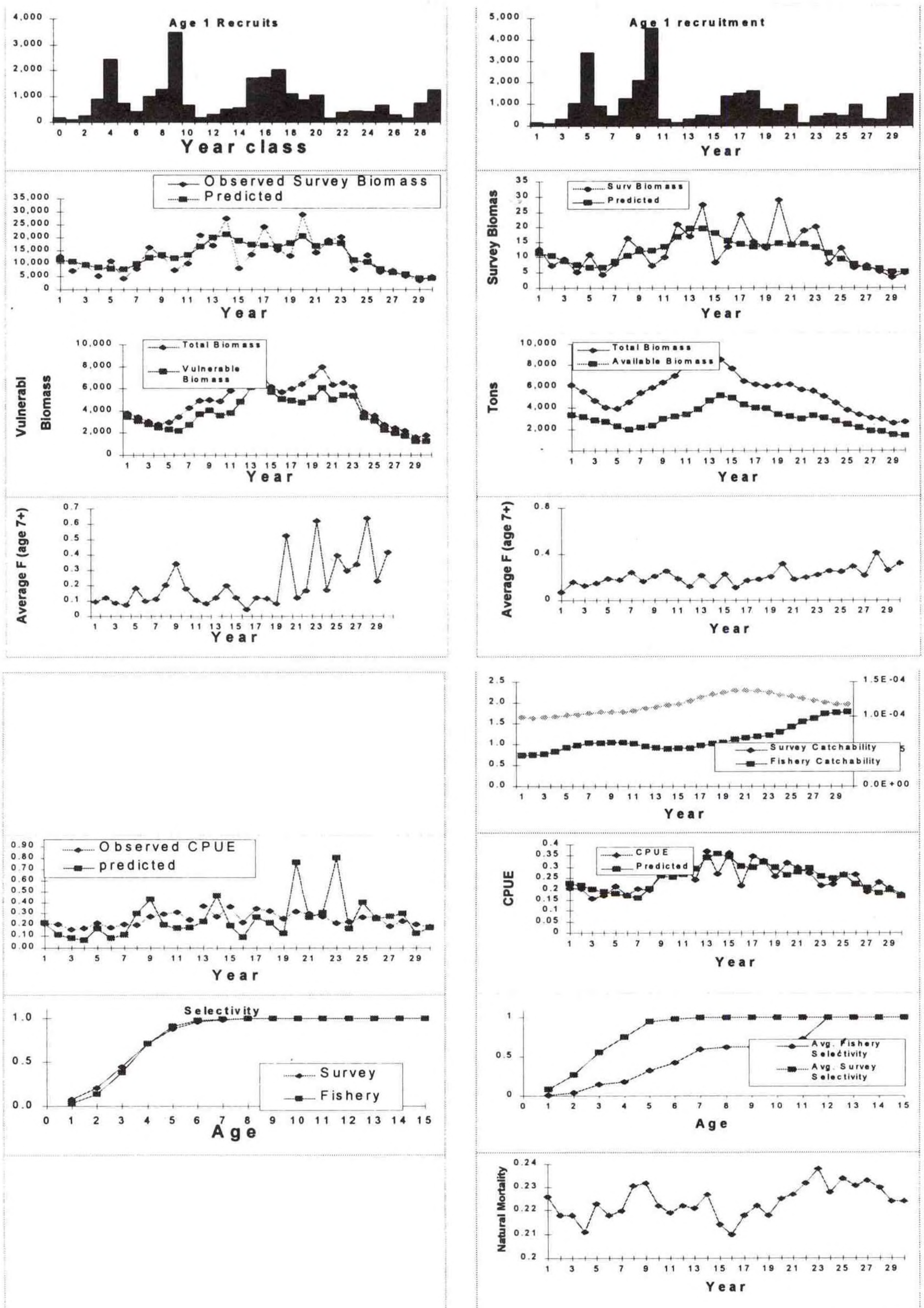

Figure 3. Analyses of data set 3 using fishery and survey data with simpler models (left) and more complex models that include random walks for some parameters (right).

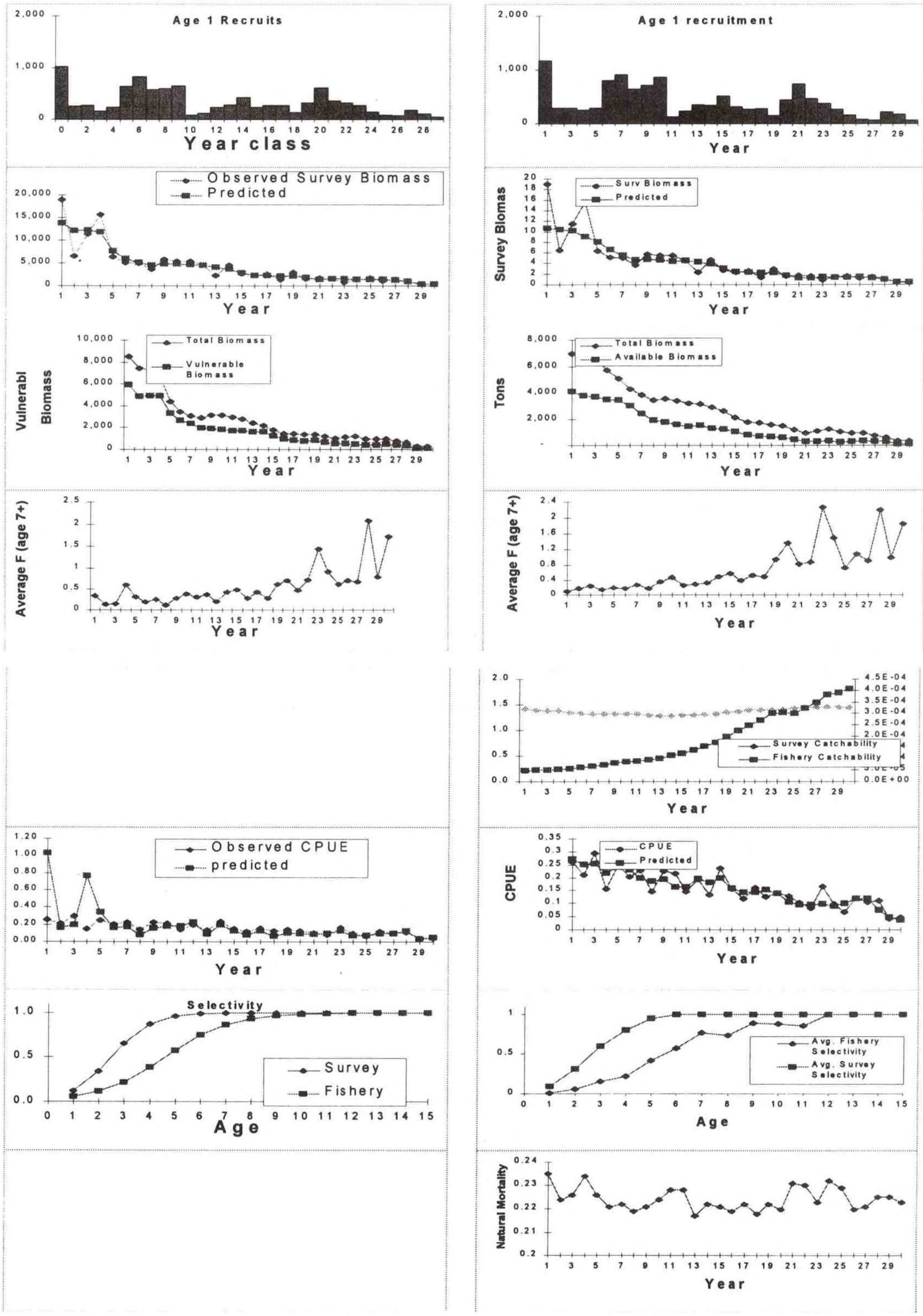

Figure 4. Analyses of data set 4 using fishery and survey data with simpler models (left) and more complex models that include random walks for some parameters (right).

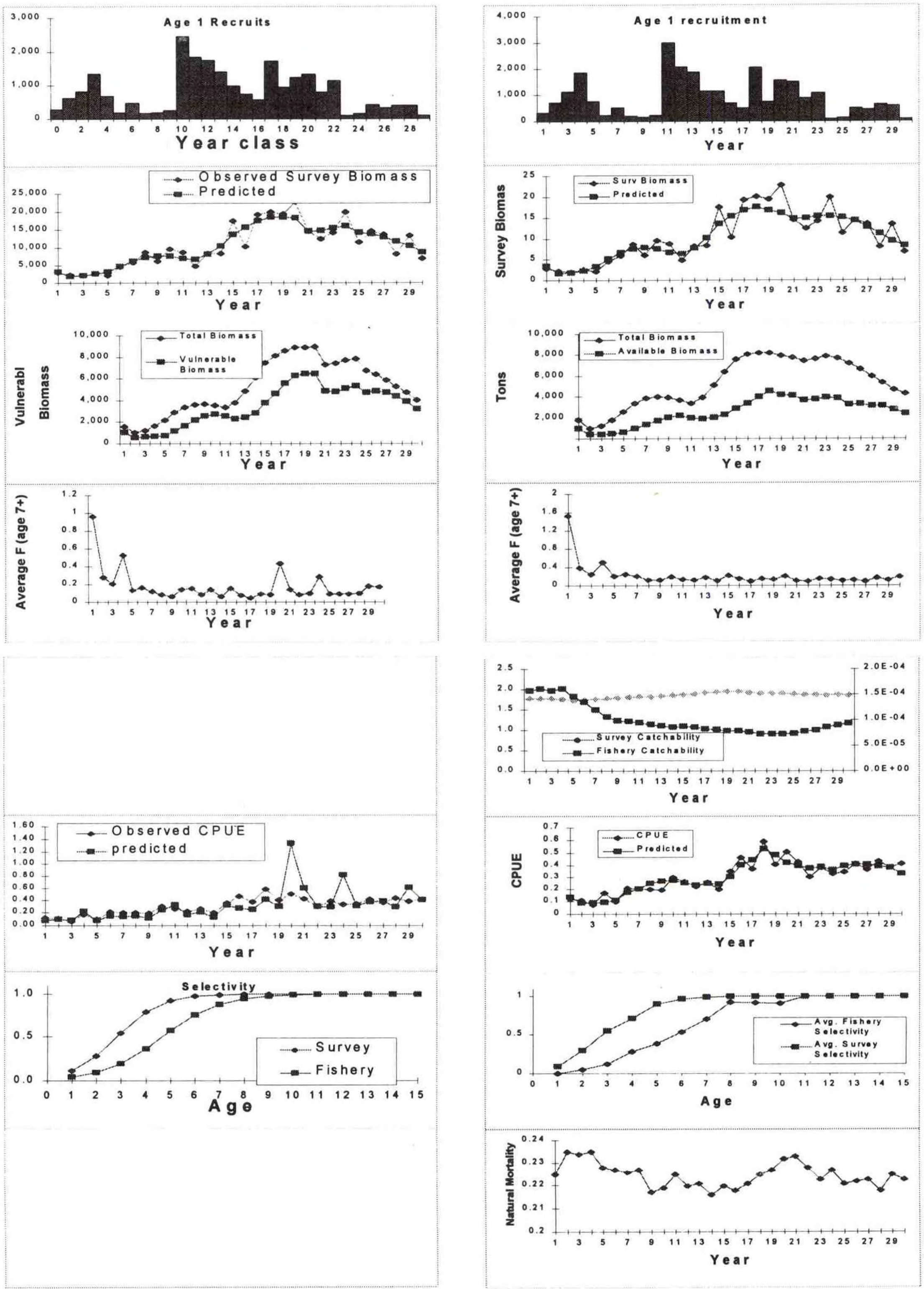

Figure 5. Analyses of data set 5 using fishery and survey data with simpler models (left) and more complex models that include random walks for some parameters (right).

Analyses with the simpler model formulation often showed pathologies in the results, especially when only fishery data were used to index abundance. These specific results are not presented here, but the pathologies can still be inferred from the relatively poor fits to the fishery CPUE data using the simpler models contrasted to those from the more complex models (Figures 1 to 5). For the more complex models, the average pattern of estimated fishery selectivity at age was different from that estimated in the simpler models, especially for data sets 1 to 3.

For data set 3 we were informed that there was a potential change in the way the survey was carried out after year 15. While we could have altered the model to specifically acknowledge this documented change (i.e., treat the survey as from two different periods with corresponding sets of relevant model parameters). Instead, we chose to ignore this information and see if the model with the random walk components detects any change in catchability (which is somewhat restricted in the amount of inter-annual variability that is allowed). Interestingly, results for data set 3 show a significant change in the latter part of the time series (Fig. 3). The pattern of survey catchability for all other data sets suggested little or no change over the 30-year periods.

Estimates of marginal posterior probability densities on the level of depletion (or stock increase) since the beginning of the time series were broader for the fishery data alone (Figure 6 shows the densities estimated from the more complex model fits). This reflects the level of information provided by the survey data. We suggest that, in lieu of knowing the "true" natural mortality rate (which would scale the population to the correct absolute stock size), a reasonable method of presentation for current stock status is in terms of relative changes, as presented here.

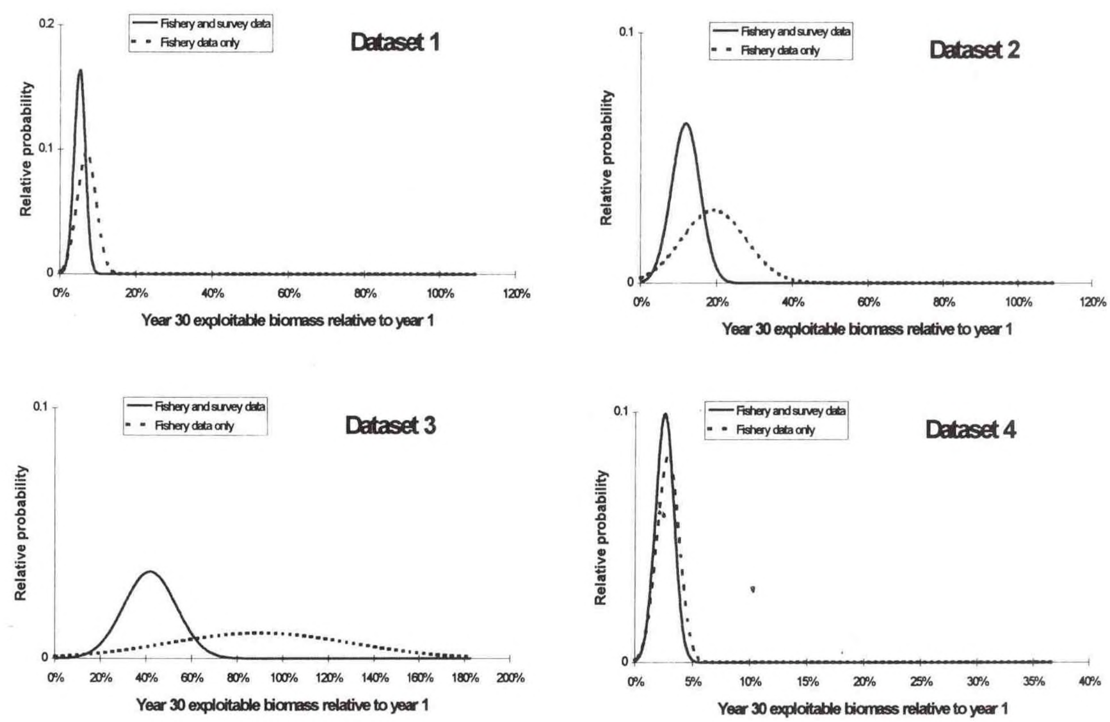

Figure 6. Estimated posterior probability distributions of depletion (or growth) level of year 30 relative to the first year using both fishery and survey data (solid line) and fishery data only (broken line), by data set.

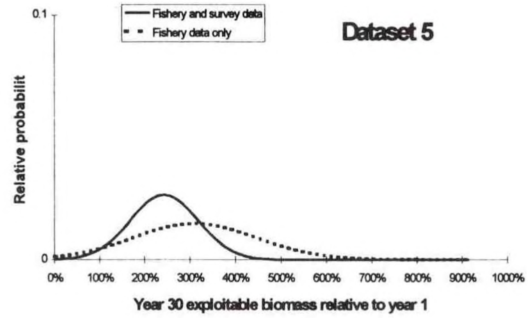

Figure 6 (cont.) Estimated posterior probability distributions of depletion (or growth) by data set.

Analyses of retrospective patterns show different patterns depending on the data set analyzed. Figures 7-11 contrast the patterns estimated from the more complex model results using either fishery data alone, or both fishery and survey data. As expected, the highest uncertainty in biomass levels was for cases where only the fishery data was used (Figs. 7-11, left-hand panels). This was also evident in the degree of variability in the retrospective patterns, not shown here. The analyses using both survey and fishery data generally had smaller estimates of variance and stable retrospective patterns. For data sets 1-3, the patterns suggested that the model tended to over estimate stock size compared the full 30-year analysis, particularly during the shortest time periods (e.g., using data from only the first 15 or 20 years). For data set 5, the retrospective pattern suggested that the model consistently underestimated the most recent year's stock size. The coefficients of variation for all years and all data sets was typically quite high, between 20-50% with the most recent estimates having the greatest level of uncertainty.

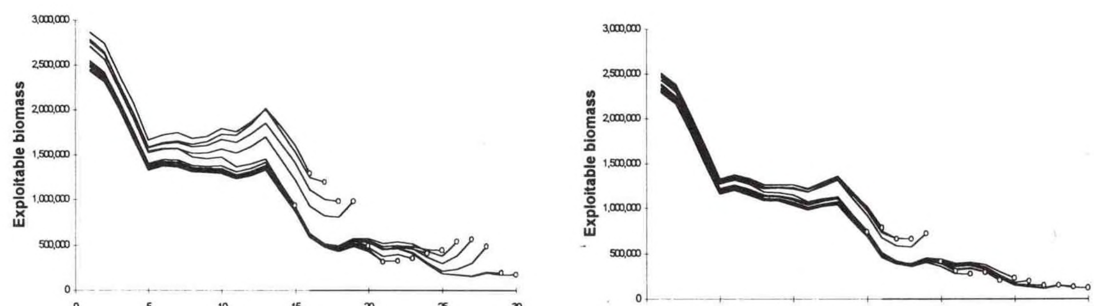

Figure 7. Retrospective analysis trajectories of vulnerable biomass for data set 1, estimated with the more complex model using fishery data only (left) or fishery and survey data (right).

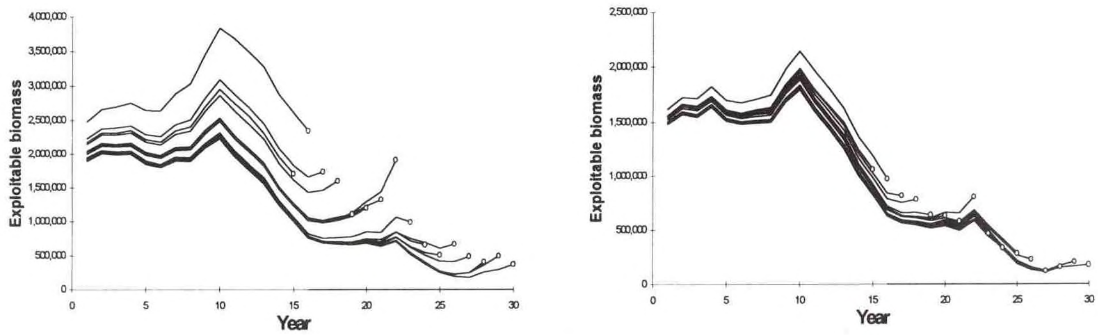

Figure 8. Retrospective analysis trajectories of vulnerable biomass for data set 2, estimated with the more complex model using fishery data only (left) or fishery and survey data (right).

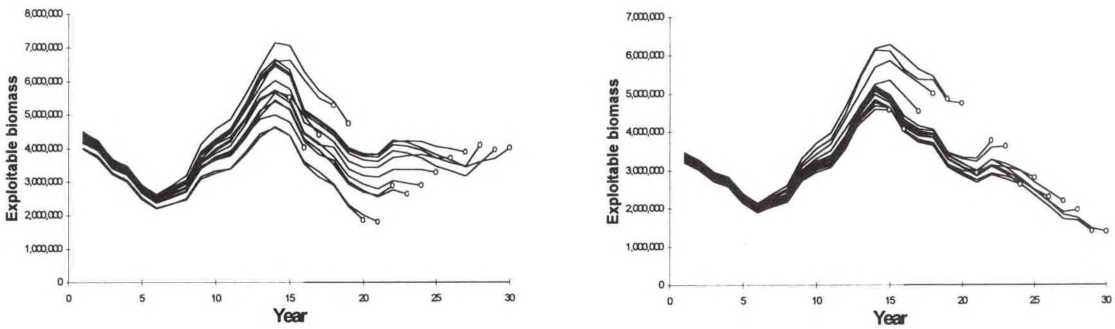

Figure 9. Retrospective analysis trajectories of vulnerable biomass for data set 3, estimated with the more complex model using fishery data only (left) or fishery and survey data (right).

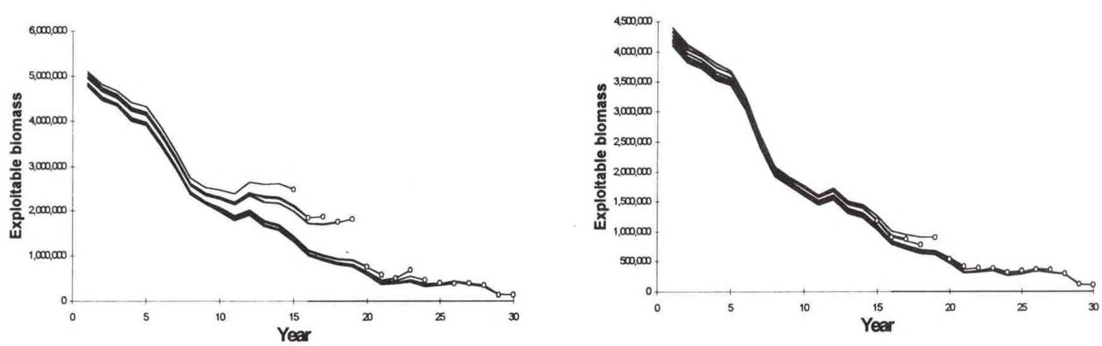

Figure 10. Retrospective analysis trajectories of vulnerable biomass for data set 4, estimated with the more complex model using fishery data only (left) or fishery and survey data (right).

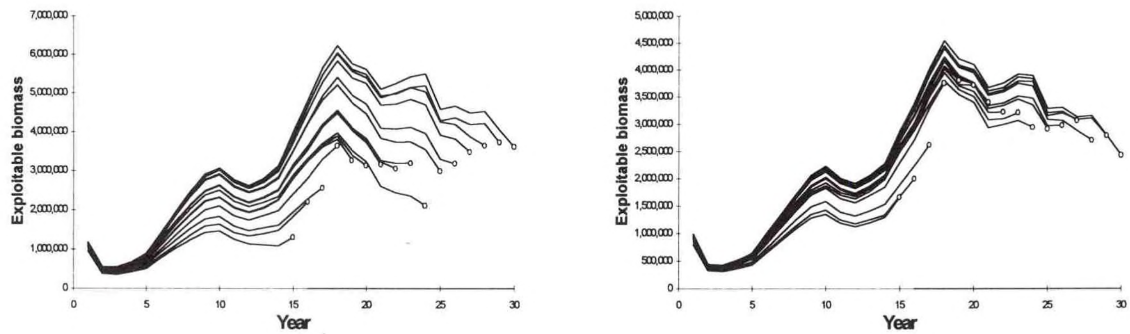

Figure 11. Retrospective analysis trajectories of vulnerable biomass for data set 5, estimated with the more complex model using fishery data only (left) or fishery and survey data (right).

Recommended quota computations as requested by the panel are given in the table below. These correspond to the latter stage model fits using fishery only or fishery and survey data combined. In all cases, the quotas estimated after inclusion of the simulated survey data were lower that with simulated fishery data only:

	Estimates of year 31 quotas at $F_{40\%}$ (1000 mt)				
Data Set:	1	2	3	4	5
Fishery data	32	66	708	17	690
Fishery and Survey	25	29	201	15	504

Conclusions

In evaluating our results it is clear that further attention is needed regarding model specification. For example, the estimated level of variability in inter-annual changes in natural mortality should be evaluated more closely. Also, sensitivity to our prior assumptions about the relative levels of variability for changes in catchability and selectivity should be examined. Finally, we treated each data set identically. Specific potential problem areas for the model were not assessed based on the outcomes of any single data analysis.

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