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

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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 average 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 30%. Commonality among capelin fisheries in the North Atlantic may facilitate the development of appropriate assessment procedures and methods for the quantification of risk.

La pêche au capelan dans la division 3L du NAFO en est presque exclusivement une de poissons matures. La gestion de cette pêche repose sur un total des prises admissibles (TPA) équivalant à 10 % de la biomasse mature prévue pour l'année suivante. Cette prévision s'inspire d'une estimation des âges de la piscipopulation de l'année en cours. Les taux de survie des poissons matures et immatures sont une source principale d'incertitude dans cette prévision. Il est démontré que les taux de survie moyens des poissons matures et immatures peuvent être estimés séparément à l'aide des données de relevé. Ces estimations divergent considérablement de celles qui sont actuellement utilisées. Le rendement de la méthode de gestion actuelle, qui a recours aux anciennes estimations des taux de survie, est évalué selon la technique de Monte-Carlo. Les résultats révèlent qu'il est fort improbable que l'exploitation réelle de quelque année ait dépassé 30 %. La relation de communauté entre les pêches au capelan de l'Atlantique Nord peut contribuer à faciliter la mise au point de méthodes et de techniques appropriées pour l'évaluation de la quantification du risque.

Capelin off the east coast of Newfoundland and Labrador were caught for decades in a small inshore fishery on mature fish to satisfy local demands for bait, fertilizer for gardens, human food and food for dog teams. An offshore fishery developed rapidly in the early 1970's and in 1974 the fishery was brought under management by ICNAF (precursor of NAFO, Northwest Atlantic Fisheries Organisation) 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. At the same time, the large offshore fishery which took immature and maturing fish was all but eliminated and a much smaller commercial fishery operating on prespawning fish in the nearshore regions developed.

The 10% rule, which has been implemented for most capelin stocks in the Northwest Atlantic, 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 1980's, 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 a conservative management approach.

In this paper we first demonstrate that average 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, 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 make a brief comparison with capelin fisheries elsewhere to determine the degree of commonality with a view to the development of improved assessment procedures and the quantification of risk.

Materials and Methods

Data Sources Used in Projections

The NAFO Div. 3L (northern Grand Bank/Avalon) stock (Fig. 1) 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 in June and July (Carscadden 1983). It is during this prespawning period that the inshore commercial fishery harvests mature females for the Japanese roe market. Annual spring (April–May) acoustic surveys prior to the inshore spawning migration 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), Miller and Carscadden (1983, 1987, 1988, 1989) and 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).

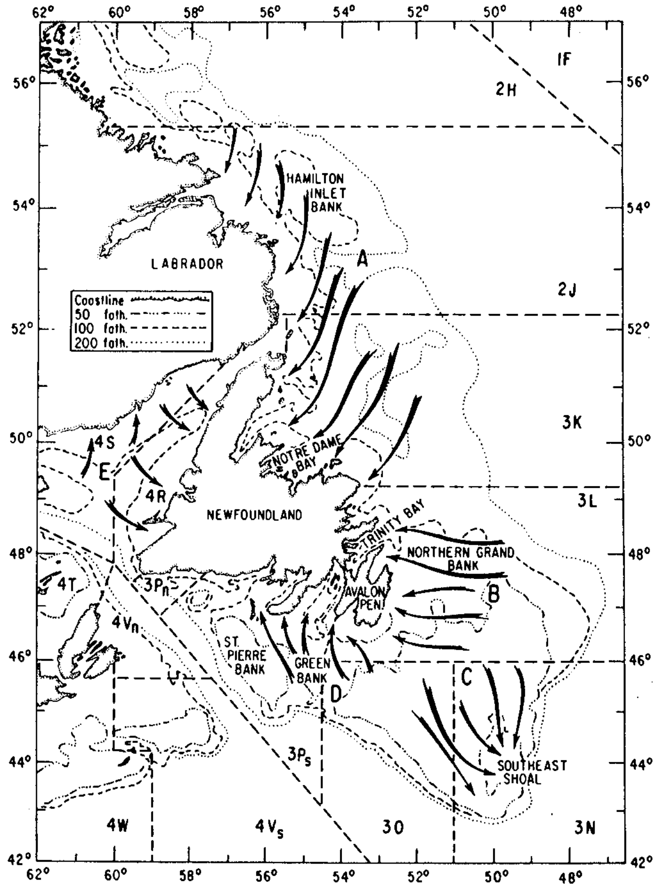

Fig. 1. Map showing major capelin stocks (A–E) and spawning migration routes of capelin in the Northwest Atlantic. A - Labrador/Northeast Newfoundland (NAFO Div. 2J3K) stock; B - Northern Grand Bank/Avalon (NAFO Div. 3L) stock; C - South Grand Bank (Southeast Shoal - NAFO Div. 3NO) stock; D - St Pierre Bank-Green Bank (NAFO Div. 3Ps) stock; E - Gulf of St Lawrence Stock. Arrows indicate the direction of the spawning migration undertaken by mature fish each summer.

Estimation of Survival Rates

A simple model for the survival of capelin cohorts is

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

where N is the number of fish estimated in the acoustic survey, C is the commercial catch by number, p is the proportion mature by number, s_1 is the average annual (finite) survival rate of immature fish, s_2 is the average 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$\left(0, \sigma^2\right)$ random variables, then ordinary least squares multiple linear regression can be used to estimate average 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 survey and catch data (Table 1) are given in Table 2. From Table 2 it can be seen that, whereas s_1 is reasonably well defined, s_2 has a large standard error. This is taken to be more a reflection of substantial variation in annual survival rate rather than a measure of precision.

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 NAFO immediately (June). At the same time, projections for the next fishing season (June/July the following year) are provided. The procedure for calculating the recommended TAC based on the 10% rule is now described.

The following notation is used: $\hat{}$ denotes an estimate from survey and/or catch data; $\bar{}$ denotes an average from the survey or catch estimates over all years; $\tilde{}$ denotes an assumed value or a value taken from the literature; B is the biomass of

Table 1. Survey numbers at age, proportions mature by age, and catch at age data used in the estimation of survival rates for capelin in NAFO Div. 3L.

Survey numbers at age $(\times 10^{-9})$.

Year	Age 2	3	4	5
82	9.594	16.195	2.4034	0.8973
83	3.383	1.904	0.8003	0.1008
84	20.132	6.209	3.0950	0.4942
85	368.612	80.379	3.7662	2.3480
86	59.473	158.003	21.2381	1.0083
87	87.513	18.292	38.8983	3.9910
88	382.869	65.696	9.7307	16.7765
89	317.094	96.011	15.3080	1.3936

Survey proportions mature

Year	Age 2	3	4	5
82	0.072	0.813	0.972	0.991
83	0.140	0.600	0.975	1.000
84	0.085	0.846	0.989	0.994
85	0.029	0.435	0.900	1.000
86	0.007	0.368	0.933	1.000
87	0.059	0.731	0.978	0.994
88	0.020	0.763	0.992	0.993
89	0.014	0.505	0.977	0.977

Catch numbers at age $(\times 10^{-9})$

Year	Age 2	3	4	5
82	0.00653	0.70147	0.08898	0.03416
83	0.03247	0.54312	0.27225	0.01106
84	0.01914	0.42060	0.57322	0.04788
85	0.10180	0.59016	0.20346	0.05849
86	0.00803	1.04304	0.55666	0.04909
87	0.03608	0.10250	0.40304	0.02988
88	0.18302	1.03253	0.25627	0.26753
89	0.02444	1.24383	0.33976	0.03663

fish from the survey; 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, and the superscripts i and m refer to immature and mature fish respectively.

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

$$\text{(2)} \qquad \widehat{N}^m_{a,t} = \frac{\widehat{B}_t \widehat{h}_{a,t} \widehat{p}_{a,t}}{\widehat{w}_{a,t}}$$

Table 2. 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	

and

$$\text{(3)} \qquad \widehat{N}^i_{a,t} = \frac{\widehat{B}_t \widehat{h}_{a,t} \left(1 - \widehat{p}_{a,t}\right)}{\widehat{w}_{a,t}}$$

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.

$$\text{(4)} \qquad N^m_{a+1,t+1} = \left(\widehat{N}^i_{a,t}\widetilde{s}_1 + \widehat{N}^m_{a,t}\widetilde{s}_2\right)\widetilde{p}_{a+1}$$

$$\text{(5)} \qquad B^m_{t+1} = \sum_a \left(N^m_{a+1,t+1}\widetilde{u}_{a+1}\right)$$

Equation (6) provides an estimate of the TAC by applying the 10% rule to the projected biomass.

$$\text{(6)} \qquad Q_{t+1} = 0.1 B^m_{t+1}$$

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 has not been done in past applications of the projection procedure because catches are small relative to the biomass and are comprised of mature fish, the majority of which die after spawning. In fact the catch between 1982 and 1989 has averaged only 4.3% of the estimated mature biomass. 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 3.

In order to evaluate the procedure, equations (2) to (6) were incorporated into a Monte Carlo simulation, described in detail in the Appendix. The simulations consisted 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 in implementing the current harvest rate procedure for capelin in NAFO Div. 3L. This provided realisations of the TAC (from the application of the harvest rate procedure) as a proportion of the *true* mature biomass. In the realisation of the *true* system, survival rates were assumed to vary in a time dependent (rather than

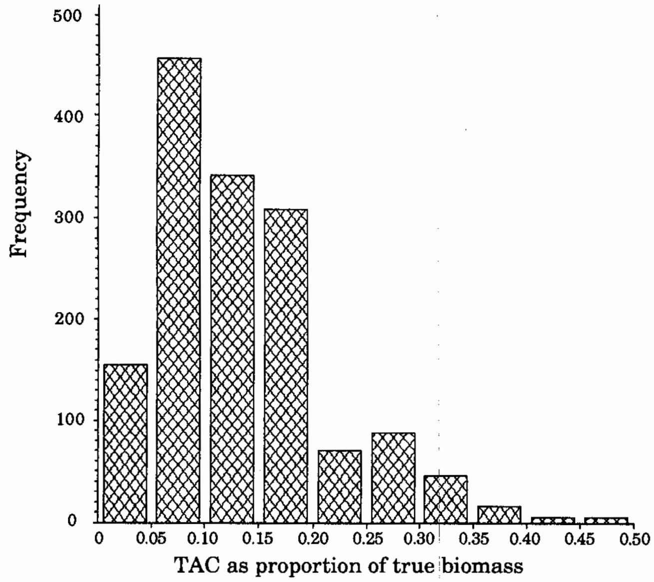

Fig. 2. The simulated TAC as a proportion of the true mature biomass using the 10% rule and assuming a survey sample error CV of 30%. Number of simulations = 3,000.

Table 3. 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		21.20	28.40	31.10	32.40
New	14.18	28.25	36.00	34.31	36.98
Proportion mature					
Old[1]	0.00	0.47	0.87	0.93	1.00
New	0.05	0.63	0.97	0.99	1.00
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).

age dependent) manner, thus year specific pairs of s_1 and s_2 estimated from the survey and catch data were randomly re-sampled to simulate this variability. Of course, the variability in year-specific survival rates also reflects measurement error. Thus the simulation procedure would tend to incorporate too much uncertainty in the survival rates, and thus be conservative. Data for ages 3 and 4 in 1984 and age 3 in 1985 were omitted in the calculation of survival rates because inclusion would result in an estimate of a survival rate greater than 1. This tends to give a negative bias to the simulated survival rates because years with high survival rates are more likely to be excluded. Again, this is conservative.

The results are presented in Fig. 2 as a frequency distribution for the simulated TAC as a proportion of the true mature biomass, assuming an acoustic survey sample error CV of 30% and no bias. Cumulative probabilities of a TAC that is less than or equal to a specific proportion of mature biomass are plotted in Fig. 3 for the case illustrated in Fig. 2 (a) as well as for a sample error CV of 40% on the acoustic estimate (b) and for a CV of 30% and a positive bias of 30% (c).

It is apparent that the existing procedure (under the assumption of an unbiased acoustic survey estimate with a sample error CV of 30%) performs reasonably well in achieving the objective with about 50% of the trials below 12% of the mature biomass and 50% above. There is only a small probability (< 0.1) that a TAC would be recommended that was actually 30% or more of the mature biomass.

This result is somewhat surprising, considering that we now believe the survival rates, particularly for immature fish, to be quite different from the values used up until now (Table 3). 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 3). These two factors compensate for the higher survival rate for immatures used in the projections.

An increase in the CV of the acoustic estimate from 30% to 40% moved the cumulative probability curve to the right as expected, but only by a small amount (Fig. 3). A 30% positive bias in the acoustic estimate had a greater effect on the cumulative probability curve with the median of the distribution of TAC as a proportion of true biomass changing from 0.12 to 0.16. The simulation thus suggests that, under the assumptions made, the performance of the 10% rule has been relatively insensitive to sample error in the acoustic survey and that a positive bias in the acoustic estimate would have to be greater than 30% in order to result in less than an 80% probability that the TAC has remained below 30% of the true biomass.

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, 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 sample error and bias in the acoustic estimate, and even with a positive bias of 30%, there appears to be more than an 80% chance of choosing a TAC which will be less than 30% of the true biomass (curve c, Fig. 3).

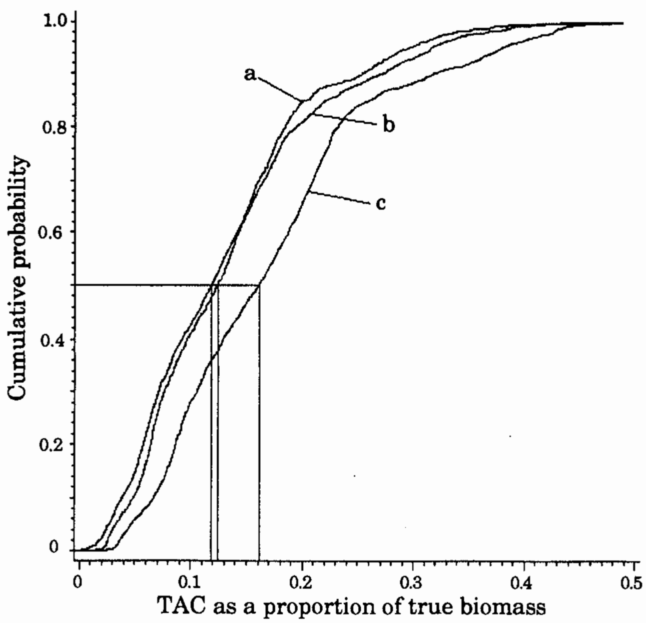

Fig. 3. The cumulative probability of the 10% rule giving rise to a TAC that is less than or equal to a specified proportion of the mature biomass for cases with different variance and bias associated with the acoustic estimate: a- CV=30%, bias=0%; b- CV=40%, bias=0%; c- CV=30%, bias=+30%.

The estimate of survival rate for the spawners has a large standard error which, under the assumptions of the model, must be attributed to considerable variability in survival among years or ages or both. In reality it could equally be a result of error in the estimates of population size, proportion mature and catch at age. 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 North West Atlantic system and reinforces the need to maintain an appropriately small fishing mortality.

There is some commonality in the capelin fishery in NAFO Div. 3L and the capelin fishery in Div. 2J3K, as well as those fisheries in the Barents Sea and off Iceland. In each case an annual acoustic estimate is made from which projections are carried out to serve as a basis for setting TAC's. All four stocks are similar in that the mature spawning biomass is composed of three-, four-, and five-year-olds and survival rate after spawning is low (assumed to be zero in Barents Sea and Iceland and estimated to be below 0.25 for NAFO Div. 2J3KL (Carscadden et al. 1985)), and an average of 0.23 in this study. The average annual survival rate estimated for immature capelin in the Barents Sea is 0.38 (Bjarte Bogstad, Marine Research Institute, Bergen, Norway, pers. comm.) compared to an average value of 0.35 estimated in this study. These values are substantially lower than the assumed value currently used in assessments in the Northwest Atlantic (0.74). It would be informative to have estimates of the average survival rate of immatures from NAFO Div. 2J3K and Iceland for comparison with the values from Div. 3L and the Barents Sea.

The Barents Sea capelin fishery is managed on the basis of a constant escapement of 500,000 tons of spawners to 31 March (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 survival rates and the assumption that fish exceeding a specified length are mature and will spawn. 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 (Vilhjalmsson 1983). Spawning takes place in March and the first half of April in shallow 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.

The basic similarities between the NAFO Div. 3L capelin fishery and the fisheries described above suggest that it is likely that the method used here to estimate survival rates, or some variant of it, would be appropriate in the other fisheries, and that assessment procedures could be developed for each of the four systems which are basically similar. Projections now carried out use only the current biomass estimate and ignore the serial correlation in estimates due to the persistence of year-classes between surveys. A Bayesian-like estimation model of the kind described by Butterworth and Bergh

(1993), which accounts for the time-series nature of the problem may be an appropriate approach and should be explored. A comparison of parameter estimates among systems and a consideration of the value of the alternative management goals (i.e., constant escapement in the Barents Sea and off Iceland versus constant proportion in the Northwest Atlantic) could prove extremely useful in the development of assessment procedures and the quantification of risk associated with these procedures.

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References

BUTTERWORTH, D. S. AND M. BERGH. 1993. The development of a management procedure for the South African anchovy resource. p. 83–99. *In* S. J. Smith, J. J. Hunt and D. Rivard [ed.] Risk evaluation and biological reference points for fisheries management. Can. Spec. Publ. Fish. Aquat. Sci. 120.

CARSCADDEN, J. E. 1983. Population dynamics and factors affecting the abundance of capelin *(Mallotus villosus)* in the Northwest Atlantic. p. 789–811. *In* G. D. Sharp and J. Csirke [ed.] Proceedings of the Expert Consultation to Examine Changes in Abundance and Species Composition of Neritic Fish Resources, San Jose, Costa Rica, 18–29 April 1983. FAO Fisheries Report 291(3).

CARSCADDEN, J. E., G. H. WINTERS AND D. S. MILLER. 1981. Assessment of the Division 3L capelin stock. NAFO SCR 81/vi/25, Ser. No. N304, 14 p.

CARSCADDEN, J. E., G. H. WINTERS, AND D. S. MILLER. 1985. An indirect method of estimating maturation rates of cohorts of capelin *(Mallotus villosus)*. J. Northw. Atl. Fish. Sci. 6: 135–140.

HAMRE, J., AND S. TJELMELAND. 1982. Sustainable yield estimates of the Barents Sea capelin stock. ICES CM 1982/H:45.

LILLY, G. R. 1991. Interannual variability in predation by cod *(Gadus morhua)* on capelin *(Mallotus villosus)* and other prey off southern Labrador and northeastern Newfoundland. ICES Mar. Sci. Symp. 193: 133–146.

MILLER, D. S. 1984. Capelin acoustic surveys in NAFO Divisions 3L and 3NO, 1983. NAFO SCR 84/56, Ser. No. N843, 7 p.

MILLER, D. S. 1985. The use of hydroacoustic surveys to estimate capelin biomass in NAFO Divisions 2J + 3KLNO. NAFO SCR 85/105, Ser. No. N1081, 18 p.

MILLER, D. S. 1986. Estimates of capelin *(Mallotus villosus)* biomass from hydroacoustic surveys in Divisions 3LNO in 1985 and 1986. NAFO SCR 86/79, Ser. No. N1200, 11 p.

MILLER, D. S. AND J. E. CARSCADDEN. 1983. Capelin acoustic surveys in NAFO Divisions 2J3K and 3LNO, 1982. NAFO SCR 83/50, Ser. No. N708, 10 p.

MILLER, D. S. AND J. E. CARSCADDEN. 1984. Capelin acoustic biomass survey for NAFO Div. 2J3K, October 1983. CAFSAC Res. Doc. 84/79, 10 p.

MILLER, D. S. AND J. E. CARSCADDEN. 1987. Capelin *(Mallotus villosus)* biomass estimates from hydroacoustic surveys in NAFO Div. 3NO (1986) and Div. 3L (1987). NAFO SCR 87/69, Ser. No. N1358, 8 p.

MILLER, D. S. AND J. E. CARSCADDEN. 1988. Capelin *(Mallotus villosus)* biomass estimates from hydroacoustic surveys in NAFO Div. 3L and 3N. NAFO SCR 87/69, Ser. No. N1358, 8 p.

MILLER, D. S. AND J. E. CARSCADDEN. 1989. Biomass estimates from two hydroacoustic surveys from capelin *(Mallotus villosus)* in NAFO Divisions 3L and 3N and observations of the Soviet fishery for capelin in Division 3NO. NAFO SCR 89/52, Ser. No. N1631, 15 p.

MILLER, D. S., B. S. NAKASHIMA, AND J. E. CARSCADDEN. 1982. Capelin acoustic surveys in NAFO Divisions 2J+3K, 3LNO, and 3L, 1981-82. NAFO SCR 82/54, Ser. No. N547, 12 p.

NAKASHIMA, B. S. AND R. W. HARNUM. 1984. The 1983 inshore capelin fishery in Div. 3L. NAFO SCR 84/vi/54, Ser. No. 841, 7 p.

NAKASHIMA, B. S. AND R. W. HARNUM. 1985. The 1984 inshore capelin fishery in Div. 3L. NAFO SCR 85/76, Ser. No. 1034, 11 p.

NAKASHIMA, B. S. AND R. W. HARNUM. 1986. The 1985 inshore capelin fishery in Div. 3L. NAFO SCR 86/15, Ser. No. 1127, 12 p.

NAKASHIMA, B. S. AND R. W. HARNUM. 1987. The 1986 inshore capelin fishery in Div. 3L. NAFO SCR 87/50, Ser. No. 1339, 11 p.

NAKASHIMA, B. S. AND R. W. HARNUM. 1988. The inshore capelin fishery in Div. 3L in 1987. NAFO SCR 88/09, Ser. No. 1445, 16 p.

NAKASHIMA, B. S. AND R. W. HARNUM. 1989. The inshore capelin fishery in Div. 3L in 1988. NAFO SCR 89/43, Ser. No. 1620, 12 p.

NAKASHIMA, B. S. AND R. W. HARNUM. 1990. The inshore capelin fishery in Div. 3L in 1989. NAFO SCR 90/60, Ser. No. 1781, 14 p.

RICKER, W. E. 1975. Computation and interpretation of biological statistics of fish populations. Bull. Fish. Res. Board. Can. 191: 382 p.

VILHJALMSSON, H. 1983. On the biology and changes in exploitation and abundance of the Icelandic Capelin. p. 537–553. *In* G. D. Sharp and J. Csirke [eds.]. Proceedings of the expert consultation to examine changes in abundance and species composition of neritic fish resources, San Jose, Costa Rica, 18–29 April 1983. FAO Fisheries Report 291(2).

WINTERS, G. H. AND J. E. CARSCADDEN. 1978. Review of capelin ecology and estimation of surplus yield from predator dynamics. ICNAF Res. Bull. 13: 21–30.

Appendix

Monte Carlo Simulations for Evaluating the Existing Procedure Used to Manage Capelin in NAFO Div. 3L

Two sets of parallel computations are repeated 3000 times, 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 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 used the new method described in the main text to estimate the survival rates for each pair of adjacent years from the survey data. In our simulations, we randomly resample the pairs of year-specific estimates of s_1 and s_2 estimated from the survey and catch data.

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. This is only true because the actual catch averaged only 4.3% of the mature biomass estimated by acoustics (i.e., the catch was a trivial proportion of the true biomass). If the exploitation rate had varied considerably so that the catch sometimes accounted for a large portion of the biomass then we would have had to specify a distribution of the biomass to be projected ahead one year. This distribution would have to account for the variability due to the initial biomass level and catch level.

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. Therefore, our simulations include an extra component of variability and are conservative in this respect.

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

Simulation Procedure

Realisation 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 true biomass, the mean weight at age over all the surveys, and the mean proportion by age over all the surveys.

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

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.

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

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.

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

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 pairs of values estimated from adjacent years of historic data.

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

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

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

Realisation 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.

$$\widehat{B}_t \sim \mathrm{N}\left(B, \sigma^2\right)$$

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 from 1982 to 1989 (same year selected for both vectors to account for possible covariance).

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

3. The perceived catch is assumed to be zero, as done in practice.

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

4. The perceived numbers at age in year $t+1$ is simulated using literature values for survival rates ("old" values in Table 3) 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.

$$N_{a+1,t+1} = \widehat{N}_{a,t}\left(1-\widehat{p}_{a,t}\right)\widetilde{s}_1 + \left(\widehat{N}_{a,t}\widehat{p}_{a,t} - C_{a,t}\right)\widetilde{s}_2$$

5. The perceived biomass in year $t+1$ is calculated using assumed and literature values for weight-at-age in the catch and proportion mature (see "old" values in Table 3).

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

6. Not applicable.

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

$$Q_{t+1} = 0.1 B^{m}_{t+1}$$

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

$$E^{*}_{t+1} = \frac{Q_{t+1}}{B^{m^*}_{t+1}}$$