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Using Monte Carlo Simulations to Account for Uncertainties in Stock Assessments and Biological Advice for Fisheries Management. Application to the Northern Stock of European Hake.

by

Benoit Mesnil
IFREMER
B.P. 7
F17137- L'Houmeau
France

Abstract.

Applications of risk analyses, in their formal definition, to fisheries management are rarely possible because managers, and the societies who mandate them, are seldom in a position to state coherent objectives for the fisheries sector and to weight the various criteria involved in specifications of utility functions. It remains possible, however, to evaluate how uncertainties affect the form and strength of scientific advice based on results of stock assessments, by analysing these results from a probabilistic perspective.

A Monte Carlo approach is presented whereby probability distributions of the quantities usually considered when framing biological advice are obtained from replications of the complete sequence of operations constituting an analytical assessment, namely:
1) Pseudo data sets of natural mortalities at age, catches at age by year, and cpue's of selected fleets are obtained by randomly perturbating the original data;
2) VPA is run and tuned using an ADAPT framework. The latter was chosen because of its generality and flexibility, and has been adapted to ICES habits.
3) VPA results are used to derive the parameters required for predictions: status quo fishing mortalities at age; weights at age in catches and stock; GM recruitment and its coefficient of variation; parameters of the Ricker Stock/Recruitment relationship and residuals about the fit. Landing ratios at age are used in all predictions to emphasize landings rather than catches;
4) Long-term equilibrium analyses: Fmax, F0.1 and the F factor such that SSB/R is a desired fraction of pristine SSB/R are searched, conditional on the estimated current exploitation pattern and natural mortality assumed in 1);
5) Short-term predictions: status quo forecast is made for the "assessment year" then the F factors required to attain a range of landings in the "TAC year" are searched;
6) Medium-term predictions: trajectories of expected landings and SSBs are computed under status quo F and an alternative sequence of fishing mortalities, with a choice of recruitment functions including the Ricker S/RR estimated in 3).

The results from all replicates are summarized into frequency distributions, giving empirical probabilities. Comparisons of results from 5) and 6) establish the equivalence of probabilities interpreted from the respective probability profiles of fishing mortalities and catches obtained under identical fishing regimes.

Introduction.

For stock and fisheries that are managed by means of TACs, which is the case of most North Atlantic fisheries, the biological advice is provided in the form of catch forecasts a few (generally 2) years ahead under varying levels of fishing mortality, with comments on how the stock is expected to change relative to its perceived current state. A major cause of uncertainty in such forecasts is the inability to predict future recruitments, which are often quite variable, and this has usually received the most attention. The problem is particularly acute when exploitation commences on age-0 fish. However, other parameters used in the predictions are also subject to uncertainties. In the first place, one would mention the population numbers at age at the start of the predictions. These are estimated by VPA which, in turn, is subject to inherent or statistical uncertainties in assumed natural mortalities, in sampled catches at age, and in catch and effort data used for tuning the VPA, among other things. Since some of the errors may cancel out, for example between VPA and short-term predictions (Pope, 1983), the robustness of the advice is not necessarily undermined. However, this is not a general rule and errors may, on the contrary, propagate in an unexpected manner through the assessment.

The object of this paper is to examplify an approach to the evaluation of the robustness, or relevance possibly, of biological advice in the face of uncertainty in the data used for stock assessment. A Monte Carlo method is used to simulate a large number of plausible analytical assessments, including VPA with tuning and predictions, in which the input data are subjected to random noise about their nominal values. Frequency distributions are obtained for the management related quantities which are conventionally considered by ICES working groups and ACFM, such as reference points in long-term equilibrium analyses; or fishing mortalities, predicted landings or catches and spawning stock biomasses in the short- and medium-term. By examination of these distributions or so-called "probability profiles", one may evaluate how firmly recommendations to alter the fishing intensity relative to *status quo* F can be stated to managers in view of the uncertainties involved.

This study uses one of the methodologies discussed by the 1993 Methods Working Group of ICES (Anon., 1993b). Deliberately, the scope has been restricted to the evaluation of quality and robustness of scientific advice, and does not extend to the evaluation of management strategies; in other words, the emphasis is on advising, rather than managing, under uncertainty. For that reason, it is not claimed to be a "risk analysis", which should involve the specification of objectives for fisheries and quantification of attributes of some loss/utility functions but, raher, a "risk assessment" according to the terminology of Pearse and Walters (1992). The intentions, thus, are to expand the assessment toolkit; to help ICES and ACFM in gaining experience with this framework; and to contribute to the design of a convenient format for passing the information to managers.

The method is applied to the case of the Northern stock of hake which has been problematic for some years. Because of doubts on catch-at-age compositions and, possibly, on the value assumed for natural mortality, ACFM did not endorse the assessment made by the 1992 Working Group on the Assessment of Southern Shelf Demersal Stocks (Anon., 1993a), the unfortunate result being that in such instances no advice is given at all. It is expected that the approach presented here would not only provide a practical solution to this problem, by explicitly taking some uncertainties into account, but would also help to reduce resistance to the provision of longer term advice for which there is a demand by managers and the industry.

1. Methodology.

The Monte Carlo method used in this study is one of the procedures suggested by the 1993 ICES Methods Working Group. It is an adaptation of the methodology used by Powers and Restrepo (1992) or Restrepo *et al.* (1992), in an implementation which owes much to these authors. It essentially consists in repeating a large number of times (500 or 1000) the complete sequence of computations which forms the normal procedure of an age-based analytical assessment, and then summarizing and analysing the distributions of outputs.

Step 1: Generate the inputs.

It was chosen here to simulate uncertainty in 3 of the crucial inputs for assessments: natural mortalities at age, catches in number at age by year, and catch-per-unit-effort at age of selected fleets by year. In each run these parameters are randomized about the nominal estimates according to prescribed error distributions, with specification of the relevant coefficients of variation. In principle, the latter are estimated together with the "mean" or "best" estimate depending on the sampling scheme or estimation method used. In this implementation, factors can be set to bracket the lower and upper values within a plausible range, in order to avoid impossible (eg, negative) values.

Natural mortality is allowed to vary with age, but the same vector is used for all years. The difficulty with this parameter is that it is generally assumed, rather than estimated in any formal way, and one also has to guess its distribution and coefficient of variation. The simplest option is to use a uniform distribution and CVs such that the estimate span a reasonable range. The bracketting factors can be used here to distort the distribution, reflecting the fact that M is probably underestimated rather than overestimated in most instances.

For catches at age, we actually want to mimic two sources of error, on the amount caught relative to what is reported or estimated (misreporting, discarding, sampling errors); and on the determination of age of the sampled fish. The former are quantified by the variance estimates appropriate to the sampling scheme used (eg, Pelletier and Gros, 1991), although this is not always feasible in practice when the fisheries are multinational, with a variety of fleets, gears, landing sites, data flows, etc. The latter are best described by multinomial distributions as discussed by Deriso *et al.* (1985). In this application, however, we have simplified matters by using log-normal distributions to represent both effects combined, as was done by Powers and Restrepo (1992) who recall that this option avoids negative catches in the randomisation. It can however produce extravagantly high values at times, and the bracketing factors may be useful to avoid this. It must be noted that, for reasons of convenience, the mean weights at age in the catch (and in the stock) and landing ratios at age remain fixed at their initial value.

Catch-per-unit-effort at age are affected by the same sorts of errors, with an additional effect due to the estimation of fishing effort. In some instances, these data can be analysed with multiplicative (Gavaris, 1980) or Generalised Linear models (Nelder and Wedderburn, 1972) that provide estimates of the error variances. When scientific surveys are considered, variance estimates can be obtained by conventional statistical analyses (eg., Smith and Gavaris, 1991). As implemented by Restrepo et al. (*op. cit.*), the user has the choice of various transformations for cpues, including logarithmic and square root. In the example, we have used a logarithmic transformation, no centering of the indices about their mean, and log-normal distribution of the random noise.

Step 2: VPA and tuning.

The core method adopted for VPA tuning is the ADAPT framework (Gavaris, 1988), and this essentially for the following reasons:
i) it is widely used in North America, but could not find its ways through ICES yet. There is no reason that this situation persists.
ii) it uses an explicit objective function that can be minimised automatically by means of appropriate computer routines (Marquardt and Levenberg algorithm in this instance). This is particularly desirable in a repetitive process where user's intervention must be minimal, and the tuning methods currently available at ICES are not fully satisfactory in this respect.
iii) it is flexible, particularly in the sense that it can accept incomplete cpue series and missing data anywhere, even in the last data year which is not required to have particular status or treatment. Moreover, it can make use of cpue data for the "assessment year" when these are available for some series, thus providing a possible solution to one of the problems addressed by the Methods Working Group (Anon., 1993b). An operational version is thus considered to be a useful complement to the ICES toolkit.

Now, ADAPT is just the framework but the procedures effectively used depend to a large extent on details of the implementation, which need to be explained. Here, the basic method has been modified in various ways to suit ICES practice. Firstly, it can use data in the now usual ICES (or so-called Lowestoft) formats. This implies that cpues series relate to a single age for each fleet, at the expense of a possibly useful option where indices cover several ages, as used by ICCAT. The tuning data are as used by XSA, *i.e.* the alpha and beta parameters are needed to adjust the indices for the timing of the catch in the year. As usual, the range of years retained for the tuning can be a subset of the data series, such that catchabilities are assumed to be reasonably constant over the period selected.

More importantly, the search algorithm still seeks to minimize a weighted sum over ages and fleets of squared deviations between observed and computed cpue indices (the objective function), but the unknown parameters have been restricted to the stock numbers surviving at the end of the last data year. This means that catchabilities at age for each tuning fleet are estimated independently by regression, in contrast with other ADAPT applications in which they are part of the searched parameters. Following common practice, the residuals are weighted by the inverse of the error variance estimated for each age and fleet, but other weighting functions are considered as well. Taper weights are used to reduce influence of earlier years both in the objective function and in the estimation of catchabilities. This is common practice at ICES and is suggested by Conser and Powers (1989) also as a means of counteracting convergence of the VPA. Prior weights can be given to some years, for example to reduce their influence when data problems are suspected (eg, 1985 and 1986 data for hake). Prior weights can be ascribed to the fleets, essentially for the case when one wants to examine the behaviour of different treatments of the same indices in context with the other series, without letting the same information have redundant influence on the final estimation. Conser and Powers insist that the combined weights should be standardised to unity. It was observed, however, that whether this is done or not hardly makes any difference in the VPA estimates. Optionally, there is an iterative procedure to recompute the weights until stable solutions are obtained, but note that the prior weights remain fixed and only the inverse variance weights are re-estimated.

ICES habits were also adopted for the treatment of the last true age and plus groups. Firstly, the plus-group is always excluded from the tuning and Marquardt search. Secondly, fishing mortalities on the oldest true age group in each year are derived as some specified fraction of the mean F over a range of earlier ages, then applied to the plus-group if it exists. For cohorts ending in the "bottom row", VPA always starts from the oldest true age, and the stock size for the plus group is estimated independently, given F and the catch number.

The Marquardt search requires that initial estimates of the parameters, together with lower and upper limits, be provided. Because of the difficulty of guessing appropriate stock numbers, it was found more convenient to enter fishing mortalities at age in the last data year and to derive the first guesses of surviving numbers using these and the catches at age in the last year. This procedure is made once for all before entering the Monte Carlo loops and the same initial guesses are re-used in each pass. Because the randomisation can produce extreme values, it may happen (in 4-5 passes out of 1,000) that the tuning procedure fails with estimates trapped into the lower or upper constraint. In this case, all the operations described hereafter are by-passed.

If the tuning is successful, a final VPA is carried out on the entire range of years. Indices of reference fishing mortality in each year are computed as the arithmetic means, and as the means weighted by stock numbers, of VPA Fs over a specified range of ages. Geometric mean recruitment is calculated over a specified range of years. Whether it is used or not for the predictions, a Ricker (1954) Stock/Recruitment relationship is fitted to the data estimated in this VPA, using a regression method with the bias correction recommended by Hilborn and Walters (1992). The average SSB in the last recent years is computed and can subsequently be used for comparisons with SSBs obtained in the predictions. The input data used (Ms, catch-Ns, cpues) and results obtained in each loop (Fs, stock-Ns and SSBs, catchabilities, tuning residuals and weights, S/RR parameters and residuals) are saved to file for eventual examination.

<u>Step 3: set up data for predictions.</u>

To run the predictions, one needs: the population numbers at age at the start of the "assessment" year (last data year +1 in a typical working group setup); vectors of reference natural mortalities, fishing mortalities and mean weights at age; and assumptions about future recruitments. The population numbers are the parameters estimated by the Marquardt search, completed with the size of the plus-group and the abundance of the recruits, which depends on the S/RR option considered. Natural mortalities being assumed constant with time, we simply use the same vector of randomized values as for the VPA. *Status quo* ("current") fishing mortalities at age are estimated as the arithmetic means of VPA Fs over a specified range of recent years. Following the practice of some ICES working groups, these means are scaled to the arithmetic mean reference F in the last data year. Mean weights at age in the catches and in the stock are calculated as the averages over the same years as for Fs, with a weighting by catch and population numbers respectively.

There are currently 4 options for recruitment, which all use the VPA results as obtained in the present pass: constant GM recruitment; GM recruitment with random noise, preferably using a log-normal distribution and either a specified CV or the standard error of the log-recruitments estimated by the VPA; recruitment drawn at random from one of the VPA estimates; Ricker S/R relationship, with parameters as estimated above, and the addition of a randomly selected residual from the fitted regression. At present, the Beverton and Holt (1957) S/R relationship is not implemented; as recalled by Hilborn and Walters (1992), this would require another minimisation procedure, and we consider that the computer has already enough to do. Although one can have reservations about using a formal stock/recruitment function, especially in a Monte Carlo setting where the validity of each estimation cannot practically be controlled, the 1993 Methods Working Group rightly points out that it is not more realistic, and probably more dangerous, to assume that recruitment is independent of stock size when the latter is likely to vary significantly. It is crucial to consider a stock/recruitment relationship when one is concerned with the definition of threshold levels (MBAL). It must be pointed out that changes had to be made to the usual catch forecast procedures to allow for use of stock/recruitment relationships when recruitment occurs at age 0: the SSB surviving at the end of each year must be computed first, from which next recruitment is estimated, and it must therefore be assumed that age group 0 does not contribute to SSB, this being the case in most stocks.

Step 4: run predictions.

As is common practice, 3 time horizons are considered for the predictions: short-term (TAC year), medium-term (typically 5-10 years), and long-term equilibrium. Given the scope of the study, attention has been focused on the following quantities, noting that all yields considered are landings rather than catches:

i) Long-term:
All calculations are made on a per-recruit basis. The F factors (multipliers applied to the *status quo* fishing mortalities at age) corresponding to Fmax and F0.1 under the assumed exploitation pattern and M vector in each pass are searched using a Newton-Raphson algorithm, and the relative gains compared to *status quo* landings per recruit are computed. The F factor such that SSB/R is some desired fraction of the pristine SSB/R (noted SBv) is searched.

ii) Short-term:
A *status quo* F prediction is made for the "assessment" year, then the F factors resulting in a given set of Allowable Biological Catches (ABCs, an interesting concept used by several North American fisheries committees to clarify the distinction with TACs which are the outcome of the managers' decisions) in the "TAC year" are searched using a pseudo-Newton algorithm. The surviving SSB for each F factor is also considered.

iii) Medium-term:
At this stage, we are not concerned with evaluations of management strategies, and we just consider the trajectories of landings and SSBs under specified fishing mortality levels over a future period, which includes the "assessment year". Two summary quantities are considered at the moment: the average landings over the period, and the number of times SSB is predicted to be less than the average in recent years, which was mentioned earlier. Obviously, with a different concern in mind, other fishing regimes or strategies can be analysed with minor changes to the available software, such that the composite strategies considered by Pelletier and Laurec (1991, 1992) and other authors, or threshold policies (Quinn *et al.*, 1990). Likewise, it is possible to envisage other summary quantities such that measures of the year-to-year variability of landings (Hall et al., 1988, Murawski and Idoine, 1989, MacLennan et al., 1992).

On completion of the specified number of Monte Carlo runs, summary statistics (minimum, maximum, mean) and frequency distributions of the inputs and results can be obtained by re-analysing the output files. These frequency distributions can be interpreted as empirical probabilities that are conditional on the assumed form and magnitude of the errors.

2. Application to the Northern Stock of hake.

As mentioned in the introduction, there have been problems for many years with the assessment of the Northern Stock of European hake, mainly arising because of difficulties in reliably estimating age in this species. Attempts have been made to utilize numerical methods to convert length- to age-compositions in order to obtain the data required by age-based analytical assessments. Although the situation has improved somewhat, the 1992 Working Group on the Assessment of Southern Shelf Demersal Stocks identified persistent problems in the data base used for this stock. In view of the uncertainties, ACFM was not in a position to give advice for the management of the fishery. It was thus deemed appropriate to use the methodology explained here in order to deal explicitly with the obvious sources of uncertainties, and to examine how advice might be framed taking these into account.

2.1. Data and assumptions.

Hopefully, some of the data deficiencies identified by the working group will be resolved in the course of this year. However, the purpose here being to illustrate an application of the method, the data considered are exactly as given in the working group's report (Anon., 1993a).

The validation of the tuning module was made by runing the program without randomisation of the inputs, using cpue data for 1982-1991. Generally speaking, the "deterministic" results are similar to those obtained by the working group with either XSA or *ad-hoc* tuning, but indicate still lower values for the estimated fishing mortalities and, as a consequence, a poorer convergence of the VPA. In this instance, it was found that the tuning method was rather sensitive to the ratio of last age to earlier ages Fs, and one way of obtaining results more in line with the ICES tuning methods was to take a ratio of 1.0 instead of 0.9. Whether we consider the "deterministic" results or the means over all Monte Carlo loops, the estimated exploitation pattern in the last year and the distributions of the tuning residuals by age and fleet are similar to those obtained by the working group.

For the Monte Carlo simulations, the next problem was to specify the coefficients of variation for randomising the inputs. As alluded to earlier, there is at present no formal way of estimating these for this stock in view of the heterogeneity of the fleets and sampling schemes involved in the various countries taking part in the fishery, and the only recourse is educated (hopefully) guesses of plausible levels of noise on Ms, catches and cpues at age. The values of the coefficients of variation (same for all years) assumed for this analysis are presented in Table 1, together with other options considered. The CVs used for the catches were set larger than those used by Restrepo et al. (1992) for the NAFO 2J+3KL cod, and by the Methods WG for the North Sea cod, to reflect larger uncertainties for this stock. In effect, these result in rather wide variations of the input data (between about 0.3 and 3 times the baseline values for catches, a larger amplitude for cpues depending on the fleets) although a broader range for Ms (0.12-0.34) might have been tried, especially for age 0.

Options for the predictions were the same as used by the working group regarding landing ratios at age, reference years (1988-1990) for *status quo* F (but scaled to 1991 F1-4) and mean weights at age. The baseline SSB for comparisons was the mean over the last 5 data years, i.e. 1987-1991. Recruitment at age 0 in the "assessment year" and in each prediction year was estimated from the Ricker S/R relationship fitted in each run with addition of a randomly selected residual about the regression.

The results discussed here are based on 500 Monte-Carlo runs. Note that these require about 30 minutes on a Sun SparcStation 2 (but ages on even a fast PC). Attempts were made to treat all variables in double precision, but the runing time became prohibitive in view of the very small differences in the results.

2.2. Long-term results.

We will concentrate on 3 results: the F factors, relative to *status quo* F (factor = 1.0), corresponding to Fmax, F0.1 and an equilibrium SSB/R of 30% of SBv, the unexploited SSB/R (this 30% figure is arbitrary, for the sake of illustration). Three representations are considered. Figure 1 shows the median value (the tick at 50% of the cumulative distribution) and bars extending from the lower to the upper quartiles. Figure 2 shows the distributions of the number of occurences of F factors within the ranges shown in abcissa. Figure 3 shows the representation known as "probability profiles", displaying the cumulated relative frequencies, i.e. probabilities, that the respective F factors are less than the discrete values in abcissa.

From different viewpoints, all graphs corroborate the same conclusions:
i) To the extent that anybody is concerned about this, there is little doubt (80% of the time) that the stock is overexploited in terms of landings per recruit at the current level of F and with the current exploitation pattern. Unless the latter is improved, fishing at Fmax would imply a reduction of fishing intensity by at least 25% in about 50% of the cases covered, given the uncertainties assumed for M and the catch data. It is noteworthy, however, that the gains in landings entailed by fishing at Fmax compared to *status quo* F would be small: the median indicates a 4% gain, and the average is 7% across all runs.
ii) There is a very large probability (94%) that current F is beyond F0.1. In 50% of the time, fishing at F0.1 would imply a further reduction of current F by 50% at least. However, there is a nearly 60% chance that this would result in losses or no gain in landings per recruit.
iii) If an objective was to achieve an equilibrium SSB of 30% of the unexploited SSB, this would imply a reduction of current F by 30% or more in 50% of the time, noting that the median of the ratio obtained under *status quo* F is 20% of the pristine SSB. In effect, the distribution of the F factors for that objective very closely follows that of the Fmax factors.
iv) For the three quantities, the distributions are skewed to the left, with the respective medians and modes being fairly close and both less than the means. The medians are also quite close to the factors obtained in the "deterministic" run.

2.3. Short-term results.

In the short-term simulations, we examine the distributions of the F factors, again relative to *status quo* F, required to achieve target landings in the range 54,000-64,000 t by steps of 2,000 t in 1993 ("TAC year"), under the assumption of *status quo* F in 1992 (the interim "assessment year"). In addition, recruitment at the start of 1993 is dependent on the 1993 SSB plus random noise, but the same value is used for all targets. Recruitment in 1994 will vary depending on the surviving SSB for each target but, as mentioned earlier, this has no effect on the 1994 SSB.

The probability profiles are shown in Figure 4, giving the probability that the F factor achieving each respective target ABC is less than the values in abcissa. If we take the 60,000 t curve for example, the interpretation is that there is a 50% chance that fishing mortality remained at or below *status quo* F (factor = 1.0) with a TAC of that amount, and of course a 50% risk that it results in *status quo* F being exceeded. However, in 73% of the cases F would be changed by a factor of no more than 1.1. In contrast, if we set a target ABC of 62,000 t, fishing mortality is expected to be less than *status quo* F in only 40% of the time; in other words, supposing that the managers' objective is to maintain fishing intensity at *status quo* level, it is rather unlikely that it would be fulfilled if a TAC of 62,000 t was decided. At the other end of the range, there is a large probability that fishing mortality would be maintained at or below *status quo* F if landings were constrained at 54,000 or even 56,000 t.

Another view is provided by Figure 5 in which the median (50%) and the lower and upper quartiles of the distributions of the F factors for each ABC target are plotted. Note that the distributions of the F factors are rather symmetric about their median, which roughly coincides with the respective mode and mean and with the value obtained in the "deterministic" run.

Normally, if a choice was to be made between these targets, consideration would also be given to the impact in terms of SSB. In this instance, however, the analysis provides little assistance since, whichever choice is made, there is hardly any difference in the SSBs remaining at the start of 1994. This is illustrated in Figure 6 where only the two extreme options are considered. In all cases, the surviving SSB would have a 50% chance of being less than about 280,000 t, with modal (most likely) values in the range 200,000-299,000 t.

This result can be put in perspective with the perceived current state of SSB as estimated by VPA. For the sake of clarity, we have only considered 3 estimates: SSB in 1991 (last data year); in 1992 (assessment year); and the average over 1987-1991. The respective results are presented as probability profiles in Figure 7 and as histograms in Figure 8. There appears to be no significant change in SSB between 1991 and 1992. In both years, the medians of the distributions would be at about 280,000 t, and 60% of the estimates would lie below 300,000 t. These are basically the same key values as those of the distributions of the 1994 SSBs given in Figure 6. A practical conclusion is that there is no indication of a trend in SSB over the period 1991-1993 and that TACs in the range 54,000-62,000 t are unlikely to cause a significant change in current stock size. Nevertheless, it is clear on the Figures that the SSB in the period considered would be less than it has been in the recent past. The median of the distribution of the mean SSB is at about 320,000 t. However, closer inspection of the VPA results reveals that the average is mainly influenced by consistently higher estimates of SSB for 1987, but that the situation has been stabilised in the subsequent years.

2.4. Medium-term results.

We will just consider a simple case in which predictions are carried out over a 5 year horizon, including the assessment year, under a constant *status quo* F strategy. We recall that recruitment in each year is generated via a Ricker S/R relationship. It must be stressed that this results in recruitments which, in the average, are smaller than GM recruitment: the median value is in the range 340-350 million recruits depending on the year considered vs. 400 millions for the GM recruitment.

Probability profiles of the predicted landings are plotted in Figure 9 for a subset of the possible range (note that the cut-off at 64,000 t excludes about 30% of the estimates in the upper end). The interpretation is as before. If we take the distribution for 1993, which is more apparent to the right of the graph, there is a 50% chance, under *status quo* F and for the assumed level of noise, that the predicted landings would be 60,000 t at most, or a 60% chance that they attain 62,000 t. Conversely, there is a 40% chance that they exceed the latter value. For the other years, we see that the probabilities of attaining 60,000 t under *status quo* F would be about 53% in 1992, 56% in 1994, 57% in 1995 and 52% in 1996. In this instance, it is perhaps clearer to refer to Figure 10 in which the medians and the lower and upper 20% percentiles of the distributions are given for the landings in each year and for the mean of the landings over the period (an equivalent alternative to cumulative landings). It confirms that the 50% probability level roughly corresponds to landings of 60,000 t, and also shows that the distributions of the landings are asymmetric with a long tail towards the larger values. In fact, the shapes of the histograms are fairly irregular and several modes are apparent.

Because of the differences in the shapes of the distributions of the landings and of the fishing mortalities, and because of the non-linearity of the relationship between catch and F, there was a doubt for a while that the probability profiles of *status quo* catches could be translated directly into probabilities (or "risk") of departing from *status quo* fishing mortality, as suggested by the Methods Working Group. Despite the heuristic nature of Monte Carlo methods, the present results tend to support the validity of such equivalence. To illustrate the point, let us consider, on the one hand, the probabilities that the F factors for various target landings in 1993 are smaller than 1.0 (*status quo* F factor) from the short-term results presented in the previous section and Figure 4 and, on the other hand, the probabilities that predicted landings in 1993 are less than some value from the probability profile for that year in this *status quo* simulation, as presented in percentages in the text-table below:

X	Prob. F factor < 1.0 given landings X	Prob. Landings < X given status quo F
56,000	69.2	30.6
58,000	58.4	41.4
60,000	49.8	50.4
62,000	39.8	60.4
64,000	33.6	65.8

As one could expect from just one empirical realisation, the values in each row do not sum exactly to 100%, but it is apparent that the probabilities are complementary, and that the differences between rows in the respective columns do match. Similar relationships were obtained for landings predicted under an F factor of 0.9 for 1993.Thus, it seems correct to translate the change in probability along each probability profile of *status quo* landings, when stepping from one X value to another, into an equivalent probability of departing from *status quo* F, and to use this property for subsequent years.

In practical terms, this means that setting a multi-annual TAC (landings only) of 58,000 t for the fishery considered would result in a probability of less than 50% of exceeding the *status quo* F in any of the 5 years. The probability increases to 50-57%, depending on the year, for a 60,000 t TAC and to 60-64% for a constant TAC of 62,000 t.

To follow the normal practice, we may also examine the effects on SSB at the end of each prediction year. The corresponding probability profiles are graphed in Figure 11, and the sequences of the medians and quartiles of each distribution in Figure 12. These show that, despite some changes up and down from year to year, a *status quo* F option would introduce no significant trend in SSB. If we examine the distribution of SSB in 1997, i.e. at the end of the 5 year period, the median is at about 280,000 t and 56% of the estimates lie below 300,000 t. Thus, there would be practically no change in the state of the stock compared to the 1991-1992 situation described in the previous section. As it was in those years, the SSB in any year during the medium-term period would be smaller than the 1987-1991 average in a vast majority of cases. Although this particular criterion does not appear to be quite adequate to define a threshold SSB for this stock, it indicates that if SSB does not deteriorate, it does not improve either.

3. Discussion

Uncertainties are an inevitable trait when dealing with the behaviour of natural systems. This is particularly true for marine resources which are not accessible to direct observations, and more so when one wants to predict their future states which depend on unpredictible natural fluctuations as well as on sequences of decisions regarding fishing levels (Hilborn, 1987). If we are to live with that state of nature, a practical way of working round the difficulty is to cast the problem of assessment and management of the resources in a probabilistic framework.

Monte Carlo simulations appear to be a convenient method of incorporating various sources and forms of uncertainty into the quantitative evaluation of how these may affect the outcome of the entire assessment process, and particularly those quantitities which are normally considered when management decisions are made. A useful property of this method is versatility. It is fairly easy to build up on the core simulation "engine" to derive, in a consistent manner, a variety of quantities which are deemed relevant to examine the management problem from various viewpoints. At this point, one would inevitably have in mind the consideration of social and economic factors, when relevant data are available (eg. Lane and Kaufmann, 1991), since these are recognised to be crucial in the specification of the objective or utility functions required for formal risk analyses. In addition, economists often contend that uncertainties about exchange rates between currencies or discount rates (Mendelssohn, 1982) are more critical than uncertainties in biological parameters, even future recruitments.

Despite the limitations of its objectives, the present analysis illustrates an important extension to some other applications of Monte Carlo methods (in a broad sense) by the fact that, following previous initiatives by Pope and Gray (1983), Pelletier and Laurec (1991, 1992), Mohn (1991) or Restrepo et al. (1992), it integrates all stages of an assessment, with all parameters (natural mortality in particular) used consistently throughout. This approach bridges some gaps between analyses that concentrate on the impact of uncertainties in data upon VPA results, which are just an intermediate stage in the whole process, and stochastic simulations that assume perfect knowledge of the current state parameters and just consider variability in parameters of the forecasts. It is thus considered to be a necessary and useful first step in the exploration of how risk assessments should be undertaken, and how they can be utilised in practice.

Even though the ambitions might be temporarily restricted to exploring new perspectives in the formulation of biological advice, there are several reasons to promote the use of such methodology in the ICES area. Firstly, it is regretable that no indication at all is given to managers when uncertainties or lack of long series of data prevent the results of analytical assessments from being used for face value. The two stocks of European hake provide good examples of such black or white dilemma. Because of recurrent arguments on the reliability of the data for the Southern stock, insufficient attention was paid to indications that the stock was declining. It became clear eventually that the stock was close to collapsing but, because managers were given no anticipation on the events, they suddenly have to deal with a catastrophy and one can really wonder how they can practically resolve the immediate socio-economic implications. For the Northern stock, everybody is well aware that the state of the data is far from perfection, but because the assessments were distrusted, the managers were left to decide TACs by themselves on the so-called precautionary bases. The outcome is a TAC of 71,500 t (sum over all Northern stock areas) for 1993, whereas the Working Group suggested landings of 56,000 t (catches of 58,000 t). One can conceivably argue about the levels of noise assumed in the present analysis, but it is evident that such a TAC figure is very unlikely to result in any sort of conservation. Instead, one can expect problems in readjusting the TAC's to more reasonable levels in the coming years. In both instances (Hilborn *et al.*, 1993 present another case in a different context), it would have been preferable to cope explicitly with the uncertainties. A valid excuse is that no operational tool was available for this purpose. To the extent that it can be used routinely and extended as required, it is expected that the method presented here will contribute to resolve this situation.

Secondly, the present system is far too myopic in the sense that advice is seldom given for more than a year in advance, and no indication is given on expected courses of events. This prevents managers and the industry from anticipating adjustments to their strategies. Furthermore, it makes it impossible to spell out the inevitable trade-off, that an excessive catch today is taken at the expense of catch possibilities for tomorrow. Scientists have often refused to produce medium-term projections, essentially because these are very dependent on future recruitments which are impossible to predict reliably. Although this difficulty will always remain and make point estimates of no relevance, it seems that a presentation in probabilistic terms may help to initiate longer-term advice, in the form of either indications of probable catches, or of a formula relating catches and stock abundance. The example treated here can open some perspectives, although we found it difficult in this framework to trace the individual trajectories, which would be useful for demonstrating the trade-off issue mentioned above. It is simply impossible to address all facets of the problem with a single method. However, if the present approach is used, more thoughts should be given to defining informative statistics to characterize the results of medium-term simulations.

Thirdly, Monte Carlo simulations produce voluminous results that need to be summarized in a way that can be useful to managers and improve their understanding of the issues involved. This probably requires a heuristic elaboration based on dialogue between scientists and managers (Wilimovski, 1985). Scientists should initiate the process by presenting to managers the graphs that they consider relevant for now, and adjust the formats to satisfy eventual requests.

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Table 1. Data and assumptions used in the hake example.

```
VPA data for Years 1978 to 1991 and Ages  0 to  8+
Oldest Age F = 1.00 * mean of 3 previous ages
Mean F in each Year over Ages  1- 4
Average Recruitment = GM 1978-1988
Mean Recent SSB over  5 previous Years

Tuning Data for  5 Fleets
First Tuning Year = 1982
Last Year with Tuning Data = 1991
CPUE data will be LOG-transformed
Taper power=  3 over   15 Years
Taper weights 1982-1991 :
 0.482 0.610 0.725 0.820 0.893 0.944 0.976 0.993 0.999 1.000
Prior weights for Years 1982- 1991
  1.000  1.000  1.000  0.500  0.700  1.000  1.000  1.000  1.000  1.000
Prior weights for each Fleet
SPAIN7 (2-10)          1.000
SPAIN8 (1-10)          1.000
LESCONIL (0-4)         1.000
LesSABLES (1-5)        1.000
RESSGASC (0-4)         1.000
Iterative Reweighting Option turned ON

Perturbations of M : Uniform
 with lower and upper factors =   0.60   4.00 and CVs:
  0.400  0.300  0.250  0.200  0.200  0.200  0.200  0.300  0.300

Perturbations of Catches-N : Log-Normal
 with lower and upper factors =   0.05  20.00 and CVs:
 1978  0.300  0.250  0.200  0.200  0.200  0.200  0.250  0.250  0.250
     ......
 1991  0.300  0.250  0.200  0.200  0.200  0.200  0.250  0.250  0.250

Perturbations of CPUEs : Log-Normal
 with lower and upper factors =   0.05  20.00 and CVs:
For Fleet SPAIN7 (2-10)
 1982  0.000  0.000  0.300  0.300  0.300  0.300  0.300  0.300
     ......
 1991  0.000  0.000  0.300  0.300  0.300  0.300  0.300  0.300
For Fleet SPAIN8 (1-10)
 1982  0.000  0.400  0.300  0.300  0.300  0.300  0.300  0.300
     ......
 1991  0.000  0.400  0.300  0.300  0.300  0.300  0.300  0.300
For Fleet LESCONIL (0-4)
 1982  0.400  0.400  0.300  0.300  0.300  0.300  0.300  0.300
     ......
 1991  0.400  0.400  0.300  0.300  0.300  0.300  0.300  0.300
For Fleet LesSABLES (1-5)
 1982  0.000  0.400  0.300  0.300  0.300  0.300  0.300  0.300
     .......
 1991  0.000  0.400  0.300  0.300  0.300  0.300  0.300  0.300
For Fleet RESSGASC (0-4)
 1982  0.600  0.500  0.400  0.400  0.300  0.300  0.300  0.300
     ......
 1991  0.600  0.500  0.400  0.400  0.300  0.300  0.300  0.300

Ref. F &  Weights at age = Mean 1988-1990

Landing Ratios at Age:
 0.650 0.520 0.860 1.000 1.000 1.000 1.000 1.000 1.000

Medium-Term predictions made for 1992-1996
First Option is Status-Quo ; F factors for second option:
  1.00  0.90  0.80  0.80  0.80
```

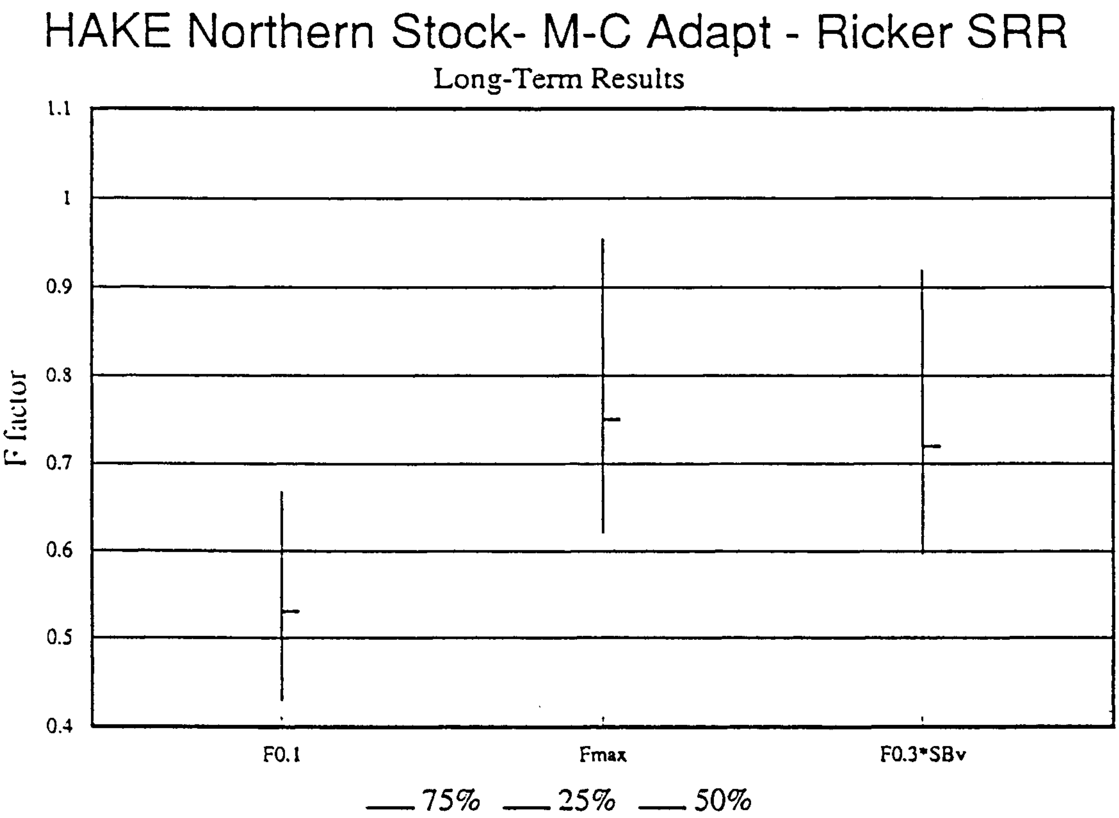

Figure 1. Long-term results. Medians and quartiles of the distributions of F factors, relative to status quo F, corresponding to F0.1, Fmax, and an SSB/R of 30% of the virgin SSB/R (SBv).

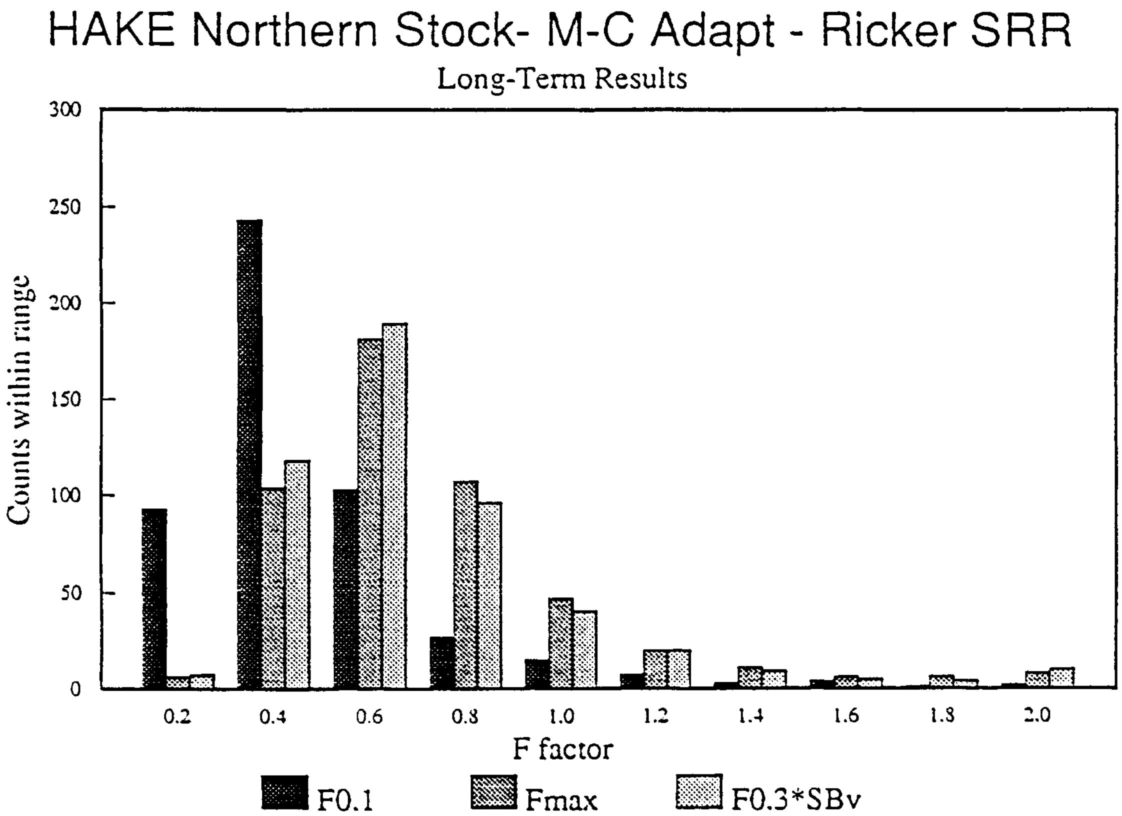

Figure 2. Long-term results. Histograms of the distributions of F factors, relative to status quo F, corresponding to F0.1, Fmax, and an SSB/R of 30% of the virgin SSB/R.

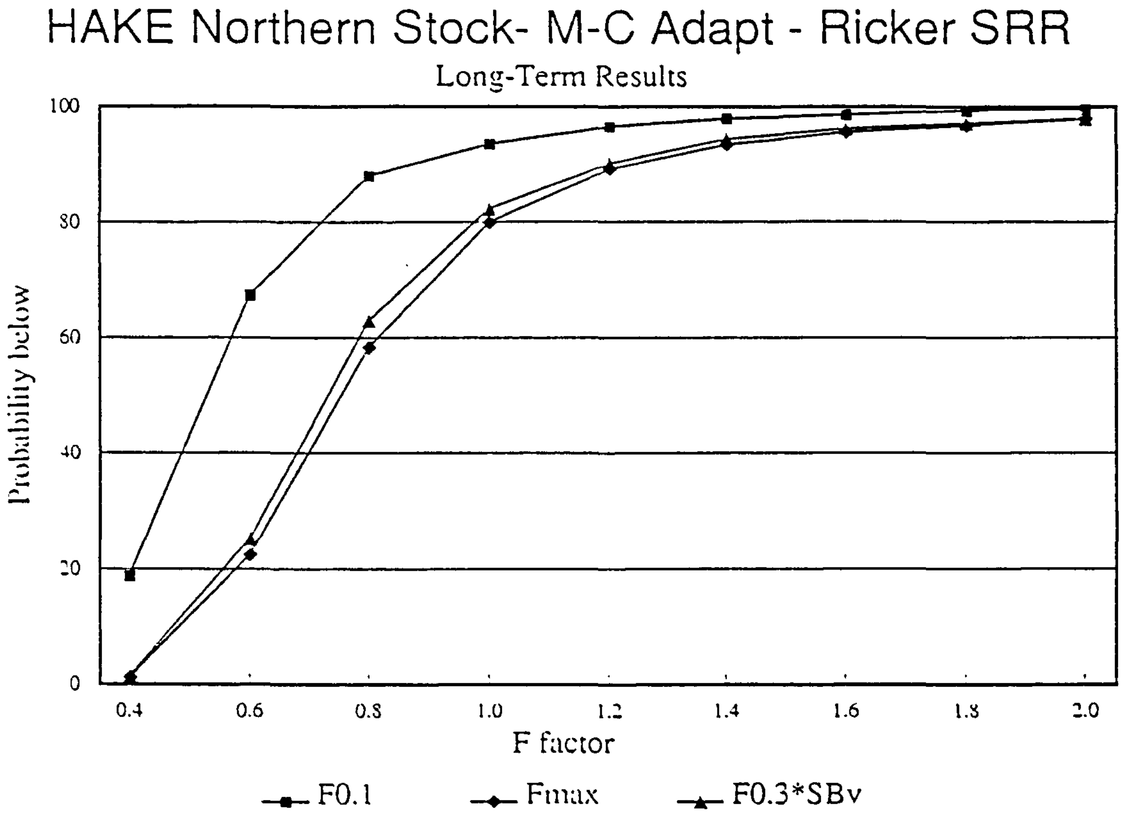

Figure 3. Long-term results. Probability profiles of F factors, relative to status quo F, corresponding to F0.1, Fmax, and an SSB/R of 30% of the virgin SSB/R.

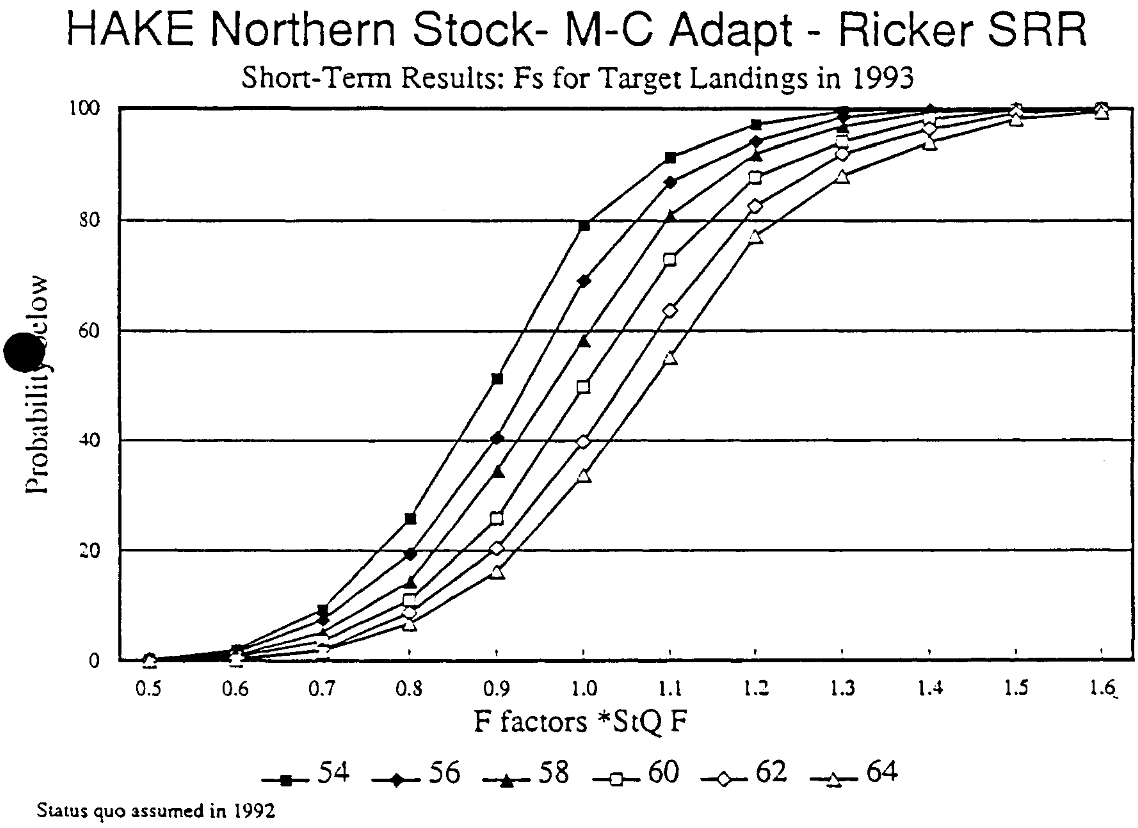

Figure 4. Short-term results. Probability profiles of F factors, relative to status quo F, resulting in a range of target landings in 1993.

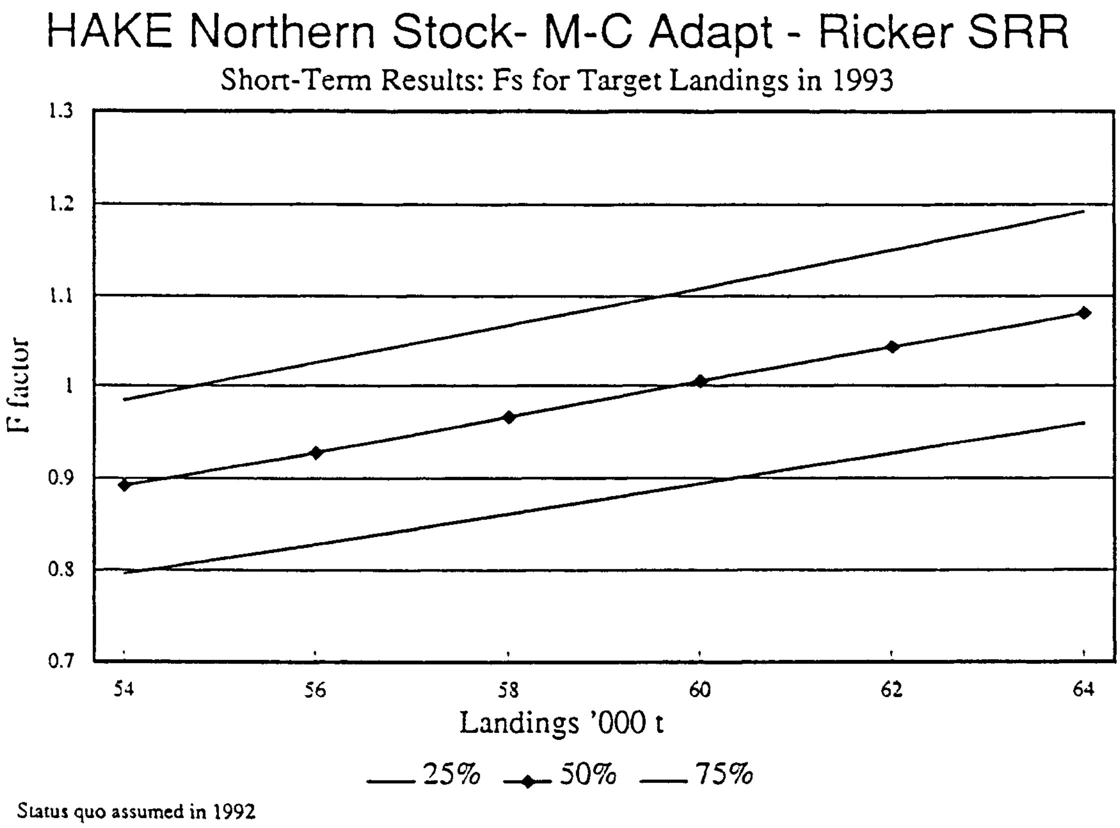

Figure 5. Short-term results. Medians and quartiles of the distributions of F factors, relative to status quo F, resulting in a range of target landings in 1993.

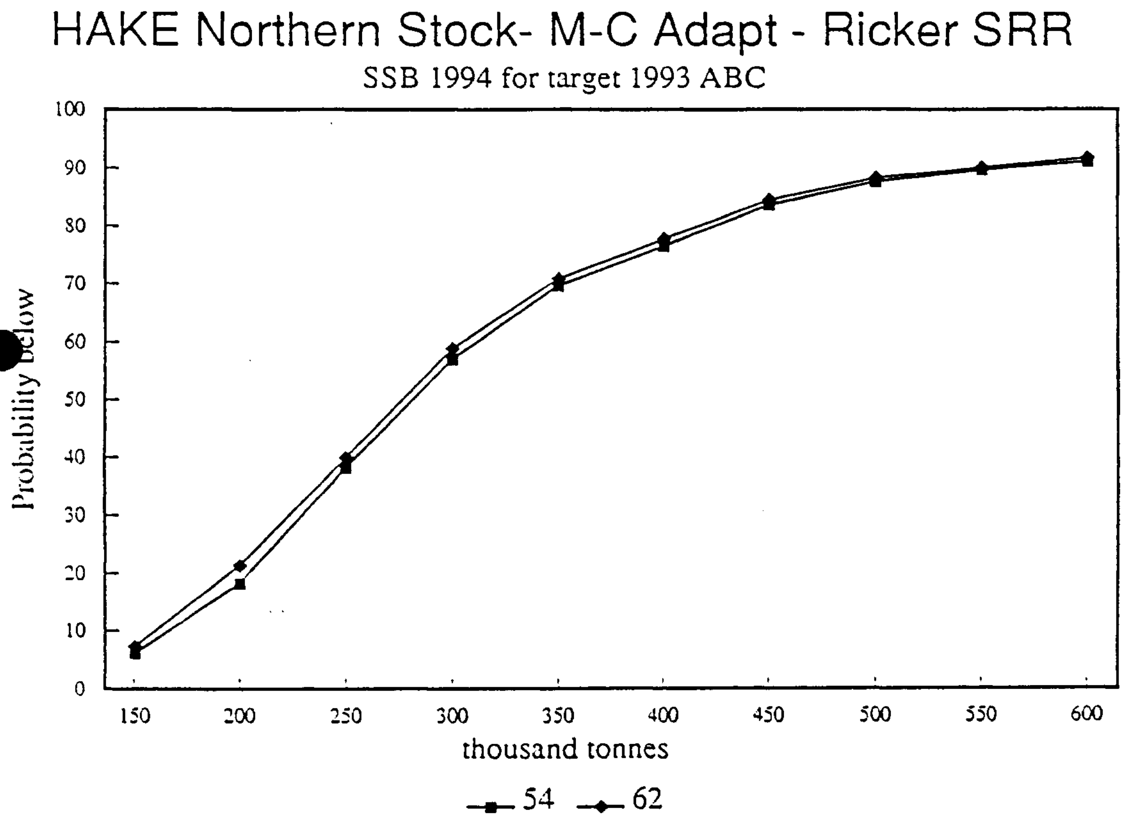

Figure 6. Short-term results. Probability profiles of the 1994 SSBs, assuming that 54,000 t or 62,000 t are landed in 1993.

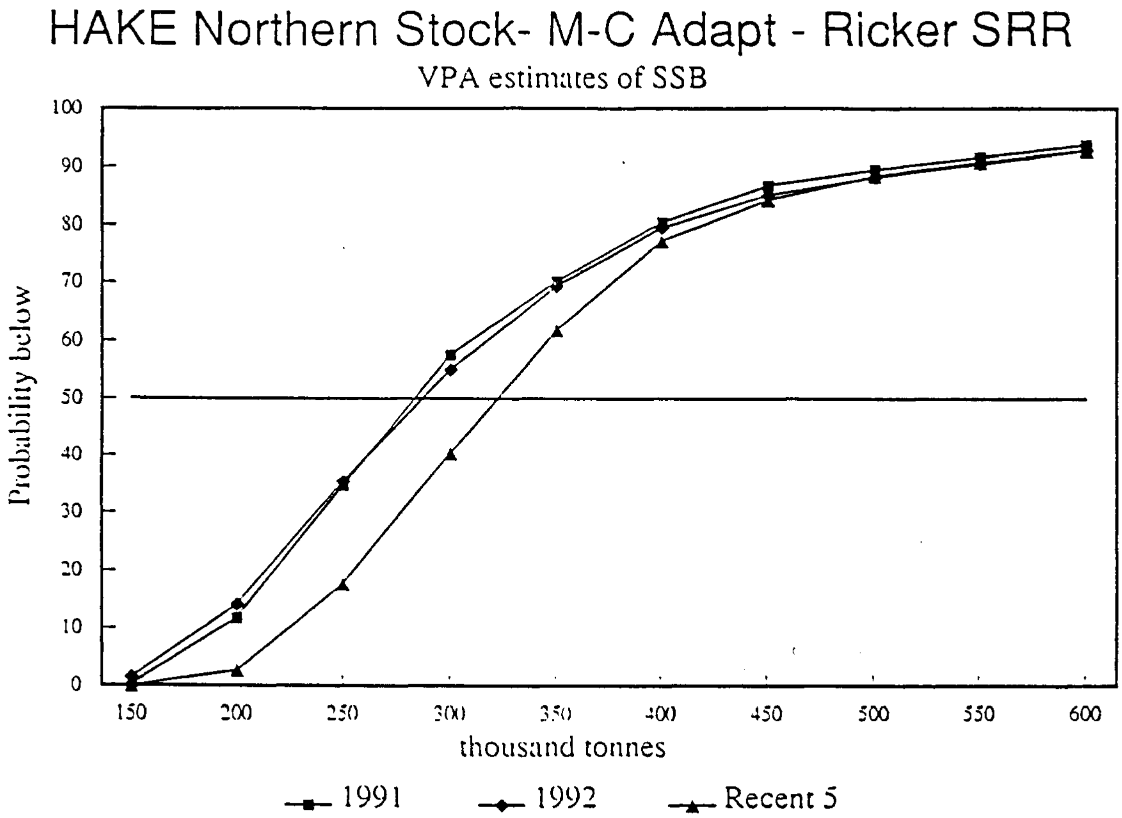

Figure 7. Probability profiles of the VPA estimates of SSB in 1991 (last data year), 1992 (assessment year), and of the 1987-1991 average.

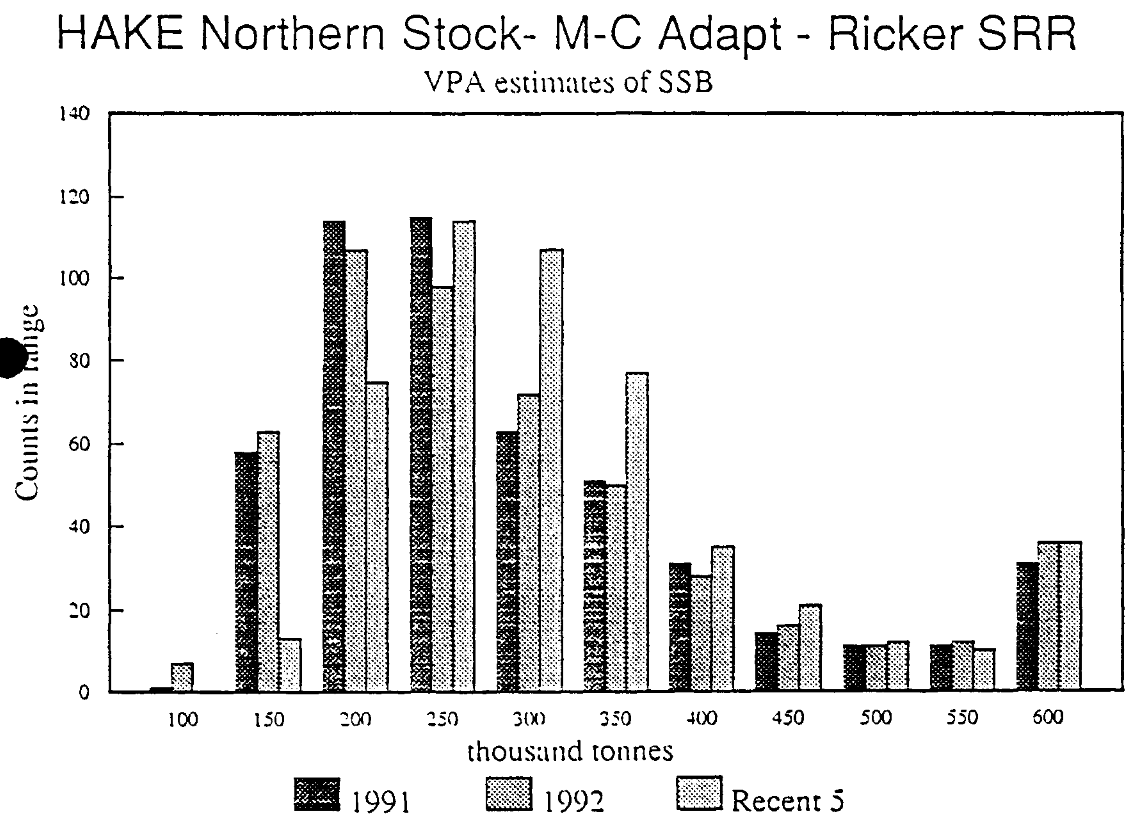

Figure 8. Distributions of the VPA estimates of SSB in 1991 and 1992, and of the 1987-1991 average.

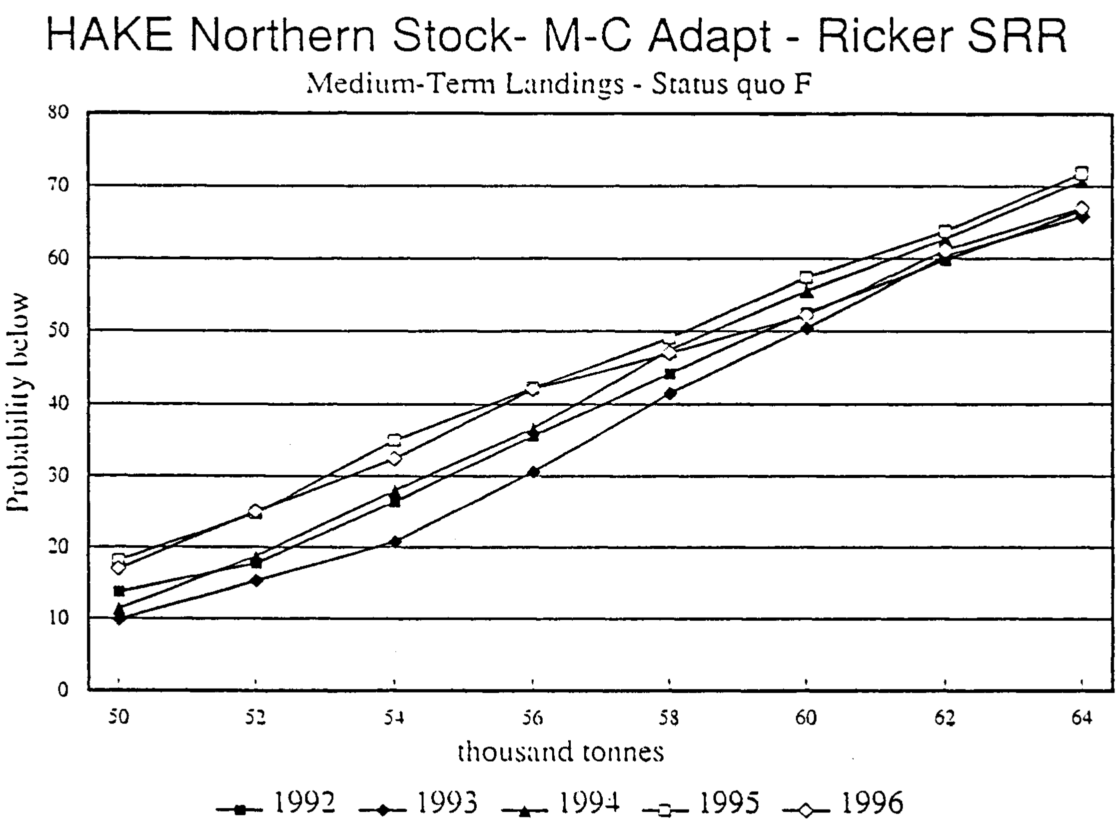

Figure 9. Medium-term results. Probability profiles of the predicted landings in 1992-1996, assuming status quo fishing mortality.

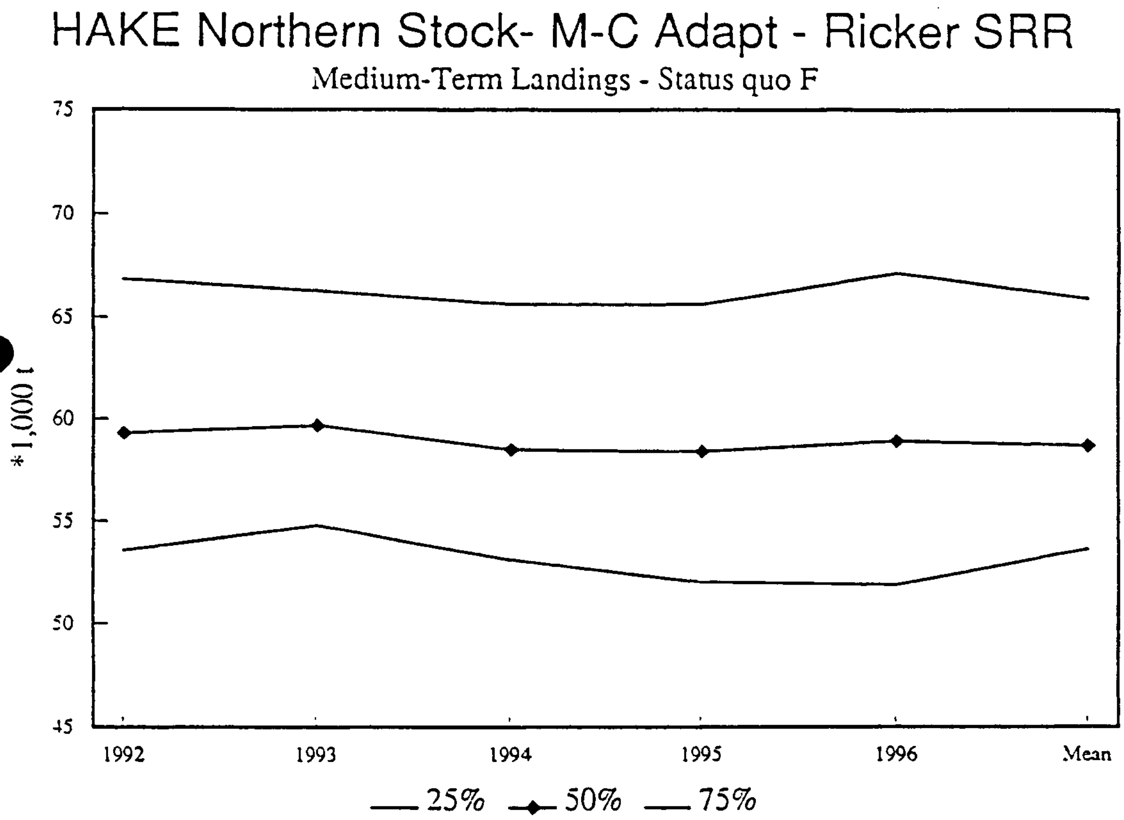

Figure 10. Medium-term results. Medians and quartiles of the distributions of the predicted landings in 1992-1996 and of their mean over the period, assuming status quo fishing mortality.

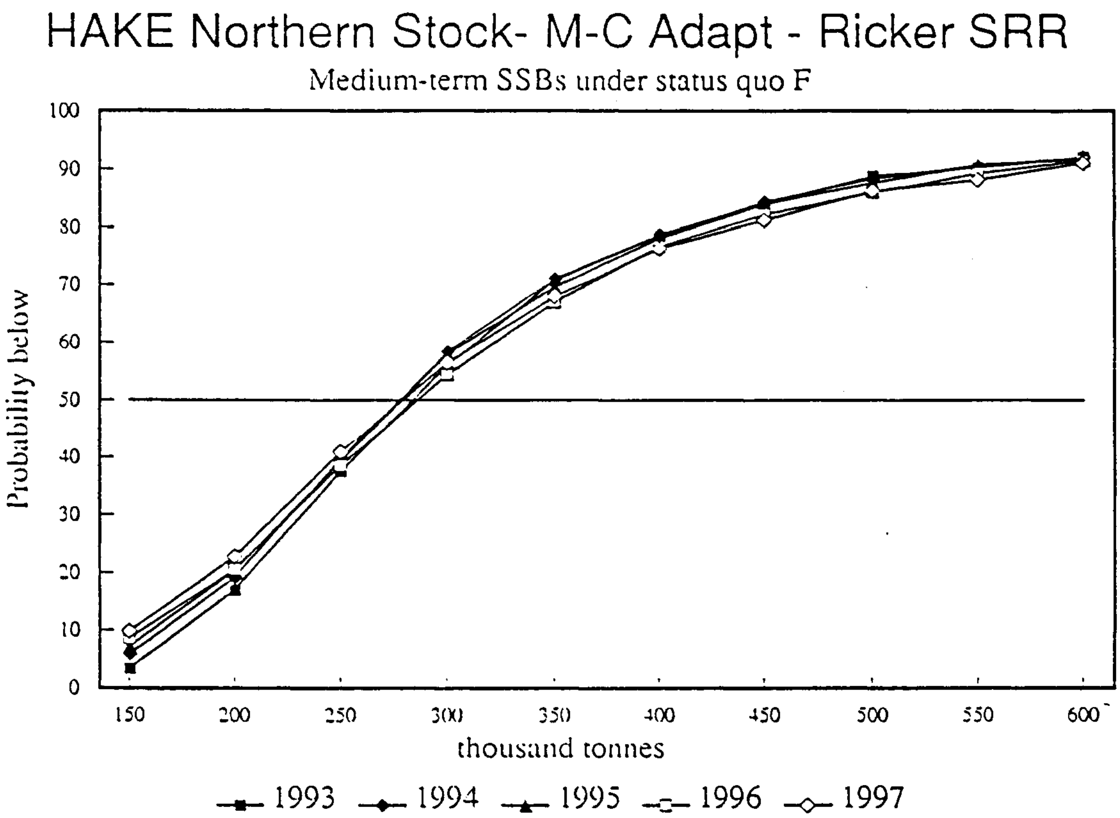

Figure 11. Medium-term results. Probability profiles of the predicted SSBs in 1993-1997, assuming status quo fishing mortality.

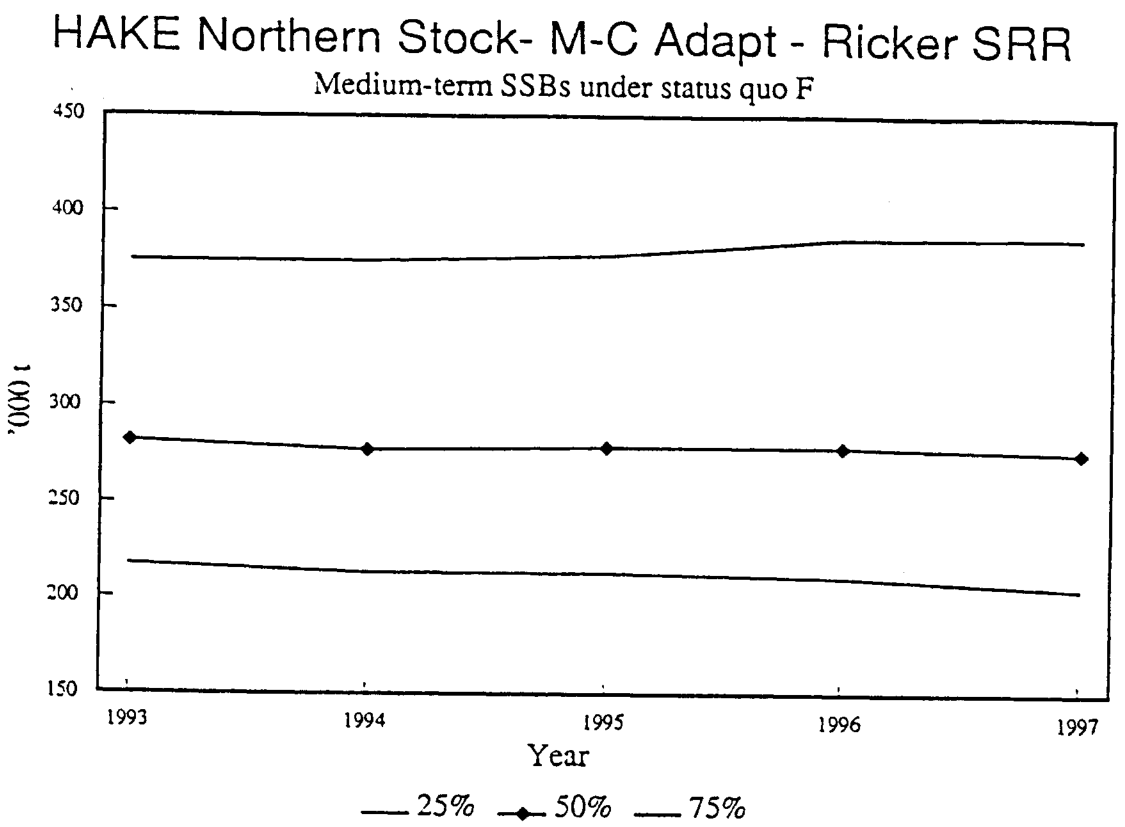

Figure 12. Medium-term results. Medians and quartiles of the distributions of the predicted SSBs in 1993-1997, assuming status quo fishing mortality.