Not to be cited without prior reference to the authors

International Council for the Exploration of the Sea

ICES C.M. 1991/D:30
Statistics Cttee
ref. Sess. S

A Practical Approach to Risk and Cost Analysis of Fishery Management Options, with Application to Northern Cod

John M. Hoenig
Department of Fisheries and Oceans, P.O. Box 5667, St. John's, NF A1C 5X1, Canada

Victor R. Restrepo
Cooperative Institute for Marine and Atmospheric Studies, University of Miami
4600 Rickenbacker Causeway, Miami, FL 33149, USA

James W. Baird
Department of Fisheries and Oceans, P.O. Box 5667, St. John's, NF A1C 5X1, Canada

Abstract.-Uncertainty in the results of sequential population analysis and associated derived statistics can be quantified by Monte Carlo simulation. Histograms can be prepared to describe (personal) probability densities for the quota necessary to obtain a given fishing mortality and for the fishing mortality that would result from a given quota. We show that such histograms can be used to describe the risk of not meeting a given management goal as a function of the quota selected. We also show how to compute the expected cost, in terms of potential yield foregone, associated with picking a conservative quota. This enables one to balance risks and costs or to allow risk to vary within proscribed limits while keeping the catch quota stable. Risks and costs were evaluated by Monte Carlo simulation for two options for managing the northern cod stock: attempting to keep the fishing mortality constant, and attempting to reduce the fishing mortality so as to move part way to the $F_{0.1}$ reference fishing mortality.

In recent years, there has been increasing interest in quantifying the uncertainty associated with stock assessments and accounting for this uncertainty in the development of management plans. Monte Carlo simulation can be used to quantify the uncertainty in parameter estimates obtained from a sequential population analysis (SPA) (Pope and Gray 1983; Rivard 1983; Bergh and Butterworth 1987; Restrepo et al. companion paper). For example, Restrepo et al. (1991) used Monte Carlo simulation to show how the uncertainty in SPA results carries over into estimates of spawning potential ratio, target fishing mortality, total allowable catch (TAC) and other quantities of interest. Their approach is general, and can be used to quantify uncertainty in a variety of situations. The approach consists of four steps: (1) assemble the required inputs for the assessment (catch at age data, abundance indices, value of natural mortality rate, etc.), (2) measure or otherwise specify the uncertainty in each of the inputs - these should be in the form of probability density functions, (3) do a large number of times (say, 1000) the following: (a) generate a pseudo-data set by randomly drawing numbers from the uncertainty distributions specified for the inputs to the assessment model, (b) conduct the assessment on the pseudo-data set, and (c) store the results of the analysis, and (4) summarize the results from all the pseudo-data sets, e.g., as histograms.

An example of the approach of Restrepo et al. (1991) is the determination of the uncertainty in the catch in the current year which would maintain the fishing mortality at the level of the previous year. A point estimate might be computed as follows. A sequential population analysis of some sort is used to estimate the population size at the end of the year previous to the current year and the fishing mortality during that year. It is assumed that recruitment in the current year is equal to the long-term average, hence the estimated population size in the current year can be computed. Finally, the harvest which causes the population to experience the same fishing mortality rate as that estimated for the previous year can be computed. To quantify the uncertainty in this result, the whole procedure can be repeated 1000 times (say), each time perturbing each input to the sequential population analysis by a random amount (as per the specified uncertainty distributions). This results in 1000 sets of estimates of population size, fishing mortality, and natural mortality rate which, together with a set of randomly drawn values for recruitment, can be used to generate 1000 estimates of the total allowable catch which will cause the fishing mortality to remain unchanged. These values can be organized into a histogram such as in Figure 1. (This histogram pertains to a slightly different situation, discussed later, where the projection is carried forward another year.) From the histogram, it appears that the most likely (modal) value for achieving the management goal is a quota of 210,000 mt, but the actual value might be anywhere from approximately 160,000 to 250,000 mt.

In this paper, we consider some tools for selecting the total allowable catch in light of the uncertainty concerning the status of the stock. In particular, we look at the risk (of not meeting a management goal) associated with the selection of a given TAC and the expected cost in terms of foregone yield associated with the TAC. The risk can be computed for a variety of biological reference points such as $F_{0.1}$, F_{max}, $F_{50\%}$, and constant biomass. We also look at the probability distribution of outcomes (e.g. fishing mortality, spawning potential ratio, relative change in biomass) as functions of the TAC. We assume, as a starting point, that one can conduct a Monte Carlo simulation of the uncertainty in certain quantities of interest - such as the catch which will meet a chosen objective. The fishery for cod off eastern Newfoundland and southeastern Labrador (NAFO Divisions 2J + 3KL) is considered as an example.

Estimating risks

Suppose that a Monte Carlo simulation study of the uncertainty in the TAC which will result in the status quo fishing mortality results in a histogram as in Figure 1. For now, we will not concern ourselves with the details of the simulation - although we discuss this at length when we consider the example.

As noted earlier, it can be seen from the histogram that the most likely value for the catch that achieves $F_{status\ quo}$ appears to be around 207,500 mt, i.e., in the middle of the histogram. If the TAC is set at 207,500 mt then it is believed there is roughly a 50% chance of the fishing mortality increasing and a 50% chance of it decreasing. Suppose one is risk averse and chooses a TAC of 197,500 mt instead. What would be the perceived risk or probability of exceeding the target fishing mortality under this quota?

The risk of exceeding the target fishing mortality ($F_{status\ quo}$) is given by the area under the histogram to the left of the TAC chosen (Figure 2). Thus,

$$\text{Prob}(F_{achieved} > F_{target}) = \sum_{i=1}^{t} p(i) \qquad (1)$$

where p(i) is the probability mass (relative frequency of outcomes) associated with the ith bar of the histogram and t is the number of bars to the left of the chosen TAC. This probability can be computed for any value of the TAC. In practice, the risk would be computed by sorting in ascending order the 1000 catch values obtained from the simulation, and then plotting the cumulative count of outcomes less than any value of the TAC versus that value of the TAC (Figure 3). One can also derive a family of risk curves. For example, separate curves could be generated for the risk of exceeding $F_{status\ quo}$ by each of several amounts. For each of the 1000 simulation runs, one computes the value of $F_{status\ quo}$ and the catch that causes current F to exceed the status quo by the specified amount. The resulting histogram of catches is summed, as in equation (1), to obtain the risk curve.

Estimating cost as yield foregone

If we choose a conservative value for the TAC in order to ensure that risk of exceeding the target fishing mortality will be small, then we are probably passing up some of the yield we could have had while still meeting our obective (e.g., see Bergh and Butterworth 1987). There are many possible ways to describe this cost in economic and biological terms. Here, we express the cost as the expected value of the potential yield foregone, which we define as follows. For any total allowable catch, x, let

$$\delta(i) = \begin{cases} 0, \text{ yield associated with ith interval of histogram} \leq x \\ 1, \text{ yield associated with ith interval of histogram} > x \end{cases}$$

Then,

$$E(\text{potential yield foregone}) = \sum_{i=1}^{\infty} p(i)\,\delta(i)\,(y(i) - x)$$

where $E(\cdot)$ denotes the expectation operator, the summation is over all intervals of the histogram (Figure 2), and y(i) is the yield associated with the ith interval of the histogram.

The expected potential yield foregone can be plotted against the corresponding TAC. Here, y(i) - x is a possible value of the yield foregone provided it is non-negative; negative values are eliminated by the indicator function $\delta(i)$; p(i) is the probability that the yield foregone is equal to $\delta(i)\ (y(i) - x)$. In practice, the expected yield foregone would be computed by setting all simulated catches which are less than the TAC equal to zero and then computing the mean of the 1000 values. The mean can then be plotted versus the TAC for various choices of TAC (Figure 3).

It should be noted that this cost relates to the upcoming year only. One can also calculate the fate of the biomass left in the water after the upcoming year. That is, one can ask whether this biomass left in the water will increase or decrease over the year. In general, for a quantity of biomass left in the water, the relative change in its biomass over the year is given by

$$\text{relative change in unfished biomass} = e^{-M} \frac{\sum_a P_a W_{a+1}}{\sum_a P_a W_a} - 1 \ .$$

Here, P_a is the proportion of the stock that is age a; W_a, the average weight of animals at age a; M, the instantaneous natural mortality rate; and the summations are over all age groups of interest.

Tradeoffs in decision making

The manager can now choose how to trade off potential yield and risk. For example, consider the option of a TAC of 195,000 mt as a means of maintaining the fishing mortality at a constant level. From Figure 3a, the perceived risk of the fishing mortality exceeding the target mortality is about 13%. The expected value of the potential yield foregone for this TAC is approximately 13,000 mt. If, instead, a TAC of 200,000 mt is selected, the risk of exceeding the target fishing mortality becomes 25% and the expected value of the potential yield foregone becomes 9,000 mt. Thus, an increase in the TAC of 5,000 mt would almost double the risk of increasing the fishing mortality and would reduce the expected potential yield foregone by about one third (from 13,000 mt to 9,000 mt).

Another way to present the results of the SPA simulations is to plot percentiles of output distributions versus the TAC selected. For example, for each SPA run on simulated data, one can take the estimated population size and iteratively seek the fishing mortalities that will result in each of several TACs. Then, for any value of TAC one can compute the median and 2.5th and 97.5th percentiles of the distribution of fishing mortalities. Since instantaneous fishing mortality may not be meaningful to some interested parties (such as fishing industry groups), one may wish to look at the distribution of changes in population size associated with particular choices of the TAC (Figure 4).

Thus, we have two approaches which we can summarize as follows. The first approach is to select a goal or objective (such as $F_{0.1}$) and then quantify the chances of achieving that goal as a function of the TAC or effort restriction selected. The second is to quantify the consequences of choosing different quotas or effort restrictions. Both approaches may be useful to managers. A manager might first ask how a specific management objective like $F_{0.1}$ can be met. A graph similar to Figure 3a makes it clear that there are few absolutes and that risks and costs must be balanced or traded off. The manager might also want to know the consequences of picking particular quotas or effort restrictions. For example, for economic or political reasons, it may be difficult to stick with a management policy if a large quota reduction is called for. In this case, the consequences to the stock of maintaining the status quo or reducing the quota by various intermediate amounts may be of interest. A graph similar to Figure 4 may be helpful for this.

Managers and industry have a strong interest in maintaining stability in a fishery. Conflicts can easily arise when annual assessments provide only point estimates of the quota required to achieve a specified goal. This is because random error in the estimates implies that annual adjustments in the quota will be proscribed even when no changes are in fact necessary.

Instead of letting the quota "float" from year to year, one can stabilize the quota and let the risks float from year to year. Thus, as long as the risks remain within certain limits, there is no need to adjust the quota. (Here, the risks can include potential stock collapse as well as foregone potential yield.)

Example: the northern cod fishery

Assessment and simulation procedures

We studied the cod fishery in NAFO Divisions 2J+3KL and based our simulations on the data and methods described in Baird et al. (1990). Additional data, described below, were obtained from the files at the Northwest Atlantic Fisheries Centre, St. John's, Newfoundland. The simulations reflect our personal beliefs about the sources and nature of the uncertainties in the assessment. The results have not been reviewed by the Canadian Atlantic Fisheries Scientific Advisory Committee and do not have official status. The selection of management objectives for simulation was made for illustrative purposes.

Only a brief description of the assessment procedure is given here since the details are not important for understanding the use of the simulation method. The method of calibrating or tuning the SPA (ADAPT) is described in Gavaris (1988). The catch at age data for ages 3 to 13 for each year from 1978 to 1989 were taken from Table 7 of Baird et al. (1990). Coefficients of variation of these catch estimates were computed using the method of Gavaris and Gavaris (1983); these coefficients were available in the files. The coefficients of variation ranged from 2 to 17%. Age- and year-specific catch rates from research vessel surveys for the period 1978 to 1989 and associated coefficients of variation (Baird et al. 1990 Table 23) were used to tune the sequential population analysis. The coefficients of variation were less than or equal to 30 % in 87 % of the cases. Age- and year-specific catch rates from the offshore commercial trawl fishery for ages 5 to 8 for the period 1983 to 1989 were standardized by the method of Gavaris (1980) for use as an index of abundance for tuning the sequential population analysis (Baird et al. 1990 Table 39). We developed estimates of the coefficients of variation for the commercial catch rate indices. In all cases these were close to 10%. Natural mortality for this stock is believed to be around 0.2 yr^{-1}.

In the simulations, the point estimates of the inputs were replaced by random variables with the same expected values and coefficients of variation as specified above. Catch at age values were generated as normal random variables while the research vessel and the commercial catch rates were generated as lognormal random variables. The value of the natural mortality rate was generated as a uniform random number between 0.15 and 0.25 yr^{-1}.

The specific formulation of the problem in the ADAPT computer program was as follows. The research vessel indices were obtained in the fall and were assumed to represent population size at the end of November. The commercial catch rate indices were assumed to represent population size at the beginning of the year. The fishing mortality F for the oldest age group (13) was calculated as 50% of the mean F for ages 7 to 9 weighted by population number at age.

The objective function to be minimized was

$$\sum_{age}\sum_{year}\left\{obs(lnRV_{i,t}) - pred(lnRV_{i,t})\right\}^2 + \sum_{age}\sum_{year}\left\{obs(lnC/E_{i,t}) - pred(lnC/E_{i,t})\right\}^2$$

where obs(·) and pred(·) refer to observed and predicted quantities, respectively; $lnRV_{i,t}$ refers to the logarithm of research vessel results (observed or predicted) for age i and year t; and similarly $lnC/E_{i,t}$ refers to the logarithm of the commercial catch per unit effort results for age i and year t. The predicted quantities are obtained by taking the logarithm of the product of the estimated population size and the appropriate estimate of age-specific catchability.

Projections for 1990 and 1991 were made using the same procedures used in the most recent annual assessment (Baird et al. 1990). Population and fishing mortality projections for 1990 were made by randomly selecting a value for recruitment from the historical set of estimated recruitments and assuming that 1) the total catch in 1990 is 200,000 mt (the fixed quota in place when the assessment was done in 1990), and 2) the partial recruitment (selectivity) vector for 1990 is like that estimated for 1989.

Catch projections for 1991 were made in two ways. In one, we set the fishing mortality for 1991 equal to that for 1990 and solved for the catch. In the other, we set the fishing mortality for 1991 equal to

$$\min\{(\hat{F}_{0.1} + \hat{F}_{1990})/2\ ,\ 2\hat{F}_{0.1}\}$$

where the ^ symbol indicates estimated quantities. This is the 50% rule formulated by the Canadian Atlantic Fisheries Scientific Advisory Committee (Canada Department of Fisheries and Oceans 1991) for a gradual movement towards $F_{0.1}$.

We also computed the fate of yield foregone and the distribution of population changes for various choices of the TAC.

Results

We generated personal risk curves for two fishing mortality objectives for 1991 (Figures 3a and 3b). These curves can be put in perspective by noting that the Canadian total allowable catch for 1990 was 199,262 mt while the total catch (Canadian plus international) may have been as high as 235,000 mt. To have a 50% risk of increasing the fishing mortality in 1991 over the 1990 level, one would set the TAC at 208,000 mt; to have a 50% chance of exceeding the fishing mortality associated with the 50% rule would entail setting the TAC at 159,000 mt. It appears that a cut in the total allowable catch would be necessary to have a reasonable chance of preventing the fishing mortality from exceeding the 1990 value. Substantial cuts in the harvest would be required to ensure a high probability of meeting the 50% rule.

For values of the TAC for which the risk is less than 25%, the expected value of the yield foregone is approximately a linear function of the TAC (Figures 3a and 3b). That is, for every change in the TAC of 1000 mt, the expected yield foregone changes by approximately 1000 mt. The fate of biomass left in the water is to increase by about 12% in a year (mean of 1000 simulations = median = 12.7%, 95% confidence band based on 2.5th and 97.5th percentiles is (7.0%,18.3%)). The relative change in biomass of fish aged 3 and above is also a linear function of the TAC (Figure 4). Note, however, that the relative change in biomass cannot be determined very precisely as evidenced by the wide confidence bands.

Discussion

We presented results of catch projections for two scenarios. Often, one might like to examine a larger number of options. For example, if current fishing mortality exceeds F_{max} then one might like to explore various ways to reduce fishing mortality in gradual steps as well as exploring the consequences of various types of "status quo" options. The simulation approach is versatile enough to handle fixed catch, fishing mortality, and biomass objectives, as well as objectives involving relative change. Thus, one could have any of the following objectives for fishing mortality: achieve $F = 0.40\ yr^{-1}$, achieve $F = F_{0.1}$, reduce F by 40%, adjust F so that biomass changes a given fixed or relative amount.

In some fisheries, catch and population projections may be highly dependent on the assumptions made about recruitment. When this is the case, it may be helpful to quantify the uncertainty for various segments of the population separately. For example, we computed the distribution of relative change in age 3+ biomass (from 1989 to 1991) for various choices of the TAC. The wide confidence bands (Figure 4) reflect the large uncertainty in future recruitment. We could have quantified the relative change in the biomass of age 5+ fish. From the ADAPT run based on 1989 data we already have an estimate of age 3 biomass in 1989. This biomass can be projected forward to age 5 in 1991; hence, we do not need to generate a random value for recruitment. The uncertainty in the biomass of age 5+ fish should thus be smaller than the uncertainty in age 3+ biomass. Unfortunately, the latter quantity may be of greater interest.

The simulation approach can be used with other assessment models. For example, one could use Monte Carlo simulation to quantify the effects of uncertainty in input data, assumptions, and model formulation on the outputs from the CAGEAN (Deriso et al. 1985) or stock synthesis (Methot 1990) methods.

It appears feasible to quantify risks and costs for a wide variety of managment options when the assessments are accomplished by any of a variety of analytical models. It remains to determine what risks (and costs) should be quantified, how much is acceptable, and over what time frame. For example, we don't know how to quantify the risk of stock collapse due to recruitment failure but we might wish to quantify the risk of the spawning biomass falling below 20% of the virgin level in three years out of five. If we assume that this represents a dangerous situation (see Beddington and Cooke 1983; Brown 1990; and Goodyear 1990 for thoughtful discussions), then the risk should be kept low. On the other hand, if we consider the risk of exceeding the economically optimal fishing mortality (however defined), then we might like the risk to be close to 50%, i.e., be as likely to be above the optimum as below it. (Of course, we should consider the relative costs of overshooting and undershooting the target mortality). If we are not close to the economic optimum fishing mortality, then one must also devise a way to determine what is the best trajectory to take for arriving at the long-term goal. It is beyond the scope of this paper to address what are appropriate goals, biological reference points, and trajectories.

Finally, it should be remembered that, for any stock assessment, the results of a Monte Carlo simulation study are necessarily conditional on what is assumed about the sources of uncertainty. Since decisions about at least some of the sources of uncertainty are subjective, the results are personal views of uncertainty, risk, cost, etc. If three scientists, say, assess a given stock, then they can generate three separate sets of simulation outputs. The combination of their simulations provides a picture of their collective uncertainty about the assessment results. Alternatively, the scientists can agree that a minimal estimate of the uncertainty is provided by the scientist whose results are the least uncertain.

Acknowledgments

Partial support for this study was provided by the Canadian Government's Atlantic Fisheries Adjustment Program (Northern Cod Science Program) and by the Cooperative Institute for Marine and Atmospheric Studies at the University of Miami through the U.S. National Oceanic and Atmospheric Administration Cooperative Agreement NA85-WCH-06134. We thank Nicholas Payton for programming assistance and Peter Shelton, Al Pinhorn and Donald Parsons for helpful comments.

Citations

Baird, J.W., C.A. Bishop, and W.B. Brodie. 1990. The assessment of the cod stock in NAFO Divisions 2J, 3K and 3L. CAFSAC Res. Doc. 90/18.

Beddington, J.R. and J.G. Cooke. 1983. The potential yield of fish stocks. FAO Fish. Tech. Pap. 242. 50p.

Bergh, M.O. and D.S. Butterworth. 1987. Towards rational harvesting of the South African anchovy considering survey imprecision and recruitment variability. S. Afr. J. Mar. Sci. 5:937-951.

Brown, B. 1990. Use of spawning stock size considerations in providing fishery management advice in the North Atlantic - a brief review. ICCAT Coll. Vol. Sci. Pap. 32(2):498-506. (SCRS/89/102)

Canada Department of Fisheries and Oceans. 1991. 1991 Atlantic groundfish management plan. Ottawa. 114 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.

Gavaris, S. 1980. Use of a multiplicative model to estimate catch rate and effort from commercial data. Can. J. Fish. Aquat. Sci. 37:2272-2275.

Gavaris, S. 1988. An adaptive framework for the estimation of population size. CAFSAC Res. Doc. 88/29.

Gavaris, S. and C.A. Gavaris. 1983. Estimation of catch at age and its variance for groundfish stocks in the Newfoundland region. Can. Spec. Pub. Fish. Aquat. Sci. 66:178-182.

Goodyear, C.P. 1990. Spawning stock biomass per recruit: the biological basis for a fisheries management tool. ICCAT Coll. Vol. Sci. Pap. 32(2):487-497. (SCRS/89/82)

Methot, R.D. 1990. Synthesis model: an adaptable framework for analysis of diverse stock assessment data. Int. Nor. Pac. Fish. Comm. Bull. 50:259-277.

Pope, J.G. and D. Gray. 1983. An investigation of the relationship between the precision of assessment data and the precision of total allowable catches. Can. Spec. Pub. Fish. Aquat. Sci. 66:151-158.

Restrepo, V.R., J.W. Baird, C.A. Bishop and J.M. Hoenig. 1990. Quantifying uncertainty in ADAPT (VPA) outputs using simulation - an example based on the assessment of cod in Divisions 2J+3KL. Presented at NAFO Special Session on Uncertainty, Halifax, 5-7 September, 1990. NAFO SCR Doc. 90/103, Ser. No. N1838.

Restrepo, V.R., J.E. Powers, S.C. Turner, and J.M. Hoenig. 1991. Using Simulation to Quantify Uncertainty in Sequential Population Analysis and Derived Statistics, with Application to the North Atlantic Swordfish Fishery. ICES C.M. 1991/D:31.

Rivard, D. 1983. Effects of systematic, analytical, and sampling errors on catch estimates: a sensitivity analysis. Can. Spec. Pub. Fish. Aquat. Sci. 66:114-129.

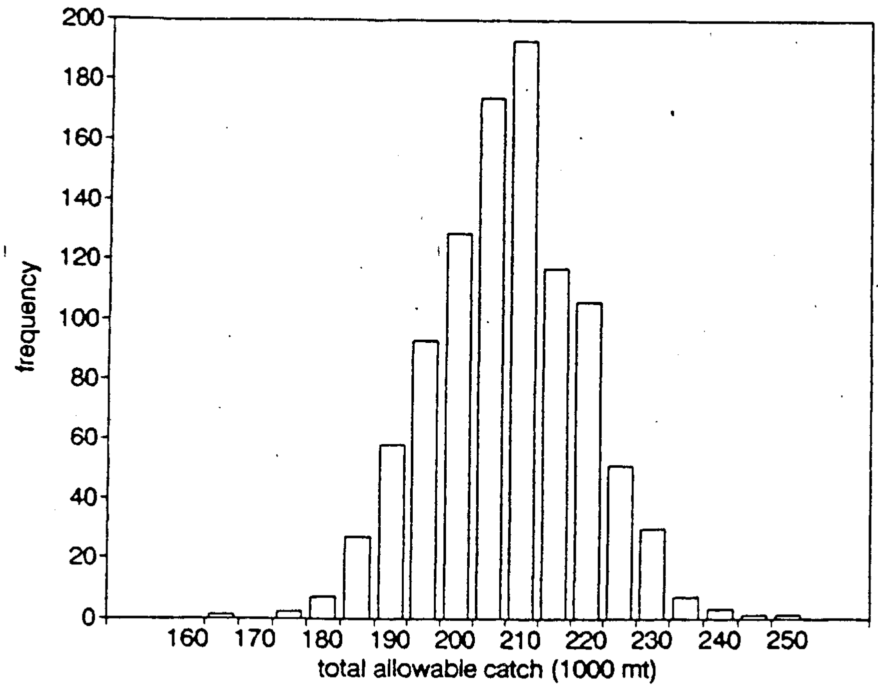

Figure 1
Frequency distribution for estimates of total allowable catch necessary to have fishing mortality in 1991 equal the fishing mortality in 1990. Estimates were obtained from 1000 simulated data sets analyzed by the ADAPT approach.

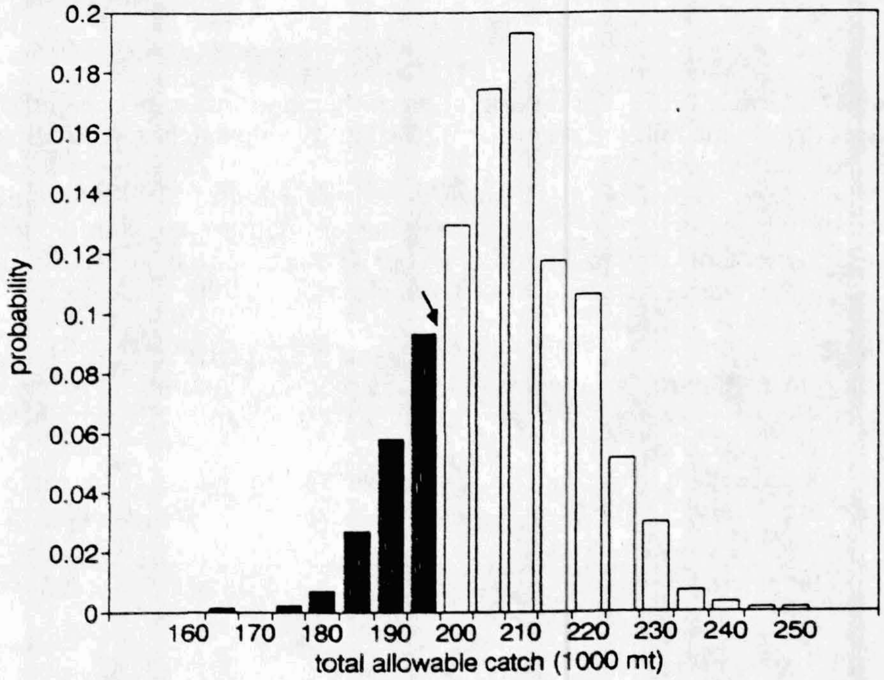

Figure 2
Same as Figure 1 except that ordinate is expressed as probability mass (frequency ÷ 1000). If a TAC of 197,500 mt is selected (arrow), the probability that the fishing mortality will exceed the status quo is estimated by the sum of the histogram bar heights to the left of 197,500 (i.e. the shaded portion).

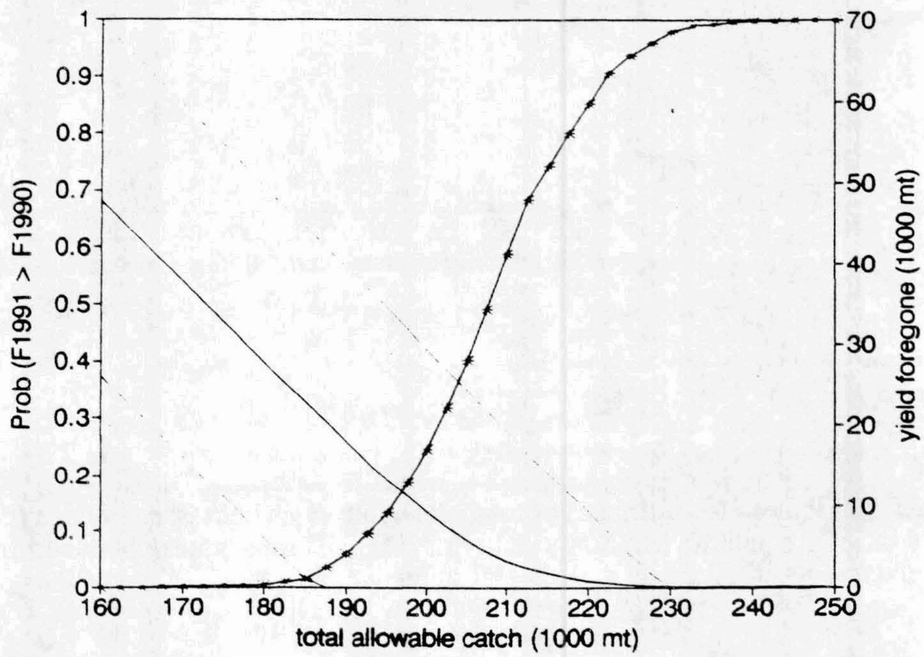

Figure 3a
Probability of exceeding the current (1990) fishing mortality and expected value of the potential yield foregone (with 95% confidence band) as functions of the TAC selected for 1991.

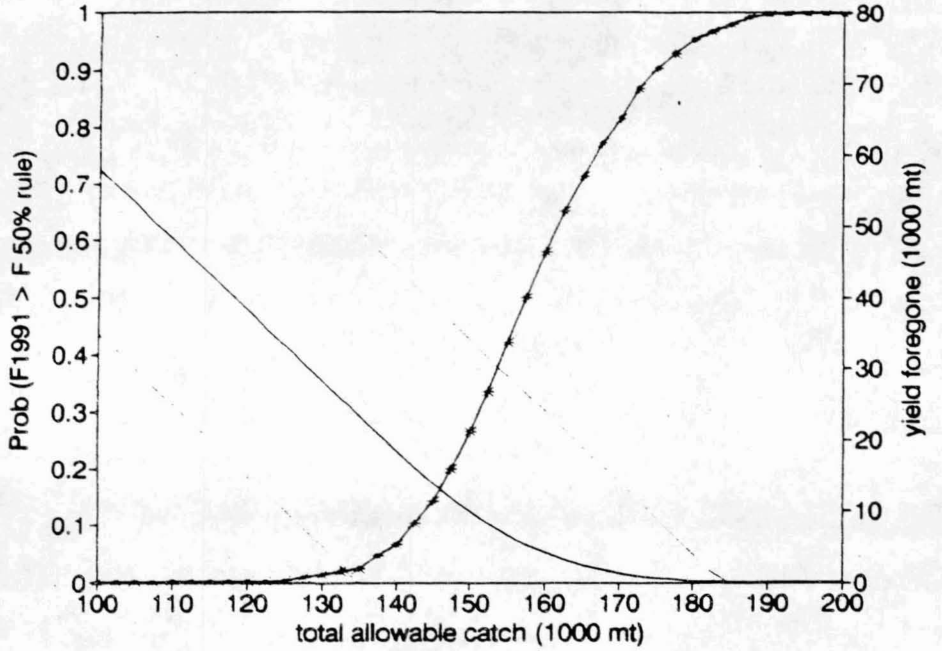

Figure 3b
Probability of the 1991 fishing mortality exceeding the 50% rule fishing mortality, and expected value of the yield foregone (with 95% confidence band), as functions of the TAC selected for 1991.

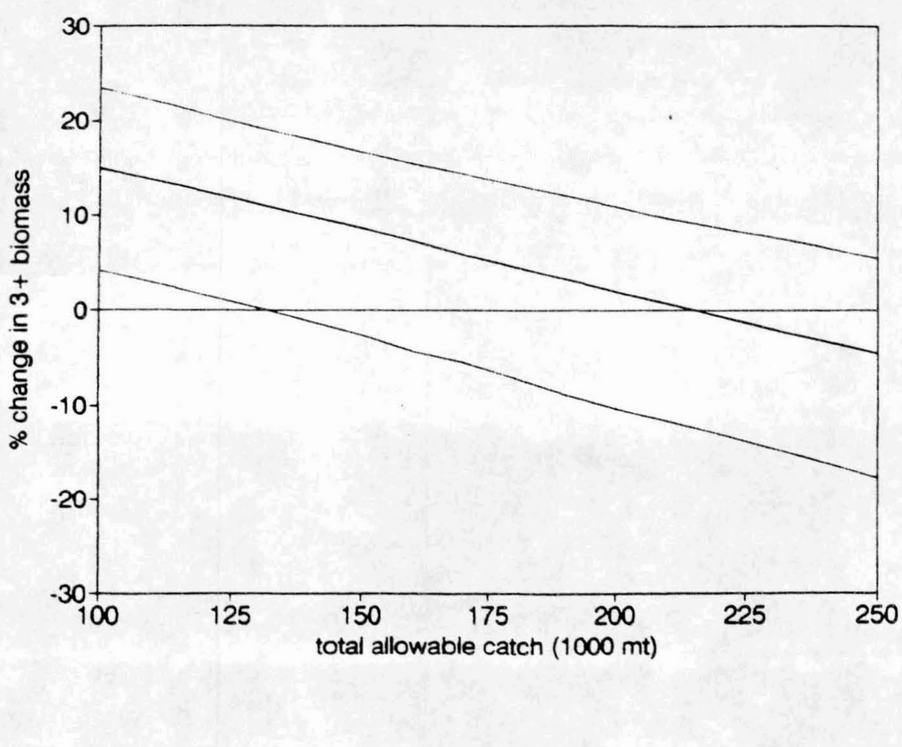

Figure 4
Percentiles of the distribution of the relative change (%) in biomass of fish age 3 and above as a function of the TAC selected for 1991. Top line: 97.5th percentile; middle line, 50th percentile; bottom line, 2.5th percentile.