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Estimates of Survival Rates and Risk Evaluation of the 10% Harvest Rate Procedure for Capelin in NAFO Division 3L

by

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The fishery for capelin in NAFO Div. 3L is almost exclusively on mature fish. Management of the fishery is based on a total allowable catch (TAC) of 10% of the projected mature biomass one year into the future. The projection is made from a survey estimate of numbers at age in the current year. Survival rates of mature and immature fish are a chief source of uncertainty in the projection. It is demonstrated that survival rates can be estimated separately for mature and immature fish using the survey data. These estimates differ substantially from those in use. The performance of the existing management procedure, which uses the old estimates of survival rates, is assessed by Monte Carlo simulation. The results indicate that it is highly unlikely that the actual exploitation in any year exceeded 20%. A new approach, which incorporates parameter estimates from the survey data, is recommended for implementation in future assessments.

Introduction

The capelin fishery off the east coast of Newfoundland and Labrador was initially small and based on mature capelin inshore. An offshore fishery developed rapidly in the early 1970s and in 1974 the fishery was brought under management by ICNAF with a total allowable catch (TAC) of 250 000 tons based on an estimate of the average surplus yield following the decline in predator stocks of cod, seals and whales (Winters and Carscadden 1978). The TAC was increased to 500 000 tons in 1975 and remained unchanged through 1978. A declining capelin stock resulted in the introduction of a new, conservative management procedure in 1979, which we will refer to as the 10% rule. This procedure, which has been implemented for most capelin stocks in the Northwest Atlantic (Carscadden 1983), is to recommend an exploitation rate that does not exceed 10% of the projected spawning stock biomass. No analysis was carried out to determine the appropriate exploitation rate for capelin stocks in the Northwest Atlantic prior to the implementation of the 10% rule and, despite the appearance of strong year classes in the 1980s, the 10% rule has been retained. The importance of capelin as a forage species, particularly for cod (Lilly 1991), and the uncertainty associated with the projections are reasons that have been presented for maintaining the conservative management approach.

In this paper we first demonstrate that survival rates can be estimated separately for mature and immature capelin using the annual acoustic survey data for the stock in NAFO Div. 3L. We then evaluate the existing projection procedure and application of the 10% rule by using Monte Carlo simulation to determine the effect of uncertainty in the assessment inputs (estimated biomass, age structure, proportion mature and survival rates). We present the results as a frequency distribution of the "perceived" TAC (i.e. as perceived by the assessment scientist) as a proportion of the "true" mature biomass (i.e. the biomass of capelin that actually exists in NAFO Div. 3L in the projected year). Finally, we outline a new assessment approach which incorporates parameter estimates from the current survey data for implementation in future assessments.

Data sources used in projections

The NAFO Div. 3L (northern Grand Bank/Avalon) stock is one of five stocks (or stock complexes) identified in the Northwest Atlantic. This stock occupies the northern Grand Bank as juveniles and once mature, migrates inshore to spawn on Newfoundland beaches (Carscadden 1983). Annual spring (April-May) acoustic surveys have been conducted on the northern Grand Bank since 1982 and results have been reported to NAFO as a basis for the provision of management advice. Standard echo integration techniques (Miller and Carscadden 1984, Miller 1985) are used in acoustic data analysis. Details of survey design, sampling techniques and results for individual surveys (1982-89) used in this analysis can be found in Miller (1984, 1985, 1986, 1991), Miller and Carscadden (1983, 1987, 1988, 1989), Miller et al. (1982). Data on length and age composition, weights at length, sex composition, and proportion mature are obtained from biological samples taken from midwater trawls carried out during the acoustic surveys. Numbers and weights at age in the catches are estimated from a sampling programme conducted on the inshore commercial fishery, described by Nakashima and Harnum (1984-90).

Estimation of survival rates

A simple model for the survival of capelin cohorts is

$$N_{a+1,t+1} = N_{a,t}(1-p_{a,t})s_1 + (N_{a,t}p_{a,t} - C_{a,t})s_2 + \varepsilon_{a+1,t+1} \qquad (1)$$

where N is the number of fish, C is the commercial catch by number, p is the proportion mature by number, s_1 is the annual (finite) survival rate of immature fish, s_2 is the annual (finite) survival rate of mature fish and ε is an error term. The subscripts a and t denote age and year, while a+1 and t+1 denote the next older age and the next year. The catch is assumed to be taken at the beginning of the year and the duration of the fishery is assumed to be short, so that fishing and natural mortality act sequentially rather than concurrently (Ricker (1975) type 1 fishery). These assumptions are valid for the capelin fishery in NAFO Div. 3L if the year is taken to commence on 1 June. If $N_{a,t}$, $p_{a,t}$ and $C_{a,t}$ are assumed to be known without error, and the $\varepsilon_{a+1,t+1}$ are assumed iid $N(0, \sigma^2)$ random variables, then ordinary least squares multiple linear regression is appropriate for estimating the survival rates s_1 and s_2. Under these assumptions the estimates are also maximum likelihood. The estimates of s_1 and s_2 from the the survey and catch data are given in Table 1, and the likelihood surface is shown in Fig. 1. From Fig. 1. and Table 1 it can be seen that, whereas s_1 is well defined, s_2 has a large standard error.

In the current application of the 10% rule, age specific values of spawning mortality are used. There does not appear to be a pattern with respect to age in the residuals from the fit of (1) to the survey and catch data (Fig. 2). The big range in residuals for the age three projection reflects the greater number of two and three year olds relative to four and five year olds. Year effects could arise in the data as a result of a number of causes. For example, in 1982 and 1984 the survey area was reduced as a result of ice and in 1983 the survey had [illegible] curtailed because of vessel availability. However, no year effect is obvious in the residuals (Fig. 3).

Although the risk analysis study was only conducted on data for the period 1982-89, estimates of survival rates have also been made for the period 1982-91 and for the period 1985-91 (i.e. leaving out the earlier years for which there may have been survey coverage problems). The estimates from the different runs are compared in Tables 1-3. Residuals plotted against year for the fit to data from 1985-91 are shown in Fig. 4. Residuals plotted against age and year for the period 1982-91 are shown in Figs. 5 and 6.

From Tables 1-3 it is apparent that the estimate of s_1, the survival rate for immatures, changes very little with respect to the three time periods selected. In all three cases the estimate is well defined and within the range of 0.31 to 0.35. In contrast, estimates of s_2, the survival rate for mature fish, differ for the different periods selected, however, these differences are not significant given the large standard errors associated with the estimates. The scatter plots for the period 1985-91 and 1982-91 (Figs. 4, 5 and 6) show that the residual for the projection from 2 to 3 years old for 1990 to 1991 is an outlier. The residuals for the other two age classes in this projection are also low. The residuals do not indicate any problem in the data for the years in which survey coverage is suspect (1982-84).

Evaluation of past applications of the 10% rule

Projections were initially based on sequential population analysis estimates of numbers at age, but from 1982 onwards acoustic population estimates have been used. In the case of capelin in Div. 3L, an annual acoustic survey of the entire stock is conducted in May and the results are reported to the Northwest Atlantic Fisheries Organisation (NAFO) immediately (June). At the same time, projections for the next fishing season (June/July the following year) are provided. The procedure followed in calculating the recommended TAC based on the 10% rule is now described.

The following notation is used: ^ denotes an estimate from survey and/or catch data; ¯ denotes an average from all the survey or catch estimates; ~ denotes an assumed value or a value taken from the literature; Q is the total allowable catch; w is the weight of an individual fish in the surveys; u is the weight of an individual fish in the catch; h is the proportion by weight of an age group of fish in the survey; k is the proportion by weight of an age group in the catch.

The projected mature biomass and TAC in year t+1 is obtained from the following equations. The current population at age for immatures and matures is estimated from survey data by

$$\widehat{N}^{m}_{a,t} = \frac{\widehat{B}_t \widehat{h}_{a,t} \widehat{p}_{a,t}}{\widehat{w}_{a,t}} \tag{2}$$

and

$$\widehat{N}^{i}_{a,t} = \frac{\widehat{B}_t \widehat{h}_{a,t} (1 - \widehat{p}_{a,t})}{\widehat{w}_{a,t}} \tag{3}$$

respectively.

The next equation is used to project the number mature at the start of the next year, and equation (5) converts numbers to biomass and sums over all ages.

$$N^{m}_{a+1,t+1} = (\widehat{N}^{i}_{a,t} \widetilde{s}_1 + \widehat{N}^{m}_{a,t} \widetilde{s}_{2_a}) \widetilde{p}_{a+1} \tag{4}$$

$$B^{m}_{t+1} = \sum_{a} (N^{m}_{a+1,\,t+1} \widetilde{u}_{a+1}) \tag{5}$$

Equation (5) provides an estimate of the TAC by applying the 10% rule to the projected biomass.

$$Q_{t+1} = 0.1\, B^{m}_{t+1} \tag{6}$$

Note that the right side of (4) is incomplete; it should have the recorded commercial catch of fish age a in year t removed. This was not done in past applications of the projection procedure because it was considered to be of minor consequence. Survey sample estimates of proportions mature, weights at age and age composition are used in equations (2) and (3) to obtain the estimates of numbers at age. However, in the projections (equations (4), (5), and (6)) literature values are used for the survival of spawners (Carscadden et al. 1985) and proportion mature (Carscadden et al. 1981). Constant values derived from inshore sampling are used for mature weights at age. An assumed value is used for the survival rate of immatures. Values used in projections are listed in Table 2.

In order to evaluate the procedure, equations (2) to (6) were incorporated into a Monte Carlo simulation which followed the procedure outlined in the Appendix. This procedure provided 3 000 realisations of the TAC as a proportion of the true mature biomass.

The results are presented as a frequency distribution in Fig. 7 and as a cumulative probability of the TAC being less than a specified proportion of the mature biomass in Fig. 8. It is apparent that the existing procedure performs reasonably well in achieving the objective with about 50% of the trials below 10% of the mature biomass and 50% above. There is only a small probability (< 0.1) that a TAC would be recommended that was actually 20% or more of the mature biomass, an exploitation rate which in itself may be considered to be reasonably conservative.

This result is somewhat surprising, considering that we now believe the survival rates to be quite different from the values used up until now (Table 2). The reason that the existing procedure performed reasonably is that the values for weights at age in the projection are less than the mean of the estimates of weight at age of fish from the catch samples, and the proportions mature are less than the mean of those estimated from the survey samples (Table 2). These two factors compensate for the higher survival rate for immatures used in the projections.

We re-ran the simulation with a coefficient of variation of 40% (as opposed to 30%) for the acoustic estimate of biomass as well as for positive biases of 20% and 40% in the estimate (Fig. 9). The results suggest that the current projection procedure is relatively insensitive to these errors.

Outline of a new assessment approach

The ability to estimate the parameters for making a projection of mature biomass from past surveys and catches suggests that a procedure be introduced in which parameter estimates and estimates of risk are updated during annual assessments. The present assessment procedure utilizes the survey data to break down the current biomass into numbers mature and immature; however, the projection is based on assumed and independently estimated survival rates, weights at age for mature fish and proportion mature in the projected year. The TAC is provided as a point estimate and uncertainties associated with the acoustic estimate and with proportions at age, weights at age, proportion mature and survival rates are ignored. We suggest that quantification of the uncertainty provides useful information for making management decisions regarding the exploitation of the stock, and should be summarised in a suitable manner for managers.

A new assessment procedure could encompass the following steps: (i) updating the estimates of survival rates from survey and catch data; (ii) Monte Carlo simulation to estimate the uncertainty associated with projections and estimates of the TAC; and (iii) construction of cumulative probability ogives to illustrate the risk of exceeding a given exploitation rate as a function of the TAC chosen. The procedure would be exercised annually so that updated estimates of the survival rates, proportions at age, weights at age and proportions mature could be obtained and used. If an age effect or trend with time is found in the survival rates, then this could be incorporated. Instead of comparing "real" and "perceived" realisations, the Monte Carlo simulation would provide a bootstrap estimate of the uncertainty associated with a projection of mature biomass and the associated TAC using all the information from past surveys and catches.

Discussion

Although the 10% rule has been exercised in NAFO Div. 3L using proportions, weights and survival rates which do not correspond to those estimated from the surveys and catches between 1982 and 1989, it has performed reasonably well in achieving the desired goal of providing a TAC of around 10% of the mature biomass. The approach used appears to be robust to variance and bias in the acoustic estimate, and even with a positive bias of 40%, there appears to be an 80% chance of choosing a TAC which will be less than 20% of the true biomass (curve d, Fig. 9). The data do not support the current use of an age-dependent survival rate for spawners. Furthermore, the data suggest that it is possible for more spawners to survive than is currently assumed. However, the estimate of survival rate for the spawners has a large standard error so that our knowledge of spawner survival is poor. Of particular importance is the estimate of survival rate of the non-spawners which, at 0.35, is substantially less than the value of 0.74 assumed up until now. This result emphasises the role of capelin as a forage species in the NW Atlantic system. Temporal changes in the abundance of major predators such as cod and harp seals may be expected to effect capelin survival rate; however, the data analysed in this study do not suggest a year effect.

A new assessment procedure is outlined for NAFO Div. 3L based on annual acoustic estimates. It seems likely that similar procedures could be introduced for NAFO Div. 2J3K capelin as well as for capelin in other areas. We briefly compare fisheries in the Barents Sea, off Iceland, and in NAFO Div. 2J3K to the fishery in Div. 3L.

All four stocks are similar in that the mature spawning biomass is composed of three-, four-, and five-year-olds and spawning survival is low (assumed to be zero in Barents Sea and Iceland and estimated to be below 25% in the Northwest Atlantic (Carscadden et al. 1985)). In each case an annual acoustic estimate is made from which projections are carried out to serve as a basis for setting TAC's.

The Barents Sea fishery is managed on the basis of a constant escapement of 500000 tons of spawners to March 31 (Hamre and Tjelmeland 1982). Fish spawn on the bottom at depths ranging from 10-100m in March and April. An acoustic survey is carried out in September to provide an estimate of the biomass and numbers at age of fish two years old and older. The stock is assessed in October and projections of mature and immature fish are made based on estimates of proportions mature and survival rates. Separate TAC's are set for winter and summer/fall fisheries. The TAC for the winter fishery is set at the appropriate level to achieve the target escapement of spawners. Post-spawning survival is assumed to be zero. The immature portion of the population (mostly three-year-olds) is projected forward to the next fall to provide a preliminary TAC for the next fall and winter fishery. This TAC is revised during the October assessment taking into account the new survey data.

The Iceland fishery is managed on the basis of a constant escapement strategy of 400 000 tons of spawners (Vilhjal[illegible]n 1983). Spawning takes place in March and the first half of April in shall[illegible] coastal waters. Fisheries take place in both the fall and winter. An acoustic survey is carried out in August and the annual assessment is carried out in October. As for the Barents Sea, a TAC for the winter fishery is set so as to reach target spawner escapement. A preliminary TAC is also set for the next fall and winter fisheries. A second acoustic survey is carried out in February-March to check on spawner escapement and in some years to provide estimates of recruitment. The TAC for the fall and winter fisheries is revised on the basis of the new survey data.

The fishery in Div. 2J3K is divided into an inshore component in summer and an offshore component in fall/winter. The summer fishery is essentially similar to the one pursued in Div. 3L (i.e. on mature fish, mainly 3- and 4-year olds), whereas the fall/winter fishery is on immature fish (mainly aged 2- and 3-years old), most of which will spawn the following year. Acoustic surveys are carried out in October each year. The stock is assessed in February of the following year. The TAC for the inshore fishery is calculated as for Div. 3L, and in addition a TAC of 10% of the total biomass as of 1 September (i.e. after spawning) is calculated for the fall offshore fishery. In the projection for the fall fishery, the geometric mean number of 2 year olds estimated in past acoustic surveys is used to represent the size of this (as yet unsurveyed) age class in the current year.

There are three basic similarities between the NAFO Div. 3L capelin stock and the stocks described above: (i) in each case an acoustic survey is undertaken to provide numbers at age from which a projection is made; (ii) the survey and catch data do not appear to be fully utilized to provide parameter estimates for making the projection; and (iii) a specific management goal is set up (e.g. an escapement of 500000 tons for the Barents Sea stock), but no attempt is made to quantify the risk of failing to meet the goal. It seems likely that assessment procedures could be defined for each of the systems along the lines of that described for NAFO Div. 3L in this paper. A comparison of parameter estimates among systems and consideration of the value of the alternative management goals could prove extremely useful.

Conclusion

This study provides new estimates of the survival rate of mature and immature capelin in NAFO Div. 3L. These rates differ substantially from those previously used in capelin assessments in this area. The existing procedure for applying the 10% rule is examined and it is found to have performed reasonably well, and to be relatively insensitive to bias and variance in the acoustic survey estimates. The adequate performance of the existing procedure is fortunate, given that the survival rates used differ substantially from those estimated from the data. A new assessment procedure is suggested which will provide estimates of the risk associated with alternative TAC's based on a bootstrap estimate of the associated uncertainty in making projections. There is some similarity between capelin fisheries in Div. 3L and those in Div. 2J3K, the Barents Sea and off Iceland, and a similar approach may be appropriate for these stocks and should be investigated.

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Table 1. Multiple linear regression estimates of s_1 and s_2 from survey and catch data for NAFO Div. 3L for the period 1982-89.

	s_1	s_2
Estimate	0.350	0.227
Standard error	0.043	0.239
Covariance		- 0.00298
r^2		0.8079

Table 2. Multiple linear regression estimates of s_1 and s_2 from survey and catch data for NAFO Div. 3L for the period 1985-91.

	s_1	s_2
Estimate	0.310	0.056
Standard error	0.055	0.265
Covariance		- 0.00419
r^2		0.691

Table 3. Multiple linear regression estimates of s_1 and s_2 from survey and catch data for NAFO Div. 3L for the period 1982-91.

	s_1	s_2
Estimate	0.313	0.059
Standard error	0.049	0.235
Covariance		- 0.00332
r^2		0.645

Table 4. Old parameter values used in the projections to date, compared with new values estimated from the catch and survey data for 1982 to 1989 in this study.

	Age				
Parameter	2	3	4	5	6
Mature weights (g)					
Old		21.2	28.4	31.1	32.4
New	14.18	28.25	36.00	34.31	36.98
Proportion mature					
Old[1]	0	0.47	0.87	0.93	1
New	0.05	0.63	0.97	0.99	1
Annual survival rates					
Immatures					
Old[1]	<-------------------------		0.74		------------------------->
New	<-------------------------		0.35		------------------------->
Matures					
Old[1]	0.18	0.18	0.14	0.08	0.08
New	<-------------------------		0.23		------------------------->

[1] Carscadden et al. (1985).

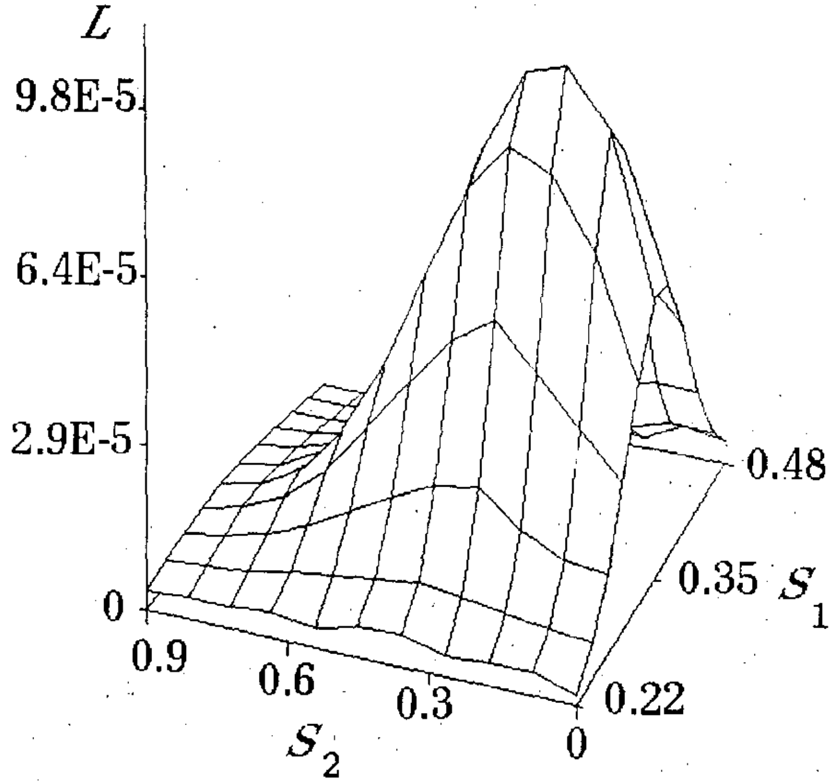

Fig 1. Surface proportional to the likelihood (L) for s_1 and s_2 estimated from the survey and catch data.

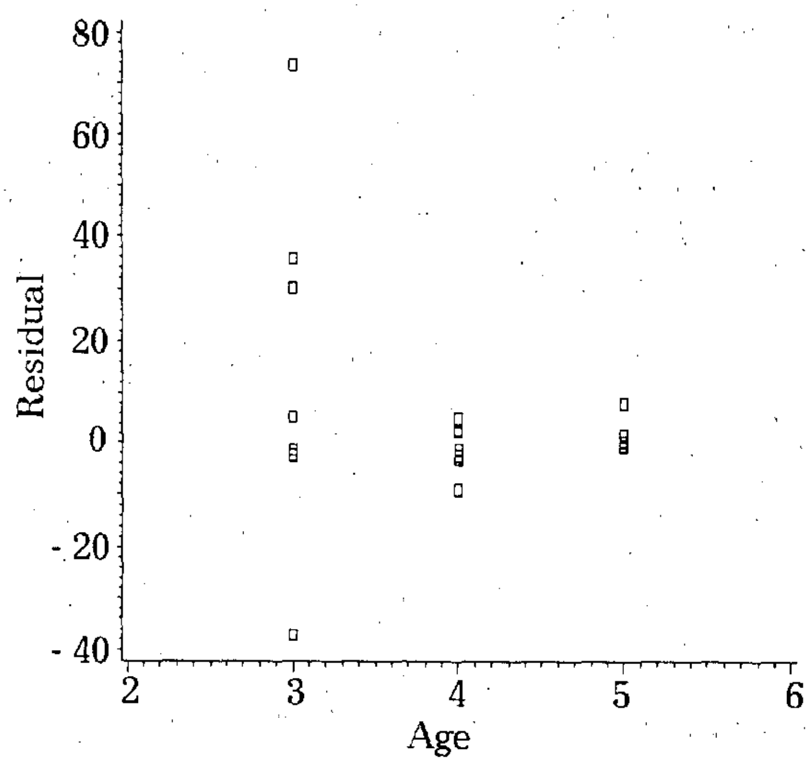

Fig. 2. Residuals from the fit to (1) for the period 1982-89 plotted against projected age.

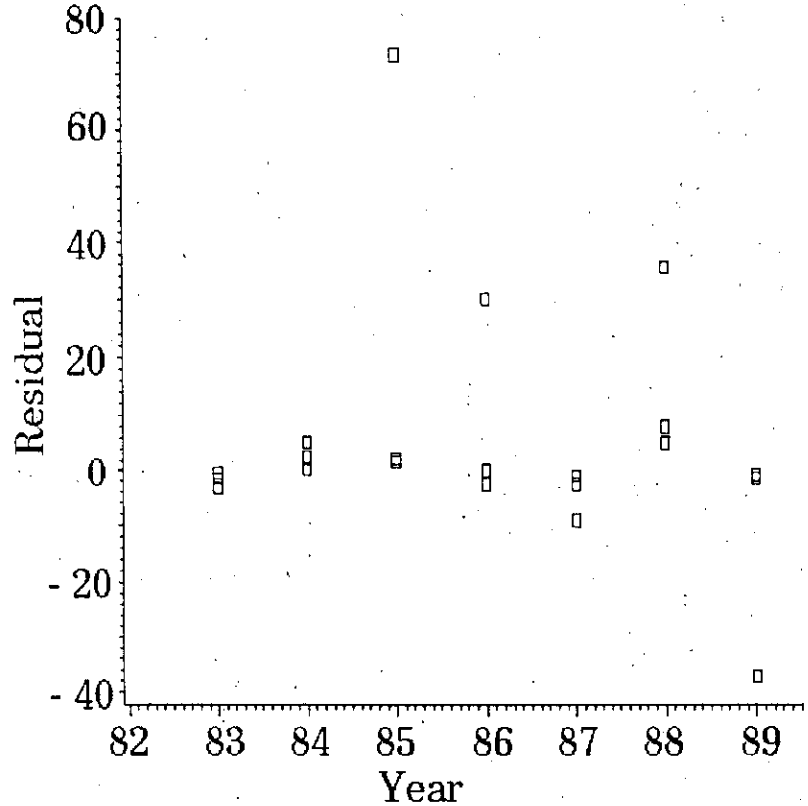

Fig. 3. Residuals from the fit to (1) for the period 1982-89 plotted against year.

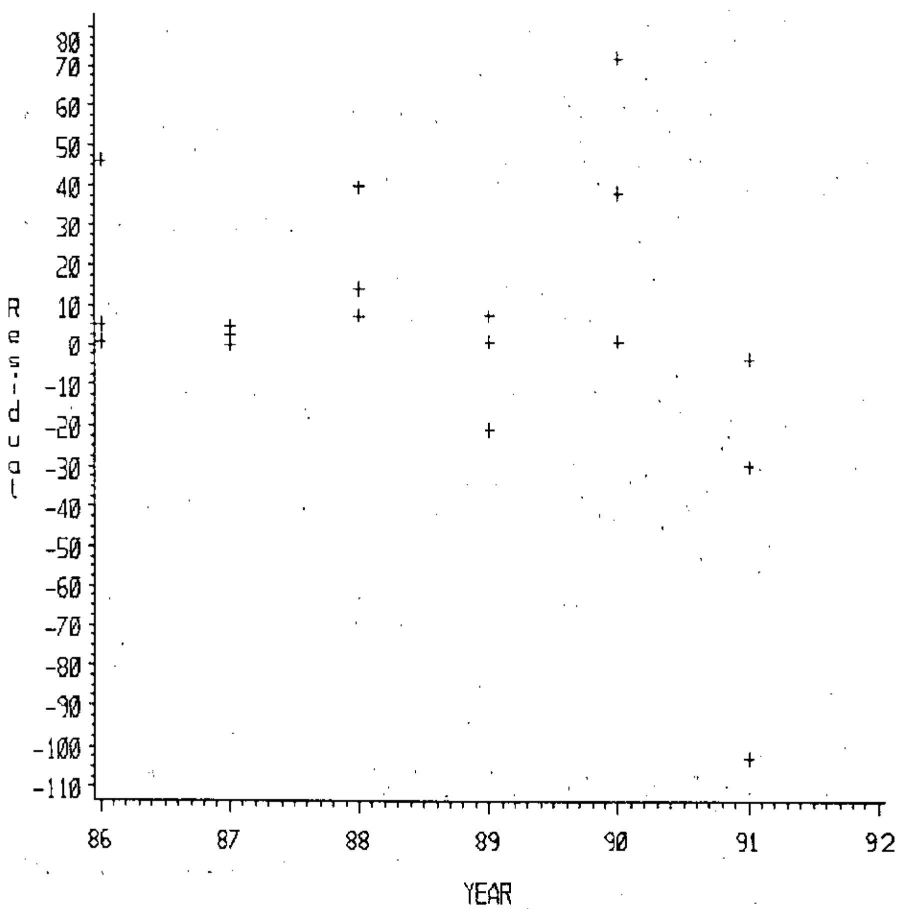

Fig. 4. Residuals from the fit to (1) for the period 1985-91 plotted against year.

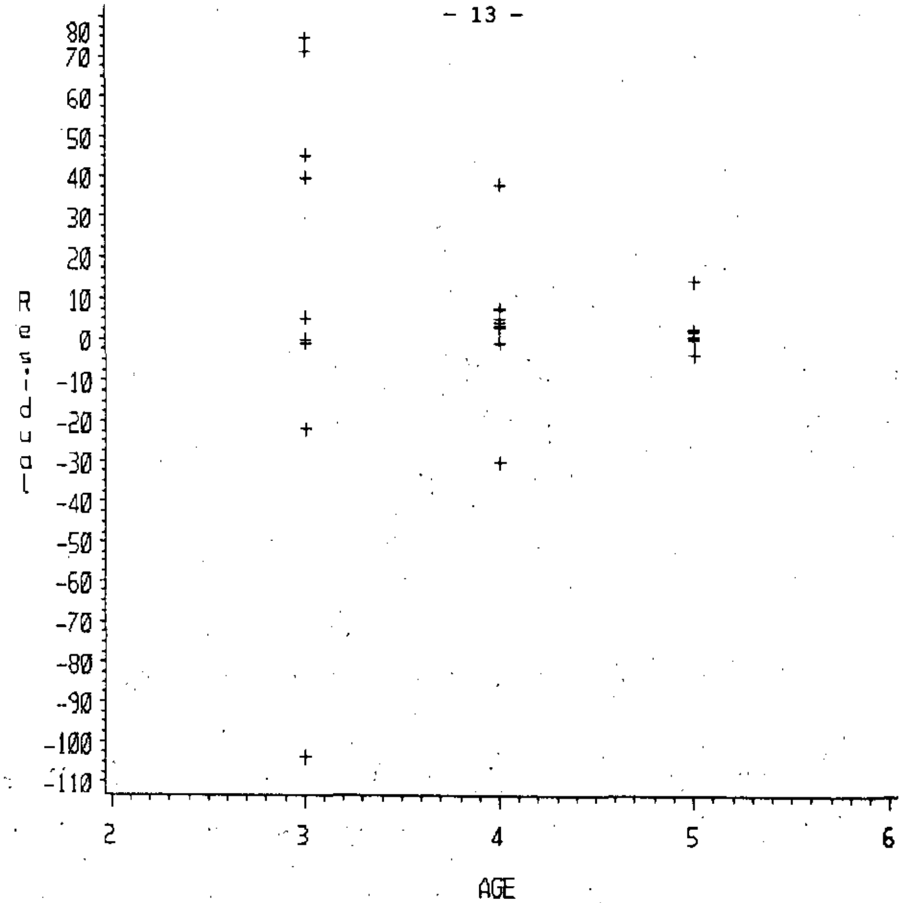

Fig. 5. Residuals from the fit to (1) for the period 1982-91 plotted against age.

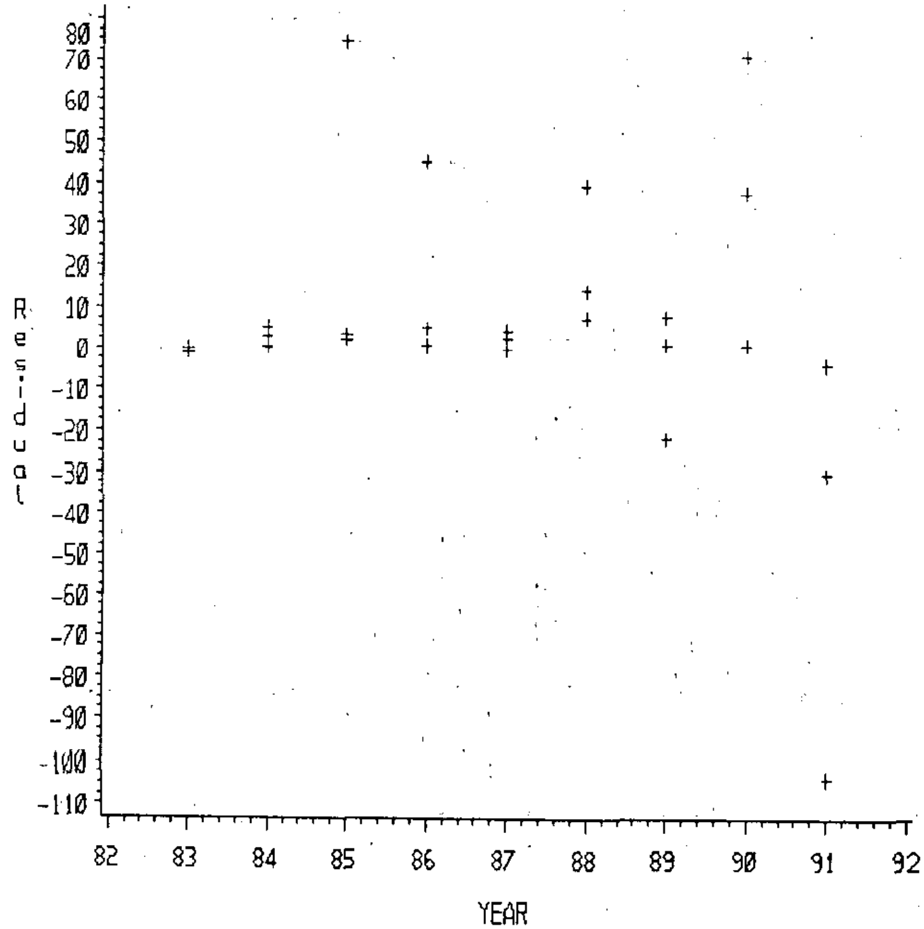

Fig. 6. Residuals from the fit to (1) for the period 1982-91 plotted against year.

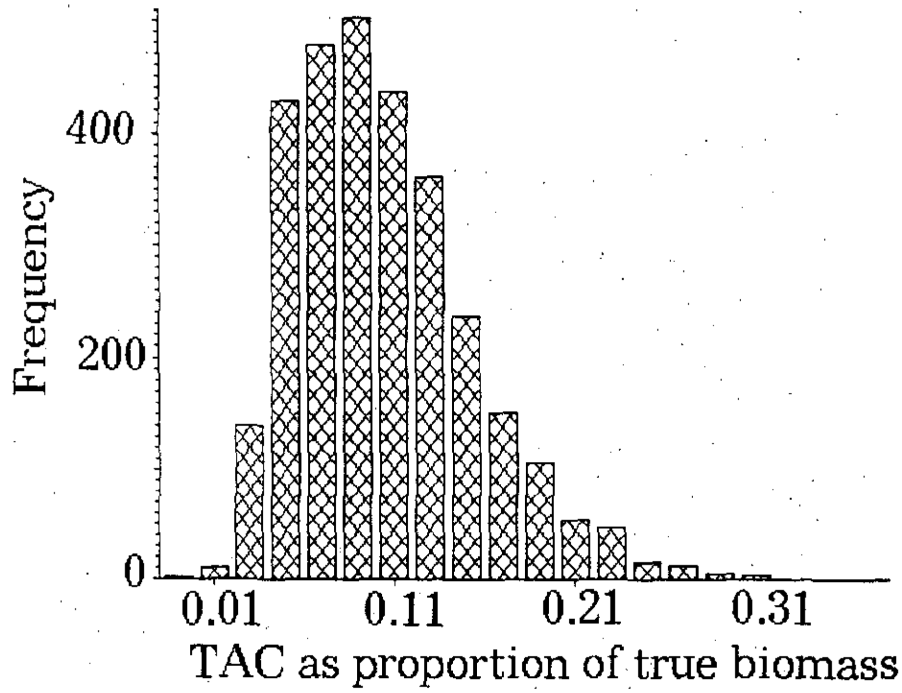

Fig.7. The simulated TAC as a proportion of the true mature biomass using the 10% rule and assuming a survey sample error CV of 30%. Number of simulations =3 000.

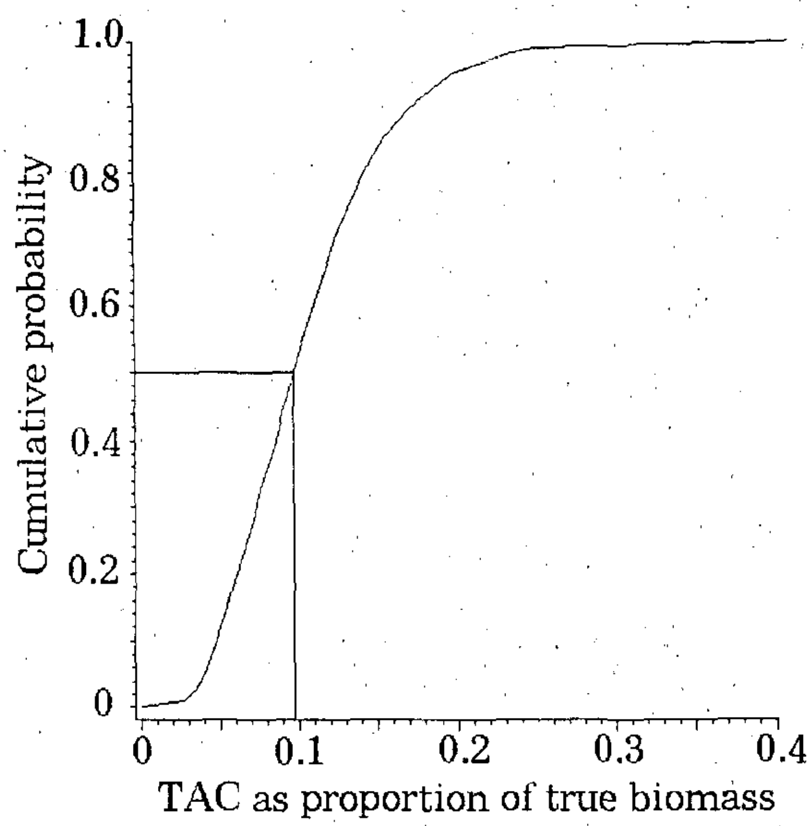

Fig. 8. The cumulative probability of the 10% rule giving rise to a TAC that is less than or equal to a specific proportion of the true mature biomass.

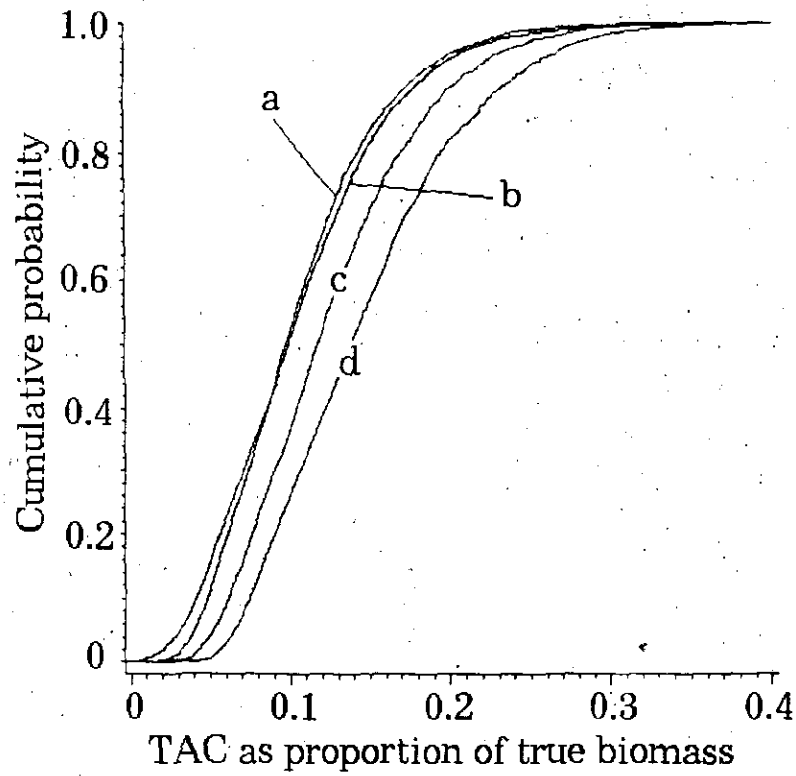

Fig. 9. The cumulative probability of the 10% rule giving rise to a TAC that is less than or equal to a specific proportion of the mature biomass for cases with different variance and bias associated with the acoustic estimate: a- CV=30%, bias=0%; b- CV=40%; bias=0%; c-CV=30%; bias=[illegible]; d- CV=30%, bias=+40%.

Appendix: Monte Carlo simulations for evaluating the existing procedure used to manage capelin in NAFO Div. 3L.

Our simulations consist of repeating 3000 times two sets of parallel computations, one dealing with the possible "true" state of nature and the other with the state "perceived" by the assessment scientist. The true state starts with an arbitrary level of biomass. A known catch is subtracted from the mature portion of the biomass. The remaining biomass is then projected ahead one year and the proportion mature is computed. The appropriate total allowable catch is 10% of the projected mature biomass. The assessment scientist attempts to quantify each of these steps to estimate what is 10% of the mature biomass one year into the future.

The steps of the model are of two types. For some steps, we can assume a value for a true state parameter and assume that the scientist attempts to estimate this parameter. For example, we assume the true biomass at the beginning of the simulation is an arbitrary value *B*, and that the assessment biologist can obtain an unbiased estimate of this with a coefficient of variation (cv) of 30%. In each run of the simulation, we represent this by generating a perceived biomass as a normal random variable with expectation *B* and cv of 30%. In other steps of the model, the assessment scientist uses assumed parameter values. Consequently, in the simulation we must generate a possible value of the true parameter. For example, in the past the assessment scientist has assumed values for the survival rates of immature and mature capelin. To represent the possible values of the true parameter values, we developed a new method for estimating the survival rates from the survey data. In our simulations, we generated possible values of the true survival rates from a bivariate normal distribution with mean vector and covariance matrix equal to those estimated from the entire survey data set.

A third type of step, not used in our simulations, is where the particular value of the true parameter is influential and the assessment scientist estimates the parameter. It is then necessary to specify possibilities for the true value and, conditional on the specified true value, to generate an estimate that the scientist might obtain. For example, in the future the assessment scientist might estimate the survival rates each year from the survey data instead of assuming a value. We may only have a poor idea of the true survival rates and the survival rates are influential. Therefore, we would want to include many possible values of the true rates in the simulations. For each possible true survival rate generated, we would need to generate a perceived survival rate centered on the current value of the true rate.

We now discuss the differences between type 1 and type 3 steps. In a type 1 step, we assume a particular value for a true parameter rather than specifying a range of possibilities for the parameter as in a type 3 step. In general, if the simulation results depend heavily on the particular value of a true parameter, then all reasonable values of the true parameter should be represented in the simulation. Otherwise, an arbitrary value of the true parameter may suffice. In some cases, it may be possible to show analytically the sensitivity of the results to the value of a particular parameter. In other cases, a sensitivity analysis may be used to establish if the additional complexity of a type 3 step is needed over the simplicity of a type 1 step.

In the example above, the initial biomass was set at an arbitrary level B^*. Since the simulations are concerned with the proportion of the biomass harvested, rather than with absolute biomass, the actual value of the biomass drops out and any value of the initial biomass would be suitable. (Note that this is only true because we are willing to assume that the catch taken just after the biomass survey was close to 4.3% of the true mature biomass in every year. If the exploitation rate had varied considerably and sometimes accounted for a large portion of the biomass then we would have had to specify a distribution of possible initial biomasses or, equivalently, a distribution of percentage harvested just after the survey.)

In some instances we assume that the true parameter value is the long-term historical mean of the available estimates, and that the collection of annual estimates comprises an empirical distribution of what might be observed in any year. For example, the proportion mature at age 3 has been estimated annually from 1982 to 1989 from the survey data. We assume in our simulations that the true proportion mature is the arithmetic mean of these historical estimates. In the "perceived" part of the simulation, the assessment scientist might make any of the historical estimates of the proportion mature. This approach is conservative. We are assuming that the variability or error in estimates of proportion mature is equal to the variability of the estimates about the long-term mean. However, the estimates vary from year to year due to both sampling error and actual change in the proportion mature. Mathematically, Var(annual estimates) = Var(parameter value over time) + Var(estimates given true values) (see Cochran 1977, p276; Seber 1977, p9). Therefore, our simulations include an extra component of variability and are conservative in this respect.

In what follows, we denote a realization of a quantity in the true system by an asterisk (*). A realization of an estimate of a parameter is denoted with a hat (^) symbol. Other symbols are as defined in the text.

Realization of true system

1. The true biomass is taken to be an arbitrary value B.

$$B_t^* = B$$

2. The true values for numbers at age in the simulation are obtained from the mean biomass, the mean weight at age in the surveys, and the mean proportion by age from the surveys.

$$N_{a,t}^* = \frac{B_t^* \bar{h}_a}{\bar{w}_a}$$

3. The true catch at age by number is derived from a catch of 4.3% of the true mature biomass. First, the mature number at age is determined.

$$N_{a,t}^{m*} = \frac{B_t^* \bar{h}_a \bar{p}_a}{\bar{w}_a}$$

Then the mature number at age is converted to biomass using mean weights at age in the catch, reduced by the average catch as a proportion of the mature biomass, and finally reconverted to numbers at age .

$$C_{a,t}^* = (0.043 (\sum_a N_{a,t}^{m*} \bar{u}_a)) \frac{\bar{k}_a}{\bar{u}_a}$$

4. The true projected numbers at age in year t+1 is then simulated using survival rates s_1 and s_2 drawn randomly from a bivariate normal distribution described by parameters given in Table 1.

$$N_{a+1,t+1}^* = N_{a,t}^*(1-\bar{p}_a)s_1 + (N_{a,t}^* \bar{p}_a - C_{a,t}^*)s_2$$

5. The true mature biomass in year t+1 is simulated using the mean weight at age in the catch from annual estimates and the mean proportion mature at age from the annual survey estimates.

$$B_{t+1}^{m*} = \sum_a (N_{a+1,t+1}^* \bar{u}_{a+1} \bar{p}_{a+1})$$

Realization of perceived system

1. The perceived biomass (i.e. estimated biomass) is generated randomly from a normal distribution with mean B and variance σ^2.

$$\hat{B}_t \sim N[B, \sigma^2]$$

2. The perceived biomass is apportioned to numbers at age based on vectors of proportion by weight and individual fish weights. These vectors are selected randomly with replacement from the matrix of survey estimates 1982 to 1989 (same year selected for both vectors to account for possible covariance).

$$\hat{N}_{a,t} = \frac{\hat{B}_t \hat{h}_{a,t}}{\hat{w}_{a,t}}$$

3. The perceived catch is assumed to be zero.

$$\hat{C}_{a,t} = 0$$

4. The perceived numbers at age in year t+1 is simulated using literature values for survival rates ("old" values in Table 2) and estimates of proportion mature simulated by randomly selecting a vector of proportion mature from the matrix of annual survey estimates for 1982 to 1989.

$$N_{a+1,t+1} = \hat{N}_{a,t}(1-\hat{p}_{a,t})\tilde{s}_1 + (\hat{N}_{a,t}\hat{p}_{a,t} - C_{a,t})\tilde{s}_2$$

5. The pereceived biomass in year t+1 is calculated using assumed and literature values for weight -at-age in the catch and proprotion mature (see "old" values in Table 2).

$$B_{t+1}^{m} = \sum_a (N_{a+1,t+1} \tilde{u}_{a+1} \tilde{p}_{a+1})$$

6. The perceived TAC for the realization is then calculated, following the 10% rule.

$$Q_{t+1} = 0.1 B_{t+1}^m$$

7. Finally, the true exploitation rate (relative to mature biomass) associated with the perceived TAC is calculated using the true mature biomass.

$$E_{t+1}^* = \frac{Q_{t+1}}{B_{t+1}^{m*}}$$