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Quantifying Uncertainty in ADAPT (VPA) Outputs Using Simulation - An Example Based on the Assessment of Cod in Divisions 2J+3KL

by

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Abstract: Assessment biologists would like to convey the degree of uncertainty associated with the outputs from stock assessment models. A convenient approach for doing this is to repeatedly simulate the measured and/or perceived uncertainty in the inputs and, for each set of simulated inputs, compute the results obtained from the assessment model. This method is demonstrated using results from the ADAPT approach for the calibration of sequential population analysis as applied to the assessment of the cod stock in NAFO Divisions 2J3KL. Uncertainty in the inputs are specified as follows: A distribution for M is assumed; A log-linear model is generated for the commercial C/E index and then, based on the residual variability, a simulated C/E index is generated with expectations equal to those predicted by the log-linear model; The measured variability in the RV data, estimated from a stratified-random design, is used to generate random error terms which are added to the RV index; Actual catch at age is assumed to be within some fixed percentage of the nominal catch figures. For each simulated data set, the ADAPT results are used to compute catch projections and other quantities of interest. The results provide pictures of the uncertainty in the outputs.

Introduction

It is not sufficient to assess stocks based solely on the "best" available information where best is defined in the sense that the parameter estimates are the "most likely values" for the true parameters. It is also necessary to examine the sensitivity of the assessment results in terms of imprecision of the parameter estimates as well as possible failures of the models. Since assessments usually require many input parameter estimates, it is generally not possible to derive meaningful analytical expressions for the combined effects of erroneous inputs. Historically, uncertainty has usually been dealt with by simple sensitivity analysis. However, a more complete description of the uncertainty, expressed in probabalistic terms, would be of obvious value. A simple but computer-intensive technique for achieving this is to simulate the uncertainty in the inputs to the assessments, by specifying distributions for the input parameters, and then see what the resulting distribution of model outputs looks like. This approach was used by Restrepo and Fox (1988) to examine uncertainty in simple yield per recruit analysis for Gulf of Mexico redfish. The method is generalized here to account for uncertainty in results from a sequential population analysis based on the ADAPT approach of Gavaris (1988). Uncertainty in the ADAPT results is then translated into uncertainty associated with more general dynamic pool models such as estimates of catch at various reference fishing mortality levels ($F_{0.1}$, F_{max}, $F_{status\ quo}$). We apply the method to data on northern cod as an illustration. We stress that, while the catch data and abundance index data in our example are from the CAFSAC assessment (Baird et al. 1990), the descriptions of the uncertainty in the inputs and model formulation are ad hoc and for illustrative purposes only.

The simulations serve as a "translator" from the uncertainty about the inputs to the uncertainty about the outputs. As an example, suppose the only uncertainty in the inputs concerned the value of natural mortality, and that it was felt that M could be anywhere in the interval from 0.15 to 0.25 yr^{-1} with equal likelihood. Then, one could compute the assessment model results for a large number of uniformly spaced values of M in this interval (say, 100) and make a histogram of the results. This, then, would represent the feelings about the relative likelihood of the output taking on various values. If not all values of M were believed to be equally likely, then one could weight the 100 outputs by the probability felt for the corresponding inputs.

The above procedure becomes awkward when there are a number of inputs subject to uncertainty because the number of combinations of parameter values becomes very large. An alternative is to use a Monte Carlo approach in which values of the inputs are drawn randomly from user-specified uncertainty distributions. These uncertainty distributions can be derived from valid statistical analysis of data, or they can represent personal feelings about the likelihood of the inputs taking on particular values. Obviously, the outputs of the simulations represent "personal probabilities" about the uncertainty in the results since at least some of the choices of what to simulate are subjective.

Description of the Simulations

The simulations were run using a version of ADAPT written in standard FORTRAN. The necessary inputs for ADAPT consist of: the catch at age matrix, one or more abundance indices used for tuning, a value of natural mortality (M), a specified objective function, designation of the fate of the oldest age group, designation of the weighting procedure for the indices, any constraints on the partial recruitment vector, specification of any transformations, and criteria for determining convergence. For the simulations, it is also necessary to specify the distribution for M, the method for generating uncertainty in the catch matrix and the abundance indices, and the number of data sets to be analysed. Outputs from the simulation are: estimates population size and fishing mortality by age and year and the value of M selected for the ADAPT analysis. These outputs are used to compute various other quantities of interest.

The ADAPT Model and the Fishery Data

The specific formulation of ADAPT is the same as used by Baird et al. (1990) and is reviewed only briefly here. Catch data for ages 3 to 13 were available from 1978 to 1989. Indices used for calibration were as follows: Research vessel abundance, estimated from a stratified-random design, for ages 3 to 12 from 1978 to 1989; and commercial C/E, estimated from a multiplicative model (Gavaris, 1980), for ages 5 to 8 from 1983 to 1989. The research vessel indices were obtained in the fall and were assumed to represent population size at the end of November. The commercial cpue 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, weighted by population number at age, for ages 7 to 9.

The objective function to be minimized is

$$\sum_{age}\sum_{year}\{obs(\ln RV_{i,t})-pred(\ln RV_{i,t})\}^2 + \sum_{age}\sum_{year}\{obs(\ln C/E_{i,t})-pred(\ln C/E_{i,t})\}^2$$

where obs(·) and pred(·) refer to observed and predicted quantities, respectively; $\ln RV_{i,t}$ refers to the logarithm of research vessel results (observed or predicted) for age i and year t; and similarly $\ln C/E_{i,t}$ 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.

Descriptions of the Uncertainty

Natural mortality was felt to lie somewhere between 0.15 and 0.25 yr^{-1}. The "most likely" value, i.e. the value used in the assessments of the stock, is 0.2. However, there is not a lot of supporting evidence for this value, so M was given a uniform distribution in the interval (0.15,0.25).

The total catch (Table 7 of Baird et al. 1990) was felt to be known quite precisely but it was recognized that there could be some error is the estimated age composition. Simulated catches were generated by the following method:

$$C_{i,t}^* = C_{i,t}(1+RND)$$

where $C_{i,t}$ is the nominal catch at age i in year t, RND is a uniform random number between -0.05 and +0.05, and $C_{i,t}^*$ is the simulated catch at age i in year t.

All values of the research vessel abundance indices were assumed to be estimated with a coefficient of variation (cv) of 25% based on Table 23 in Baird et al. (1990). Hence,

$$CV = .25 = \text{standard error/mean}$$

and

$$\text{variance} = (\text{standard error})^2 = (.25\text{mean})^2.$$

To all values of the research vessel indices (obtained from the stratified-random design), a normally distributed random number was added with mean equal to 0 and variance as above.

The same procedure as used for the research vessel abundance indices was used for the commercial C/E indices except that the coefficient of variation was assumed to be 15%. The commercial catch rate data were presumed to be less variable than the research vessel data since they are based on much larger samples.

ADAPT Outputs - Population Size and Fishing Mortality

The simulation provides 1000 estimates of the matrix of population size by age by year corresponding to the 1000 simulated data sets. It is of interest to see how the uncertainty in population estimates varies with year and with age. This can be accomplished by computing the coefficient of variation for the estimates for each age-year combination (Figure 1). As expected, the estimates are most uncertain in the most recent years and for the youngest age groups. The lowest uncertainties (smallest cv's) are associated with ages 6, 7 and 8 which are dominant in the catches.

Median age 3 population estimates (recruits) by year, along with the 2.5th and 97.5th percentiles of the 1000 iterations are presented in Figure 2. It can be seen that a larger degree of uncertainty occurs in the terminal year than in the "converged" portion of the time series. The range of probable recruits in 1989 is about between half and double the median value.

Variability in the estimates of fishing mortality (Figure 3) show the same pattern as the variability in population estimates, with the estimates in the terminal year and at the youngest age groups most variable. It is interesting to note that the coefficients of variation for the estimates at age 13 in most years are lower than the estimates at age 12. This is due to the particular way in which the estimates for age 13 were computed: these estimates were set at one half the mean of the estimates for the fully recruited age groups 7 to 9. Thus, the coefficients of variation for age 13 estimates are solely a function of the uncertainties in the estimates at ages 7, 8 and 9. This underscores the important fact that the simulation results are conditional on whatever assumptions are made in the data analysis step.

Median annual fishing mortality (the average of ages 7-9 weighted by population numbers), with 2.5th and 97.5th percentiles, also indicate the degree of uncertainty in the terminal year (Figure 4). The range of probable fully recruited F's is between 0.45 and 0.75. The mean value is about 0.60 (Figure 5) and there are no estimates of age 7-9 F in 1989 below 0.40 or above 0.85.

Derived Statistics - Multipliers to Reach $F_{0.1}$ and F_{max}, and Total Allowable Catches

Obtaining estimates of population size and fishing mortality are usually not the ultimate goal of an assessment. Interest is frequently centered on statistics which are derived from the results of the sequential population analysis. Managers want to consider catch projections, compute appropriate quotas or effort restrictions, and conduct risk analyses. The output distributions from the simulated data sets analyzed with ADAPT can be fed into yield per recruit and other analyses to quantify the uncertainty in these derived statistics.

Multipliers for Fishing Mortality

Some fisheries are managed by attempting to control the fishing mortality, e.g. to achieve the $F_{0.1}$ or F_{max} level. The necessary weight at age information was taken from Table 54 of Baird et al. (1990). We determined the multiplier for the current vector of fishing mortality (i.e. F's in 1989) that would maximize yield (achieve F_{max}) and, similarly, that would meet the $F_{0.1}$ criterion given the ADAPT results for the simulated data set (Figure 6). From the 1000 simulations, it seems that fishing mortality would have to be cut to about 40%-50% of its current value (whatever that may be) in order to achieve the $F_{0.1}$ level. In contrast, it appears that the best estimate is that fishing mortality would remain approximately the same in order to achieve F_{max} but this is by no means clear since the spread in the distribution of multipliers is very much wider than that for achieving $F_{0.1}$.

Total Allowable Catches

To make projections to the future requires a prediction of future recruitment. For each simulated data set, we used the arithmetic mean of the number of three year olds between 1978 and 1989 as the projected recruitment.

The distributions of estimated total allowable catches (in metric tons) necessary to achieve $F_{0.1}$, F_{max}, and $F_{status\ quo}$ are shown in Figures 7, 8, and 9, respectively. The same information is also presented in a single graph (Figure 10) for ease of comparison of the catches from the three options of reference F. Of particular interest is the distribution of catches for achieving $F_{status\ quo}$. The current total allowable catch of 197,500 mt is well to the left of the center of the distribution. Thus, the chances appear quite good (to us) that the fishing mortality will not be higher in 1990 than in 1989. (Bear in mind the caveat that the specifications of uncertainty in this example are ad hoc and intended for illustrative purposes only!) However, it is not inconceivable for the fishing mortality to increase under this quota.

Another possibility is to compute the catch that would leave the population with the same biomass at the end of the year as at the beginning. This option has occasionally been considered in Atlantic Canada but is not presented here.

Sensitivity Analysis - Effects of Improving Indices and Improving Estimates of M

An interesting question is "to what extent is the uncertainty in the assessment model outputs dependent on the uncertainty in individual inputs?". For example, one might wish to explore how much the uncertainty can be reduced if one reduces the uncertainty (variance) in the abundance index estimates, and whether this would be worth the additional sampling effort given that there is such uncertainty in the estimate of natural mortality. These kinds of questions can be answered by conducting additional sets of simulations with a variety of input distributions and comparing the results with the baseline or "best guess" simulations.

In conducting such simulations, one can achieve improved efficiency if one uses the same streams of random numbers for each scenario considered. Use of common random numbers is a standard technique for variance reduction in simulations (Law and Kelton 1982).

Discussion

The method we have presented is intuitive and very *general*. The uncertainties in the assessment model can be specified in any way the user wishes. One can even incorporate data-dependent decisions about model formulation in the simulation. For example, if in practice one discards any calibration index which fails certain preliminary tests, one can employ the same procedure for each simulated data set.

Regardless of how the uncertainty is specified, the results of the simulation must be regarded as being conditional on whatever is being assumed. For example, in our simulation study we assumed the catch equation is valid. If, in fact, there is some error associated with this assumption (due, say, to fishing mortality being variable over the course of the year) then this additional uncertainty will not be properly reflected in the simulation results. It should be noted that one can obtain standard errors directly from the ADAPT approach, but, these estimates are even more highly conditional on assumptions than the results from our simulation. We believe that, in general, the ADAPT standard errors are much to optimistic.

Since the descriptions of uncertainty in the outputs are based in part on perceived (rather than measured) uncertainties in the inputs, the simulation results are necessarily subjective. This is by no means a fatal flaw, however. In any simulation there will be differences of opinion about the nature of the inputs. The simulation approach encourages scientists to openly specify their judgements and then enables these judgements of uncertainty to be translated into personal uncertainties about the assessment outputs. The approach can therefore lead to more open and honest evaluation of the fishery.

We also wish to stress that the sort of simulation we recommend quantifies uncertainty in outputs based on perceived and/or measured uncertainty in inputs; it does not give "ultimate truth". This type of simulation cannot be used to evaluate the performance of an assessment method or to decide between competing methods. Evaluation of methods can only be done by testing the methods on artificial populations for which the parameters are known.

Acknowledgments

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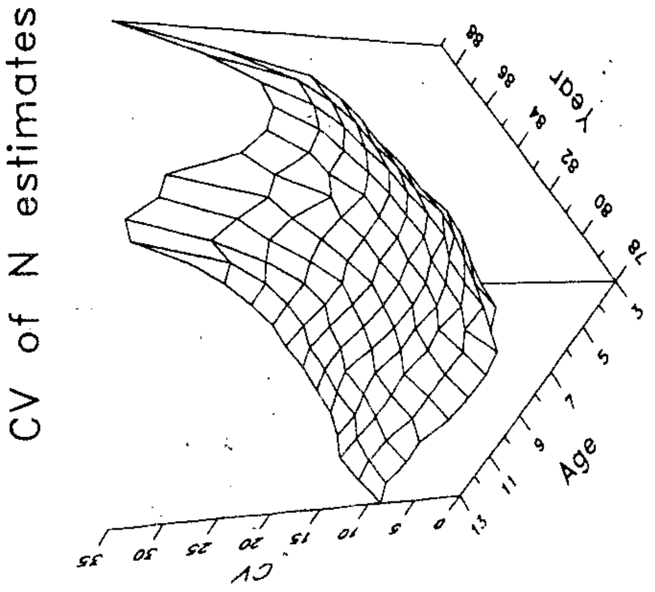

Figure 1. Coefficients of variation for age- and year- specific estimates of population size (N, in numbers) for 1000 simulated data sets analysed by ADAPT.

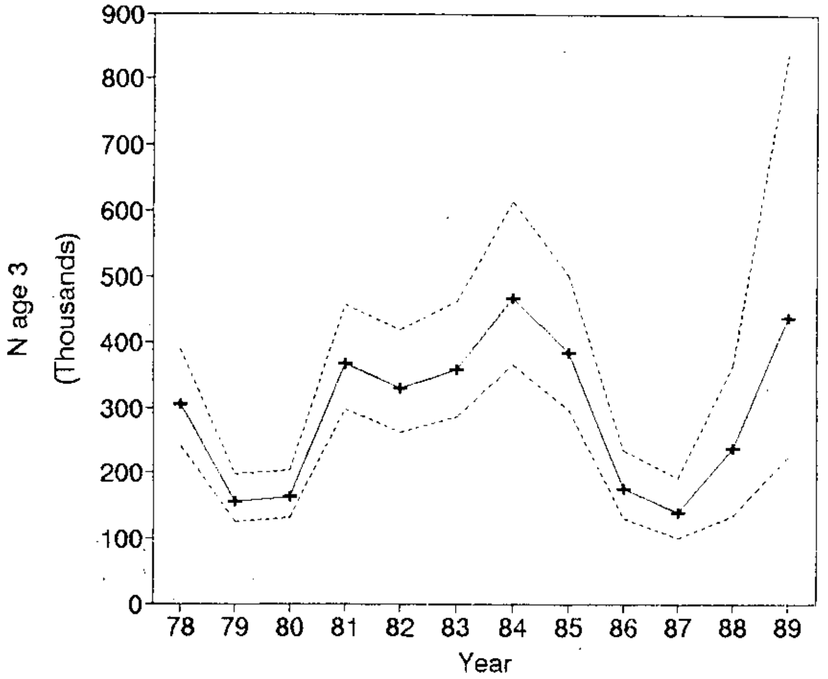

Figure 2. Median age 3 population estimates by year along with 2.5th and 97.5th percentile from the 1000 outputs of ADAPT.

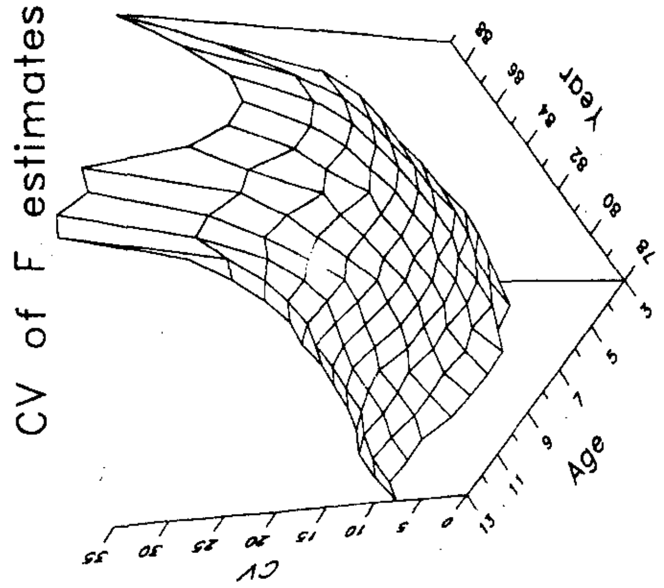

Figure 3. Coefficients of variation for age- and year-specific estimates of fishing mortality (F, per year) from 1000 outputs of ADAPT.

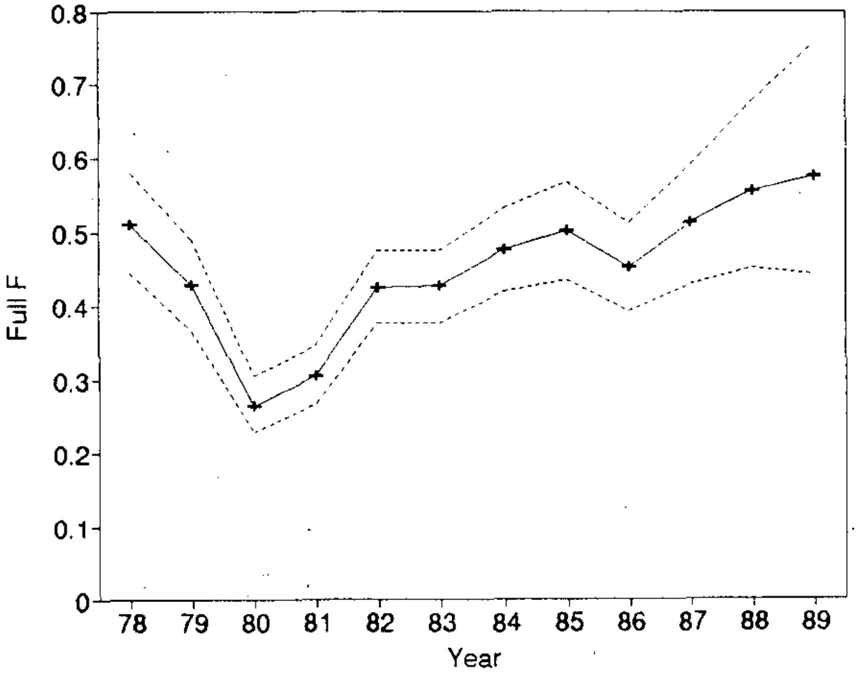

Figure 4. Median fishing mortality estimates (mean F ages 7-9, weighted by population numbers) by year along with 2.5th and 97.5th percentile from the 1000 outputs of ADAPT.

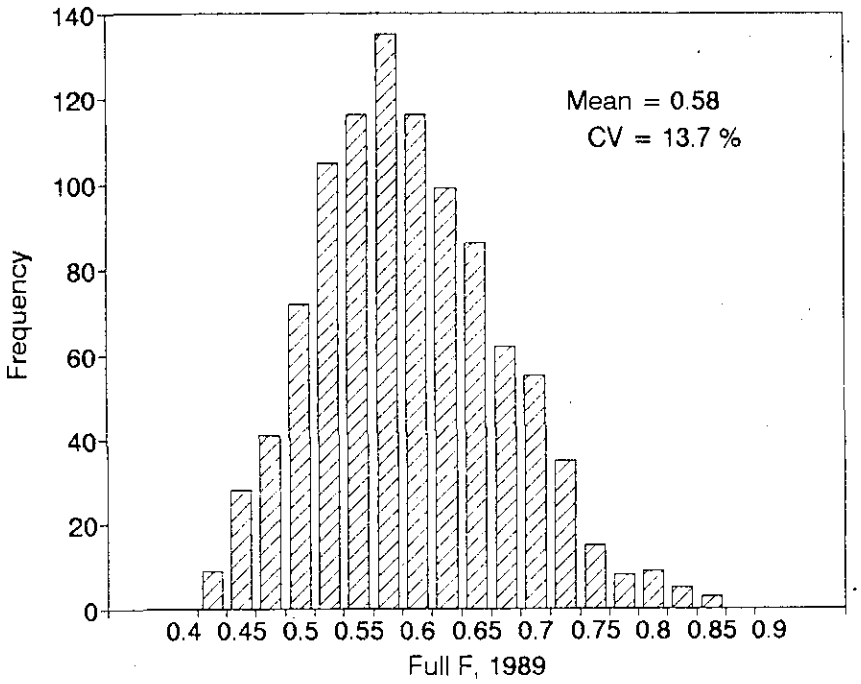

Figure 5. Frequency distribution of fishing mortality (mean F ages 7-9 weighted by population numbers) for 1989 from 1000 outputs of ADAPT.

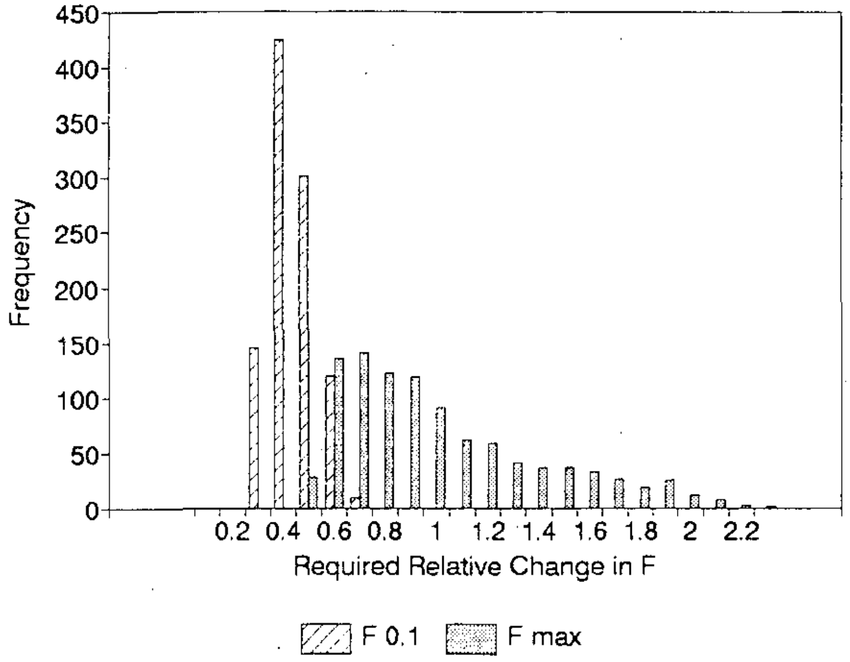

Figure 6. Frequency distribution for estimates of the F-multiplier necessary to achieve $F_{0.1}$ and F_{max} in 1990 for 1000 simulated data sets analyzed by ADAPT.

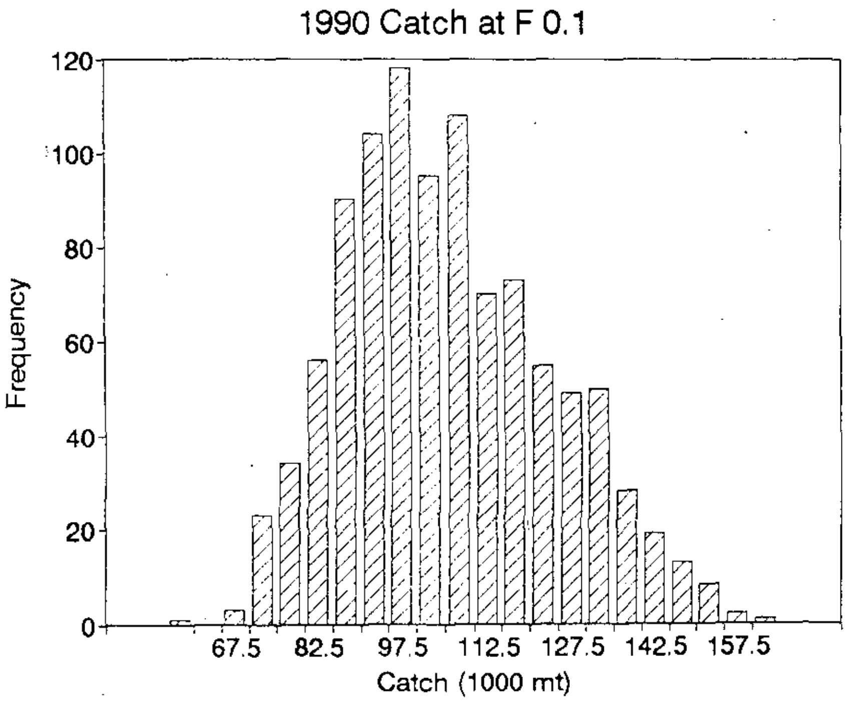

Figure 7. Frequency distribution for estimates of catch necessary to achieve $F_{0.1}$ in 1990 from 1000 outputs of ADAPT.

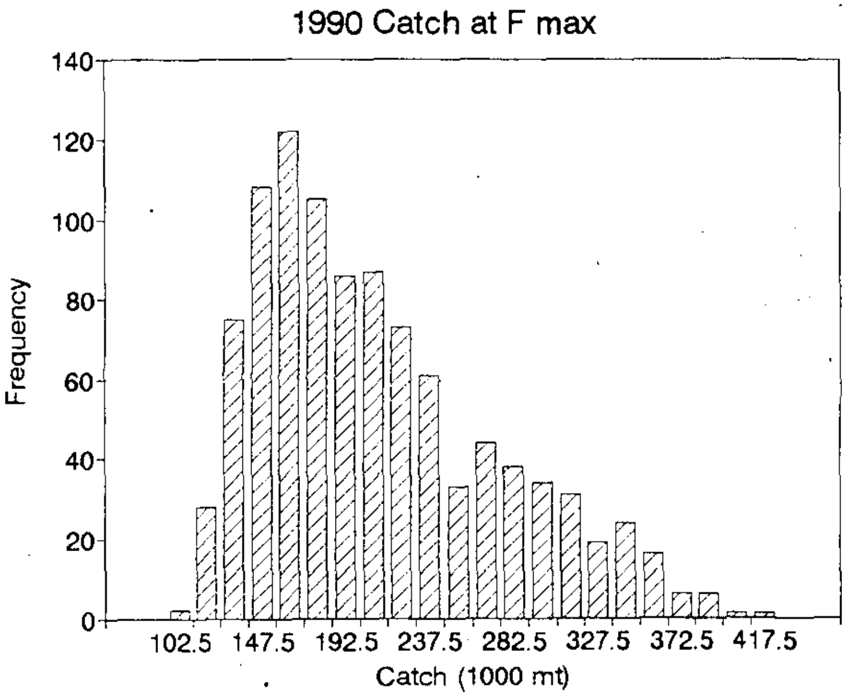

Figure 8. Frequency distribution for estimates of catch necessary to achieve F_{max} in 1990 from 1000 outputs of ADAPT.

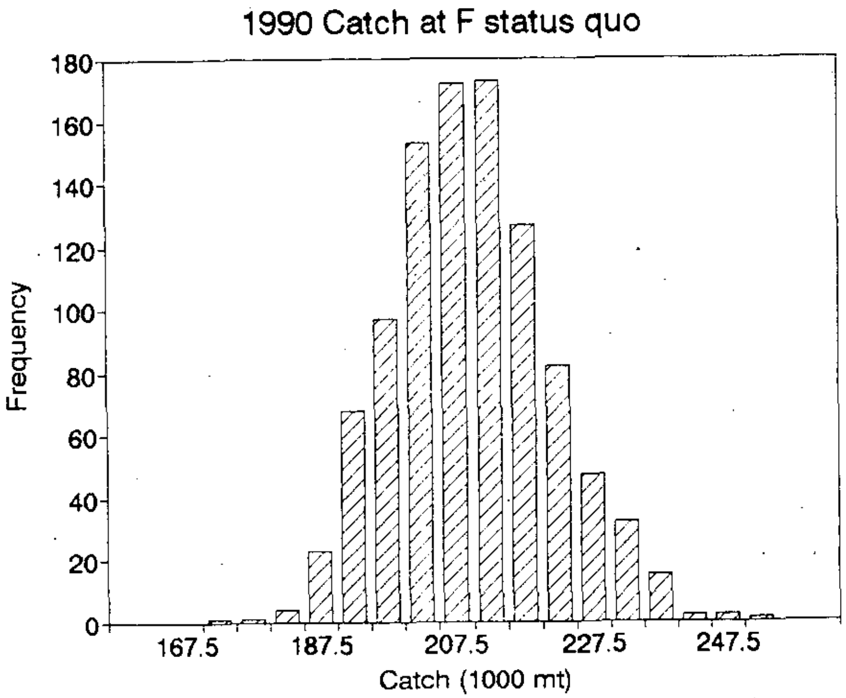

Figure 9. Frequency distribution for estimates of catch necessary to achieve $F_{status\ quo}$ in 1990 from 1000 outputs of ADAPT.

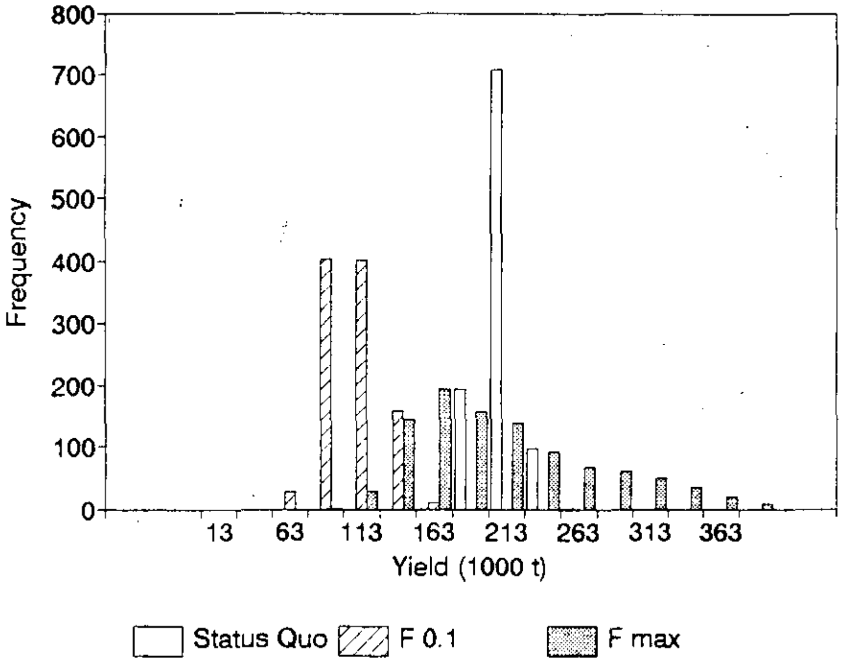

Figure 10. Frequency distribution for estimates of catch necessary to achieve $F_{0.1}$, F_{max} and $F_{status\ quo}$ in 1990 from 1000 outputs of ADAPT.