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NAFO Divisions 3NO Cod Stock - Spawner Stock Biomass and Recruitment Required for Replacement

by

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Abstract

Spawning stock biomass is calculated using annual estimates of proportion mature at age for the period 1972 to 1992. Past recruitment is compared to the amount required to replace the spawner stock. Three heuristics for determining the replacement threshold are applied and compared. We conclude that the stock has been fished above replacement in recent years. The nature of the stock-recruit relationship is examined. A non-parametric analysis is used to predict the probability of recruitment being less than or equal to that required to meet replacement at the spawner biomass and fishing mortality values estimated for 1990-92. It is concluded that the stock has been below the replacement threshold from 1983 to 1989, and that it is probable that the 1990-92 year classes were also below replacement at the prevailing levels of fishing mortality.

Introduction

Recent fishing mortalities have exceeded the target $F_{0.1}$ for most Canadian Atlantic gadoid stocks (Maguire and Mace 1993). This has led to a *crie-de-coeur* for an acceptable "biological" bottom line for restricting exploitation, which would override any economic, social or political objectives (Smith et al. 1993). A clear biological threshold at low spawner stock size is replacement - sufficient egg production, subsequent survival, growth and maturation to replace the existing spawner biomass. Failure to meet replacement will result in further declines in spawner stock biomass.

A variety of heuristics have been developed for defining the replacement threshold in a fish stock. Sissenwine and Shepherd (1987) suggested F_{rep} as a threshold whereas Mace and Sissenwine (1993) recommend replacement *%SPR*. We have introduced a further related procedure for determining a replacement threshold termed "annual replacement" (Shelton and Morgan 1993a, b, in press). In this paper we use the assessment of Davis et al. (1993) to show that the cod stock in NAFO Divs. 3NO has been fished at levels which exceed F_{rep}, replacement *%SPR* and annual replacement in recent years.

Spawner stock biomass

We use the ADAPT estimates of the beginning of the year numbers at age from the assessment of Davis et al. (1993), estimates of the beginning of the year weights at age from samples of the commercial catches (Fig. 1), and model estimates of proportions mature at age (Fig. 2) to calculate annual spawner biomass for the period 1972 to 1992 (Fig. 3). Model estimates of proportions mature at age come from a generalized linear model with age and year effects fitted to sample data from the spring research trawl survey in Divs. 3NO, using the methods outlined in Shelton and Morgan (1993a, b).

A comparison of spawner biomass calculated using maturity at age data with that calculated from the 6+ biomass (Fig. 3) shows that the 6+ biomass can overestimate the spawner biomass by as much as 45,000 tons. Although total biomass peaked in 1984, spawner biomass rose slightly during the early 1980s and only started to decline in 1987. This lag is primarily an effect of strong year classes of the early 1980s feeding into the spawner biomass, and not a consequence of compensatory changes in body growth or maturity. However, concomitant with the decline in spawning biomass, there is an indication of a possible compensatory increase in proportion mature at ages 5-7 after 1988, which ameliorated the decline in spawner biomass (Figs. 2, 3).

F_{rep}

F_{rep} is defined as the level of fishing pressure that reduces the spawning biomass of a year class over its lifetime below the spawning biomass of it parents on average (Sissenwine and Shepherd 1987). Recruitment values were taken from the number of 3 year olds estimated by ADAPT in the assessment by Davis et al. (1993), assigned to their birth year. Spawner biomass was taken from the estimates using maturity data presented above. The annual instantaneous rate of natural mortality was assumed to be 0.2, in keeping with the ADAPT formulation for this stock. Following Sissenwine and Shepherd (1987) we estimated F_{rep} from from the median "survival ratio" F_{med} (Fig. 4).

We calculated the F_0 replacement line using average weights and proportions mature at age for the past 5 years. The $F_{0.1}$ replacement line was calculated using mid year average weights at age and average partial recruitments for the 1985-89 period. We calculated two further reference replacement lines, $F_{88\text{-}92}$ using average weights, proportions mature and fishing mortalities at age for the period 1985-92 and $F_{85\text{-}89}$ using averages for the 1985-89 period. The stock-recruit scatter shows no coherent pattern with respect to spawner biomass. The cluster of low recruitment values for the 1983-87 period at an historically intermediate biomass (see data for 1959-92 in Davis et al. 1993) is somewhat perplexing.

The plot shows that recruitment has been below the F_0 replacement line from 1983-88, and below Frep from 1982-89. The 1972 and 1981-89 year classes were below replacement $F_{85\text{-}89}$ and all year classes were below replacement at $F_{88\text{-}92}$.

%*SPR*

%*SPR* is the amount of spawner biomass obtained from a single recruit at the average prevailing levels of fishing mortality, weights and proportions mature at age, relative to that obtained at F=0, expressed as a percentage. Mace and Sissenwine (1993) argue that in most contexts %*SPR* is preferable to F_{rep} as a basis for defining biological thresholds because the latter is a vector of numbers related to partial recruitment whereas the former is independent of partial recruitment. *%SPR* has been widely adopted by U.S. Fishery Management Councils (Mace and Sissenwine 1993) with levels of overfishing variously defined, mostly within the range of 20-30% *SPR*. We calculated *%SPR* for average values of fishing mortality, weights and proportions mature at age for the 1985-89, 1988-92 time periods as well as for the entire 1972-92 time period (Table 1) using equations (3) and (4) in Shelton and Morgan (1993a). These equations address the related problem of "How many recruits are required to give X tons spawners?" and can therefore be readily applied to *%SPR* calculations to answer the question "How many tons of spawners are obtained from one recruit?". A terminal age of 13 years was used in the calculations.

SPR at F=0 varies little depending upon the time period averaged. This reflects the relatively small variation in weights and proportions mature at age over the 1972-92 time period. *SPR* at the average prevailing F, however, varies considerably depending on the time period averaged. The 1988-92 time period gives the lowest *SPR* as a result of the elevated levels of fishing mortality in recent years.

Although no threshold *%SPR* has been identified for this stock, the *%SPR* values at the prevailing F levels shown in Table 1 are worse than the levels commonly used to define overfishing by U.S. Fisheries Management Councils (20-35%). Mace and Sissenwine (1993) recommend replacement *%SPR* as a reference point for defining overfishing. This is the *SPR* at F_{rep} relative to the *SPR* at F=0, expressed as a percentage. *SPR* at F_{rep} can be obtained graphically from Fig. 4 and is approximately 3.2, giving a replacement *%SPR* threshold of around 28%. This threshold is close to *%SPR* at the $F_{0.1}$ target. Fishing mortalities were in excess of the replacement *%SPR* threshold in all time periods examined.

Annual replacement

F_{rep} and replacement *%SPR* are useful heuristics related to determining a biological threshold. A third heuristic is "annual replacement" (Shelton and Morgan 1993a, b, in press). Annual replacement answers the question "How much recruitment is required to replace the spawner stock that gave rise to it at the age specific fishing mortalities, weights and proportions mature that *pertain to that year?*" Under conditions in which the population's ability to replace itself is deteriorating as a consequence of increasing fishing mortality or decreasing weights and proportions mature at age, annual replacement should provide a sensitive and conservative threshold compared to F_{rep} and replacement *%SPR*, which are based on averages (see e.g. Mace and Sissenwine 1993). We calculated annual replacement recruitment for the period 1972-92 and compared these with the estimated values of recruitment for the period 1972-89 (Fig. 5). Annual replacement at F=0 is provided for comparison (Fig. 6).

Recruitment has been below the annual replacement threshold at the prevailing level of F (Fig. 5) and below annual replacement at F=0 from 1983 onwards (Fig. 6), with the exception of 1989 year class relative to the F=0 replacement level. The annual replacement threshold at the prevailing level of F increased through the late 1970s and 1980s, largely as a result of the trend of increasing fishing mortality (see Davis et al 1993). Changes in the replacement level at F=0 (Fig. 6) are largely due to changes in spawner biomass rather than changes in weights or proportions mature at age.

If the probability distributions of recruitment for the last three years, for which no recruitment estimates are yet available from ADAPT, can be computed from spawner stock size, then the probability that recruitment exceeded replacement in the 1990-92 period can be determined.

In order to compute the probability distribution of recruitment at different stock sizes we applied the non-parametric approach of Evans and Rice (1988). We used a Gaussian probability density function as the weighting and estimated the shape parameter by minimizing the jackknifed prediction sums of squares.

The non-parametric model gave a 25% improvement in the jackknifed prediction sums of squares over the unweighted arithmetic mean recruitment (Fig. 7). The probability that the observed reduction in in the prediction sums of squares could be due to chance alone was estimated to be 0.06 by means of an approximate randomization test in which recruitment was randomly shuffled 500 times relative to spawner stock, the shape parameter estimated, and the prediction sums of squares computed. Details of the procedure can be found in Shelton and Morgan (1993a, b, in press).

The cumulative probability of recruitment at the 1990, 1991 and 1992 estimates of spawner stock size are plotted in Fig. 8. The shift to the right in the cumulative probability plot for 1992 reflects the increased probability of good recruitment at intermediate stock size, as indicated by the stock-recruit data. The position of annual replacement thresholds on the abscissa are off the graph to the right for all three years (i.e. there is a probability of 1 that recruitment was less than replacement for the 1990-92 year classes).

The positions of the replacement thresholds for hypothetical situations in which the annual fishing mortality is reduced by 50% are indicated by the vertical arrows. This indicates a substantial reduction in the risk of not meeting replacement could have been achieved through reduction in fishing mortality in those years. For the hypothetical situation of $F = 0$ the thresholds are in the left corner of the plot indicating a probability of close to 1 of exceeding replacement had fishing ceased entirely.

Conclusion

Each of the three alternative procedures for determining biological thresholds suggest that the NAFO Divs. 3NO stock is being overfished. The merits and robustness of these and other alternative procedures for determining biological thresholds for northwest Atlantic groundfish stocks need to be carefully examined by simulation (Sinclair 1993, Shelton in prep.). However, the agreement in those procedures applied in this analysis provides strong evidence of biological overfishing on this stock. The results also indicate that fishing mortalities would have had to have been substantially reduced to prevent a decline of the spawner biomass.

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Table 1. *SPR* and *%SPR* calculated using fishing mortalities, weights and proportions mature at age averaged for different periods. *SPR* is in the units kg spawner biomass per 3 year old.

Period averaged	*SPR*	*SPR* at F=0	*SPR* at $F_{0.1}$	*%SPR*
1988-92	0.6686	11.5246	3.2435	5.80
1985-89	2.4972	11.2058	3.3304	22.28
1972-92	1.5596	11.3102	3.3376	13.79

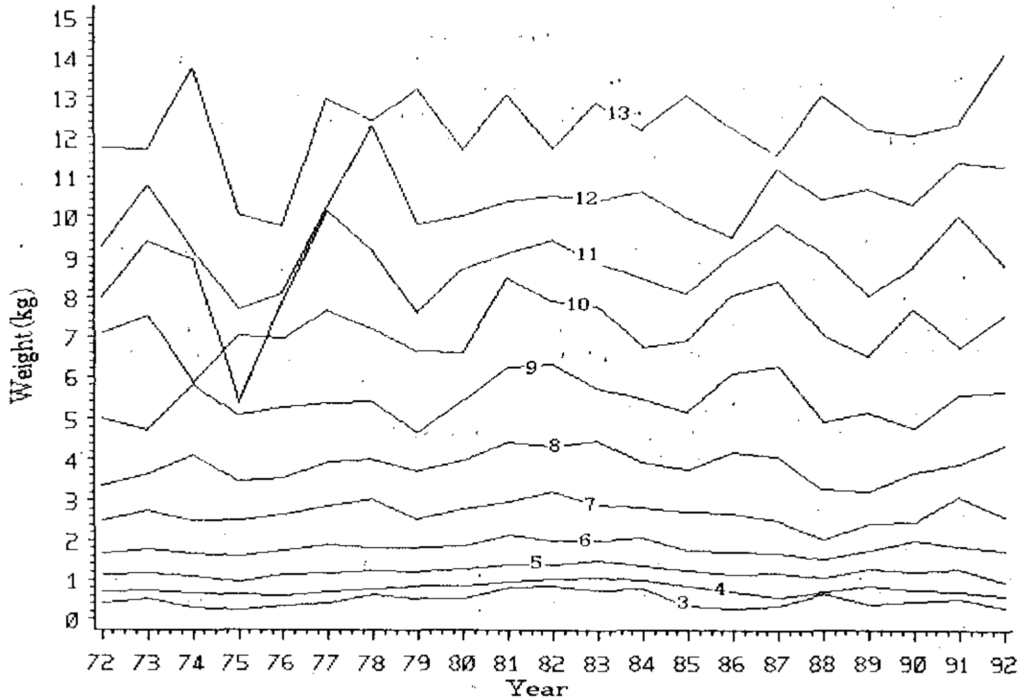

Fig. 1. Average beginning of the year weights at age estimated from samples of the commercial catch.

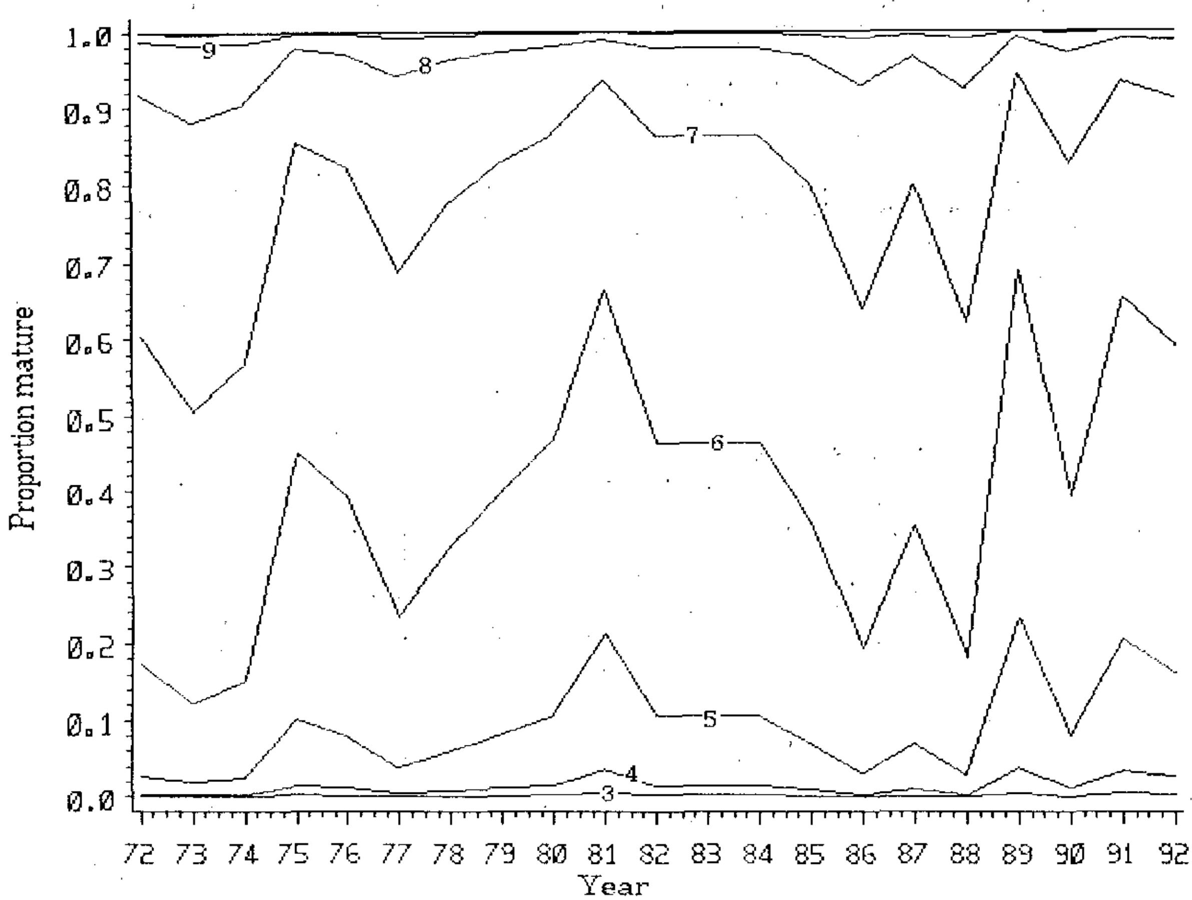

Fig. 2. Model estimates of proportion mature at age estimated from survey data.

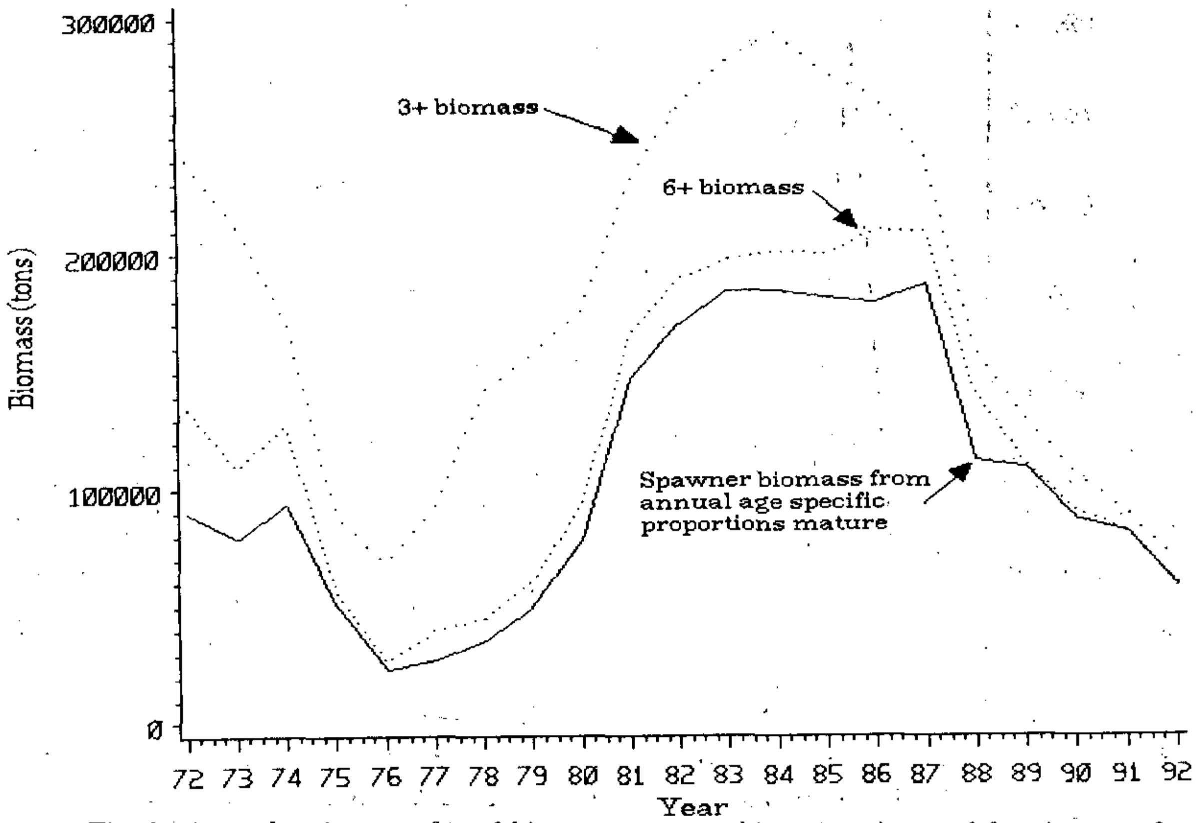

Fig. 3. Annual estimates of total biomass, spawner biomass using model estimates of proportions mature at age and the 6+ biomass. Total (3+) biomass is also shown for comparison.

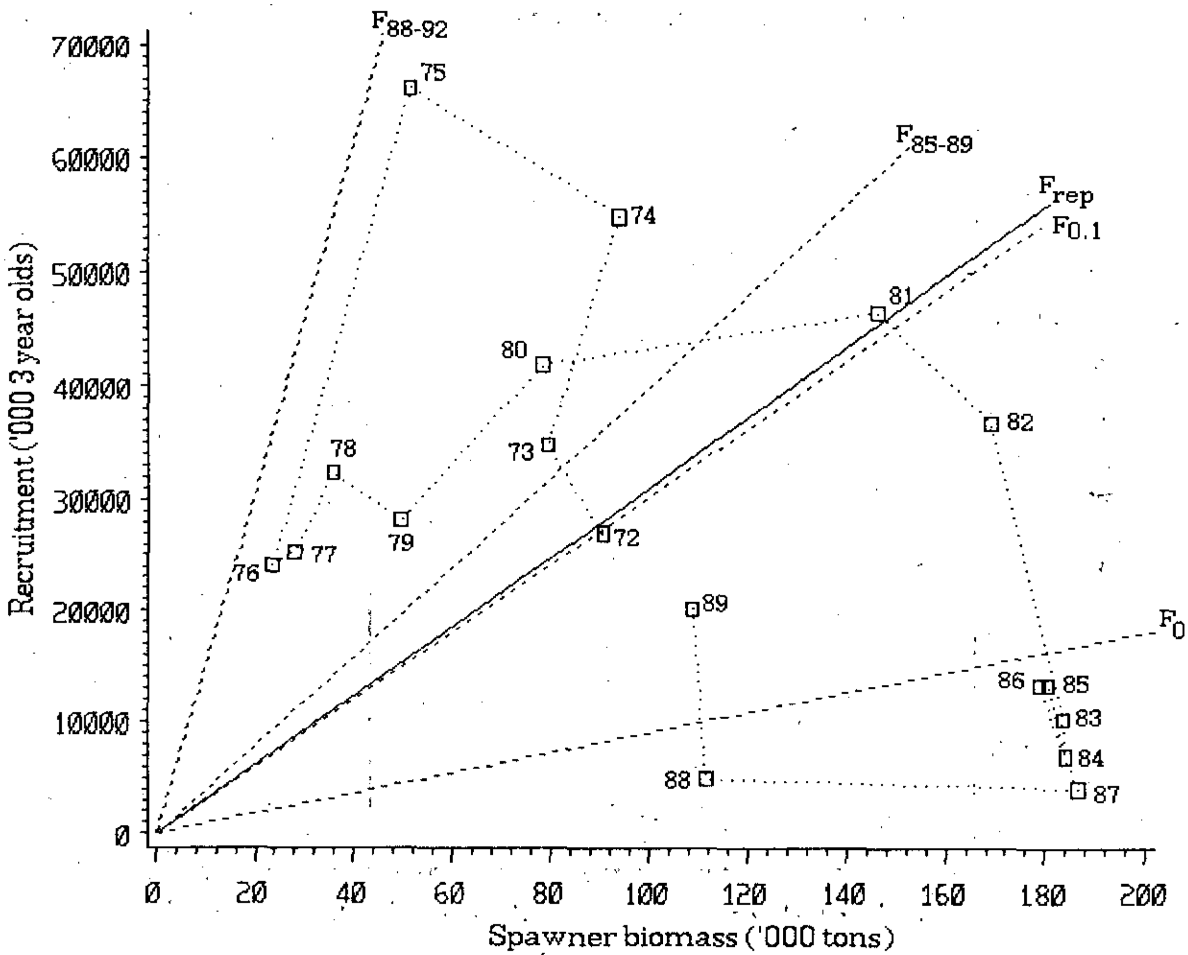

Fig. 4. Stock-recruit scatter with F_{rep}, F_0 and $F_{0.1}$ replacement lines superimposed. Two further replacement lines, calculated using average fishing mortality, weights and proportions mature at age for 1985-89 and 1988-92, are shown.

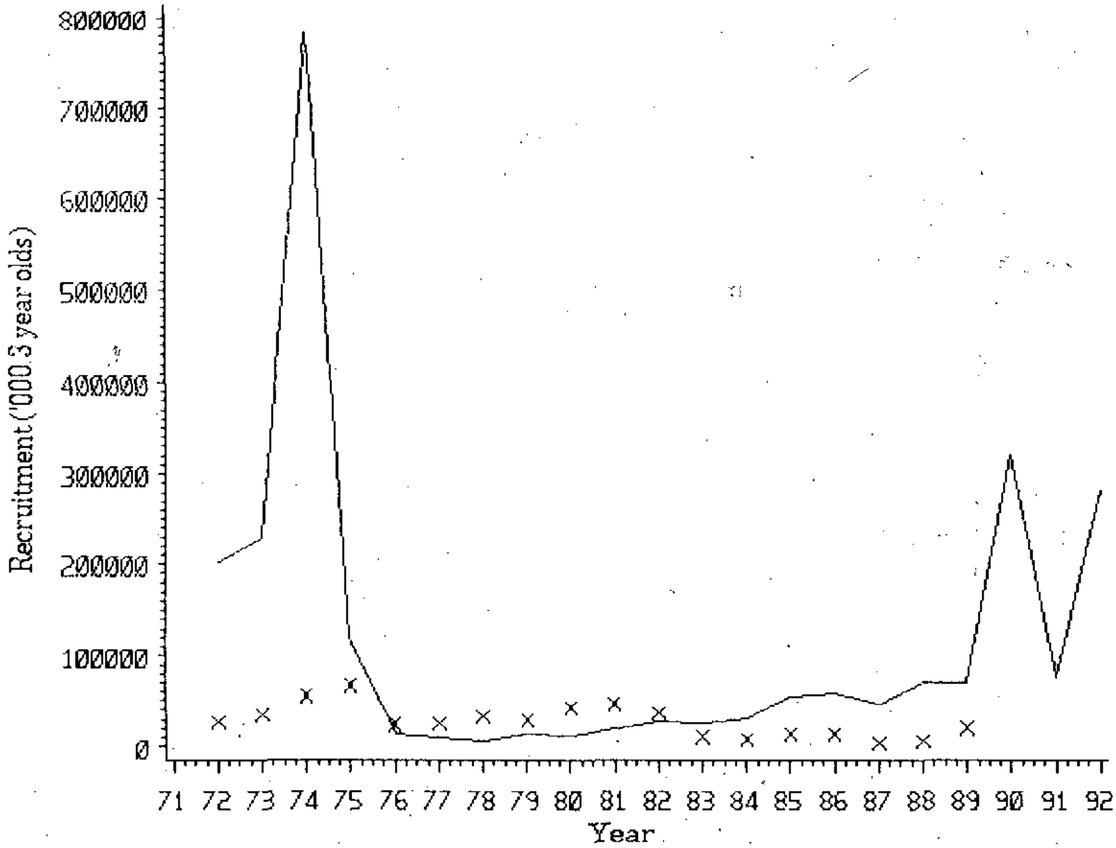

Fig. 5. Annual recruitment (x) plotted together with the amount of recruitment required to replace the spawner biomass at the prevailing annual levels of fishing mortality, weights and proportions mature at age (solid line).

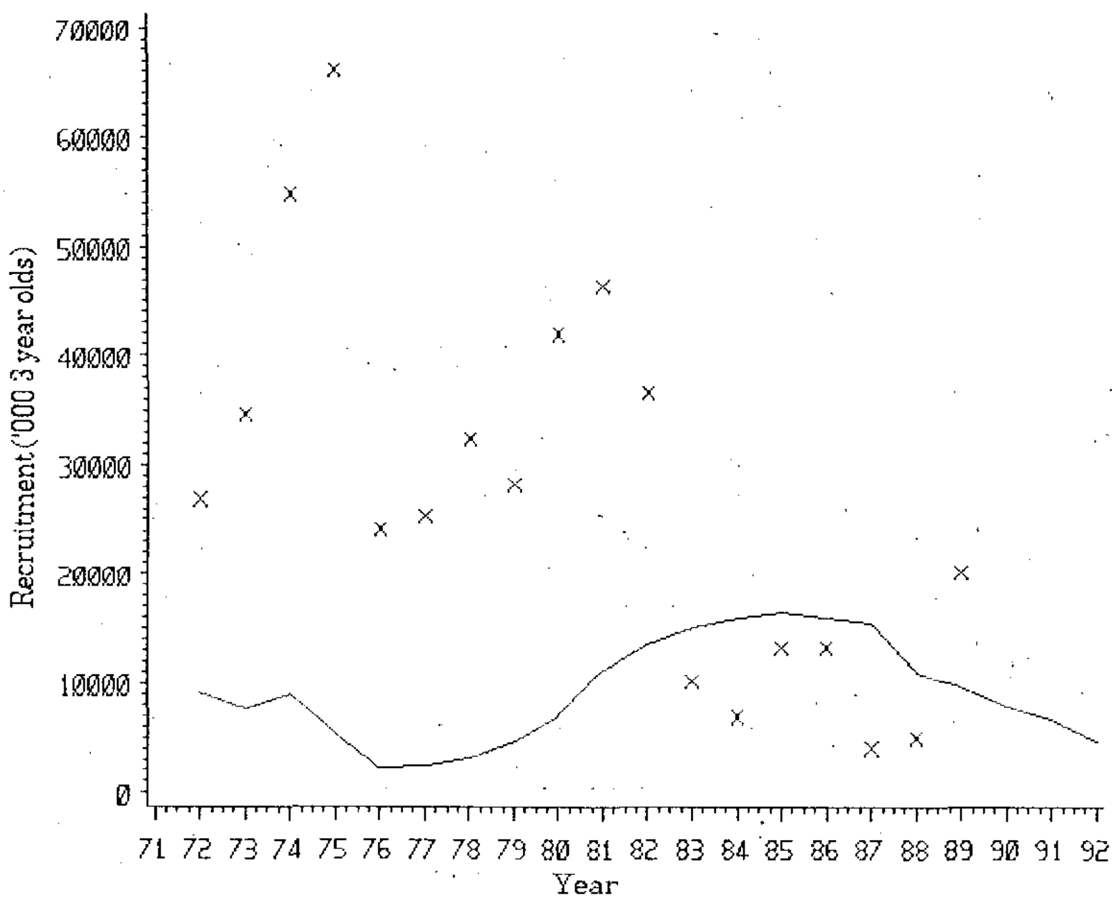

Fig. 6 Annual recruitment (x) plotted together with the amount of recruitment required to replace the spawner biomass at the prevailing annual weights and proportions mature at age, but with fishing mortality set to zero (solid line).

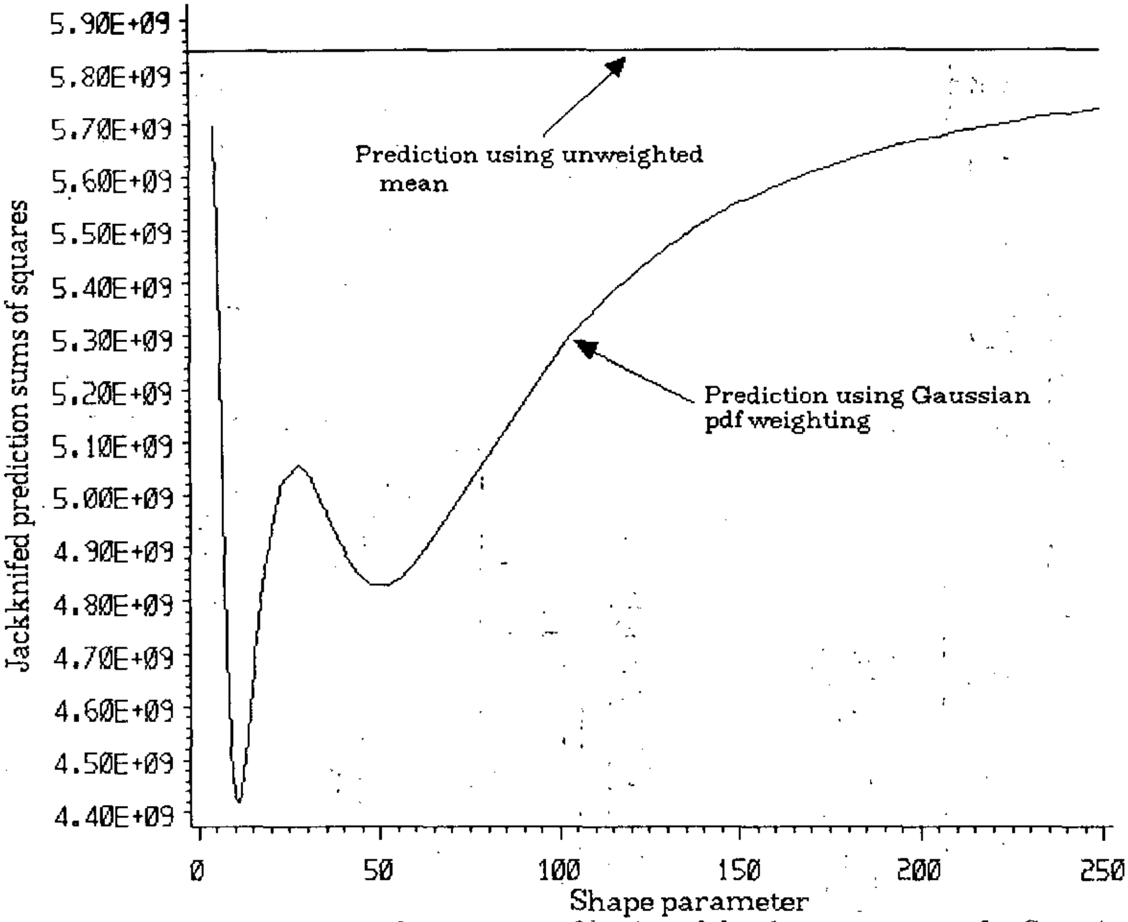

Fig. 7. Prediction sums of squares as a function of the shape parameter for Gaussian weighting in the non-parametric stock-recruit model.

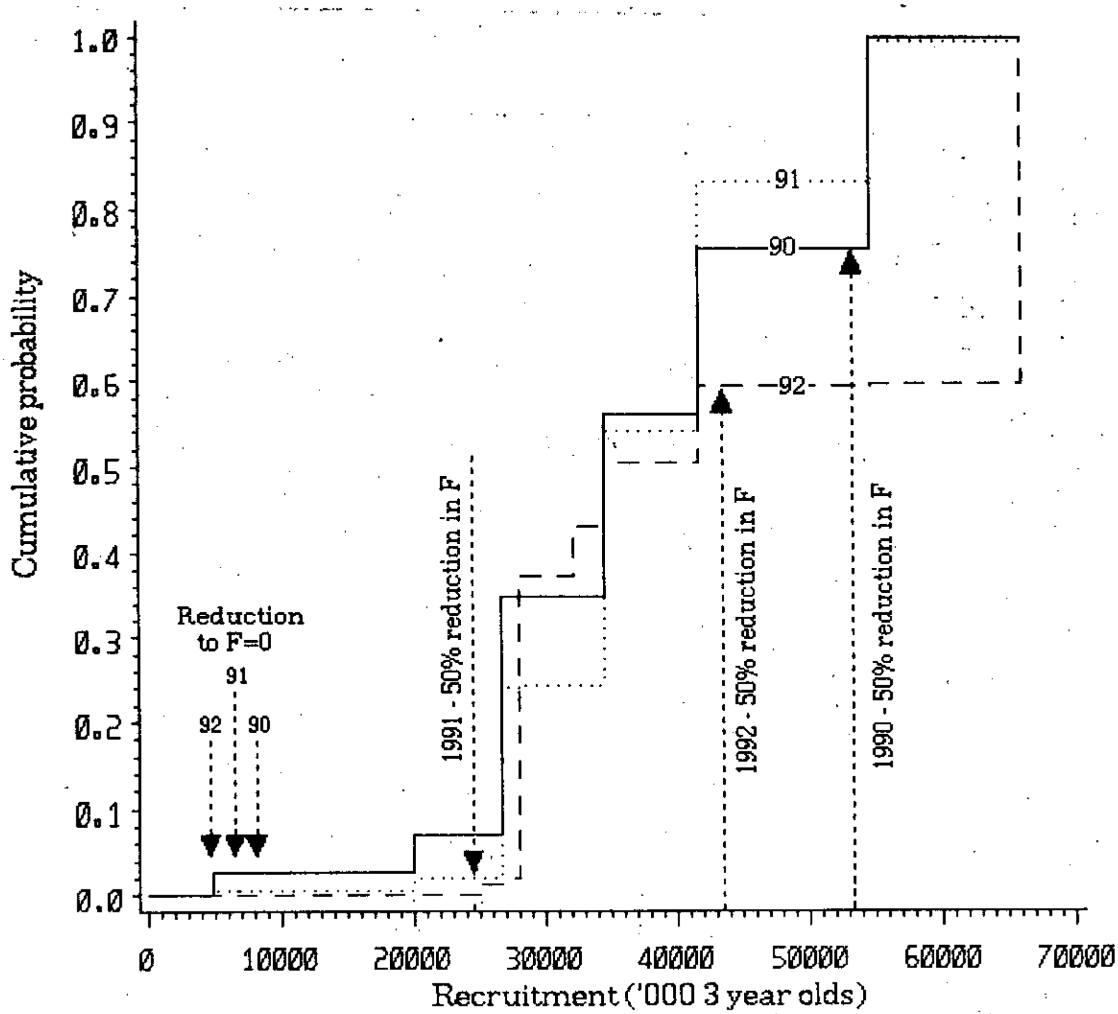

Fig. 8. Cumulative probability distributions for recruitment at estimated spawning stock biomass values for 1990-92. Vertical arrows indicate hypothetical recruitment required for replacement had fishing mortality been 50% of estimated fishing mortality actually applied, or had fishing mortality been set to zero.