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# Comparisons of Long-Term Yields from Catch Quotas and Effort Quotas Under Conditions of Variable Recruitment[1]

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## ABSTRACT

Simulation studies of a model of the Georges Bank herring stock and fishery were conducted to compare long-term catch rates from fixed catch quotas vs. fixed effort quotas, when recruitment varied from year to year.

Production capabilities of the population under varying spawner-recruit curves and catchability coefficients were determined using the general production model. Flat S-R curves caused relatively flat production curves and domed S-R curves gave more peaked production curves. The catchability coefficient had a significant effect on the peak of the production curve. Random fluctuations in recruitment did not substantially change estimates of harvest parameters (CMAX, fOPT). In general, the error of estimates of CMAX was greater than that for fOPT.

When recruitment varies and quotas are accurately set, effort quotas usually produce higher long-term CPUEs unless the production curve is flat-topped. Then, catch quotas give higher CPUEs. Effort quotas in general give higher CPUEs as the production curve becomes more peaked and variations in recruitment increase. Increases in the catchability coefficient do not alter these conclusions. When quotas are overestimated, effort quotas give higher CPUEs. When they are underestimated, catch quotas give higher CPUEs. The advantage of the catch quota in this situation is diminished as the production curve becomes more peaked. Increases in q do not alter these conclusions, either.

## INTRODUCTION

Yields obtained from a fishery in which fishing mortality is controlled by a catch quota may differ from yields from a fishery regulated by an effort quota. Such a difference would occur because variable recruitment occurs in most fisheries. In simple terms,

$$\text{annual yield to fishery} = \text{annual instantaneous fishing rate} \times \text{average population size during year}$$

it can be seen that if a strong year class enters a fishery in which the annual yield is fixed by quota, the fishing rate will be decreased, the population increased, and the annual catch

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will be below its maximum potential unless the quota is adjusted upward. On the other hand, as a weak year class moves through the fishery, a fixed catch quota would lead to an increased fishing rate. Even if it is possible to make adjustments in a catch quota, for example, by prediction of recruitment, errors of prediction of recruitment will always reduce the long-term yield below the maximum sustainable yield (MSY). Under a fixed effort quota, the annual yield will fluctuate with the size of the population, maintaining a constant exploitation rate which, if set at the right level, will increase long-term catch.

Examination of this formulation leads to the conclusion that if catch or effort are regulated by setting them at a constant amount over a period of years, and if they are set correctly at the MSY point, variations in recruitment will cause the average catch to be less than the long-term maximum yield when catch quotas are used. Even when the catch is adjusted for variations in recruitment, any errors in this adjustment will lead to average catch less than the maximum. This factor does not apply to regulation of effort. One may of course set both the catch and effort at the wrong level, but variable recruitment would still be a factor having consequences similar to those outlined above.

The purpose of this paper is to examine more exactly the effects of two regulatory methods, catch quotas and effort quotas, upon the long-term yield of a fishery, when recruitment varies. To do this a fish population and fishery were studied using a computer simulation model. This type of modeling greatly facilitates the bookkeeping necessary to keep track of the various age groups in a population which is increasing due to growth and recruitment and is decreasing due to natural and fishing deaths, over a number of years. Data from the Georges Bank herring stock and fishery were used as an example for the modeling. The intent has been to emphasize comparisons of regulatory methods, and not to account for all the details of the fishery itself. Thus, a rather simple representation of the fishery has been constructed which does not include all the possible complexities involved in the dynamics of the Georges Bank herring population and fishery.

## THE MODEL

The model used for the simulations was modified from that described by Walters (1969) which was based upon the Beverton and Holt yield equation. The model assumes a unit stock with a specified stock-recruitment relationship. For any year of simulation, the following sequence is followed:

1. Fishing and natural mortality rates are applied to the initial age structure from the beginning of the year up until spawning time to determine the size and structure of the population at spawning time. The size of the spawning population is determined by multiplying the numbers in each age group surviving to spawning time by the age specific relative fecundity indices and summing over age groups.

2. The spawner-recruit relationship determines the number of young (recruits produced from this year's spawning population) to enter at the beginning of the next year. The age structure at spawning time is stored for future use in the event of a time lag between spawning and recruitment into the population.

3. Annual yield from the population is calculated employing the Beverton and Holt yield equation, using inputs of natural and fishing mortalities and growth parameters. Annual fishing mortality is adjusted to account for age-specific gear selectivity and is calculated from the input value of effort and the coefficient of catchability. The annual catch quota, also an input, is attained by incrementing effort up to a specified limit, which is used to prevent the population from going to extinction.

4. The population surviving to the end of the year is calculated by age group based upon fishing and natural mortality rates. This population structure is then advanced to the beginning of the next year, with the oldest age group being replaced by the recruits generated from step 2. The simulation continues with step 1 above.

Annual catches and CPUEs are then simulated over a specific number of years. The population information utilized by the model includes population size and age composition for the initial year of the simulation, growth parameters, age-specific natural mortality rates and relative fecundity indices and a stock-recruitment (S-R) relationship for the population. Fishery information required includes annual effort (days fished), catchability coefficients, selection curves (percent retained by the gear by age group), and annual catch and effort quotas. Data pertaining to fishing effort and catchability coefficients are year-specific but not age-specific. The spawning time, the time lag between birth and recruitment and age of the youngest age group fished, the Von Bertalanffy growth parameters and the form and parameters of the spawner-recruit relationship are specified by the modeler. For this study, the model has been modified to allow the setting of annual catch quotas to control fishing mortality. An upper limit to fishing mortality is specified to prevent infinite fishing when low stock sizes make it impossible to reach a given annual catch quota. Also, provisions have been made for random recruitment variations in the stock-recruitment relationship; annual recruitment values are chosen at random from a normal distribution specified by the mean and standard deviation. Thus, recruitment variations during simulations may be attributed to two sources: (1) those due to spawning stock size, and (2) those due to random variation about the S-R curve.

## DATA FOR THE MODEL

Most of the parameters and data for the model were taken from Schumacher and Anthony (1972) and are shown in Table 1. Estimates of natural mortality (M) were taken from their Table 12, and initial numbers from their Table 15, which gives calculated stock sizes based upon an increasing age-specific M schedule. The age composition shown in Table 1 represents an average over the years 1961-1971. Estimates of the percent retained in the gear by age are somewhat arbitrary, but based on the knowledge that age two herring are seldom caught in the Georges Bank fishery, ages three and four are recruiting, and age five fish and older are fully recruited to the gear. The estimated growth parameters (for Georges Bank) were used. A spawning time (expressed as a fraction of the basic time unit of one year) of .7 was used to represent the fall spawning habit of this stock. A lag of two years between birth and recruitment to the population was used, as little data is available on the population dynamics of the early life stages.

Age-specific relative fecundity values were calculated from information on fecundity and growth. The eggs-length relationship given by Perkins and Anthony (1969) for herring from Georges Bank was converted to eggs-at-age by obtaining length at each age from Von Bertalanffy parameters. Relative fecundity values were specified as the eggs at each age as a proportion of the total overall mature age groups, multiplied by a scaling factor of 10. This factor was necessary since the "effective" size of the spawning population each year is calculated by multiplying the numbers in each age group by the relative fecundity index. Age four was taken as the age of first maturity.

Two estimates of the catchability coefficient were made from the data given by Schumacher and Anthony. One estimate was taken from data on fishing effort (adjusted for learning and for the years 1965 and 1966) and instantaneous fishing mortality (F) from their Tables 3 and 8. Annual values of q were computed as the ratio of annual F to annual effort. These values were then averaged to obtain an overall figure. The other estimate was obtained from the fit of the general production model (Fox, 1973) to data in Schumacher and Anthony's Table 3, using PRODFIT (Fox, 1972), which provides estimates of q. Since the estimates obtained from the two methods differed substantially, both values were used during simulations. In all runs an arbitrary upper limit of F=2.0 was set to prevent continued fishing when catch quotas could not be reached because of low stock size.

Least known of all the data input requirements for the model is the nature of the spawner-recruit curve. Thus, two different curve forms were chosen to provide a range for study. These are shown in Figure 1; the asymptotic-shaped curve of Beverton and Holt, and the domed-shaped Ricker-type curve. The values on the axes of the curves in Figure 1 were established by assuming that the initial population age composition used for simulations represents a stable population, whereby recruitments are just sufficient to maintain the spawning population at a constant level. That is, $330 \times 10^7$ spawners (population total, ages 4 through 10 from initial age composition weighted by relative fecundity indices) continually produce $170 \times 10^7$ age two recruits (from initial age composition) under natural or pre-exploitation conditions. This point was taken as the start population level for simulations, and served as a common point for the spawner-recruit curves. The spawner-recruit parameters for the simulation model were estimated by reading values of corresponding spawning stock and recruitments from the curves, and then fitting these values by the Beverton-Holt model,

$$R = \frac{1}{a + b/S},$$

and by the Ricker model,

$$R = aSe^{-bS} \quad ,$$

where R = recruits, S = spawners, and a and b are constants, by least squares techniques after linearization to the forms

$$S/R = a\,S + b \text{ and}$$

$$\ln\,(R/S) = \ln(a) - bS, \text{ respectively.}$$

The parameters a and b (Table 1) were used as inputs to the computer model.

## ESTIMATION OF POPULATION PRODUCTION

The production model (e.g., Pella and Tomlinson's, 1969) provides a logical framework for the comparison of catch and effort quotas. The actual production capabilities of the computer population and the effort required to harvest this production must be determined before comparisons of regulation methods can be made, and the general production model provides a ready means of doing this.

Values of maximum sustained yield (CMAX)and the effort required to harvest it (fOPT) were estimated, for four sets of data from the simulated population by fitting the generalized production curve to the data sets using the computer program PRODFIT (Fox, 1972). The four data sets were generated by simulating yields from the population, using the two spawner-recruit curves just described (but without random variability), each with two values of the catchability coefficient. Average annual catches were determined from 32-year simulations for ten levels of constant effort for each data set.

Use of the general production model approach requires that equilibrium conditions prevail, i.e, that the rate of harvest each year removes the surplus not needed for reproduction of the stock. While effort levels did not change, disequilibrium was inherent in the simulations owing to fluctuating recruitment. These fluctuations are caused by the nature of the Ricker-type spawner-recruit curve, where compensatory mortality operates to cause fluctuations in recruitment due to spawning stock-size. In addition, random fluctuations in recruitment, to be introduced later into the simulation study, also contribute to disequilibrium conditions. In order to fulfill the equilibrium conditions of the yield model, average annual potential yield (Shaeffer, 1957) was estimated from annual catches and changes in stock size, where annual potential yield is equal to the annual catch plus the change in stock size during the year (see Appendix Ib). Thus, potential yields, instead of annual catches, were used in the production model analysis. Average annual efforts associated with potential yields were also calculated as shown in the appendix. This was done so that potential yields could be related to effort (instead of stock size, as is usually done) so that fOPT could be estimated from the fits of the general production model.

Predicted yield curves are shown in Figure 2 and the estimated harvest parameters given in Table 2. The influence of the spawner-recruit curve and the catchability coefficient can readily be seen. The Beverton and Holt-type S-R curve with essentially constant recruitment at most stock sizes gives a very flat-domed production curve. As q is increased the curve takes on a more pronounced peak with fOPT occurring at a lower value, which is to be expected since fishing mortality has been increased by the increase in q. The Ricker-type S-R curve produces a more domed-shaped production curve with a more steeply ascending right-hand limb. As before, an increase in q produces a more pronounced peak, with a shift in fOPT. It should be pointed out that the extremities of the right-hand limb of the predicted curves are somewhat overestimated, and probably drop off to zero yield sooner than is indicated in the figure. Each point on the potential yield curve represents the average yield for a 32-year simulation. The "accumulated stock" present in year one of a simulation is included in the average and tends to give high estimates of potential yield, especially for the higher values of effort where stock sizes contributing to the average potential yield are low.

The values shown in Table 2 were obtained in the absence of random fluctuations in recruitment. These values are used as catch and effort quotas in the following sections for comparing the two regulatory methods. For these comparisons, recruitment is allowed to vary. Thus, the affect of random recruitment variations on the stability of the estimates of CMAX and fOPT obtained as described above is of interest. In order to study these effects, simulation runs with random recruitments were conducted to estimate the production curves of the population. Procedures similar to those described above were used, except that random error was introduced around the spawner-recruit curves to produce fluctuations in annual recruitment. Three estimates of CMAX and fOPT were made for each set (S-R, q combination)[1] . Each estimate was calculated from simulations with different random recruitment sequences, but with each sequence having the same standard deviation.

The results of these fittings are shown in Table 3 and Figure 3 by run. The position of the estimates of CMAX and fOPT change only slightly within a set indicating that random recruitment changes do not greatly affect estimates of these parameters. The intervals around the estimates in the figure are precision intervals which incorporate the variance indices (Table 3) which are calculated by the PRODFIT program. Ratios of these indices to their respective values of CMAX and fOPT (Table 3) suggest that there is greater relative error around the estimates of CMAX than around fOPT estimates, especially for the more dome-shaped production curves.

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[1] One of the four sets (Ricker, q=.000025) could not be successfully fitted with PRODFIT.

## COMPARISONS OF CATCH AND EFFORT QUOTAS

### CMAX and fOPT Known Without Error

Let us assume that the productive potential of the population, and the effort required to harvest it, is known without error. Let us further assume that catch and effort are set at CMAX and fOPT and remain fixed through the duration of the fishery. That is, no adjustments are made in the harvest parameters for changing recruitment. Several stocks under quota management by the International Commission for the North Atlantic Fisheries are currently managed on this basis because detailed annual assessment studies are lacking (e.g., cod in Division 5Y and redfish in Subarea 5). Under these conditions we would expect that an effort quota would be superior, in terms of CPUE, to a catch quota, owing to the advantage of effort regulation in allowing automatic adjustment of catches with changing recruitments.

To test this premise, 16-year simulations were run whereby, for each of the previously described four data sets, catch and effort quotas were set equal to respective estimates of CMAX and fOPT and random annual fluctuations in recruitment were introduced at three levels of magnitude (standard deviation). Thus, three simulations were made for each type of regulation for each of the data sets.

The introduction of random recruitments precludes exact comparisons between catch and effort quotas. This is because the patterns of fishing mortality generated by the two types of quotas are different. This results in different spawning stock sizes, which results in variations in yearly recruitment levels predicted by the spawner-recruit relationship. With the method used for random number generation, for any year the predicted value of recruitment influences the random value picked for that year's recruitment. Unless the values of recruitment predicted from the S-R curve are precisely the same, the sequence of random recruitments for any two simulation runs will be somewhat different. Unless predicted recruitment is constant for all spawning stock sizes, differences in fishing mortality patterns caused by the different quota regulations (i.e., the exploitation rate will change under a catch quota and remain fixed with an effort quota when recruitment varies) will cause different annual stock sizes, thus causing variations in predicted recruitment. Because of this problem, some simulations were rerun, using different random number sequences, to obtain closer comparability between quota types in terms of average recruitment levels, and their standard deviations.

Results of these simulations are shown by run in Table 4 with corresponding population time paths given in appendix II. CPUE's are in general higher for effort quotas as compared to fixed catch quotas and average stock sizes are in general higher for effort quotas (appendix II). The notable exception is for the data set representing the Beverton and Holt S-R curve with q equal to .000014. Here we see that for all levels of variation in recruitment that catch quotas have higher CPUEs than effort quotas, owing to the fact that an effort significantly less than fOPT is required to obtain the catch quota. This can be explained by the shape of the production curve. When recruitment varies, the flat-topped dome of this data set's production curve allows a greater chance that the catch quota will be reached with an effort less than fOPT. This characteristic of the production curve affords the advantage, in terms of long-term CPUE, to catch quota regulation by allowing an economy of effort which overshadows the advantage of flexible yields inherent in the effort quota.

When the production curve is more peaked, the possibilities for catches within the range of CMAX, and yet with efforts below fOPT, are reduced. This allows the advantage of effort quotas in responding to fluctuating recruitment to come into play. Thus, we see that for the more peaked curves effort quotas in general produce higher CPUEs than catch quotas. Also, the differences between CPUEs increases as the production curve becomes more peaked. This advantage should be amplified with greater variations in recruitment. Although somewhat obscured by lack of exact comparability of recruitment patterns, there does appear to be a trend in this direction (Table 4). Differences between CPUEs also become greater in general with the more peaked production curves, and lesser with the flat curve as recruitment variations increase. For the second data set, represented by a moderately dome-shaped production curve, lower variation in recruitment results in a slight advantage for a catch quota. With greater variations in recruitment the advantages of an effort quota become more apparent. There appears to be no consistent pattern of difference between catch and effort regulation in terms of average annual yield. In most cases yields are similar.

One obvious disadvantage to effort regulation is that, even though a prescribed level of effort remains the same, the mortality exerted by it on the stock may increase because of increases in the fishing efficiency of the fleet or because of changes in availability. This may lead to a less-than-optimum regulatory situation. The effect of the above results of increases in fleet efficiency have been examined by rerunning some of the simulations of Table 4, allowing the catchability coefficient to increase by various amounts. It is realistic to believe that increases in q would in time be detected by the management agency and that corrective adjustments would be made. To simulate this situation, q was increased over a two-year period by 20, 40, and 80%, was allowed to remain at that level for five years, and was then reduced to its original level for the remainder of the 16-year simulation.

The results are given in Table 5 with corresponding stock sizes in appendix IIIa. While the complicating effect of non-comparable recruitment patterns hamper these comparisons also, some general conclusions can be made. Average annual stock size decreases with increases in q, because of increased fishing mortality. The maximum decrease in biomass, taking into account varying recruitment levels, is approximately on the order of 15-20%. However, these increases in q, even up to 80%, cause little change in the long-term CPUE values for effort quotas. In some cases, CPUEs increase somewhat. It is thus concluded that increases in fleet efficiency of this magnitude and form and at these stock levels do not detract from the conclusions regarding comparisons of quota methods.

## Effects of Error in CMAX and fOPT

Let us now relax the assumption of no error in CMAX or fOPT. In its place we shall presume that the management agency's estimates of these parameters are 50% off the true value, plus or minus. Predicted catch and effort quota values were altered by this amount. In the simulations for each data set, quotas were set 50% too high for the length of a run; in the next run, 50% too low.

The results can be seen in Table 6 with stock trends given in appendix IV. The general result is that when quotas are overestimated, effort quotas give higher CPUEs; when quotas are underestimated, catch quotas give higher CPUEs. This can be explained again by the shape of the production curve. The region of fOPT is the region of the curve with least slope. Therefore, errors in fOPT will have less effect on obtaining optimum catches than will equivalent errors in CMAX. When CMAX is overestimated initial catches are high but the long-term effect on CPUE is to depress it. However, when quotas are underestimated, catch quotas produce higher CPUEs, because effort is reduced substantially. Catch is also, of course, reduced substantially and average stock sizes are higher. When underestimated by a given percentage fOPT changes less than CMAX and the higher effort produces a lower CPUE. The advantage of a catch quota when underestimation occurs is reduced, however, as the production curve becomes more peaked in shape. Effort quotas give relatively higher CPUEs because of the interaction between recruitment variations and the shape of the curve. Theoretically, we would expect the advantage of effort quotas in the overestimation situation to be diminished as the production curve becomes more peaked because errors in fOPT would produce greater changes in catch. This result is not seen in the data of Table 6 partly because of the confounding effect of variations in recruitment pattern and partly because of the above-mentioned interaction between recruitment and shape of the production curve.

The effect of increases in fleet efficiency were examined in the same way as described previously for the case of no error in the harvest parameters. However, only the case of an 80% increase in q was studied. The results, shown in Table 7, are similar to those found previously. CPUEs decrease only slightly as average stock size is decreased by roughly 10-20%. Thus, again, increases in fleet efficiency of this magnitude don't alter the conclusions reached regarding the effect of errors in the parameters CMAX and fOPT.

## DISCUSSION

This study indicates that an effort quota in general produces higher CPUEs than a fixed catch quota when the stock being fished undergoes random variations in recruitment. This conclusion depends to some degree, however, on the shape of the production curve for the population. Thus, if the production curve is quite flat-topped (implying that the underlying relationship between the size of recruitments and the parent spawning population is essentially constant at most stock sizes) and the catchability coefficient is small (usually implying a large stock), a catch quota will yield higher long-term catch rates. Under these conditions, a catch quota would be advisable if the objective is to obtain the greatest catch with the least effort. If other objectives are viable, e.g., maintaining a certain level of effort, then an effort quota would be a better management action. However, for domed-shaped production curves, effort quotas produce higher long-term CPUE's than catch quotas, when recruitment varies.

When recruitment varies randomly, fOPT is less subject to error (and thus less subject to change) than CMAX. Unless the production curve is very peaked, there is less to be lost in long-term CPUE by maintaining a constant fOPT in the face of changing recruitment, than by maintaining a constant CMAX. Also, errors in determining fOPT will be less crucial to long-term CPUE than corresponding errors in CMAX, because a given change in fOPT will exert a less than proportional change in the catch. This feature is pertinent to the effect of increases in fleet efficiency. An increase in the catchability coefficient has the effect of increasing fishing effort above fOPT, but the effect of the increase is moderated by the production curve if it is moderately dome-shaped or flat.

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Table 1. Georges Bank herring population information used in computer simulations.

| Age | Initial numbers | Instantaneous natural mortality | Relative fecundity | Percent retained by fishing gear |
|---|---|---|---|---|
| 2 | $1700 \times 10^6$ | .20 | 0.00 | 0 |
| 3 | $1210 \times 10^6$ | .15 | 0.00 | 33 |
| 4 | $1216 \times 10^6$ | .15 | 0.60 | 67 |
| 5 | $1007 \times 10^6$ | .23 | 1.00 | 100 |
| 6 | $655 \times 10^6$ | .36 | 1.30 | 100 |
| 7 | $257 \times 10^6$ | .50 | 1.60 | 100 |
| 8 | $88 \times 10^6$ | .64 | 1.70 | 100 |
| 9 | $44 \times 10^6$ | .83 | 1.90 | 100 |
| 10 | $20 \times 10^6$ | 1.03 | 1.90 | 100 |

Von Bertalanffy growth parameters: $W_\infty$ = 380 grams
k = .347

Catchability coefficient = .000014, .000025

Youngest age fished = 3 years old

Lag between birth and recruitment to the simulated population = 2 years

Spawning time, as a fraction of the year = .7

| | Beverton & Holt | Ricker |
|---|---|---|
| Parameters of the spawner-recruit function: | $a = 6 \times 10^{-10}$<br>$b = .1 \times 10^{-1}$ | $a = 5.5$<br>$b = 7 \times 10^{-10}$ |

Table 2. Estimates of CMAX and fOPT derived from simulations for four data sets for Georges Bank herring.

| | CMAX (m.t.) | fOPT (days) |
|---|---|---|
| Beverton and Holt<br>q = .000014 | 183000 | 68000 |
| Beverton and Holt<br>q = .000025 | 210000 | 41000 |
| Ricker<br>q = .000014 | 281000 | 46000 |
| Ricker<br>q = .000025 | 290000 | 22000 |

Table 3. Comparisons of estimates of CMAX and f OPT and their errors for three random simulations for each of three data sets for Georges Bank herring.

| Data Set | Run | (a) CMAX m.t. | (b) Variance index | (b)/(a) | (c) FOPT (days) | (d) Variance index | (d)/(c) |
|---|---|---|---|---|---|---|---|
| Beverton & Holt, q=.000014 | 1 | 169568 | $.132\times10^{8}$ | 78 | 65251 | $.208\times10^{8}$ | 319 |
| | 2 | 173959 | $.397\times10^{8}$ | 228 | 62897 | $.260\times10^{8}$ | 413 |
| | 3 | 176921 | $.357\times10^{8}$ | 202 | 61109 | $.200\times10^{8}$ | 327 |
| Beverton & Holt, q=.000025 | 1 | 189938 | $.129\times10^{9}$ | 679 | 33536 | $.151\times10^{8}$ | 450 |
| | 2 | 194113 | $.201\times10^{9}$ | 1035 | 35771 | $.223\times10^{8}$ | 623 |
| | 3 | 197005 | $.273\times10^{9}$ | 1386 | 34564 | $.293\times10^{8}$ | 848 |
| Ricker, q=.000014 | 1 | 269461 | $.458\times10^{9}$ | 1700 | 49376 | $.228\times10^{8}$ | 462 |
| | 2 | 272286 | $.975\times10^{9}$ | 3581 | 41999 | $.389\times10^{8}$ | 926 |
| | 3 | 267195 | $.377\times10^{9}$ | 1411 | 44044 | $.161\times10^{8}$ | 365 |
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Table 4. Comparisons of yields under catch and effort quotas known without error, for four data sets.

| | Quota* | Average Annual Yield (m.t.) | Average Annual Effort (days) | CPUE | Diff-erence | Recruitment (Nos. x$10^{-7}$) Average | Recruitment (Nos. x$10^{-7}$) S.D. | Run |
|---|---|---|---|---|---|---|---|---|
| Beverton & Holt, q=.000014 | 183000-C | 185616 | 35714 | 5.20 | 2.21 | 179 | 29 | 1 |
| | 68000-E | 203352 | 68000 | 2.99 | | 182 | 29 | 2 |
| | 183000-C | 185929 | 45408 | 4.09 | 1.39 | 157 | 62 | 3 |
| | 68000-E | 183523 | 68000 | 2.70 | | 164 | 84 | 4 |
| | 183000-C | 185396 | 53571 | 3.46 | 1.00 | 165 | 109 | 5 |
| | 68000-E | 167114 | 68000 | 2.46 | | 173 | 129 | 6 |
| Beverton & Holt, q=.000025 | 210000-C | 212017 | 36143 | 5.87 | 1.25 | 169 | 38 | 7 |
| | 41000-E | 189215 | 41000 | 4.62 | | 164 | 52 | 8 |
| | 210000-C | 180733 | 61285 | 2.95 | -1.48 | 142 | 68 | 9 |
| | 41000-E | 181596 | 41000 | 4.43 | | 176 | 94 | 10 |
| | 210000-C | 184076 | 60828 | 3.03 | -1.65 | 157 | 94 | 11 |
| | 41000-E | 191982 | 41000 | 4.68 | | 162 | 79 | 12 |
| Ricker, q=.000014 | 281000-C | 276906 | 82755 | 3.35 | -2.91 | 277 | 60 | 13 |
| | 46000-E | 287829 | 46000 | 6.26 | | 282 | 42 | 14 |
| | 281000-C | 284792 | 45306 | 6.29 | -0.17 | 315 | 104 | 15 |
| | 46000-E | 297028 | 46000 | 6.46 | | 283 | 65 | 16 |
| | 281000-C | 273894 | 92652 | 2.96 | -2.90 | 233 | 119 | 17 |
| | 46000-E | 269752 | 46000 | 5.86 | | 265 | 123 | 18 |
| Ricker, q=.000025 | 290000-C | 292154 | 30771 | 9.49 | -3.46 | 278 | 56 | 19 |
| | 22000-E | 284913 | 22000 | 12.95 | | 278 | 47 | 20 |
| | 290000-C | 292106 | 33000 | 8.85 | -3.26 | 271 | 63 | 21 |
| | 22000-E | 266368 | 22000 | 12.11 | | 273 | 59 | 22 |
| | 290000-C | 292454 | 36714 | 7.97 | -4.64 | 242 | 114 | 23 |
| | 22000-E | 277361 | 22000 | 12.61 | | 290 | 113 | 24 |

*C = Catch quota, E = Effort quota

Table 5. Effects of increases in the catchability coefficient on the comparisons of Table 4 (runs 4, 10, 16, 22).

| | Quota | Run | CPUE (q constant) | Average Annual | | % Increase in q | CPUE | Average Annual | | % Change in stock | Run |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Recruits (Nos.x10$^{-7}$) | Stock (m.t.x10$^{-3}$) | | | Recruits (Nos.x10$^{-7}$) | Stock (m.t.x10$^{-3}$) | | |
| Beverton & Holt q = .000014 | 68000-E | 4 | 2.70 | 164 | 281 | +20 | 3.01 | 164 | 301 | + | 25 |
| | | | | | | +40 | 2.82 | 159 | 272 | -3 | 26 |
| | | | | | | +80 | 2.75 | 164 | 250 | -16 | 27 |
| Beverton & Holt, q = .000025 | 41000-E | 10 | 4.43 | 176 | 269 | +20 | 4.17 | 150 | 245 | -9 | 28 |
| | | | | | | +40 | 3.36 | 119 | 199 | -31 | 29 |
| | | | | | | +80 | 4.89 | 178 | 258 | -4 | 30 |
| Ricker, q = .000014 | 46000-E | 16 | 6.46 | 283 | 559 | +20 | 6.51 | 274 | 533 | -5 | 31 |
| | | | | | | +40 | 6.31 | 271 | 498 | -11 | 32 |
| | | | | | | +80 | 5.97 | 255 | 446 | -20 | 33 |
| Ricker, q = .000025 | 22000-E | 22 | 12.11 | 273 | 574 | +20 | 13.64 | 300 | 601 | + | 34 |
| | | | | | | +40 | 13.67 | 281 | 580 | + | 35 |
| | | | | | | +80 | 14.49 | 304 | 563 | -2 | 36 |

Table 6. Comparisons of yields under catch and effort quotas, set with ± 50% error, for four data sets.

| | Quota* | Average Annual | | CPUE | Difference | Recruitment (Nos.x10$^{-7}$) | | Run |
|---|---|---|---|---|---|---|---|---|
| | | Yield (m.t.) | Effort (days) | | | Average | S.D. | |
| Beverton & Holt, q=.000014 | 275000-C+50% | 207624 | 127039 | 1.63 | -0.19 | 160 | 95 | 37 |
| | 102000-E+50 | 186134 | 102000 | 1.82 | | 156 | 89 | 38 |
| | 92000-C-50 | 99712 | 11735 | 8.50 | 4.30 | 169 | 81 | 39 |
| | 34000-E-50 | 142961 | 34000 | 4.20 | | 147 | 53 | 40 |
| Beverton & Holt, q=.000025 | 315000-C+50 | 186756 | 78599 | 2.58 | -0.19 | 165 | 80 | 41 |
| | 62000-E+50 | 171855 | 62000 | 2.77 | | 140 | 55 | 42 |
| | 105000-C-50 | 111639 | 7571 | 14.74 | 7.37 | 186 | 82 | 43 |
| | 21000-E-50 | 154849 | 21000 | 7.37 | | 149 | 70 | 44 |
| Ricker, q=.000014 | 422000-C+50 | 168265 | 144283 | 1.17 | -2.45 | 138 | 94 | 45 |
| | 69000-E+50 | 249603 | 69000 | 3.62 | | 235 | 78 | 46 |
| | 141000-C-50 | 149050 | 13673 | 10.90 | 1.34 | 234 | 64 | 47 |
| | 23000-E-50 | 219769 | 23000 | 9.56 | | 265 | 78 | 48 |
| Ricker, q=.000025 | 435000-C+50 | 148298 | 80599 | 1.84 | -7.03 | 119 | 96 | 49 |
| | 33000-E+50 | 292552 | 33000 | 8.87 | | 279 | 87 | 50 |
| | 145000-C-50 | 150203 | 9400 | 15.98 | 0.71 | 226 | 107 | 51 |
| | 11000-E-50 | 167941 | 11000 | 15.27 | | 219 | 81 | 52 |

*C+50% = catch quota, overestimated by 50%

E-50% = effort quota, underestimated by 50%

Table 7. Effects of increases in the catchability coefficient on the comparisons of Table 6.

| Quota* | Run | CPUE (q constant) | Average Annual |  | % increase in q | CPUE | Average Annual |  | % Change in stock | Run |
|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  | Recruits (Nos. x10$^{-7}$) | Stock (m.t.x10$^{-3}$) |  |  | Recruits (Nos.x10$^{-7}$) | Stock (m.t.x10$^{-3}$) |  |  |
| 102000-E+50 | 38 | 1.82 | 156 | 229 | +80 | 1.84 | 155 | 210 | -8 | 53 |
| 34000-E-50 | 40 | 4.20 | 147 | 368 | +80 | 5.48 | 161 | 389 | + | 54 |
| 62000-E+50 | 42 | 2.77 | 140 | 202 | +80 | 2.47 | 137 | 168 | -17 | 55 |
| 21000-E-50 | 44 | 7.37 | 149 | 366 | +80 | 6.46 | 124 | 282 | -23 | 56 |
| 69000-E+50 | 46 | 3.62 | 235 | 367 | +80 | 3.55 | 202 | 315 | -14 | 57 |
| 23000-E-50 | 48 | 9.56 | 265 | 739 | +80 | 10.29 | 261 | 645 | -13 | 58 |
| 33000-E+50 | 50 | 8.87 | 279 | 468 | +80 | 8.66 | 259 | 391 | -17 | 59 |
| 11000-E-50 | 52 | 15.27 | 219 | 657 | +80 | 20.47 | 259 | 696 | + | 60 |

*E+50 = effort quota overestimated by 50%

E-50 = effort quota underestimated by 50%

Appendix Ia. Simulated data used to estimate CMAX and FOPT for four data sets for Georges Bank herring.

Beverton and Holt-type Spawner-Recruit Curve

| Effort (days) | q = .000014 |  |  | q = .000025 |  |  |
|---|---|---|---|---|---|---|
|  | Catch (m.t.) | Potential yield (m.t.) | Calculated effort (days) | Catch (m.t.) | Potential yield (m.t.) | Calculated effort (days) |
| 10000 | 87550 | 88800 | 10142 | 127500 | 125000 | 9804 |
| 30000 | 162500 | 157000 | 28983 | 188600 | 179000 | 28471 |
| 50000 | 186600 | 177000 | 47428 | 194200 | 182000 | 46859 |
| 70000 | 193700 | 182000 | 65775 | 188700 | 175000 | 64911 |
| 90000 | 194200 | 182000 | 84337 | 179000 | 164000 | 82453 |
| 110000 | 191700 | 178000 | 102123 | 165800 | 150000 | 99536 |
| 130000 | 187300 | 174000 | 120749 | 148200 | 132000 | 115789 |
| 150000 | 182000 | 168000 | 138500 | 126100 | 110000 | 130797 |
| 170000 | 175900 | 161000 | 155556 | 100900 | 83800 | 141077 |
| 190000 | 168400 | 153000 | 172686 | 77850 | 60400 | 147317 |

Ricker-type Spawner-Recruit Curve

| Effort (days) | q = .000014 |  |  | q = .000025 |  |  |
|---|---|---|---|---|---|---|
|  | Catch (m.t.) | Potential yield (m.t.) | Calculated effort (days) | Catch (m.t.) | Potential yield (m.t.) | Calculated effort (days) |
| 10000 | 105500 | 112000 | 10616 | 172200 | 177000 | 10279 |
| 30000 | 248400 | 251000 | 30314 | 308300 | 306000 | 29775 |
| 50000 | 306400 | 304000 | 49608 | 221500 | 210000 | 47404 |
| 70000 | 287500 | 281000 | 68420 | 117900 | 102000 | 60570 |
| 90000 | 218300 | 207000 | 85236 | 77480 | 60300 | 70035 |
| 110000 | 151100 | 136000 | 98981 | 60650 | 43000 | 78040 |
| 130000 | 109100 | 93000 | 110846 | 51460 | 33500 | 84596 |
| 150000 | 85700 | 68800 | 120490 | 45640 | 27500 | 90461 |
| 170000 | 71870 | 54500 | 128842 | 41680 | 23400 | 95510 |
| 190000 | 63290 | 45600 | 136937 | 39160 | 20600 | 100000 |

Appendix Ib. Method of calculating effort corresponding to potential yield, for estimating harvest parameters for production curves for Georges Bank herring.

Potential yield,

$PY_i = C_i + (W_{i+1} - W_i)$, where $W_i$ is the population biomass at the beginning of year i,

and the effort corresponding to $PY_i$ is calculated as

$$f_i = \frac{PY_i}{C_i/f_i}$$

assuming $PY_i = qf_iW_i$ and $W_i = \frac{C_i}{qf_i}$, then $f_i = \frac{PY_i}{q\,\frac{(C_i)}{(qf_i)}}$

Appendix II. Average annual biomass ($m.t.x10^{-3}$) at the midpoint of each simulation year for comparisons of yields under quotas known without error (Table 4).

| Simulation | CATCH QUOTA RUNS | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| year | 1 | 3 | 5 | 7 | 9 | 11 | 13 | 15 | 17 | 19 | 21 | 23 |
| 1 | 590 | 592 | 597 | 581 | 572 | 583 | 553 | 554 | 550 | 551 | 549 | 553 |
| 2 | 541 | 560 | 572 | 516 | 486 | 528 | 462 | 449 | 446 | 454 | 446 | 447 |
| 3 | 493 | 554 | 551 | 456 | 395 | 487 | 426 | 394 | 382 | 410 | 396 | 371 |
| 4 | 447 | 569 | 519 | 409 | 336 | 442 | 443 | 414 | 357 | 421 | 406 | 337 |
| 5 | 404 | 576 | 460 | 376 | 318 | 356 | 478 | 482 | 354 | 452 | 439 | 350 |
| 6 | 375 | 550 | 377 | 357 | 311 | 231 | 493 | 528 | 377 | 472 | 455 | 396 |
| 7 | 309 | 494 | 288 | 344 | 277 | 144 | 466 | 518 | 426 | 479 | 447 | 441 |
| 8 | 385 | 426 | 233 | 324 | 222 | 156 | 415 | 503 | 464 | 492 | 446 | 465 |
| 9 | 414 | 368 | 245 | 292 | 172 | 189 | 372 | 550 | 459 | 513 | 473 | 481 |
| 10 | 443 | 344 | 295 | 265 | 152 | 177 | 354 | 655 | 420 | 524 | 512 | 526 |
| 11 | 466 | 355 | 321 | 261 | 134 | 149 | 352 | 750 | 360 | 518 | 537 | 601 |
| 12 | 480 | 372 | 315 | 281 | 111 | 130 | 345 | 796 | 300 | 515 | 544 | 649 |
| 13 | 485 | 353 | 311 | 304 | 109 | 142 | 320 | 802 | 265 | 533 | 536 | 617 |
| 14 | 478 | 293 | 317 | 307 | 134 | 190 | 275 | 794 | 240 | 563 | 513 | 517 |
| 15 | 462 | 225 | 308 | 281 | 163 | 249 | 222 | 808 | 212 | 579 | 492 | 401 |
| AVG. | 455 | 442 | 381 | 357 | 259 | 277 | 398 | 600 | 374 | 498 | 479 | 477 |
| | EFFORT QUOTA RUNS | | | | | | | | | | | |
| | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 | 22 | 24 |
| 1 | 505 | 499 | 489 | 487 | 493 | 486 | 543 | 542 | 546 | 555 | 552 | 557 |
| 2 | 368 | 333 | 309 | 322 | 328 | 320 | 454 | 448 | 484 | 493 | 473 | 499 |
| 3 | 334 | 259 | 225 | 283 | 261 | 275 | 449 | 440 | 502 | 507 | 459 | 505 |
| 4 | 318 | 236 | 201 | 305 | 231 | 270 | 479 | 488 | 528 | 548 | 503 | 531 |
| 5 | 297 | 243 | 217 | 323 | 230 | 265 | 510 | 541 | 557 | 579 | 574 | 536 |
| 6 | 282 | 250 | 232 | 300 | 237 | 275 | 534 | 564 | 588 | 599 | 628 | 525 |
| 7 | 279 | 239 | 203 | 254 | 246 | 284 | 554 | 558 | 575 | 615 | 648 | 529 |
| 8 | 284 | 212 | 178 | 227 | 290 | 246 | 572 | 547 | 496 | 636 | 641 | 576 |
| 9 | 283 | 186 | 205 | 230 | 345 | 192 | 593 | 543 | 399 | 670 | 617 | 669 |
| 10 | 278 | 179 | 244 | 248 | 334 | 204 | 611 | 554 | 360 | 702 | 585 | 745 |
| 11 | 274 | 215 | 257 | 265 | 261 | 266 | 609 | 570 | 410 | 707 | 575 | 754 |
| 12 | 274 | 293 | 252 | 258 | 197 | 297 | 583 | 590 | 515 | 687 | 592 | 710 |
| 13 | 279 | 362 | 235 | 234 | 170 | 284 | 559 | 632 | 600 | 652 | 600 | 638 |
| 14 | 288 | 373 | 262 | 217 | 180 | 271 | 563 | 682 | 607 | 614 | 584 | 582 |
| 15 | 291 | 335 | 360 | 221 | 226 | 264 | 582 | 685 | 555 | 590 | 576 | 587 |
| AVG. | 309 | 281 | 258 | 278 | 269 | 280 | 546 | 559 | 515 | 610 | 574 | 561 |

Appendix III. Average annual biomass (m.t.x$10^{-3}$) at the midpoint of each simulation year for runs demonstrating the effects of increases in q (Tables 5 and 7).

| Simulation year | a. EFFORT QUOTA RUNS (without error, table 5) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 |
| 1 | 506 | 496 | 490 | 485 | 489 | 495 | 543 | 553 | 535 | 555 | 557 | 558 |
| 2 | 377 | 327 | 312 | 313 | 315 | 357 | 450 | 502 | 428 | 487 | 507 | 511 |
| 3 | 356 | 256 | 242 | 258 | 248 | 322 | 426 | 537 | 392 | 484 | 542 | 563 |
| 4 | 346 | 237 | 253 | 257 | 219 | 283 | 443 | 571 | 406 | 521 | 607 | 654 |
| 5 | 299 | 262 | 305 | 248 | 190 | 259 | 501 | 564 | 437 | 570 | 661 | 716 |
| 6 | 224 | 304 | 322 | 207 | 157 | 281 | 578 | 521 | 436 | 607 | 698 | 698 |
| 7 | 196 | 302 | 281 | 171 | 134 | 280 | 618 | 471 | 402 | 630 | 689 | 611 |
| 8 | 227 | 263 | 223 | 179 | 147 | 224 | 598 | 466 | 387 | 662 | 605 | 540 |
| 9 | 255 | 242 | 195 | 212 | 178 | 178 | 547 | 488 | 403 | 684 | 479 | 511 |
| 10 | 277 | 245 | 186 | 229 | 169 | 158 | 503 | 468 | 414 | 668 | 415 | 482 |
| 11 | 311 | 244 | 169 | 218 | 126 | 149 | 493 | 413 | 403 | 629 | 461 | 441 |
| 12 | 346 | 257 | 171 | 209 | 100 | 173 | 536 | 408 | 437 | 613 | 580 | 457 |
| 13 | 337 | 268 | 185 | 217 | 114 | 218 | 590 | 460 | 511 | 625 | 676 | 529 |
| 14 | 269 | 222 | 197 | 232 | 170 | 241 | 597 | 513 | 550 | 633 | 661 | 582 |
| 15 | 188 | 159 | 224 | 239 | 225 | 248 | 570 | 534 | 545 | 649 | 567 | 592 |
| AVG. | 301 | 272 | 250 | 245 | 199 | 258 | 533 | 498 | 446 | 601 | 580 | 563 |
| | b. EFFORT QUOTA RUNS (± 50% error, table 7) | | | | | | | | | | | |
| | 53 | 54 | 55 | 56 | 57 | 58 | 59 | 60 | | | | |
| 1 | 462 | 561 | 441 | 554 | 503 | 606 | 518 | 607 | | | | |
| 2 | 294 | 469 | 231 | 454 | 366 | 623 | 407 | 626 | | | | |
| 3 | 278 | 404 | 192 | 390 | 342 | 681 | 399 | 671 | | | | |
| 4 | 266 | 372 | 200 | 347 | 358 | 736 | 433 | 710 | | | | |
| 5 | 217 | 386 | 187 | 309 | 403 | 756 | 467 | 732 | | | | |
| 6 | 142 | 419 | 138 | 257 | 427 | 716 | 454 | 728 | | | | |
| 7 | 130 | 414 | 102 | 205 | 381 | 634 | 406 | 712 | | | | |
| 8 | 158 | 375 | 116 | 197 | 307 | 584 | 396 | 686 | | | | |
| 9 | 160 | 344 | 139 | 225 | 253 | 573 | 394 | 633 | | | | |
| 10 | 167 | 337 | 132 | 227 | 220 | 554 | 350 | 581 | | | | |
| 11 | 185 | 335 | 105 | 189 | 207 | 522 | 293 | 580 | | | | |
| 12 | 214 | 361 | 103 | 163 | 241 | 549 | 289 | 658 | | | | |
| 13 | 215 | 394 | 128 | 180 | 271 | 638 | 329 | 766 | | | | |
| 14 | 160 | 366 | 152 | 235 | 241 | 724 | 353 | 851 | | | | |
| 15 | 105 | 300 | 160 | 303 | 198 | 777 | 375 | 900 | | | | |
| AVG. | 210 | 389 | 168 | 282 | 315 | 645 | 391 | 696 | | | | |

Appendix IV. Average annual biomass (m.t.x$10^{-3}$) at the midpoint of each simulation year for comparisons of yields under quotas set with ± 50% error (Table 6).

| Simulation year | CATCH QUOTA RUNS 37 | 39 | 41 | 43 | 45 | 47 | 49 | 51 |
|---|---|---|---|---|---|---|---|---|
| 1 | 561 | 617 | 542 | 618 | 505 | 613 | 498 | 602 |
| 2 | 474 | 609 | 408 | 635 | 345 | 627 | 324 | 592 |
| 3 | 421 | 585 | 282 | 662 | 290 | 672 | 253 | 607 |
| 4 | 378 | 576 | 174 | 712 | 272 | 741 | 229 | 666 |
| 5 | 304 | 607 | 132 | 767 | 217 | 817 | 191 | 760 |
| 6 | 192 | 676 | 154 | 795 | 146 | 887 | 147 | 848 |
| 7 | 148 | 753 | 195 | 767 | 107 | 937 | 121 | 898 |
| 8 | 178 | 799 | 197 | 684 | 130 | 962 | 94 | 916 |
| 9 | 187 | 802 | 154 | 589 | 159 | 961 | 63 | 910 |
| 10 | 197 | 774 | 133 | 518 | 140 | 923 | 77 | 873 |
| 11 | 221 | 722 | 148 | 482 | 106 | 863 | 116 | 796 |
| 12 | 227 | 659 | 166 | 483 | 93 | 815 | 135 | 692 |
| 13 | 191 | 598 | 168 | 533 | 88 | 789 | 118 | 599 |
| 14 | 127 | 551 | 149 | 632 | 87 | 788 | 82 | 537 |
| 15 | 80 | 535 | 159 | 736 | 94 | 803 | 76 | 519 |
| AVG. | 259 | 658 | 211 | 641 | 185 | 813 | 168 | 721 |

| | EFFORT QUOTA RUNS 38 | 40 | 42 | 44 | 46 | 48 | 50 | 52 |
|---|---|---|---|---|---|---|---|---|
| 1 | 452 | 563 | 443 | 556 | 500 | 598 | 521 | 605 |
| 2 | 244 | 475 | 239 | 464 | 349 | 588 | 432 | 616 |
| 3 | 187 | 416 | 199 | 406 | 305 | 617 | 468 | 658 |
| 4 | 179 | 386 | 209 | 357 | 317 | 672 | 528 | 713 |
| 5 | 208 | 374 | 230 | 321 | 356 | 737 | 531 | 766 |
| 6 | 256 | 375 | 228 | 308 | 385 | 818 | 485 | 814 |
| 7 | 269 | 382 | 200 | 296 | 378 | 895 | 457 | 838 |
| 8 | 243 | 371 | 172 | 273 | 333 | 926 | 483 | 805 |
| 9 | 227 | 327 | 157 | 255 | 291 | 892 | 539 | 713 |
| 10 | 233 | 275 | 155 | 272 | 305 | 822 | 562 | 600 |
| 11 | 233 | 249 | 170 | 324 | 371 | 760 | 508 | 519 |
| 12 | 231 | 268 | 177 | 390 | 434 | 721 | 406 | 492 |
| 13 | 217 | 311 | 155 | 433 | 440 | 700 | 339 | 516 |
| 14 | 158 | 355 | 144 | 435 | 389 | 682 | 350 | 571 |
| 15 | 103 | 394 | 155 | 400 | 345 | 658 | 411 | 629 |
| AVG. | 229 | 368 | 202 | 366 | 367 | 739 | 468 | 657 |

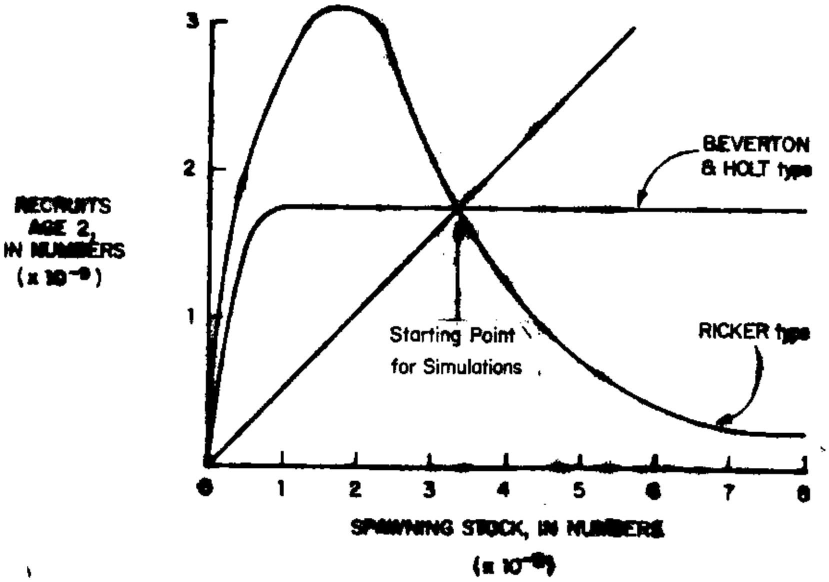

Fig. 1. Spawner-recruit curves used in simulations studies of catch and effort quotas for Georges Bank herring.

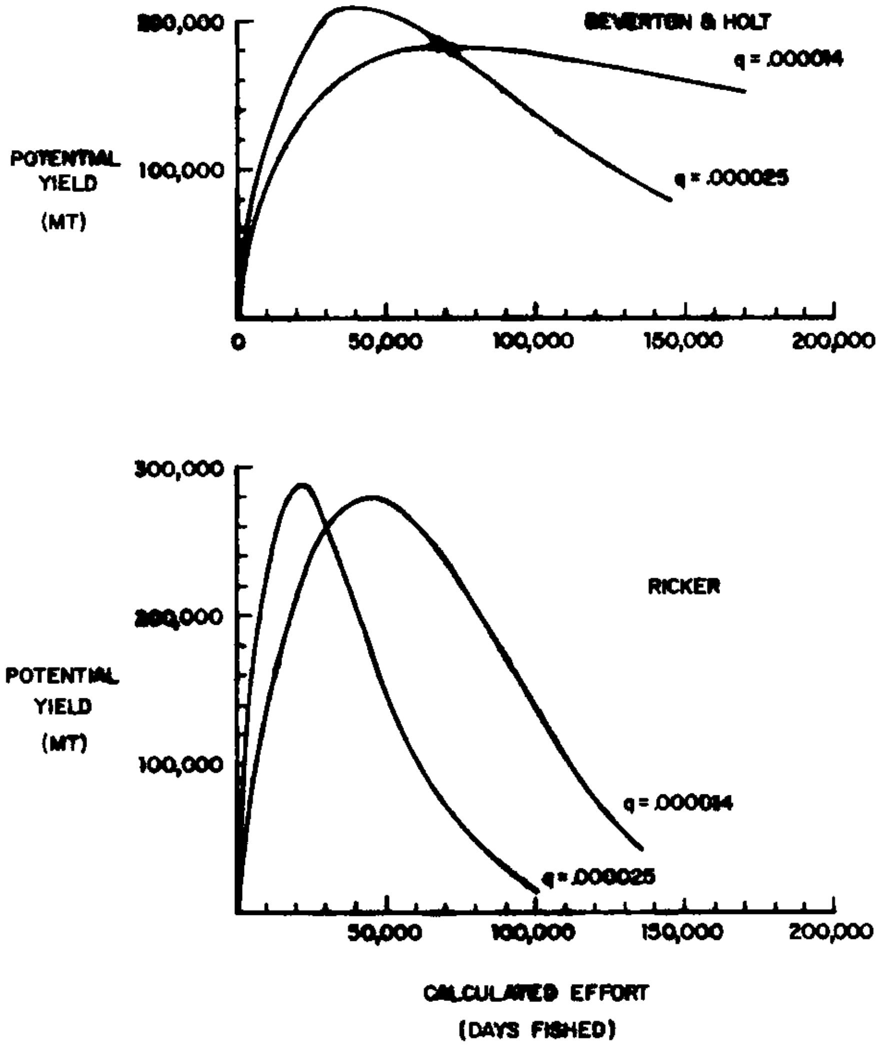

Fig. 2. Production curves estimated from simulations using four data set combinations for Georges Bank herring.

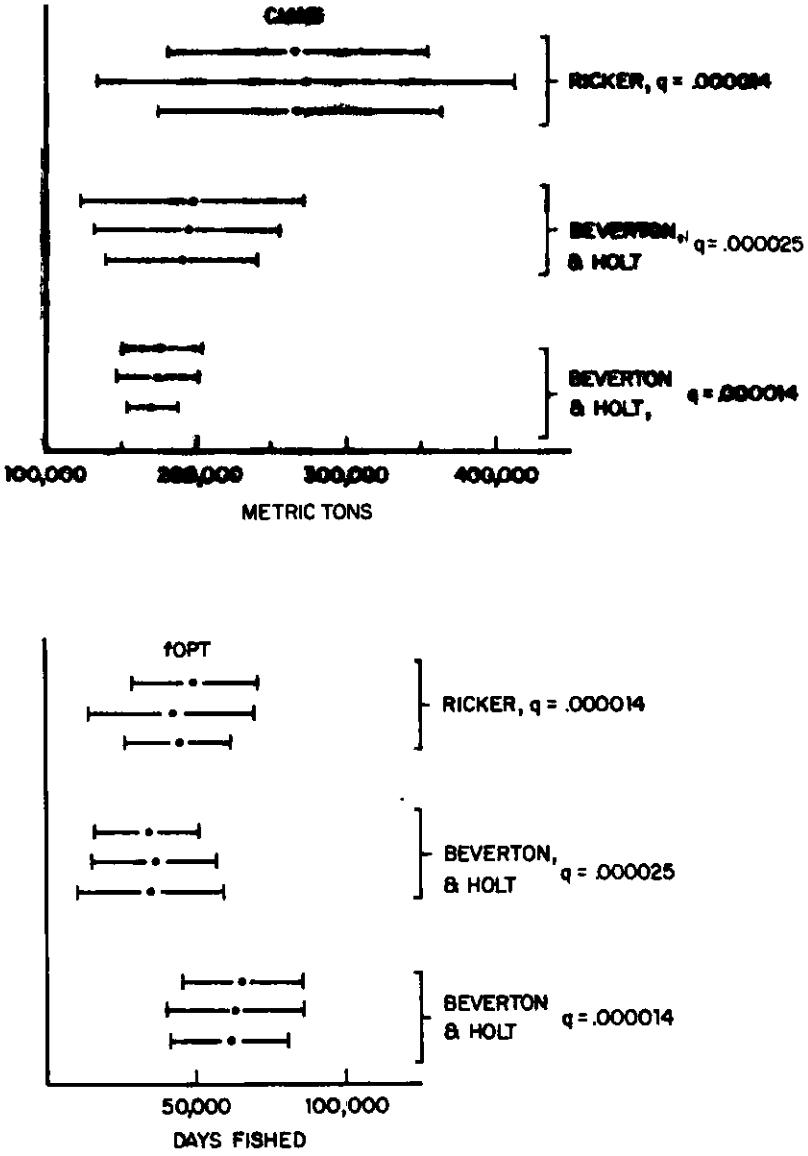

Fig. 3. Comparisons of estimates of CMAX and FOPT and their errors for three random simulations for each of three data sets for Georges Bank herring.