Hecate Strait Pacific Cod Stock Assessment for 1998 and Recommended Yield Options for 1999

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V9R 5K6

2002

Canadian Technical Report of Fisheries and Aquatic Sciences 2382

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Canadian Technical Report of
Fisheries and Aquatic Sciences

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by

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Cat. No. Fs 97-6/2382E ISSN 0706-6457

Correct citation for this publication:

Haist, V. and D. Fournier. 2002. Hecate Strait Pacific cod stock assessment for 1998 and recommended yield options for 1999. Can. Tech. Rep. Fish. Aquat. Sci. 2382: 46 p.

ABSTRACT

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Reconstructions of the Hecate Strait Pacific cod stock were conducted using a catch-at-length model (MULTIFAN CL), as in previous assessments. The major modification to this years' assessment was the inclusion of data from the multi-species Hecate Strait survey. While Pacific cod abundance indices from this survey are not precise, the survey has been conducted in a consistent manner since 1984, and should provide information on the general trends in relative abundance.

Stock analyses were conducted under two different assumptions. One, that selectivity for 60 cm fish was constant among commercial fisheries (time periods and fishing quarters), and the other that selectivity for 70 cm fish constant among the fisheries. The 60 cm assumption is a more restrictive parameterization. Both analyses suggest that stock abundance remains near historic low levels, that recruitment of the last 9 year-classes is below the median level, and that the 1998 year-class is the smallest ever. The last result is largely dependent on the length structure observed in the 1998 Hecate Strait survey.

Stock projections were conducted for the years 1999 through 2002 using stochastic simulations, where the stochastic elements were the 1998 number-at-age and the 1999 through 2002 recruitment levels. These stock projections suggest that the spawning stock biomass will continue to decrease through 2001 with a small probability of increase in 2002. Potential yield in 1999, based on target age-5 fishing mortality rates from 0.30 to 0.50, were 600 to 890 tonnes for the common selectivity at 60 cm assumption and 1090 to 1560 tonnes for the common selectivity at 70 cm assumption.

RÉSUMÉ

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Des reconstitutions du stock de morue du Pacifique du détroit d'Hécate ont été effectuées à l'aide d'un modèle de capture selon la longueur (MULTIFAN CL), comme pour les évaluations antérieures. La plus importante modification apportée à l'évaluation de cette année a consisté à inclure des données recueillies lors du relevé multispécifique dans le détroit d'Hécate. Bien que les indices d'abondance de la morue du Pacifique obtenus grâce à ce relevé ne sont pas précis, le relevé est effectué de la même façon depuis 1984 et devrait donc renseigner sur les tendances générales de l'abondance relative.

Les analyses du stock ont été réalisées en fonction de deux postulats différents : selon le premier postulat, la sélectivité de capture des poissons de 60 cm est constante d'une pêcherie commerciale à l'autre (périodes et lieux de pêche) et, selon le deuxième postulat, la sélectivité de capture des poissons de 70 cm est constante d'une pêcherie à l'autre. Le premier postulat constitue un paramétrage plus restrictif que l'autre. Les deux analyses laissent croire que l'abondance du stock est toujours près des niveaux les plus bas enregistrés par le passé, que le recrutement des neuf dernières classes d'âge est toujours inférieur à la médiane et que la classe d'âge de 1998 est la plus petite jamais observée. Ce dernier résultat dépend en grande partie de la structure de longueur observée lors du relevé de 1998 dans le détroit d'Hécate.

Des prévisions du stock ont été effectuées pour les années 1999 à 2002 à l'aide de simulations stochastiques, où les éléments stochastiques étaient l'abondance par âge en 1998 et les niveaux de recrutement pour les années 1999 à 2002. Ces prévisions du stock portent à croire que la biomasse du stock de géniteurs continuera de baisser en 2001, avec une légère probabilité qu'elle augmente en 2002. Fondé sur des taux de mortalité par pêche des poissons de cinq ans allant de 0,30 à 0,50, le rendement potentiel en 1999 était de 600 à 890 tonnes selon le premier postulat (sélectivité - 60 cm) et de 1090 à 1560 tonnes selon le deuxième postulat (sélectivité - 70 cm).

INTRODUCTION

Pacific cod (*Gadus macrocephalus*) is a major component of the domestic trawl fishery. In Canadian waters, Pacific cod is close to the southern limit of its commercial abundance and exhibits rapid growth and a short life span. Pacific cod are not aged using hardparts but ages are inferred from length-frequency analysis.

Since 1995, a catch-at-length model (MULTIFAN CL) has been used to analyze and reconstruct the stock histories for the Hecate Strait stock (Major Areas 5C and 5D). Previous assessments have incorporated commercial fishery-based catch per unit effort (CPUE) statistics in the analyses to provide information on stock trajectories. However, as noted in last years' assessment (Haist and Fournier 1998), the relationship between commercial fishery-based CPUE statistics and stock abundance has likely changed in recent years because of changes in the management of the fishery. The significant changes include; regulations for larger-mesh cod-ends, an individual quota (IQ) management system, and mandated (industry-pay) observers on-board all commercial trawl vessels. In the most recent stock assessment, the catch-length model was revised to allow for a shift in the size selectivity of the fishery which would be expected as a result of the changes in cod-end mesh size. Even with this modification, the uncertainty in current stock size was extremely high as a result of the inconsistency between the observed increase in the commercial CPUE statistics and the absence of smaller, younger fish in the catch sampling data.

In an attempt to overcome the problems inherent in the commercial fishery-based data, information from the multi-species Hecate Strait Survey is included in the this years' assessment of Hecate Strait Pacific cod. This survey has been conducted semi-regularly since 1984 but has not been used in previous stock assessments because survey abundance indices are not expected to be strongly related to Pacific cod abundance (Fargo and Tyler, 1992). While Pacific Cod CPUE statistics from this survey may be highly imprecise, the survey has been conducted in a relatively consistent manner since its inception, and hence overall trends should reflect longer-term changes in cod abundance. An additional benefit of using the data from this survey is that Pacific cod year classes are observed one to two years earlier in the survey than in the commercial fishery.

This document summarizes the results of analyses conducted to estimate the current status, forecast future status, and evaluate harvest options for Hecate Strait Pacific cod. We present the results of an evaluation of alternative model structures for the reconstruction of the stock for 1956 to 1988. We present results of a simulation study to estimate average catch and spawning stock biomass under various harvest rates for two model formulations. And we project potential catch and spawning stock biomass for the 1999-2001 period.

THE FISHERY

In B.C., Pacific cod are caught primarily by trawl gear and historically have comprised a significant component of the domestic trawl catch. The landed catches of Pacific cod in Hecate Strait and other regions of the coast are shown in Table 1 for the 1956-1997 period.

The trawl fishery in B.C. has undergone a number of significant changes in recent years that may influence the quality and comparability of data collected from the fisheries. A brief summary of management initiatives related to the Pacific cod fishery follows.

Prior to 1992 the total catch of Pacific cod by the trawl fleet in B.C. was unrestricted and the main management measures were area/seasonal closures. Total allowable catches (TAC's) were introduced for the management of Pacific cod fisheries in Hecate Strait in 1992 and for fisheries on the west coast of Vancouver Island in 1994 (Table 2). Additionally, trip limits (i.e. limits on the quantity of fish landed per trip) were introduced and these decreased steadily between 1992 and 1995. The Hecate Strait quotas were not achieved between 1993 and 1995 and the west coast Vancouver Island TAC's were not achieved in 1994 and 1995. For the 1996 season, trawl fisheries in both Hecate Strait and on the west coast of Vancouver Island were restricted to by-catch only for Pacific cod because of stock concerns. In 1997, an individual vessel quota system (IVQ) was introduced for the B.C. trawl fishery, and coincidentally the fishing season was changed from a calendar year to an April-March season.

Beginning with the 1991 Pacific Groundfish Trawl Management Plan, it was suggested that fishermen voluntarily adopt a 140mm minimum cod-end mesh size for bottom-trawl gear operating in Hecate Strait (the coast-wide regulation was a 76 mm minimum). This suggestion was continued in later management plans until 1995 when the 140mm minimum was legislated for the Hecate Strait region.

CATCH-EFFORT STATISTICS

It is generally recognized that catch-per-unit-effort (CPUE) statistics calculated from fisheries data can be unreliable indices of stock abundance because of factors such as technology improvements and the non-random distribution of both fishing effort and fish. Beyond these concerns, the collection of catch and effort data from the commercial trawl fishery in B.C. has undergone changes, which may effect the comparability of the data over time.

Prior to 1991 catch and effort data were obtained through a voluntary log book program. Data were reported for each trip made, and estimates of the total effort and species catch were reported by location and depth stratum for each area fished during the trip. We refer to this data as "trip-based". Since 1991 the maintenance of logbook data records is mandatory in the trawl fishery and the detail of information reported in logbooks has increased. Species catch, effort, and location/depth information is recorded for each tow made. We refer to this data as "tow-based". The groundfish data base system was modified to generate data records that summarized the tow-based data to a form more consistent with the trip-based data, so for the 1991-1995 period the data can be analyzed either as tow-based or trip-based. Since 1996, a mandatory observer program was instituted in the B.C. trawl fishery and observers report tow-based data on species catch (landed and discarded), effort and location/depth. Fishermen continue to maintain logbook records, but this information is not being computerized. At this time, the observer data is not available in a trip-based form. In summary, for years prior to 1991 data is only available as "trip-based" summaries and for 1996 to 1998 the data is only available as "observer-recorded tow-based" records. For the 1991-1995 period, the fisherman-recorded catch-effort data can be used either way. The 1997 Pacific cod stock assessment (Haist and Fournier 1998) documents some of the potential biases that may result from these changes in data collection.

For the current assessment, CPUE indices are calculated as the sum of catch divided by the sum of effort for all data qualified at the 10% level. Trip-based data are used for 1956-1990 and tow-based data for 1991-1997. Effort, the data used in the catch-length model, is calculated as the total catch divided by CPUE.

HECATE STRAIT SURVEY DATA

A multi-species bottom trawl survey has been conducted semi-regularly in Hecate Strait since 1984 (Fargo and Tyler 1992; Perry et al. 1994). Surveys were conducted between May and June in 1984, 1987, 1989, 1991, 1993, 1995, 1996 and 1998. A survey conducted during the winter of 1986 is not included in the current analysis. The survey is generally comprised of approximately 100 15-30 minute tows conducted throughout the Hecate Strait area. For the survey a 20 by 20 nautical mile (nm) grid is imposed on the Hecate Strait area, and in general the survey aims to conduct one tow in each 10 fathom depth interval in each of approximately 35 grid blocks. Fishing has been conducted using both commercial and research vessels, and specific location of tows was at the discretion of the fishing master.

Figure 1 shows boxplots of the distribution of Pacific cod CPUE for each of the survey years. Because 45% of all observations have no Pacific cod catch, the quartiles plotted in Figure 1 are all centered on the zero line. All tows with significant Pacific cod catch are denoted outliers in these plots.

Pacific cod abundance indices are calculated from the survey data using sample survey based estimates. We consider a number of ways to stratify the observations to see if survey stratification will improve the precision of estimates. Three forms of stratification are considered. One is based strictly on the sample depths, with strata for each 10 fathom depth interval. The second stratification scheme is based on tow locations and we define 4 strata separating Hecate Strait along the North-South axis. The third stratification considers both depth and location, using the 4 location strata from the second scheme and 20fm depth intervals. Strata weightings, proportional to strata size, are estimated assuming that all depth intervals sampled in a grid block are equal in size. Because the strata were determined after the surveys were conducted we use post-stratification estimation methods (Cochran 1963, page 135).

Estimates of the stratified mean CPUE's (kg/hour) and their standard errors are shown in Table 10 for the three stratification scheme and for no-stratification. Strata means are presented in Tables 11 to 13. The CPUE indices are similar among the different stratification schemes, with the area stratification indicating somewhat greater variability in indices over the time period. The depth stratification scheme produces the smallest standard errors of the estimates for all years except 1998. The estimated standard errors from both the area and area/depth stratifications are higher than those when no stratification is used for most of the years. For the catch-at-length analyses the mean CPUE statistics from the depth stratification scheme are used.

CATCH-AT-LENGTH ANALYSIS

A catch-at-length model, MULTIFAN CL has been used for analysis of Pacific cod fisheries data since 1985 (eg. Haist and Fournier 1995). MULTIFAN CL integrates length-frequency analysis with catch-age analysis so that growth parameters and catch equation parameters are estimated simultaneously, rather than through a step-wise procedure. The model is described in Appendix "A".

Data requirements for the analyses include catch estimates (in numbers), effort indices, and length-frequency data. The data were compiled and analyzed by quarter (Q1-Q4) for the period January 1956 to June 1998. Sample sizes for the length-frequency data are shown in Table 3. The length frequencies of Pacific cod sampled from the commercial fisheries show decreased proportions of smaller fish through the early 1990's (Appendix B), resulting from the change in cod-end mesh size regulation. The move to larger cod-end mesh was first suggested in the 1991 management plan, and was regulated in 1995. Many fishermen changed their nets prior to 1995. We model a change in selectivity-at-length beginning in 1993. The length frequency data also indicate that a change in the proportion of small Pacific cod landed occurred around 1972 (because of market restrictions), and a third selectivity period is modeled to account for this observed change. Data from the Hecate Strait Survey is incorporated in the model as an additional fishery, with independent catchability and selectivity parameters. The following table shows the thirteen fisheries that are modeled and the common catchability (q) and selectivity parameters between them.

time-period	Q 1 (Jan. - Mar.)	Q2 (Apr. – June)	Q3 (July – Aug.)	Q4 (Sept. – Dec.)
1956 - 1971	fishery – 1 sel – 1 q - 1	fishery – 2 sel – 1 q – 2	fishery – 3 sel – 1 q – 3	fishery – 4 sel – 1 q – 4
1972 – 1992	fishery – 5 sel – 2 q – 1	fishery – 6 sel - 2 q – 2	fishery – 7 sel - 2 q - 3	fishery – 8 sel – 2 q – 4
1993 –1 997	fishery – 9 sel – 3 q - 1	fishery – 10 sel – 3 q - 2	fishery – 11 sel – 3 q – 3	fishery – 12 sel – 3 q – 4
Hecate Strait Survey 1984 - 1998		fishery – 13 sel – 4 q - 5		

For MULTIFAN CL analysis the standard procedure for model development and selection of the most appropriate model formulation is the same as that developed for MULTIFAN analysis (Fournier et al. 1990, Fournier et al. 1991). That is, for each model formulation the data is fit at a range of initial K estimates (von Bertalanffy growth coefficient), M estimates (natural mortality rate), and number of age-classes. For each formulation the best fit across K, M, and age-classes is selected based on likelihood ratio tests. Similarly, a more complex model formulation (i.e. more parameters) is selected over a simpler formulation when the likelihood ratio test suggests there is significant improvement in model fit for the more complex formulation. Modifications to this procedure, adopted for the current assessment, are discussed below.

Initial analyses for this years' assessments showed significantly different patterns than observed in previous years' analyses, a result of including the Hecate Strait Survey data. Analyses suggested the catch-length data represented a minimum of 12 year-classes. We did not do runs to see if increasing the number of age-classes beyond 12 would continue to improvement the model fit. The mean lengths-at-age did not change with the addition of year-classes, rather the improvement in model fit came from the increased flexibility in parameterization of selectivity. Additionally, small changes in initial K values sometime resulted in significantly different model fits, implying major problems with the model reaching local rather than global minima.

A simpler length-based selectivity parameterization (described in Appendix A) appeared to minimize the problems with local minima. For the current analysis length-dependent selectivities are constrained to be non-decreasing, and to have common values at a specified length. The lengths for "common selectivity" evaluated in this analysis are 60 and 70 cm. Thus, all fisheries with the exception of the Hecate Strait survey have the same relative selectivity at the specified length.

Published estimates of the instantaneous natural mortality rate for Pacific cod in Hecate Strait range from 0.38 to 0.99 (Westrheim 1996). Previous analyses using the MULTIFAN CL model for B.C. cod stocks showed that better fits were obtained with M=0.65 than with M=0.40 (Haist and Fournier 1995). Because the inclusion of the Hecate Strait Survey data adds information on 1-2 age classes younger than those sampled by the commercial fishery, we investigate values of M ranging from 0.45-0.65 in the current analysis.

We limit the number of age-classes in the analyses to a maximum of 8. Previous assessment all indicated a maximum of 4 significant age-classes in the Pacific cod commercial fishery data. The Hecate Strait Survey data adds information on no more that two additional 2 age-classes. A full range of initial K values was not investigated in the current analysis because of time constraints, rather a subset of the model runs were checked at alternate K values to see if different minima occurred.
Additional model structure that is evaluated in a step-wise procedure is length-dependent standared deviations of length-at-age and seasonal growth.

For the first series of model runs the natural morality was fixed at 0.65, and we evaluate common among-fishery selectivity at 60 cm and 70 cm, the inclusion of length-dependent standard deviations and seasonal growth. Values of the objective function for the alternate model formulations are shown in Table 4. For both the runs with common fishery-selectivities at 60cm and at 70 cm, as the model complexity increases, each additional component of the model structure significantly improves the model fit. Also, the best fits are observed with the maximum of 8 age-classes in the population . Model fits to the data observations are better for the analyses assuming common fishery-selectivity at 70 cm, but this is expected because this is a less restrictive parameterization and hence does not constitute a significantly better fit.

Additional model runs were done to investigate alternate M values. For these analyses we restricted the model formulations to 8 age-classes and included seasonal growth and length-dependent standard deviations of length-at-age. Estimates of the function value and of the 1998 age 3+ biomass resulting from these runs are shown in Table 5. Assuming a common fishery selectivity at 60 cm, the best model fit is obtained with M=0.45, although this fit is not significantly better than that with M=0.55. With the common among-fishery selectivity fixed at 70 cm the best fits of the model to the data are obtained at M=0.55. The estimates of 1988 age 3+ biomass do not change much with changes in M, but are relatively different between the assumption of common selectivity at 60 cm and at 70 cm. The estimated 1988 age 3+ biomass ranges from 3750 t. to 4400 t when common selectivity at 60 cm is assumed and ranges from 5970 t. to 7020 t. when. common selectivity at 70 cm is assumed. We present and discuss additional results from the analyses for two of the runs, one assuming common among-fishery selectivity at 60 cm and M=0.45 and the other assuming common selectivity at 70 cm and M=0.55. For ease of terminology we will call these specific analyses "60 cm common selectivity" and "70 cm common selectivity".

Estimates of the mean selectivity-at-age for the three commercial fishery time periods (1956-1971, 1972-1992, 1993-1998) and for the Hecate Strait Survey are shown in Figure 2. For both the analysis assuming 60 cm common selectivity and the analysis assuming 70 cm common selectivity, the estimates of selectivity-at-age are significantly lower than in previous Pacific cod assessments. In last years assessment the estimates of selectivity for fish at age 4 ranged from 0.82 to 0.85 (1956-71 and 1972-92 fisheries). The estimates for the same age class range from 0.07 to 0.29 for the "70 cm common selectivity" assumption and from 0.16 to 0.24 for the "60 cm common selectivity" assumption in the current analysis. The selectivity estimates indicate that Pacific cod are not fully recruited to the fishery until age 6, or older. The lower selectivity for younger ages, and resulting higher fishing mortality at older ages allows the model to "get rid of" older fish in the population and fit the observed length-frequency data which indicate few large, old fish.

Tables 6 and 7 show estimates of the numbers-at-age from 1956 through 1998 for both the common selectivity at 60 cm and common selectivity at 70 cm stock reconstructions. Estimates of the recruitments, with their standard errors, and of age 3+ biomass are plotted in Figure 3 for the same period. Both stock reconstructions suggest that spawning stock biomass was at historic low levels between 1994 and 1996 and it increased slightly in the following two years. However, the estimate of for the 1997 year-class is the lowest in the time-series, indicating stock recovery is not imminent. The standard errors of recruitment estimates are relatively small, even for the most recent year-classes recruiting to the stock (Figure 3). In previous assessments, uncertainty in the estimates of the last two year-classes were large, however the inclusion of length-frequency data from the Hecate Strait survey in the current analysis provides tighter bounds for the values of these parameters.

HARVEST LEVELS AND STOCK PROJECTIONS

For the 1995 Pacific cod stock assessment, analyses related to harvest dynamics were presented (Haist and Fournier 1995). The recommendations arising from those analyses were for a target fishing mortality rate (fully recruited F) of 0.30, and for threshold spawning stock biomass (SSB) levels below which cessation of fisheries would be suggested. These recommendations have been the basis for harvest options presented in Pacific cod stock assessment documents since then. Given the changes in estimates of fishery selectivites and revision of the estimate of M in the current assessment, a re-evaluation of stock and catch performance under alternate fishing mortality (F) levels is required.

We calculated the exploitable biomass-at-age for a fixed level of recruiment (1000 fish) to see how the current estimates of selectivity, and alternative estimates of F impact this parameter. This is a deterministic calculation, based on natural mortality M, the specifed F, and the fishery selectivity parameters (estimates for 1993-1998 period used). The levels of F (F's for 5 year-old fish) ranged from 0 to 0.5. Results, based on the values of M and the selectivity parameters from both the common selectivity at 60 cm and common selectivity at 70 cm stock reconstructions, are shown in Figure 4. The results suggest that most of the exploitable biomass in the stock is the result of fish aged 5 and older. With zero fishing mortality there is significant exploitable biomass for fish at age 8 and older. As fishing mortality rates increase, the age-distribution of exploitable fish is compressed, and at age-5 F equal to 0.50 few fish older than age 6 remain in the exploitable stock.

We conducted a set of simulation experiments to estimate average levels of catch and of spawning stock biomass under different fixed levels of F. The simulations consisted of a series of 1000 20-year simulations at each F level. Recruitment in the first simulated year was chosen by randomly selecting from the 1956-1998 series of recruitment estimates from the MULTIFAN CL analysis. The number of fish recruiting in the following 19 years were then the next 19 years of recruitment estimates from the assessment. When the last year was reached, the cycle was initialized to 1956. For example, if the recruitment for the first year of the simulation was that estimated for 1980, then the time series of recruitments for the simulation were the values estimated for 1980, 1981, ...,1998,1956, 1957,1957. The numbers-at-age in the first year were simulated assuming an equilibrium age-structure for the specified fishing mortality level, fishery selectivities, M, and first years recruitment level. With the exception of recruitments, the simulations were deterministic. Two sets of simulations were conducted, one using parameter estimates from the MULTIFAN CL analysis assuming common fishery selectivity at 60 cm and one using results from the 70 cm assumption. The simulations assumed the fishery was conducted at a constant rate throughout the year. The simulations were conducted for quarterly periods so changes in size-at-age and resulting changes in selectivity-at-age through a year were incorporated in the analysis. Fishery selectivity parameters were those estimated for the final (1993-1998) period in the MULTIFAN CL analysis. The range of age 5 fishing mortality evaluated was 0 to 0.70.

Estimates of the mean catch and spawning stock biomass for the alternate fishing mortality levels and for the two sets of stock parameters are shown in Figure 5. The results for the two sets of analyses, one assuming common fishing selectivity at 60 cm and the other at 70 cm, are similar, both in terms of the average catch and the average spawing stock biomass at different F levels. Harvest levels in the range of age-5 F of 0.30 to 0.50 probably provide a reasonable trade-off between maximizing catch and maintaining spawning stock biomass. The higher end of this range does reduce the age-structure of the population (Figure 4).

The Hecate Strait Pacific cod stock is projected forward to 2001 for values of age 5-fishing mortality ranging from 0.30 to 0.50. Two sets of stock projections are made. One is based on the stock reconstruction assuming common fishery selectivity at 60 cm and the other on the reconstruction assuming common fishery selectivity at 70 cm. Projections for each year are based on the results of 1000 stochastic simulations.

Estimates of numbers-at-age at the beginning of 1998 and the standard errors of these estimates are available from the MULTIFAN CL analysis. Stock abundance is projected to January 1999 based on these estimates and an assumed F for 1998. Pacific cod catch in Hecate Strait between January 1 and June 30, 1998 was 767t. Based on the annual fishing pattern in recent years we estimate that approximately 1000 tonnes will be landed in 1998. The 1998 F was fixed to obtain approximately 1000 t of catch in 1998. Stock projections are stocastic in that random variation is introduced in the numbers of fish-at-age at the beginning of 1998 and in the recruitment of age 1 fish in 1999, 2000, and 2001. The recruitments are generated by randomly selecting from the 1956-1998 time series of estimates from the stock assessment. Only the 1999 recruitment impacts the projections, because the others are too young to effect catch or spawning stock biomass estimates in the projection years.

Projected spawning stock biomass and potential catch at the 10^{th}, 25^{th}, 50^{th}, 75^{th}, and 90^{th} percentiles of their distributions are presented in Tables 8 and 9 for 1999 through 2001. For both sets of assumptions regarding size at common selectivity, spawning stock biomass for 1999 through 2002 is projected to be below all historic (1956-1998) levels. Potential catch levels for the analyses assuming common selectivity at 70 cm are more optimistic, with 1999 median levels ranging from 1090 to 1560 tonnes for age-5 F levels of 0.3 to 0.5. The equivalent estimates for the analyses assuming common selectivity at 60 cm are 600 to 890 t. The short-term projections for this stock are not optimistic, with spawning stock biomass decreasing again in 2000. These results are, of course, highly dependent on the size-structure of the 1998 Hecate Strait survey. Given the small numbers of larger, older fish sampled in this survey, results may be biased.

REFERENCES

Cochran, W. G. 1963. Sampling Techniques. John Wiley and Sons, New York. 413 p.

Fargo, J. and A.V. Tyler. 1992. Statistical testing of research trawl data with implications for survey design. Netherlands Journal of the Sea Research. 29 (1-3): 97-108 p.

Fournier, D.A., J.R. Sibert, J. Majkowski, and J. Hampton. 1990. MULTIFAN: a likelihood-based method for estimating growth parameters and age composition from multiple length frequency data sets illustrated using data for southern bluefin tuna (*Thunnus maccoyii*). Can. J. Fish. Aquat. Sci. 47: 301-317 p.

Fournier, D.A., J.R. Sibert, and M. Terceiro. 1991. Analysis of length frequency samples with relative abundance data for the Gulf of Maine northern shrimp (*Pandalus borealis*) by the MULTIFAN method. Can J. Fish. Aquat. Sci. 48: 591-598 p.

Haist, V., and D. Fournier. 1998. Hecate Strait Pacific cod stock assessments for 1997 and recommended yield options for 1998/99. PSARC Working Paper G97-3. 43 p.

Haist, V., and D. Fournier. 1995. Pacific cod stock assessments for 1995 and recommended yield options for 1996. PSARC Working Paper G95-3: 62 p.

Perry, R. I., M. Stocker, and J. Fargo. 1994. Environmental effects on the distribution of groundfish in Hecate Strait, British Columbia. Can. J. Fish. Aquat. Sci. 51: 1401-1409 p.

Westrheim, S. J. 1996. On the Pacific cod (*Gadus macrocephalus*) in British Columbia waters, and a comparison with Pacific cod elsewhere, and Atlantic cod (*G. morhua*). Can. Tech. Rep. Fish. Aquat. Sci. 2092: 390 p.

Table 1. Annual Pacific cod landed catch (tonnes) estimates for the Strait of Georgia (SoG), west coast of Vancouver Island (WCVI), Queen Charlotte Sound (QSD) and Hecate Strait (HS) for the period 1956-1997.

Year	SoG	WCVI	QSD	HS	Coastwide
1956	578.	1468.	1753.	1046.	2679.
1957	607.	1814.	2744.	1106.	4027.
1958	650.	850.	1178.	3058.	4722.
1959	1047.	907.	946.	2203.	4284.
1960	744.	635.	618.	2360.	3119.
1961	415.	420.	240.	1616.	2083.
1962	478.	633.	422.	1690.	2722.
1963	675.	1231.	677.	2927.	4107.
1964	713.	1221.	1275.	5228.	7279.
1965	484.	2768.	1940.	9119.	11224.
1966	297.	3136.	1811.	9519.	12276.
1967	472.	1941.	1501.	5112.	6778.
1968	349.	1425.	960.	5165.	6741.
1969	388.	1092.	699.	2987.	4445.
1970	502.	1095.	299.	1315.	2878.
1971	740.	3328.	928.	1477.	5004.
1972	630.	5629.	2320.	2696.	8639.
1973	441.	3712.	1914.	3996.	7467.
1974	681.	3474.	2292.	4766.	8886.
1975	991.	4000.	2444.	5036.	10311.
1976	927.	3797.	2271.	4993.	10082.
1977	1148.	2948.	1268.	3510.	7650.
1978	1373.	1998.	1959.	2103.	6674.
1979	1202.	1861.	1904.	4699.	9549.
1980	1611.	1126.	1383.	4542.	8703.
1981	1749.	896.	853.	3190.	6694.
1982	1012.	1123.	596.	2066.	4798.
1983	904.	694.	183.	2715.	4497.
1984	652.	675.	383.	1748.	3461.
1985	463.	492.	299.	1064.	2329.
1986	804.	498.	241.	2099.	3651.
1987	1015.	809.	3243.	8870.	13941.
1988	1223.	1807.	1849.	6199.	11095.
1989	604.	2991.	763.	4788.	9152.
1990	114.	1953.	772.	3607.	6455.
1991	68.	2177.	2018.	7655.	11921.
1992	412.	2773.	2043.	5103.	10340.
1993	158.	2527.	1449.	3965.	8105.
1994	90.	1211.	679.	1561.	3547.
1995	24.	652.	345.	1322.	2346.
1996	11.	109.	176.	403.	710.
1997				1115.	

Table 2. The recommended yields, TAC's, and landed catches (tonnes) for the Hecate Strait and the West Coast Vancouver Island (WCVI) Pacific cod stocks, 1992-1998.

	Hecate Strait			WCVI		
Year	Recommended Yield	TAC	Landed Catch	Recommended Yield	TAC	Landed Catch
1998/99		1000		No assessment/ no advice	694	
1997/98	L: 1075 H: 2165	1620		0	694	
1996	0	by-catch only	403	L: 694 H: 916	by-catch only	109
1995	L: 1870 M: 3040 H: 5520	1870	1322	L: 1300 M: 2200 H: 5330	1300	652
1994	L: 1670 M: 3850 H: 7790	3850	1561	L: 650 M: 2170 H: 5880	2170	1211
1993	L: 3200 H: 6500	5100	3965	no advice	no quota	2527
1992	L: 600 M: 2800 H: 3800	3400	5103	no advice	no quota	2773

Table 3. The number of measured fish and the number of samples (in brackets) used in the MULTIFAN CL analysis of the Hecate Strait stock by year and quarter

Year	Q1	Q2	Q3	Q4
1956	481 (4)	560 (4)	296 (2)	0 (0)
1957	426 (3)	461 (3)	0 (0)	227 (1)
1958	2314 (13)	1209 (6)	664 (3)	2033 (10)
1959	4213 (20)	1949 (11)	3623 (16)	404 (2)
1960	1851 (9)	1840 (6)	3604 (15)	2031 (12)
1961	2778 (12)	4175 (16)	2743 (9)	1330 (6)
1962	4972 (18)	1488 (6)	1215 (4)	1093 (4)
1963	4607 (19)	3121 (11)	1403 (5)	1629 (6)
1964	4077 (19)	6332 (25)	3767 (14)	1649 (7)
1965	5993 (25)	5732 (21)	4040 (16)	2524 (11)
1966	3528 (14)	7459 (30)	3709 (15)	2131 (10)
1967	4341 (16)	2424 (9)	3580 (14)	3085 (15)
1968	3196 (14)	4701 (22)	2062 (9)	858 (4)
1969	2017 (10)	3561 (15)	1391 (7)	196 (1)
1970	1012 (5)	1145 (6)	713 (3)	172 (1)
1971	1692 (9)	1723 (9)	135 (1)	0 (0)
1972	458 (2)	804 (3)	548 (2)	1228 (6)
1973	682 (3)	2854 (11)	2727 (13)	1595 (10)
1974	451 (2)	2097 (10)	2151 (11)	2133 (10)
1975	2443 (14)	3206 (14)	120 (1)	884 (5)
1976	1590 (12)	1845 (15)	1051 (9)	457 (4)
1977	770 (6)	1793 (14)	2372 (20)	960 (8)
1978	816 (7)	2694 (21)	1316 (11)	797 (8)
1979	1656 (13)	3639 (23)	2500 (17)	634 (5)
1980	3774 (26)	2191 (16)	596 (5)	120 (1)
1981	0 (0)	120 (1)	478 (4)	240 (2)
1982	1576 (9)	2333 (10)	2192 (10)	228 (1)
1983	2807 (15)	3888 (20)	923 (4)	0 (0)
1984	1874 (8)	2170 (9)	1402 (6)	1259 (5)
1985	1723 (8)	1174 (5)	907 (4)	0 (0)
1986	1844 (8)	4120 (17)	416 (2)	236 (1)
1987	5497 (14)	2846 (7)	1406 (3)	540 (2)
1988	1689 (5)	1464 (4)	368 (1)	350 (1)
1989	752 (2)	731 (2)	0 (0)	400 (1)
1990	2583 (8)	231 (1)	912 (2)	789 (4)
1991	955 (6)	2475 (14)	756 (4)	147 (1)
1992	1697 (11)	1604 (10)	292 (2)	0 (0)
1993	873 (7)	1643 (13)	276 (2)	0 (0)
1994	945 (8)	348 (3)	116 (1)	0 (0)
1995	558 (5)	558 (5)	123 (1)	0 (0)
1996	0 (0)	404 (3)	569 (4)	0 (0)
1997	782 (8)	355 (3)	130 (1)	0 (0)
1998	1151 (11)[a]	2971 (23)[b]		

[a] - 2 samples from observers
[b] - 15 samples from observers

Table 4. Estimate of the log-likelihood function value for MULTIFAN CL analyses of Hecate Strait Pacific cod fisheries data. Model formulation is progressive in that analyses with length-dependent standard deviations incorporate baseline model structure (with one additional independent parameter) and analyses with seasonal growth incorporate all length-dependent standard deviation model structure (with two additional independent parameters).

		Common fishery selectivity at 60cm			Common fishery selectivity at 70 cm		
		Model structure					
Number Age classes	Number of parameters for baseline	Baseline	Length-dependent st. devs.	Seasonal growth	Baseline	Length-dependent st.devs	Seasonal growth
6	256	-8771.1	-8808.2	-8823.9	-8819.9	-8846.7	-8889.3
7	261	-8821.0	-8851.5	-8885.6	-8881.5	-8916.0	-8952.9
8	266	-8853.1	-8884.6	-8918.2	-8913.4	-8954.9	-8984.4

Table 5. Estimate of the log-likelihood function value and 1998 age 3+ biomass from MULTIFAN CL analyses of Hecate Strait Pacific cod fisheries data employing alternate assumptions about the value of natural mortality (M). The model structure assumes 8 age-classes and includes length-dependent standard deviations and seasonal growth parameters.

Common fishery	Function value			1998 age 3+ biomass (tonnes)		
selectivity at	M=0.65	M=0.55	M=0.45	M=0.65	M=0.55	M=0.45
60 cm	-8918.2	-8921.9	-8923.1	4040	3940	3750
70 cm	-8984.4	-8989.6	-8988.6	7020	6225	5970

Table 6. Number-at-age and age 3+ biomass for Hecate Strait Pacific cod estimated from catch-at-length analysis assuming 8 age-classes, M=0.45 and common fishery selectivity at 60 cm.

	Numbers-at-age (1000's)								Age 3+ biomass (tonnes)
	1	2	3	4	5	6	7	8+	
1956	2218	4539	1811	214	266	65	3	0	3665
1957	5741	1414	2893	1089	99	83	15	1	6344
1958	3519	3661	901	1733	505	31	19	3	6323
1959	3253	2244	2329	506	551	67	2	1	5729
1960	6143	2074	1427	1301	164	80	5	0	5160
1961	10240	3916	1320	782	376	18	4	0	4367
1962	30236	6529	2494	767	295	72	2	0	5701
1963	10383	19278	4157	1435	285	58	9	0	8961
1964	10946	6620	12271	2344	473	42	4	0	20899
1965	11087	6979	4213	6838	761	72	3	0	21353
1966	2032	7069	4442	2336	2174	112	6	0	16995
1967	4060	1295	4498	2369	599	199	4	0	12748
1968	490	2588	823	2452	736	88	16	0	8570
1969	5120	312	1648	460	727	82	4	1	5429
1970	13459	3264	199	892	122	69	3	0	2701
1971	5580	8581	2078	115	322	21	7	0	3788
1972	11652	3557	5464	1142	32	33	1	0	9021
1973	10010	7428	2247	2650	374	5	3	0	9156
1974	4860	6381	4696	1103	885	60	0	0	10703
1975	11002	3098	4026	2145	320	104	3	0	10496
1976	2669	7014	1954	1873	607	37	5	0	8087
1977	11911	1701	4405	801	406	39	1	0	8224
1978	5077	7593	1070	1875	200	34	1	0	5791
1979	9446	3237	4814	572	749	47	5	0	9338
1980	4326	6022	2040	2065	137	59	1	0	7238
1981	2415	2758	3789	830	400	7	1	0	7399
1982	5954	1540	1744	1818	237	47	0	0	6630
1983	1311	3796	977	946	748	60	7	0	5594
1984	3116	836	2409	522	353	155	6	1	5646
1985	31532	1987	530	1299	216	90	25	1	4400
1986	10538	20105	1264	313	657	85	27	7	4643
1987	3746	6719	12766	699	132	176	14	5	17783
1988	11126	2388	4193	4671	107	4	1	0	14713
1989	16456	7094	1512	2119	1430	15	0	0	10415
1990	3431	10492	4503	826	803	312	2	0	10709
1991	3807	2187	6648	2409	326	187	43	0	14712
1992	762	2427	1379	3007	632	32	7	1	9757
1993	3482	486	1537	693	989	100	2	1	6616
1994	1788	2217	307	875	212	94	5	0	3176
1995	2081	1139	1408	185	372	43	11	1	3403
1996	2708	1326	723	837	72	62	4	1	3044
1997	240	1726	844	449	450	30	23	2	3518
1998	1785	153	1098	521	228	153	8	6	3747

Table 7. Number-at-age and age 3+ biomass for Hecate Strait Pacific cod estimated from catch-at-length analysis assuming 8 age-classes, M=0.55 and common fishery selectivity at 70 cm.

	Numbers-at-age (1000's)								Age 3+ biomass (tonnes)
	1	2	3	4	5	6	7	8+	
1956	3048	6161	2098	196	276	55	3	0	3986
1957	8124	1759	3553	1150	75	70	13	1	7165
1958	4935	4687	1014	1946	460	21	19	4	6753
1959	4209	2847	2700	535	558	63	2	3	6290
1960	8197	2428	1640	1393	140	73	7	1	5548
1961	13465	4729	1399	840	329	14	6	1	4463
1962	44836	7768	2726	746	260	53	2	1	5789
1963	15740	25867	4477	1431	212	39	7	0	9087
1964	14631	9081	14901	2307	347	22	3	1	23632
1965	16539	8441	5231	7650	567	42	2	0	23632
1966	2876	9542	4864	2744	2194	91	6	0	18416
1967	5634	1659	5497	2455	577	198	7	0	14141
1968	652	3250	955	2784	612	79	24	1	9088
1969	7379	376	1874	502	729	68	7	2	5798
1970	19813	4257	217	946	102	58	5	1	2755
1971	8089	11431	2454	116	291	16	8	1	4161
1972	16689	4667	6587	1238	22	19	1	0	10527
1973	14395	9627	2673	2987	386	3	2	0	10430
1974	6798	8304	5518	1226	951	62	0	0	12209
1975	15944	3921	4752	2364	338	111	4	0	11962
1976	3880	9198	2243	2080	649	40	6	0	9048
1977	16865	2238	5245	878	443	44	1	0	9569
1978	7048	9728	1278	2125	213	40	2	0	6648
1979	13940	4066	5589	633	801	49	6	0	10616
1980	6588	8041	2325	2266	147	64	2	0	8083
1981	3555	3801	4593	903	435	8	1	0	8669
1982	9157	2051	2179	2078	254	54	0	0	7804
1983	1993	5283	1179	1096	812	64	9	0	6395
1984	4274	1150	3037	585	393	169	7	1	6750
1985	44237	2465	661	1522	230	100	29	1	5146
1986	15666	25522	1420	358	715	86	29	8	5150
1987	5086	9038	14677	720	140	180	14	5	20263
1988	16228	2933	5124	5123	108	5	1	0	16842
1989	23465	9362	1683	2417	1526	15	0	0	11586
1990	5528	13537	5383	848	873	326	2	0	12151
1991	5875	3189	7771	2655	314	195	45	0	16654
1992	1460	3389	1824	3296	667	30	8	1	11042
1993	5947	842	1945	853	1034	104	2	1	7624
1994	4242	3428	483	1012	312	75	2	0	3891
1995	4471	2446	1971	264	455	54	4	0	4513
1996	5953	2578	1407	1079	121	85	4	0	4608
1997	546	3434	1486	794	568	46	25	1	5438
1998	3604	315	1979	838	413	199	10	5	6225

Table 8. Projected catch and spawning stock biomass for Hecate Strait Pacific cod with age 5 fishing mortality rates from 0.3 to 0.5. Results are based 1000 simulations using parameters from the "common selectivity at 60 cm" stock reconstruction. The estimated values at the 10th, 25th, 50th, 75th and 90th percentile of their distributions are shown.

age5 F	year (catch/ spawning)	spawning stock biomass (t.) percentile					catch (t.) percentile				
		10	25	50	75	90	10	25	50	75	90
	1998/99	1523	1615	1739	1897	2027	913	957	1002	1047	1093
0.3	1999/00	1177	1263	1375	1514	1639	530	558	595	635	673
	2000/01	1233	1336	1450	1581	1726	527	561	608	668	720
	2001/02	1381	1765	2409	4166	4764	475	517	574	642	715
0.4	1999/00	1075	1161	1269	1386	1504	668	704	750	802	850
	2000/01	1079	1163	1277	1402	1533	599	645	702	764	826
	2001/02	1283	1609	2188	3933	4439	521	567	637	714	805
0.5	1999/00	984	1073	1169	1276	1381	796	842	892	945	999
	2000/01	957	1042	1145	1262	1377	656	706	764	834	897
	2001/02	1174	1568	2215	3826	4415	552	608	684	773	873

Table 9. Projected catch and spawning stock biomass for Hecate Strait Pacific cod with age 5 fishing mortality rates from 0.3 to 0.5. Results are based 1000 simulations using parameters from the "common selectivity at 70 cm" stock reconstruction. The estimated values at the 10th, 25th, 50th, 75th and 90th percentile of their distributions are shown.

age5 F	year (catch/ spawning)	spawning stock biomass (t.) percentile					catch (t.) percentile				
		10	25	50	75	90	10	25	50	75	90
	1998/99	2620	2778	2993	3242	3451	895	944	998	1059	1112
0.3	1999/00	1774	1899	2076	2282	2465	973	1028	1085	1149	1207
	2000/01	1619	1761	1923	2100	2306	926	982	1063	1164	1250
	2001/02	1653	2099	2710	4615	5322	680	738	812	903	999
0.4	1999/00	1611	1745	1909	2084	2266	1211	1269	1339	1417	1491
	2000/01	1406	1518	1686	1854	2035	1018	1093	1191	1293	1399
	2001/02	1533	1908	2474	4345	4947	703	764	851	945	1054
0.5	1999/00	1470	1609	1758	1925	2085	1416	1483	1563	1651	1737
	2000/01	1244	1368	1512	1679	1845	1083	1170	1267	1375	1482
	2001/02	1468	1861	2484	4224	4886	713	785	871	979	1088

Table 10. Estimates of the mean and the standard error for annual Pacific cod CPUE (kg/hr) abundance indices from the Hecate Strait survey under different stratification schemes.

year	no. of tows	no stratification		area stratified		area/depth stratified		depth stratified	
		mean	s.e.	mean	s.e.	mean	s.e.	mean	s.e
1984	146	34.4	8.7	39.6	9.6	36.6	10.2	32.1	8.4
1987	90	113.1	47.2	149.3	68.4	118.6	50.1	96.4	37.3
1989	95	117.3	52.6	141.6	59.6	157.1	81.5	108.8	48.4
1991	99	33.0	7.8	41.3	10.1	29.2	7.2	27.0	6.6
1993	94	38.9	10.2	49.6	14.7	38.4	8.4	33.9	8.1
1995	100	37.9	14.7	36.2	13.0	36.2	12.6	33.2	10.8
1996	102	41.2	16.7	40.2	14.4	42.5	19.9	34.0	13.5
1998	88	72.0	29.1	96.4	44.7	57.3	30.0	58.4	31.0

Table 11. Estimates of the strata means (kg/hr) for the area stratification scheme used to estimate abundance indices from the Hecate Strait survey.

	area strata			
year	AB	CD	EFGH	IJKL
1984	38.9	83.6	29.3	20.8
1987	135.1	163.4	183.3	17.7
1989	57.6	709.7	80.0	17.5
1991	10.6	79.5	25.6	43.2
1993	41.7	33.7	53.1	25.5
1995	71.1	108.5	16.2	11.6
1996	37.5	174.0	24.8	2.1
1998	46.0	56.5	127.0	28.9

Table 12. Estimates of the strata means (kg/hr) for the depth stratification scheme used to estimate abundance indices from the Hecate Strait survey.

year	depth strata (fathoms)						
	<20	20-29	30-39	40-49	50-59	60-69	70+
1984	8.6	52.5	16.7	23.1	46.7	62.3	27.7
1987	10.8	162.2	281.1	13.0	240.0	14.6	37.3
1989	2.7	194.9	477.2	133.1	35.6	16.3	14.9
1991	0.8	22.1	36.7	70.3	60.7	19.1	4.5
1993	1.2	66.1	25.4	85.0	14.4	26.7	45.8
1995	0.6	63.1	73.2	39.3	37.1	36.8	8.0
1996	0.6	108.6	58.9	36.8	36.7	13.3	6.2
1998	NA	19.8	297.1	14.4	9.7	82.1	52.2

Table 13. Estimates of the strata means (kg/hr) for the area/depth stratification scheme used to estimate abundance indices from the Hecate Strait survey.

year	area/depth strata (depth in fathoms)													
	area AB				area CD		area EFGH				area IJKL			
	<30	30-49	50-69	70+	<30	30-49	<30	30-49	50-69	70+	<30	30-49	50-69	70+
1984	34.4	28.1	56.1	28.3	141.6	22.1	0.2	30.0	49.5	57.5	0.3	2.1	51.9	10.4
1987	3.3	424.0	18.6	18.3	242.5	84.6	80.2	77.5	528.6	95.9	0.4	73.1	4.8	8.9
1989	0.0	134.0	51.3	13.3	370.0	1274.2	66.1	187.5	12.9	20.8	0.0	45.7	10.3	13.0
1991	1.7	14.9	14.2	6.0	0.0	122.5	38.8	24.5	26.4	4.8	0.0	90.4	64.2	NA
1993	0.0	53.8	69.5	8.9	3.3	80.0	61.5	94.0	7.9	44.2	38.1	2.5	4.8	69.3
1995	14.0	135.7	70.8	NA	142.6	32.0	0.5	46.7	25.0	1.0	1.2	9.1	27.8	NA
1996	5.0	45.7	55.8	0.0	275.7	109.2	16.9	46.4	18.7	12.0	0.3	2.2	2.2	5.0
1998	NA	152.0	4.1	29.5	0.0	0.0	NA	380.3	11.6	95.8	0.0	0.0	126.4	2.9

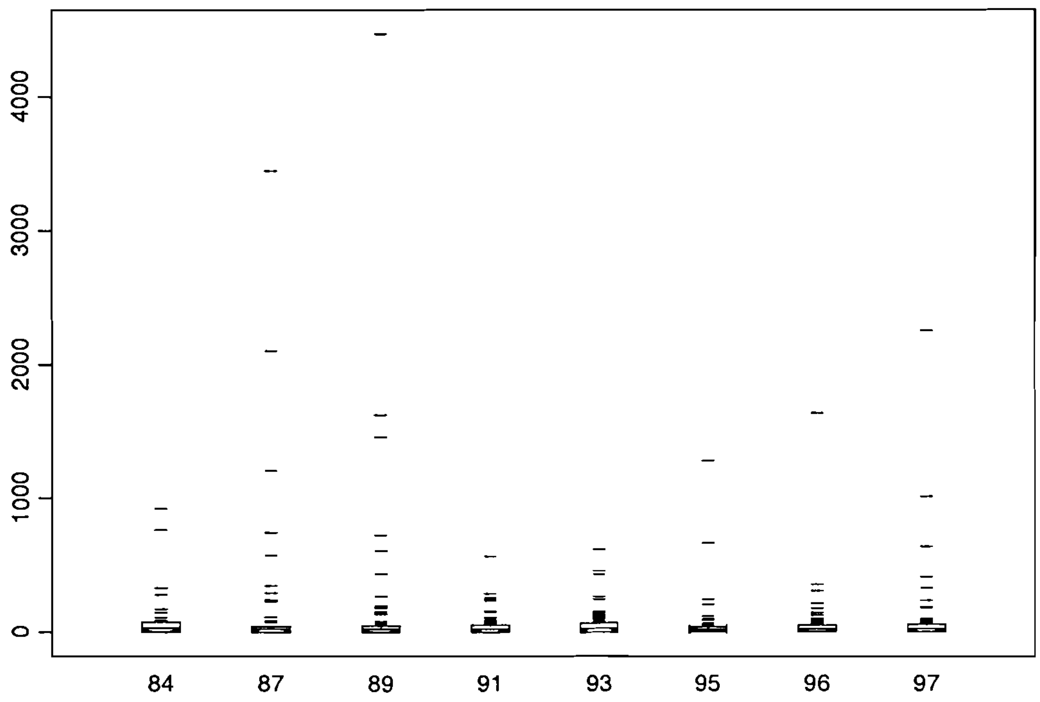


Fig. 1. Boxplots of Pacific cod CPUE (kg/hour) from indiviual tows for the Hecate Strait Survey, 1984-1998.

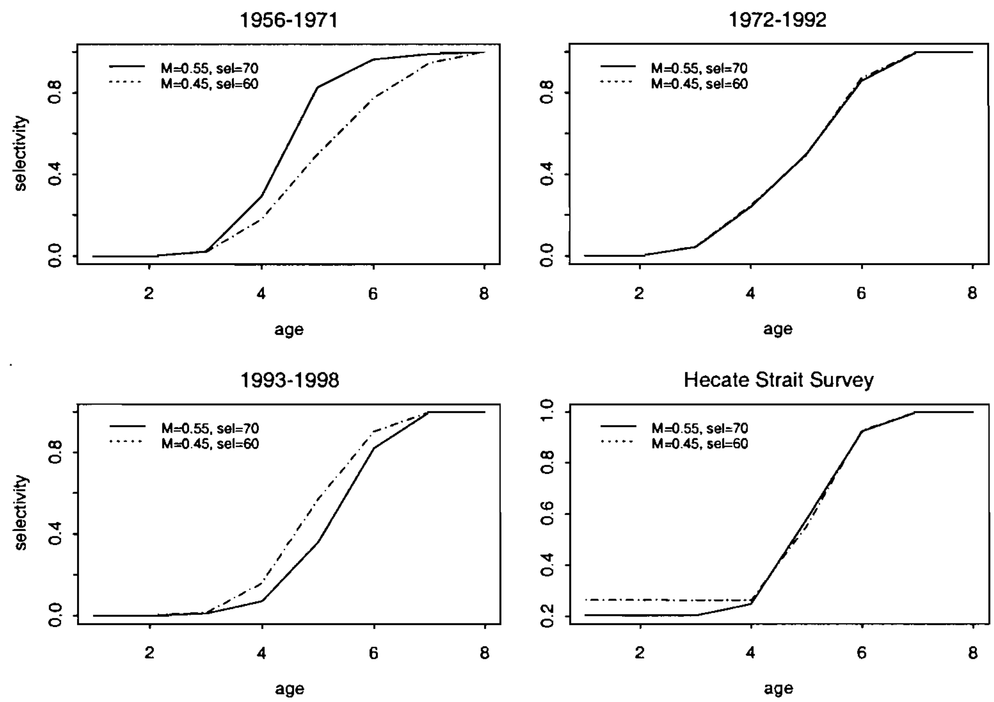


Fig. 2. Estimated selectivity-at-age for the three commercial fishery time-periods and for the Hecate Strait Survey. Shown are estimates from an analysis with M=0.55 and common fishery selectivity for fish at 70 cm and an analysis with M=0.45 and common fishery selectivity for fish at 60 cm.

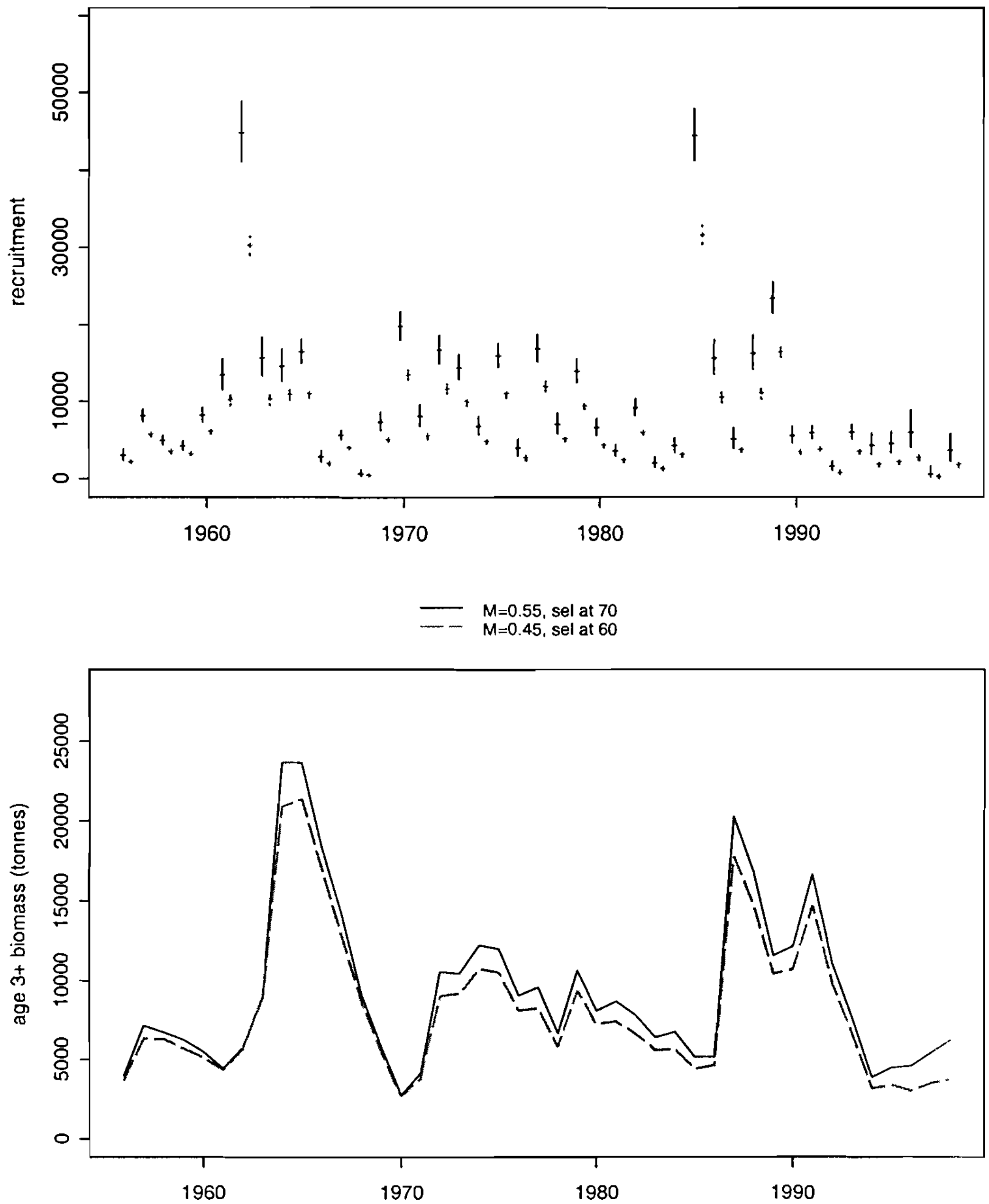


Fig. 3. Estimates of the 1956-1998 time series of recruitment and spawning stock biomass from MULTIFAN CL analyses of Hecate Strait Pacific cod assuming either M=0.45 and common fishery selectvity at 60 cm or M=0.55 and common fishery selectivity at 70 cm. The vertical lines on the recruitment figure represent the standard errors of the estimates.

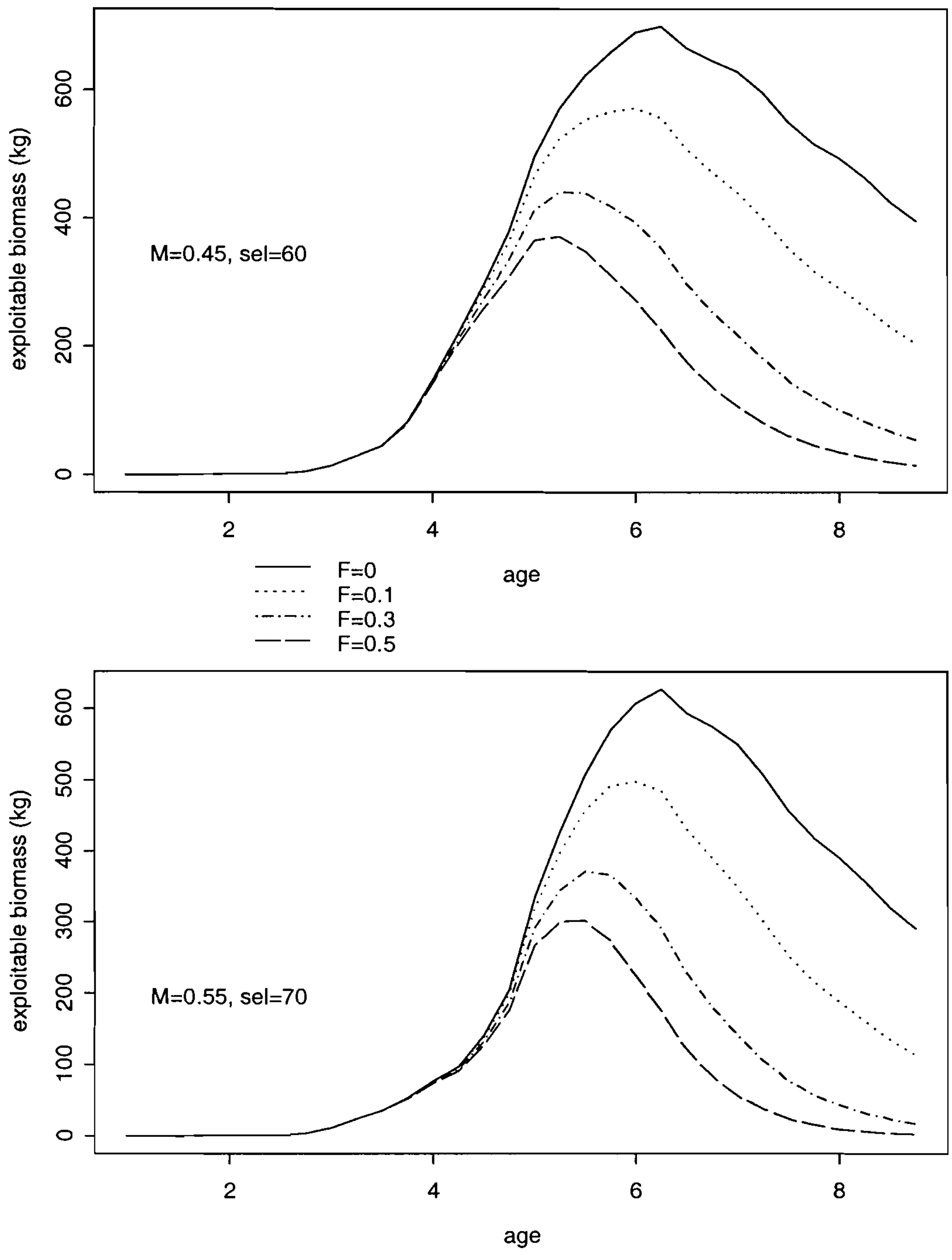


Fig. 4. Estimates of exploitable biomass-at-age for 1000 fish recruiting at age 1 for levels of age-5 fishing mortality (F) ranging from 0 to 0.50. Results are shown for analyses based on parameters from the stock reconstructions assuming M=0.45 and common fishery selectivity at 60 cm and M=0.55 and common fishery selectivity at 70 cm.

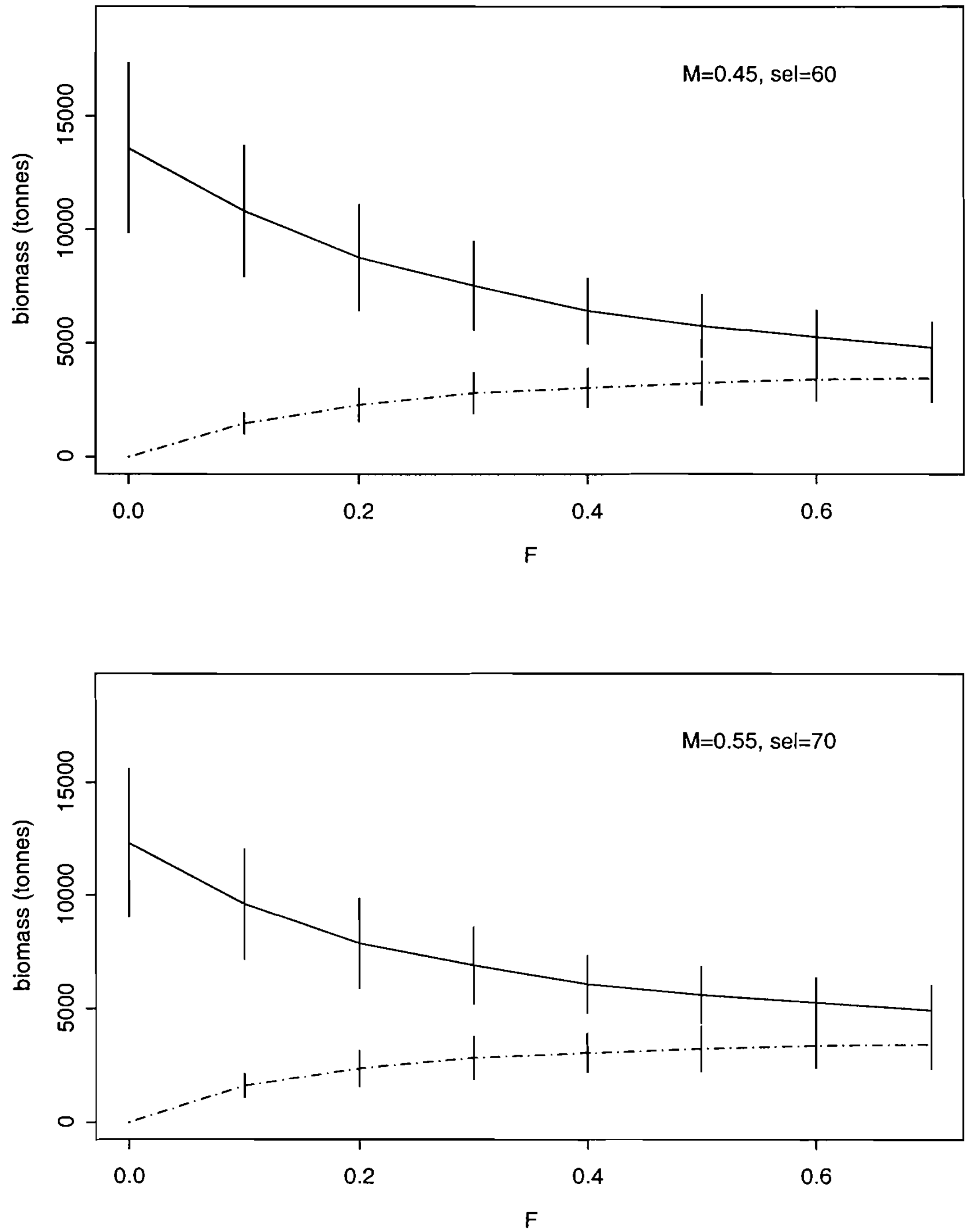


Fig. 5. Estimates of mean catch (solid lines) and mean spawning stock biomass (dashed lines) for levels of age-5 fishing mortality (F) ranging from 0 to 0.70. Results are shown for analyses based on parameters from the stock reconstructions assuming M=0.45 and common fishery selectivity at 60 cm and M=0.55 and common fishery selectivity at 70 cm. The vertical lines show the standard deviations of the estimates.

APPENDIX "A"

The description of the model, MULTIFAN-CL, in the following pages is extracted from a paper that describes aspects of the model and its application to South Pacific Albacore [Fournier, David A, John Hampton and John R. Sibert. (in press). MULTIFAN-CL: A length-based, age-structured model for fisheries stock assessment, with application to South Pacific Albacore *Thunnus Alalunga*.]. As such, some components of the model structure that are described are not used in the B.C. Pacific cod stock assessment and there are additional model components for the Pacific cod assesment that are not described in the document.

Aspects of the Pacific cod implementation which are not consistent with the model description are:

- only a single region is modeled (therefore, no movement parameters are estimated)

- natural mortality is constant over years and ages

- catchability (q) is time-invariant, however we estimate separate catchability parameters for each quarter of the year

- we estimate separate selectivity parameters for three time periods and the Hecate Strait survey, but assume a common selectivity for commercial fisheries at either 60 cm or 70 cm.

In this paper, we describe an age-structured model that extends the MULTIFAN method of estimating catch age composition from length composition (Fournier et al. 1990). An important feature of our model, which we call MULTIFAN-CL (Catch at Length), is that it is fully integrated – growth and catch age structure are estimated simultaneously with recruitment, selectivity, catchability, natural mortality, and other parameters. Estimated confidence intervals are therefore conditional not on catch-at-age, but catch-at-length data. The statistical framework of the model is amenable to the formulation and testing of various hypotheses regarding the dynamics of the stock. Some of the model hypotheses that we formulate and test in this paper include the number of significant age classes in the catch, spatial structuring of the population and fisheries, density-dependent growth, time-series trends and seasonal cycles in catchability, age-dependent rates of natural mortality, and age-dependent fish movement.

DATA STRUCTURES

The fundamental data structure of the model is based on the notion of a fishery, which is defined as a collection of fishing units operating in a particular geographical region, and which have similar catchability and selectivity characteristics with respect to the target species. Each occurrence of a fishery at a particular time is termed a fishing incident. In reality, fishing is more or less continuous, so the data for each fishery need to be aggregated over appropriate time intervals.

THE CATCH EQUATIONS

It is assumed for simplicity of notation in this description that there is only one fishery operating in each region and that there is only one fishing incident per fishery per year. The model is designed to accommodate a variable number of different fisheries per region and fishing incidents per fishery per year; the equations that follow could easily be generalized in this way.

The catch equations relate the numbers of fish in the population to the numbers of fish in the catch of the fisheries. The form of the catch equations used in the model is described by the following relationships:

$$C_{ijk} = \frac{F_{ijk}}{Z_{ijk}}\left[1-\exp\left(-Z_{ijk}\right)\right]N_{ijk} \quad \text{for} \quad 1 \le i \le n, \quad 1 \le j \le a, \quad 1 \le k \le r \tag{1}$$

$$T_{i+1,j+1,k} = \exp\left(-Z_{ijk}\right)N_{ijk} \quad \text{for} \quad 1 \le i \le n, \quad 1 \le j < a, \quad 1 \le k \le r \tag{2}$$

$$T_{i+1,ak} = \exp\left(-Z_{i,a-1,k}\right)N_{i,a-1,k} + \exp\left(-Z_{iak}\right)N_{iak} \quad \text{for} \quad 1 \le i < n, \quad 1 \le k \le r \tag{3}$$

$$T_{i1k} = \gamma_k R_i \quad \text{for} \quad 1 \le i < n, \quad 1 \le k \le r \quad \text{where} \quad \sum_k \gamma_k = 1 \quad \text{and} \quad \gamma_k \ge 0 \tag{4}$$

$$N_{ijk} = \sum_{l} \beta_{jkl} T_{ijl} \quad \text{for} \quad 1 \le i \le n, \;\; 1 \le j \le a, \;\; 1 \le k \le r, \;\; 1 \le l \le r \qquad (5)$$

$$Z_{ijk} = F_{ijk} + M_{ijk} \quad \text{for} \quad 1 \le i \le n, \;\; 1 \le j \le a, \;\; 1 \le k \le r \qquad (6)$$

$$C_{i \cdot k} = \sum_{j} C_{ijk} \quad \text{for} \quad 1 \le i \le n, \;\; 1 \le j \le a, \;\; 1 \le k \le r \qquad (7)$$

where

- i indexes year,
- j indexes age class,
- k indexes region,
- n is the number of years of fishing,
- a is the number of age classes in the population,
- r is the number of regions,
- C_{ijk} is the catch (in number of fish) of age class j fish in region k in year i,
- $C_{i \cdot k}$ is the total catch observed in region k in year i,
- F_{ijk} is the instantaneous fishing mortality rate for age class j fish in region k in year i,
- M_{ijk} is the instantaneous natural mortality rate for age class j fish in region k in year i,
- Z_{ijk} is the instantaneous total mortality rate for age class j fish in region k in year i,
- T_{ijk} is the number of age class j fish in the population in region k at the beginning of year i before movement has taken place,
- N_{ijk} is the number of age class j fish in the population in region k at the beginning of year i after movement has taken place,
- R_i is the recruitment at the beginning of year i,
- γ_k is the proportion of recruitment occurring in region k, and

β_{jkl} is a k by k diffusion matrix $\mathbf{B}_j$ for age class j fish.

Note that the last (a th) age class consists of all the older fish in the population, which is useful when, as often occurs, the aging estimates are especially inaccurate for the older age classes (Fournier and Archibald 1982). It is also useful when analyzing catch-at-length data to group the older age classes together after the fish reach an age where they essentially stop growing (Fournier et al. 1991).

MOVEMENT HYPOTHESIS

For each j, the elements of $\mathbf{B}_j$ must be specified. In the case of South Pacific albacore, we use a one-dimensional diffusion model operating in three regions (k=3). In this case, the elements of $\mathbf{B}_j$ are given by

$$\begin{bmatrix} 1+\theta_j & -d_2\theta_j & 0 \\ -\theta_j & 1+2d_2\theta_j & -d_3\theta_j \\ 0 & -d_2\theta_j & 1+d_3\theta_j \end{bmatrix}^{-1} \tag{8}$$

where 1, d_2 and d_3 ($d_2>0$ and $d_3>0$) specify the relative distribution of cohort abundance among regions at equilibrium and θ_j is the age-dependent diffusion rate. We employ a flexible parameterization of θ_j which can result in increasing, decreasing or constant diffusion rate with increasing age:

$$\begin{aligned} \theta_j &= \phi_0 \exp\left\{\phi_1\left[-(-\kappa_j)^{\phi_3}\right]\right\} \quad \text{where} \quad \phi_0 \geq 0,\ \phi_1 \geq 0 \text{ and } \kappa_j < 0 \\ \theta_j &= \phi_0 \exp\left\{\phi_1 \kappa_j^{\phi_3}\right\} \quad \text{where} \quad \phi_0 \geq 0,\ \phi_1 \geq 0 \text{ and } \kappa_j \geq 0 \end{aligned} \tag{9}$$

where $\kappa_j = \dfrac{2(j-1)}{a-1} - 1$, which expresses age scaled between -1 and 1.

A one-dimensional movement hypothesis was considered appropriate for South Pacific albacore on the basis of tagging data (Labelle 1993) and the variation in albacore size with latitude (smallest in the south, increasing towards the equator). Other movement hypotheses and/or spatial configurations (including homogeneity) could easily be incorporated into the model, as warranted by the particular case being studied.

ASSUMPTIONS REGARDING CONSTRAINTS ON NATURAL AND FISHING MORTALITY RATES

A fundamental characteristic of statistical age-structured models is that they constrain the variation of mortality rates by age and time in a regular fashion. The objective of such constraints is to create degrees of freedom that enable a statistical estimation of parameters to proceed. Constraints are normally placed separately on the variability of natural and fishing mortality rates.

NATURAL MORTALITY

In the South Pacific albacore application, we assumed that the instantaneous natural mortality rate is independent of year and region, but may vary with age. Later, we show that this age dependency is justified on statistical grounds. For a given application, a range of more and less restrictive constraints on natural mortality can be tested.

FISHING MORTALITY

We restrict the variation in the instantaneous fishing mortality rates F_{ijk} according to the "separability" assumption. Consider for simplicity an individual fishery (i.e. drop the k subscript). We assume that

$$\log_e(F_{ij}) = \log_e(s_j) + \log_e(q_i) + \log_e(E_i) + \varepsilon_i \qquad (10)$$

and

$$\log_e(q_{i+1}) = \log_e(q_i) + \eta_i \qquad (11)$$

where

s_j is the selectivity for age class j (assumed constant over time),

q_i is the catchability in year i,

E_i is the observed fishing effort in year i,

ε_i are normally distributed random variables representing large transient deviations in the effort–fishing mortality relationship, and

η_i are normally distributed random variables representing small permanent changes in catchability.

The notion, as implied in equation (10), that fishing mortality consists of a "separable" age-dependent effect (selectivity) and a time-dependent effect (catchability) was first introduced by Doubleday (1976) and later elaborated upon by Paloheimo (1980) and Fournier and Archibald (1982).

Selectivity

It is possible to model selectivity as a function of age class, for example using a gamma function (Deriso et al. 1985). We have preferred to allow the s_j to be separate parameters but have applied a transformation that essentially makes selectivity a length-based rather than age-based concept. The transformation is as follows:

$$s_j = \sum_{k=-2}^{2} \omega_k \left\{ t\left[\psi_1\left(\mu_j + k\sigma_j\right)\right] + \psi_2\left(\mu_j + k\sigma_j\right)\left(t\left[\psi_1\left(\mu_j + k\sigma_j\right)+1\right] - t\left[\psi_1\left(\mu_j + k\sigma_j\right)\right]\right)\right\} \quad (12)$$

where

ω_k are weights determined from the normal distribution of length-at-age k standard deviations from the mean,

ψ_1 is the integer part of the age class number corresponding to length $\mu_j + k\sigma_j$,

ψ_2 is the fractional part of the age class number corresponding to length $\mu_j + k\sigma_j$,

μ_j is the mean length of age class j fish,

σ_j is the standard deviation of length of age class j fish, and

t is an estimated parameter.

This transformation effectively ensures relatively small differences in s_j between adjacent age classes having large overlap of their length distributions, as would be expected where selectivity is fundamentally length-based.

Catchability

Catchability is allowed to vary slowly over time. We assume that the q_i have the simple time series structure of a random walk (equation 11), which is the simplest statistical model of a slowly varying random quantity. The assumption that catchability has a time series structure was introduced by Gudmundsson (1994) for the analysis of catch-at-age data. Gudmundsson also included trend components in his time series formulation.

We make the prior assumption that the variance of η_i is small compared to ε_i, i.e. the ε_i represent relatively large transient effects (noise) while the η_i represent relatively small permanent changes in the catchability.

In the simple case of annual fishing incidents, η_i modifies catchability at each successive fishing incident. In general, each step of the random walk can be taken less frequently, as might be appropriate when multiple fishing incidents by one fishery occur within a year. In the albacore analysis (where the frequency of fishing incidents is quarterly for the longline fisheries and monthly for the surface fisheries), random walk steps are taken annually for all fisheries.

Where the frequency of fishing incidents is quarterly or more, we may allow catchability within a year to vary with a regular seasonal pattern. Equation (10) then becomes

$$\log_e(F_{ij}) = \log_e(s_j) + \log_e(q_i) + \log_e(E_i) + c_1 \sin[24\pi(m - c_2)] + \varepsilon_i \qquad (13)$$

where m is the month in which the fishing incident occurred and c_1 and c_2 are the seasonality parameters.

ASSUMPTIONS REGARDING LENGTH-AT-AGE

MULTIFAN-CL uses length data to estimate age structure and therefore makes assumptions concerning the length distribution of the fish that are very similar to the assumptions used in Fournier et al., 1990:

1. The lengths of the fish in each age class are normally distributed (see equation 14).
2. The mean lengths-at-age lie on (or near) a von Bertalanffy growth curve (see equation 16) modified to include, where appropriate, density-dependent growth (see equation 18).
3. The standard deviations of the lengths for each age class are a simple function of the mean length-at-age (see equation 19).

The following symbols are used in the mathematical expression of these assumptions:

α subscript indexing the length frequency intervals.

N_l the number of length intervals in each length frequency data set.

S_i the number of fish in the i th length frequency data set.

$f_{\alpha i}$ the number of fish whose lengths lie in the αth length interval in the i th length frequency data set.

$p_{ij\alpha}$ the probability that an age class j fish picked at random from the fish which were sampled to get the i th length frequency data set has a length lying in length interval α.

$Q_{\alpha i}$ the probability that an animal picked at random from the fish which composed the i th length frequency data set has a length lying in length interval α.

$\tilde{Q}_{\alpha i}$ the observed proportion of fish in the i th length frequency data set having a length lying in length interval α.

μ_{ij} the mean length of the age class j fish in the i th length frequency data set.

σ_{ij} the standard deviation of the length distribution of the age class j fish in the i th length frequency data set.

x_i the midpoint of the i th length frequency interval.

w the width of the length frequency intervals.

L_1 the mean length of the first age class on the von Bertalanffy curve in month 1.

L_r the mean length of the last age class on the von Bertalanffy curve in month 1.

K the von Bertalanffy K parameter.

ρ the Brody growth coefficient ($K = -\log_e(\rho)$).

λ_1, λ_2 parameters determining the standard deviations $\sigma_{j\alpha}$.

$\xi_{i\alpha}$ parameters determining the relative variances of the sampling errors within the ith length frequency data set.

τ parameter determining the overall variance of the sampling errors in all the length frequency data sets.

Assumption 1: Normal distribution of length-at-age

If the lengths of the age class j fish in the αth length frequency data set are normally distributed around their mean $\mu_{j\alpha}$ with standard deviations $\sigma_{j\alpha}$, the $p_{ij\alpha}$ can be expressed in terms of $\mu_{j\alpha}$ and $\sigma_{j\alpha}$ by

$$p_{ij\alpha}(\mu_{j\alpha}, \sigma_{j\alpha}) = \frac{1}{\sqrt{2\pi}\sigma_{j\alpha}} \int_{x_i - w/2}^{x_i + w/2} \exp\left\{\frac{-(x - \mu_{j\alpha})^2}{2\sigma_{j\alpha}^2}\right\} dx \quad (14)$$

As long as $\sigma_{j\alpha} > w$, the integral can be approximated sufficiently well by setting

$$p_{ij\alpha}(\mu_{j\alpha}, \sigma_{j\alpha}) = \frac{w}{\sqrt{2\pi}\sigma_{j\alpha}} \exp\left\{\frac{-(x - \mu_{j\alpha})^2}{2\sigma_{j\alpha}^2}\right\} \quad (15)$$

Assumption 2: Relationship of length to age

Parameterization of von Bertalanffy growth: If the mean lengths μ_{ja} lie on a von Bertalanffy curve, then, using the parameterization given by Schnute and Fournier (1980)

$$\mu_{j\alpha} = L_1 + (L_{N_J} - L_1)\left[\frac{1-\rho^{j-1+(m(\alpha)-1)/12}}{1-\rho^{N_{J-1}}}\right] \tag{16}$$

where L_1, the mean length of the first age class, L_{N_J}, the mean length of the last age class, and ρ, the Brody growth coefficient, are the three parameters that determine the form of the von Bertalanffy curve, and $m(\alpha)-1$ is the number of months after the presumed birth month of the fish in the αth length frequency data set.

Density-dependent growth: For many species it is suspected that individuals of small (in numbers of fish) cohorts may grow more quickly than those of large cohorts (i.e. density-dependent growth). If true, this phenomenon could have a large effect on the conclusions drawn from a length-based stock assessment. To test for evidence of the existence of the dependence of the mean length-at-age on cohort strength we have incorporated density-dependent growth into the model in the following fashion.

Consider a cohort k at age j in year i. If we denote recruitment as occurring at age 1, the strength of cohort k is N_{k1}, where $k = i - j + 1$. Let $A = \frac{1}{n}\sum_k N_{k1}$ be the average recruitment. The normalized relative cohort strength is given by

$$R_k = \frac{(N_{k1} - A)}{\sqrt{\sum_k N_{k1}^2}}. \tag{17}$$

The changes in mean length are effected by changing the apparent age of the fish before the length-at-age is calculated. If the age class is j the apparent age a is

$$a = j + 1.9\left[\frac{1}{1+\exp(-dR_k)} - 0.5\right] \tag{18}$$

where d determines the amount of density-dependent growth; if $d = 0$, $a = j$. Since the standard deviation of the R_k has been normalized to 1, the "generic" variation in the R_k will be about -2 to 2. Thus the difference in a between the largest and smallest cohorts of any given age class will be approximately $1.9\left[\frac{1}{1+\exp(-2d)} - \frac{1}{1+\exp(2d)}\right]$. For d=-1.08 (which is the estimate for the albacore data) this yields a generic variation of about -1.5 years, i.e. the apparent age of the largest cohort is about 1.5 years more than that of the smallest cohort.

Assumption 3: Relationship of standard deviations in length-at-age to mean length-at-age

The standard deviations $\sigma_{j\alpha}$ are parameterized as a simple function of length involving two parameters λ_1 and λ_2:

$$\sigma_{j\alpha} = \lambda_1 \exp\left\{\lambda_2\left[-1+2\left(\frac{1-\rho^{j-1+(m(\alpha)-1)/12}}{1-\rho^{N_{J-1}}}\right)\right]\right\} \tag{19}$$

where the term enclosed in square brackets expresses the length dependency of the standard deviations independently of the numerical values of the parameters L_1 and L_{N_J} (cf. equation 16). The two coefficients, λ_1 and λ_2, transform the re-scaled length to the standard deviations. λ_1 determines the magnitude of the standard deviations, and λ_2 determines the length–dependent trend in the standard deviations. If $\lambda_2 = 0$, the standard deviations are length–independent.

MAXIMUM LIKELIHOOD ESTIMATION

The parameters of the model are estimated by maximizing the log-likelihood function (or more generally by maximizing the sum of the log-likelihood function and the log of the density of the Bayesian prior distribution). The log-likelihood function consists of the sum of several components, the most important of which correspond to the length frequency data and the total catch estimates.

THE LOG-LIKELIHOOD CONTRIBUTION FOR THE LENGTH FREQUENCY DATA

Due to the large variability in the length samples that often occurs for length frequency data, we employ a robust maximum likelihood estimation procedure. The motivation for using this procedure and the technicalities behind the procedure are described in Fournier et al. (1990). We shall not repeat this discussion here, but for convenient reference we briefly describe the form of the log–likelihood function employed.

If the $\tilde{Q}_{\alpha i}$ are derived from a random sample of size S_i, they would be random variables with means $Q_{\alpha i}$ and variances $(1-Q_{\alpha i})Q_{\alpha i}/S_i$. Two modifications have been made to this formula. If $Q_{\alpha i}=0$ the formula implies that the variance of $\tilde{Q}_{\alpha i}=0$. To decrease the influence of areas where no observations are expected, we add a small number to the variance formula in such cases. To reduce the influence of very large sample sizes we have assumed that sample sizes >1,000 are no more accurate than sample sizes of 1,000. Set $\xi_{i\alpha}=(1-Q_{\alpha i})Q_{\alpha i}$ and set

$\tau_i^2 = 1/\min(S_i, 1000)$. Assume the variance of $\tilde{Q}_{\alpha i}$ is given by $(\xi_{i\alpha} + .1/N_l)\tau_i^2$. The likelihood function contribution for the length frequency data is then

$$\prod_{\alpha=1}^{N_A}\prod_{i=1}^{N_l}\left[\frac{1}{\sqrt{2\pi(\xi_{i\alpha}+.1/N_l)}\tau}\left(\exp\left\{-\frac{(\tilde{Q}_{i\alpha}-Q_{i\alpha})^2}{2(\xi_{i\alpha}+.1/N_l)\tau^2}\right\}+.01\right)\right] \tag{20}$$

Taking the logarithm of expression (20) we obtain the log–likelihood function for the length frequency data:

$$\begin{aligned} &-1/2\sum_{\alpha=1}^{N_A}\sum_{i=1}^{N_l}\log_e\left[2\pi(\xi_{i\alpha}+.1/N_l)\right] \\ &-\sum_{\alpha=1}^{N_A} N_l \log_e(\tau) \\ &+\sum_{\alpha=1}^{N_A}\sum_{i=1}^{N_l}\log_e\left[\exp\left\{\frac{-(\tilde{Q}_{i\alpha}-Q_{i\alpha})^2}{2(\xi_{i\alpha}+.1/N_l)\tau^2}\right\}+0.01\right]\end{aligned} \tag{21}$$

THE LOG-LIKELIHOOD CONTRIBUTION FOR THE OBSERVED TOTAL CATCHES

Assuming for simplicity that there is only one fishery per year, the log-likelihood contribution for the observed total catches is given by

$$p_c\sum_i\left(\log\left(C_{i.}^{obs}\right)-\log\left(C_{i.}\right)\right)^2 \tag{22}$$

where p_c is determined by the prior assumption made about the accuracy of the observed catch data. For the albacore analysis, we assumed p_c=200, which is consistent with a coefficient of variation of about 0.07.

THE LOG-LIKELIHOOD CONTRIBUTION FOR THE BAYESIAN PRIORS ON THE EFFORT–FISHING MORTALITY RELATIONSHIP

Given the random walk structure assumed to operate for time-series changes in catchability, it follows that the prior distribution for the η_i is normal. However, the prior distribution for ε_i is assumed to be a robustified normal distribution, i.e. the probability of events at the tails of the distribution is increased relative to a standard normal distribution. Then, the log-likelihood contribution for the Bayesian priors on the η_i and ε_i, (see equations 10 and 11) is given by

$$p_\eta \sum_i \eta_i^2 - \sum_i \log_e\left[\exp\left(-p_\varepsilon \varepsilon_i^2\right) + 0.01\right]. \qquad (23)$$

The size of the constants p_η and p_ε are adjusted to reflect prior assumptions about the variances of these random variables. For the albacore analysis, we assumed $p_\eta = 25$ and $p_\varepsilon = 10$, which is equivalent to assuming that the coefficients of variation of η_i and ε_i are 0.14 and 0.22, respectively. Note that the second term of equation (23) is a component of the log-likelihood function that corresponds to an improper density. As a result, the variance corresponding to the weight p_ε cannot be estimated and must be specified.

NONLINEAR OPTIMIZATION

The parameters of the model are estimated by maximizing the log-likelihood function (or posterior density in the Bayesian framework) as described above. The maximization was performed using the nonlinear modeling package AD Model Builder, which employs an efficient optimization using exact derivatives with respect to the model parameters. The derivatives were calculated using an extension of the technique known as automatic differentiation (Griewank and Corliss 1991). This approach is especially useful for models with large numbers of parameters. It also provides quick and accurate estimates of the Hessian matrix at the maximum, which can be used to obtain estimates of the covariance matrix and confidence limits for the parameters of interest (see later).

HYPOTHESIS TESTING

It is frequently of interest in statistical modeling to add model structure in the form of one or more hypotheses concerning some process(es) of interest, and to observe the resulting change in model performance. Two approaches are taken to the addition and testing of hypotheses – a frequentist approach and a Bayesian approach.

With the frequentist approach to hypothesis testing, parameters representing a more complex model are added to the simpler model and the resulting improvement in fit is calculated. If this improvement in fit is large enough, the more complicated model is accepted. Otherwise the more complicated model is rejected and the simpler model is accepted as providing an adequate description of the data. Various more complicated models may be investigated in this fashion. There are various statistical criteria that might be used to decide whether to accept or reject a more complex model, such as likelihood-ratio tests (e.g. as applied in Fournier et al. 1990) or the Akaike Information Criterion (e.g. as applied in Bigelow et al. 1995). Note that such tests are approximate and that the strict statistical conditions assumed rarely hold in practice. However, in the case of likelihood-ratio tests, simulations have indicated that such tests still provide a useful method of model screening even when the strict statistical conditions are not met (Hastie and Tibshirani 1990). This is the approach adopted in this paper.

Some hypotheses that are useful in length-based stock assessment cannot be well represented in a frequentist context. An example is the existence of a time-series (random walk) trend in catchability for a fishery. For such hypotheses, the results of the analysis are not as clear-cut as they are for the frequentist approach. We neither accept nor reject the existence of a trend in catchability. Instead, the analysis will produce a probability distribution for quantities of interest. For example, we can obtain an approximate probability distribution for the ratio of the catchability for the first year of a fishery to the catchability for the last year of the fishery. This can be used to produce, for example, an estimate of the probability that the catchability has increased by 30% or more.

ESTIMATION OF CONFIDENCE INTERVALS

A great advantage of an integrated model such as this is that the estimates of the uncertainty in the parameter estimates automatically take into account the effect of all of the model's assumptions, such as the uncertainty in the age at length, the possibility of trends in catchability, effects caused by variability in the length frequency data and errors in the estimates of fishing effort.

Confidence limits for the parameter estimates are calculated by employing the usual second order approximation to the posterior distribution at its mode. Let $\theta_1,\ldots,\theta_n$ denote a minimal set of n model parameters from which all model parameters can be calculated, and let $p(\theta_1,\ldots,\theta_n)$ be some parameter of interest, while $L(\theta_1,\ldots,\theta_n)$ is the logarithm of the posterior distribution. Then the estimated standard deviation p_σ for p is given by the square root of $\sum_{ij} \partial p/\partial\theta_i \, \partial p/\partial\theta_j \, \Lambda_{ij}$ where $\Lambda = \left(\partial^2 L/\partial\theta_i \partial\theta_j\right)^{-1}$ and the calculations are carried out at the mode of the posterior distribution. Then, 0.95 confidence limits for the p are given by $[p-1.96p_\sigma,\ p+1.96p_\sigma]$. These confidence limits are not invariant under reparameterization. To compensate somewhat for this, the confidence limits for parameters which must be positive, such as estimates of biomass, are calculated by computing the confidence limits for the logarithms of these parameters and then transforming the confidence limits. This yields the confidence limits $[p\exp(-1.96\, p_\sigma/p), p\exp(1.96 p_\sigma/p)]$.

The above procedure provides approximate confidence intervals for the model parameters (initial cohort size, selectivity and catchability coefficients, natural mortality rates, growth parameters, etc). For stock assessment purposes, it may be desirable to have confidence intervals for quantities of interest, such as adult biomass, that are functions of the model parameters. The variances (and hence confidence intervals) for such quantities may be determined using the delta method.

Note that confidence intervals derived as described above are conditional on the model structure used. It may be possible to define the best model from a finite range of alternatives for a particular set of data on the basis of the maximum likelihood criterion.

However, there is never any guarantee that any given model is the best of all possible models. Uncertainty regarding what is the best model is not incorporated into the confidence intervals; therefore such confidence intervals will tend to understate the true uncertainty in the model parameters and other quantities of interest.

REFERENCES

Bigelow, K.A., J.T. Jones, and G.T. DiNardo. 1995. Growth of the Pacific pomfret, *Brama japonica*: a comparison between otolith and length-frequency (MULTIFAN) analysis. Can. J. Fish. Aquat. Sci. 52: 2747-2756 p.

Deriso, R.B., T.J. Quinn II, and P.R. Neal. 1985. Catch-age analysis with auxiliary information. Can. J. Fish. Aquat. Sci. 42: 815-824 p.

Doubleday, W.G. 1976. A least squares approach to analyzing catch at age data. Int. Comm. Northw. Atl. Fish. Res. Bull. 12: 69-81 p.

Fournier, D., and C.P. Archibald. 1982. A general theory for analyzing catch at age data. Can. J. Fish. Aquat. Sci. 39: 1195-1207 p.

Fournier, D.A., J.R. Sibert, J. Majkowski and J. Hampton. 1990. MULTIFAN: a likelihood-based method for estimating growth parameters and age composition from multiple length frequency data sets illustrated using data for southern bluefin tuna (*Thunnus maccoyii*). Can. J. Fish. Aquat. Sci. 47: 301-317 p.

Fournier, D.A., J.R. Sibert, and M. Terceiro. 1991. Analysis of length frequency samples with relative abundance data for the Gulf of Maine northern shrimp (*Pandalus borealis*) by the MULTIFAN method. Can J. Fish. Aquat. Sci. 48: 591-598 p.

Griewank, A., and G.F. Corliss (eds). 1991. Automatic differentiation of algorithms: theory, implementation and application. In Proceedings of the SIAM Workshop on the Automatic Differentiation of Algorithms, held January 6-8, in Breckenridge, Colorado. Society for Industrial and Applied Mathematics, Philadelphia.

Gudmundsson, G. 1994. Time-series analysis of catch-at-age observations. Appl. Statist. 43: 117-126 p.

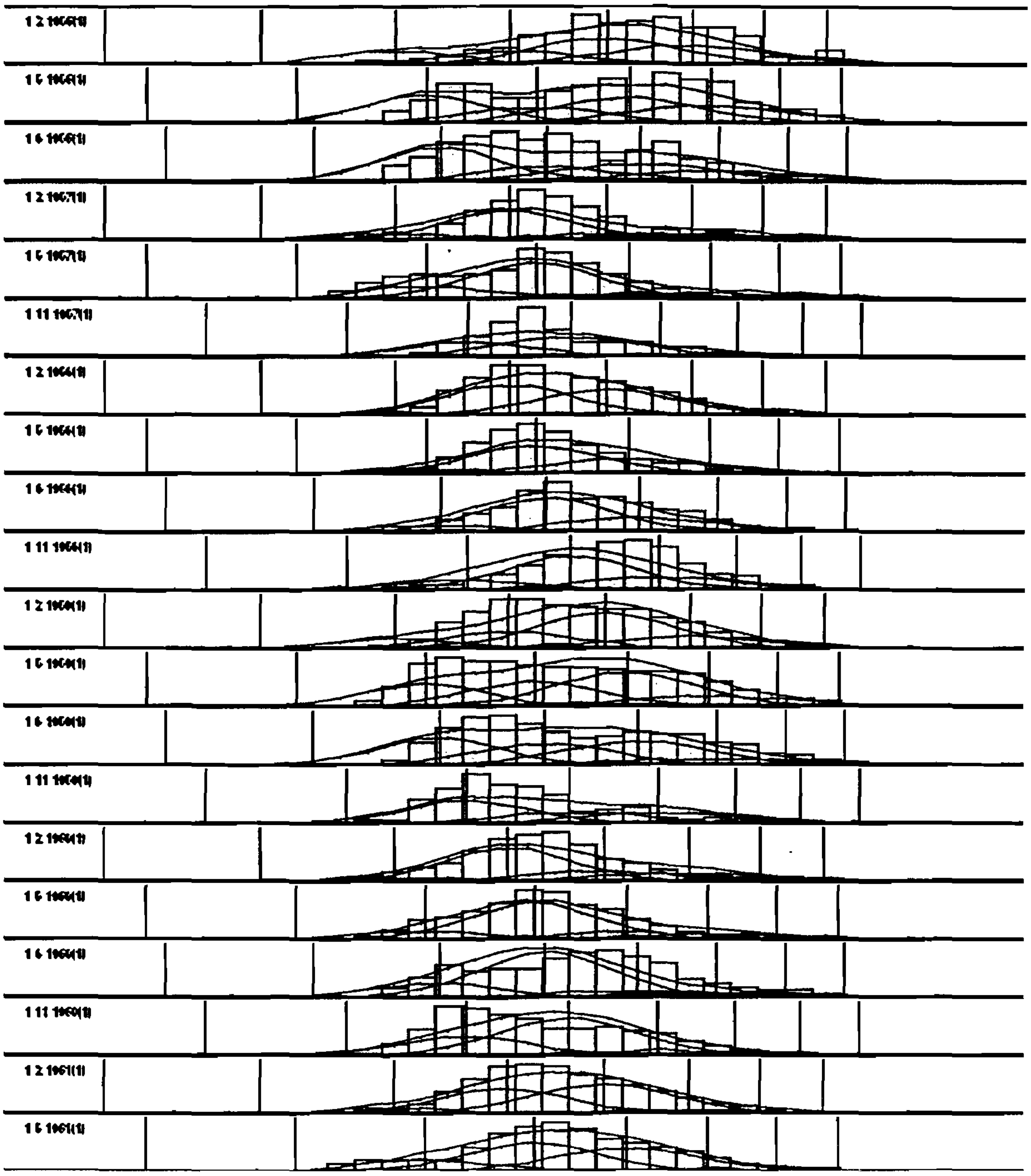
Hastie, T.J. and R.J. Tibshirani. 1990. Generalized additive models. Chapman & Hall, London. 335 p.

Labelle, M. 1993. A review of albacore tagging in the South Pacific. Tuna and Billfish Assessment Programme Technical Report No. 33. South Pacific Commission, Noumea, New Caledonia, 17 p.

Paloheimo, J.E. 1980. Estimation of mortality rates in fish populations. Trans. Am. Fish. Soc. 109: 378-386 p.

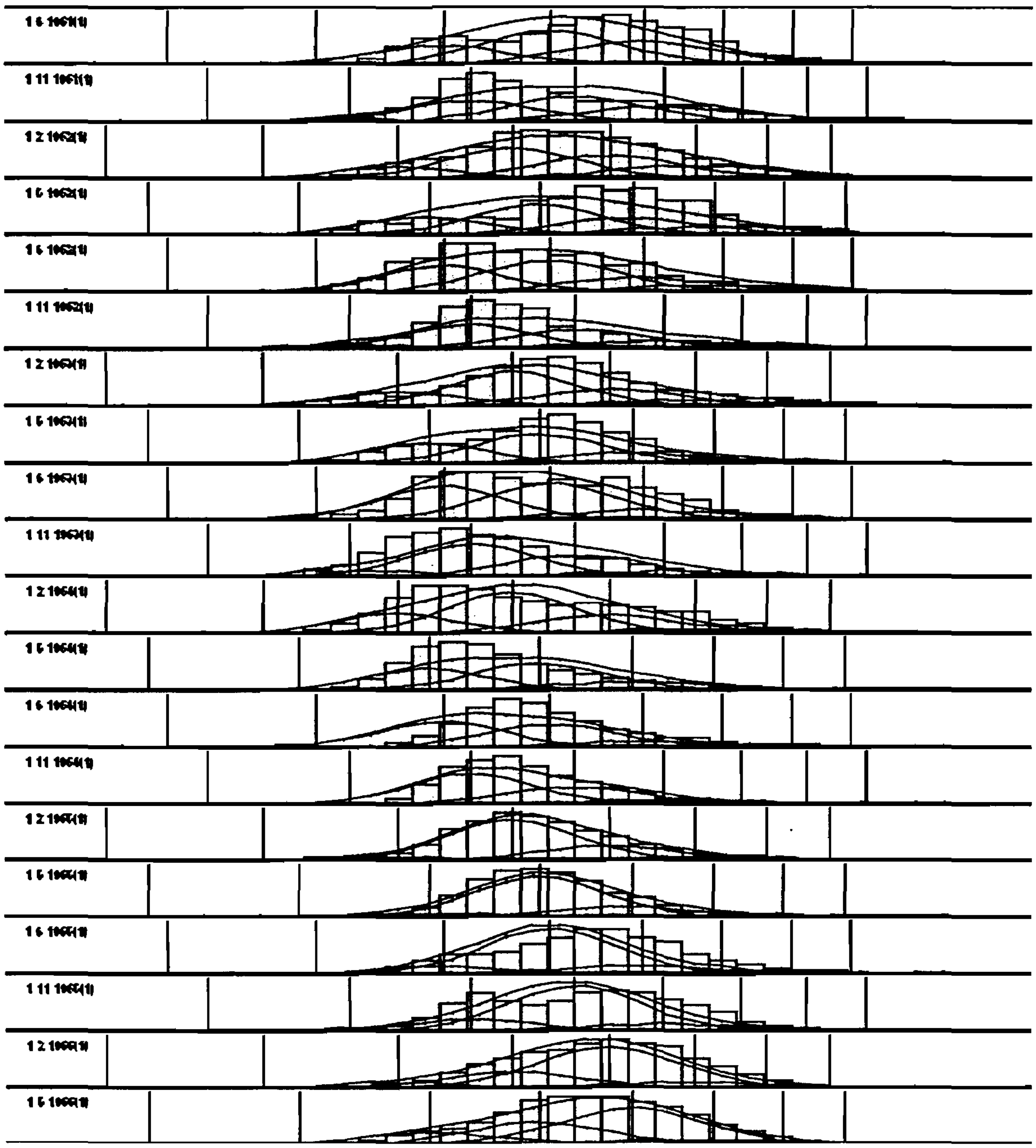
Schnute, J., and D.A. Fournier. 1980. A new approach to length frequency analysis: growth structure. J. Fish. Res. Board Can. 37: 1337-1351 p.

Appendix "B" contains figures showing the observed and predicted length-frequency distributions from Multifan CL analysis of Hecate Strait Pacific cod data. The predicted values result from an analysis assuming 8 age-classes in the population, a natural mortality rate (M) of 0.55, and a common selectivity among commercial fisheries at a fish length of 70 cm.



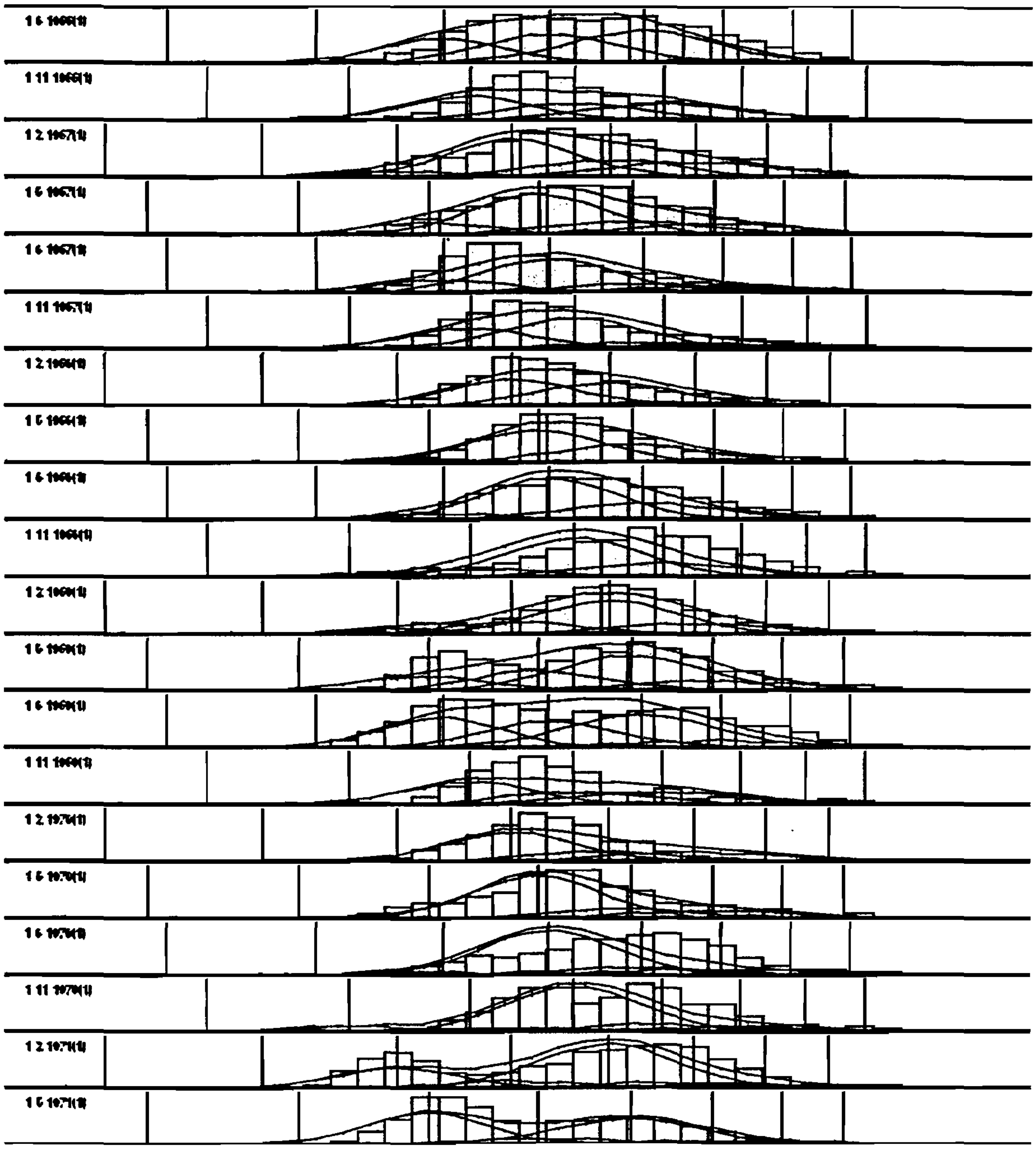
Appendix B. Observed proportions-at-length-interval (histograms) and predicted mean lengths-at-age (vertical lines) and proportions-at-age (smooth lines) from Multifan CL analysis of Hecate Strait Pacific cod assuming M=0.55, 8 age-classes, and common fishery selectivity at 70 cm.

Appendix B – cont'd



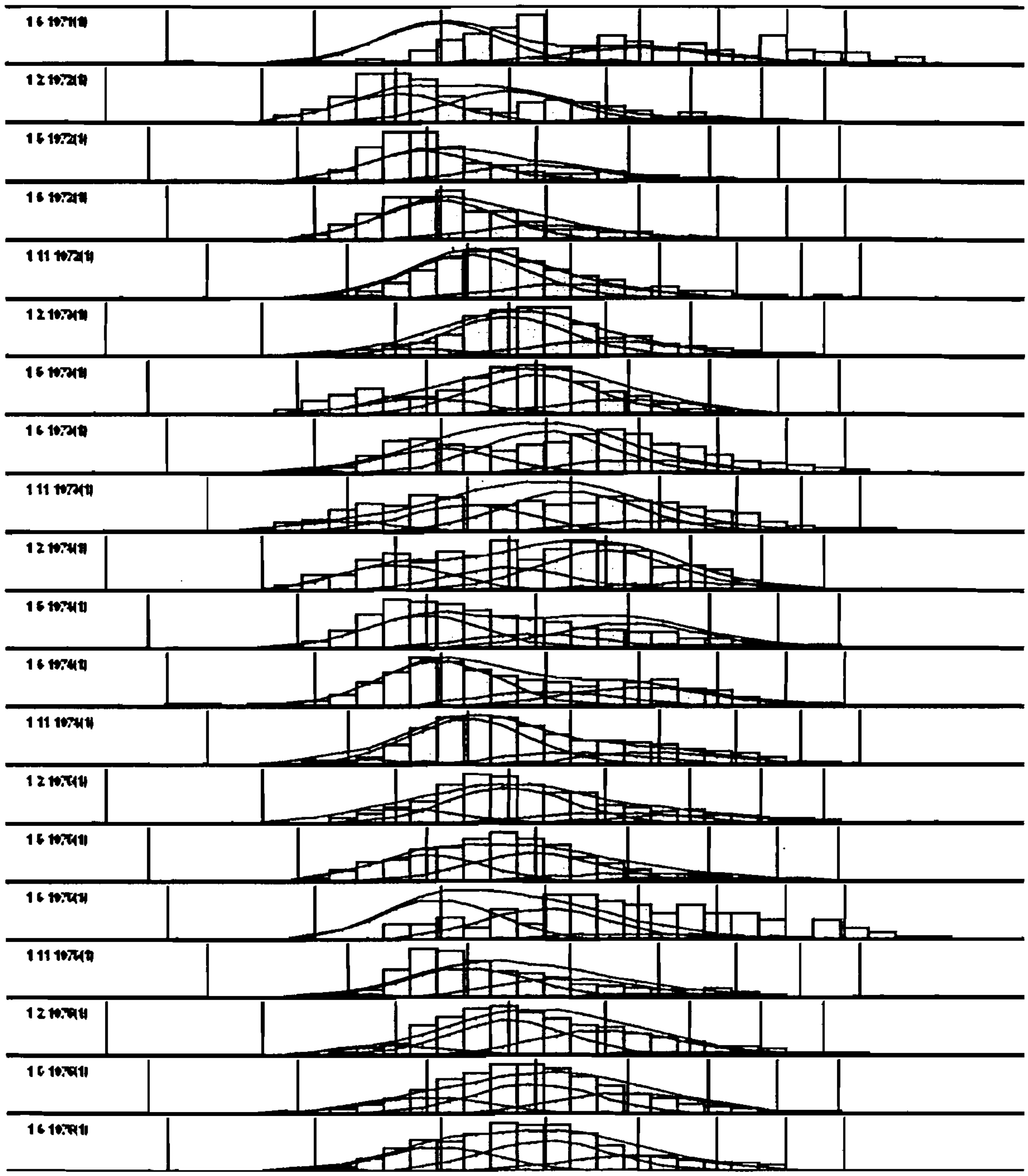
Appendix B. Observed proportions-at-length-interval (histograms) and predicted mean lengths-at-age (vertical lines) and proportions-at-age (smooth lines) from Multifan CL analysis of Hecate Strait Pacific cod assuming M=0.55, 8 age-classes, and common fishery selectivity at 70 cm.

Appendix B – cont'd



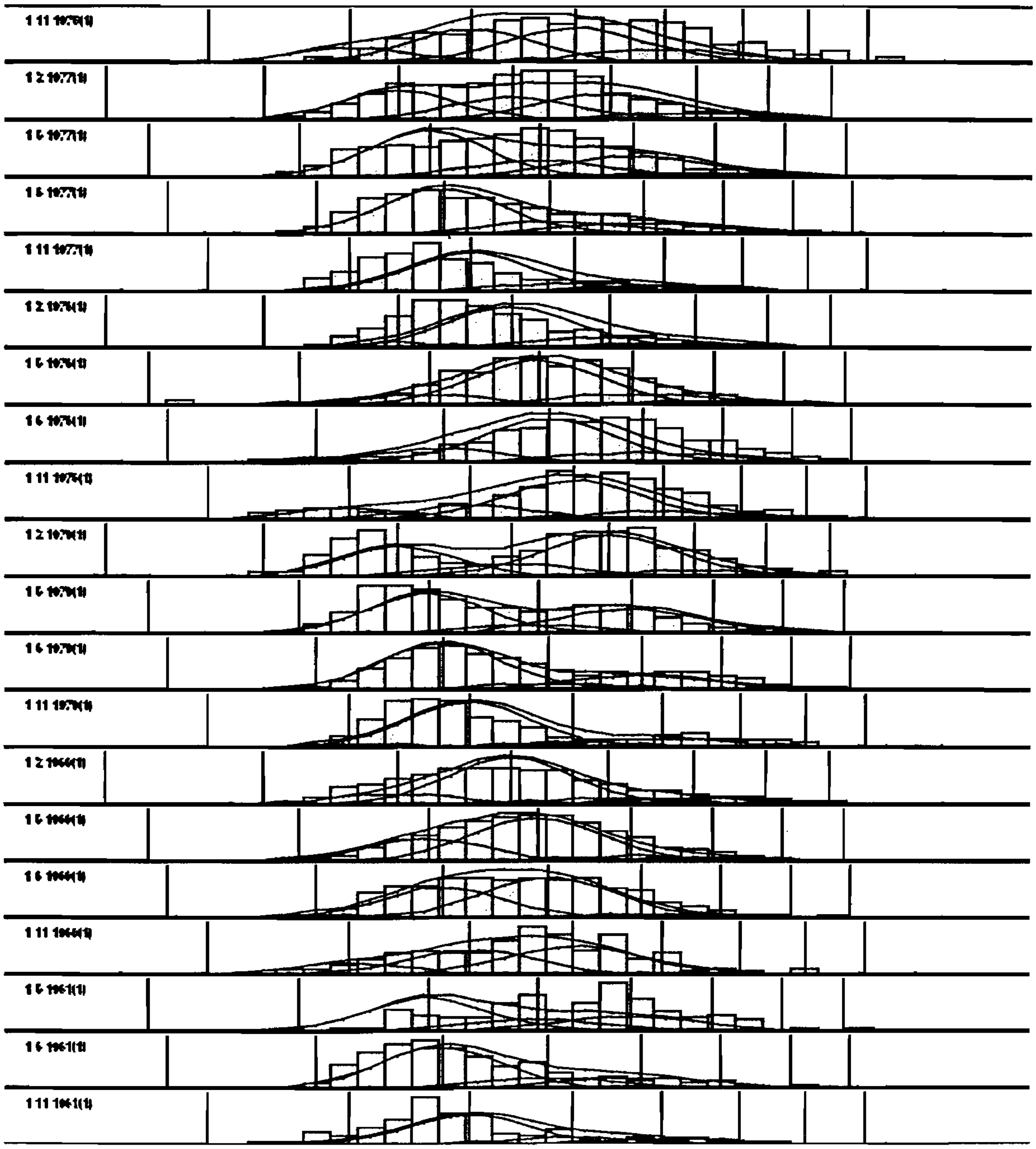
Appendix B. Observed proportions-at-length-interval (histograms) and predicted mean lengths-at-age (vertical lines) and proportions-at-age (smooth lines) from Multifan CL analysis of Hecate Strait Pacific cod assuming M=0.55, 8 age-classes, and common fishery selectivity at 70 cm.

Appendix B – cont'd



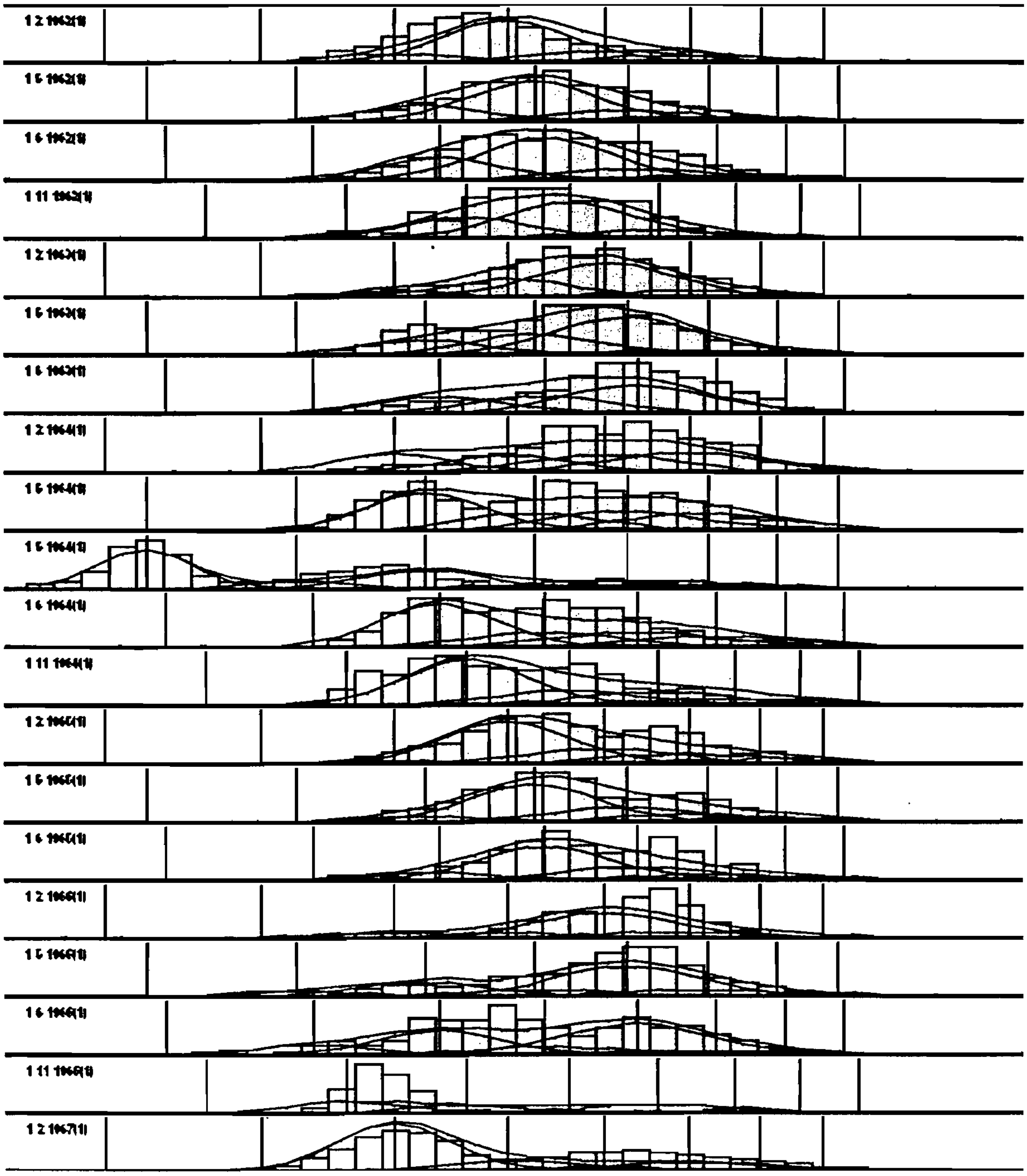
Appendix B. Observed proportions-at-length-interval (histograms) and predicted mean lengths-at-age (vertical lines) and proportions-at-age (smooth lines) from Multifan CL analysis of Hecate Strait Pacific cod assuming M=0.55, 8 age-classes, and common fishery selectivity at 70 cm.

Appendix B – cont'd



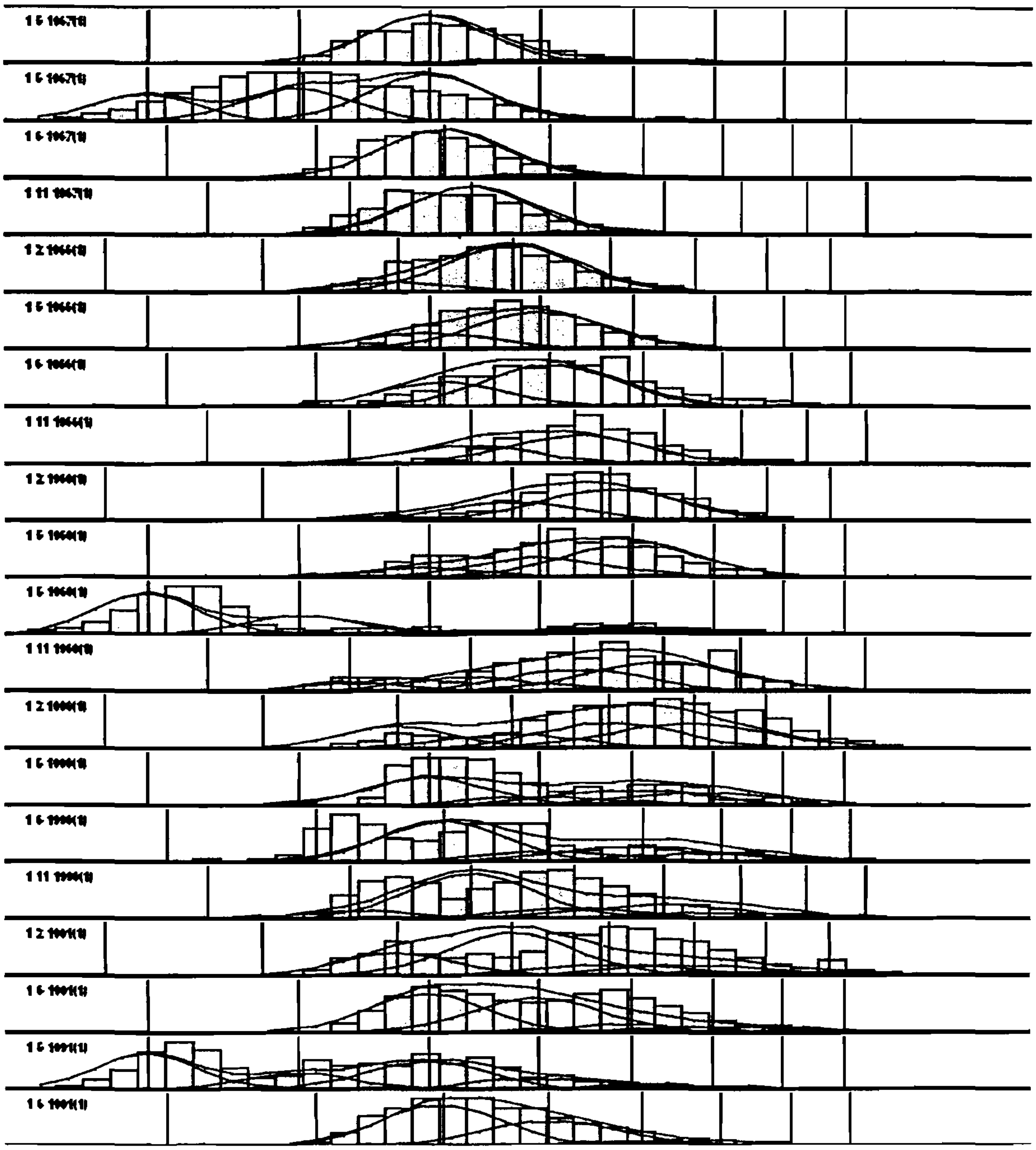
Appendix B. Observed proportions-at-length-interval (histograms) and predicted mean lengths-at-age (vertical lines) and proportions-at-age (smooth lines) from Multifan CL analysis of Hecate Strait Pacific cod assuming M=0.55, 8 age-classes, and common fishery selectivity at 70 cm.

Appendix B – cont'd



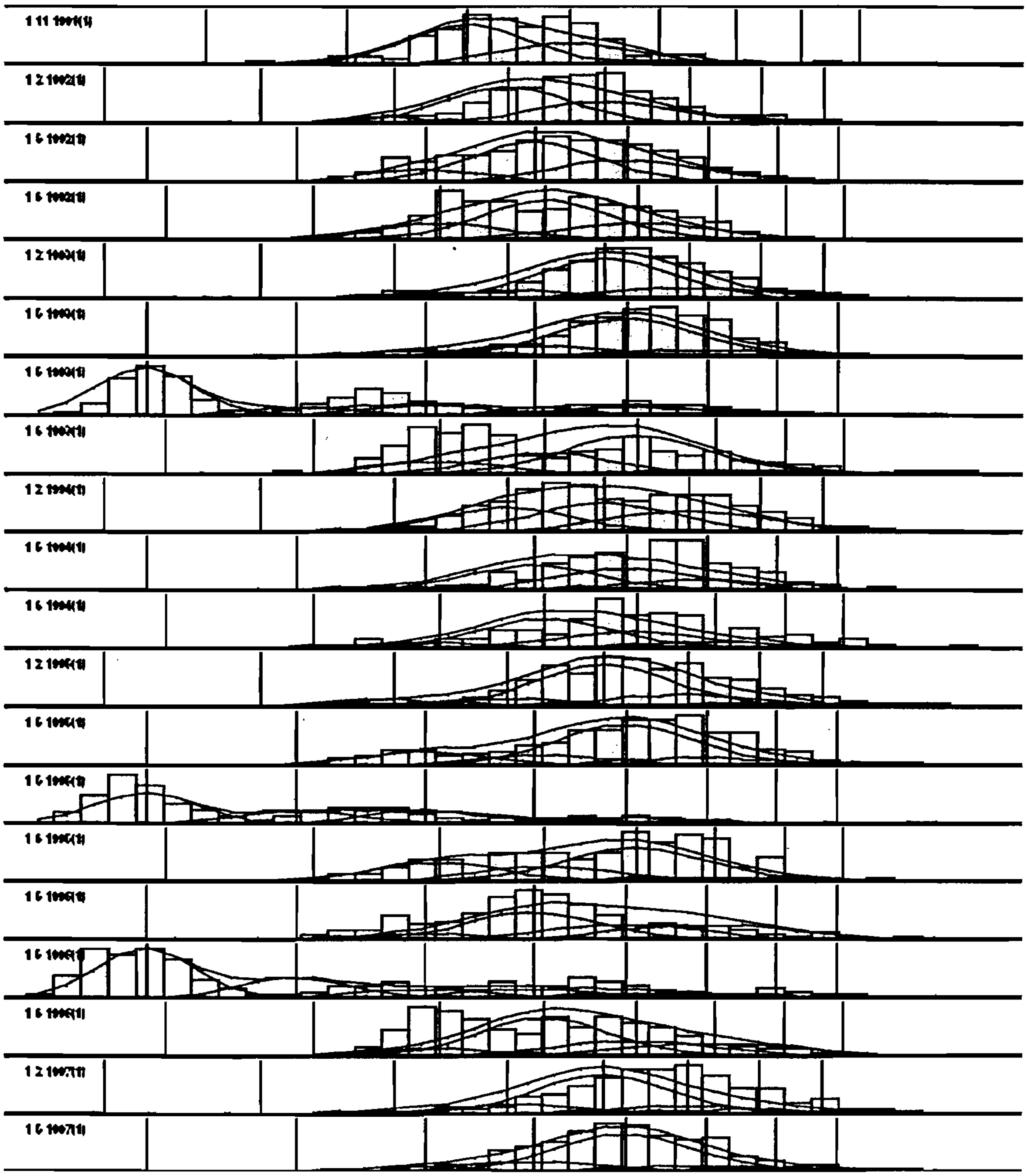
Appendix B. Observed proportions-at-length-interval (histograms) and predicted mean lengths-at-age (vertical lines) and proportions-at-age (smooth lines) from Multifan CL analysis of Hecate Strait Pacific cod assuming M=0.55, 8 age-classes, and common fishery selectivity at 70 cm.

Appendix B – cont'd



Appendix B. Observed proportions-at-length-interval (histograms) and predicted mean lengths-at-age (vertical lines) and proportions-at-age (smooth lines) from Multifan CL analysis of Hecate Strait Pacific cod assuming M=0.55, 8 age-classes, and common fishery selectivity at 70 cm.

Appendix B – cont'd



Appendix B. Observed proportions-at-length-interval (histograms) and predicted mean lengths-at-age (vertical lines) and proportions-at-age (smooth lines) from Multifan CL analysis of Hecate Strait Pacific cod assuming M=0.55, 8 age-classes, and common fishery selectivity at 70 cm.