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Assessing the risk of failing to achieve replacement recruitment

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Replacement of the spawner stock is necessary for a population to persist. The risk of not achieving replacement will depend on weight at age, proportion mature at age and weight specific fecundity, and may be expected to increase as fishing mortality increases. Weights at age and proportion mature at age are routinely measured for many fish stocks and have been shown to vary over time. Using average values may give a false impression of whether replacement was met or not, particularly when there are trends in the values. We analyse data for NAFO Div. 2J3KL cod to demonstrate this, and show how recruitment probabilities estimated from a nonparametric analysis could be used to assess the probability of failing to achieve replacement recruitment at different spawner biomass levels.

Introduction

For a fish population to persist, recruitment (*R*) must, on average, be sufficient to replace the spawner stock biomass (*SSB*) that gave rise to it. The amount of recruitment required is determined by the spawner per recruit (*SPR*) ratio, the per capita lifetime production of *SSB*. The *SPR* ratio is influenced by the survival rate, body growth rate and maturity at age schedule. If a stock-recruit (*S-R*) relationship exists, then expected *R* varies with *SSB*. This may take the form of the recruit per spawner (*RPS*) ratio being a decreasing function of *SSB* as a result of density dependence in egg production, fertilisation or pre-recruit survival. *RPS* may also vary over time as a function of changes in the environment.

Singly or in combination, *SSB*, *S-R*, *SPR* and *RPS* can be used to provide insight into the status of a fish stock. These quantities and relationships can be used to define conservation and overfishing and to determine management targets. In this paper we examine these quantities and relationships for the cod stock in NAFO Division 2J3KL and demonstrate the potential usefulness of determining the risk of failing to meet replacement at different levels of fishing mortality. The term 'risk' is used here to denote the 'chance of bad consequences', following Fowler and Fowler (1934). We stress that a good chance of failing to meet replacement recruitment is a bad consequence of high fishing mortality.

Spawner stock biomass

The approximate spawner biomass of both males and females in the Div. 2J3KL cod population is frequently calculated by summing the 7+ biomass estimated from an ADAPT formulation (e.g. Baird et al. 1992). While this is a useful first approximation, it would seem more appropriate to use year-specific proportions mature by age to calculate mature biomass where such data are available. Because maturity at age differs between the sexes and because the female biomass is of primary importance with respect to egg production and subsequent recruitment, it may also be useful to use an estimate of the sex ratio to obtain mature female biomass. In the case of Div. 2J3KL the sex ratio does not appear to differ significantly from 1:1, and, for comparability with ADAPT estimates, we treat spawner biomass as the biomass of both males and females, even though the proportions mature used to obtain it in this study are derived only from females.

Prior to 1971, groundfish trawl surveys in Div. 2J3KL were carried out using mainly a line transect sampling design. From 1971 onwards a stratified random sampling design was implemented giving better spatial distribution of samples. Maturity data from fall surveys in Div. 2J3K for 1978-91, fall surveys in Div. 3L for 1981-91 (with the exception of 1984 because in that year the survey ended 2 months before the fall survey started in any other year), and spring surveys for Div. 3L for 1973 to 92 were used in the analysis. Spring surveys in Div. 3L were carried out in 1971 and 1972 but the maturity data were unavailable at the time of this analysis.

For the period 1978-92 sexed length frequencies were used to estimate catch numbers at length from the research surveys, for use in correcting the length stratified sampling of age (see below). Sexed length frequency data do not exist before 1978. Sexed length frequencies for 1978-92 indicate that the sex ratio for that period did not differ from 1:1. Therefore, prior to 1978 a sex ratio of 1:1 was assumed in determining catch at length by sex from the length frequency data.

Fish were assigned to the category 'mature' or 'immature' based on the scheme of Templeman et al. (1978). In this scheme there are nine maturity stages for females. The first stage is immature and all other stages show some evidence of maturing to spawn or of having spawned and are therefore classified as mature in this study.

Otoliths were collected by the Gadoids Section of the Department of Fisheries and Oceans in St John's for age determination from fish caught in stratified random research trawl surveys using a length stratified sampling scheme. In this scheme 25 fish per 3 cm length class are sampled for each division. A given age can straddle several length classes. Further, the possibility of being mature at a given age is influenced by length. This can result in inaccuracies in the estimation of proportion mature at age if length and catch at length are not taken into account. A formula for correcting for this sample scheme developed by Morgan and Hoenig (1993) was used:

$$p_j^{m'} = \frac{\sum_{i=1}^{n}(C_i \, p_{ij} \, p_{ij}^{m})}{\sum_{i=1}^{n}(C_i \, p_{ij})}$$

where C_i = catch in length class i

p_{ij} = proportion of length class i that is age j

p_{ij}^{m} = the proportion of length class i that is age j and that is mature

$p_j^{m'}$ = the corrected proportion of age j that is mature

n = the number of length classes

The catch in length class i (C_i) was calculated from research vessel survey length frequencies using stratified analysis programs (STRAP, Smith and Somerton, 1981) which weight the catch from a stratum by the size of the stratum.

In order to produce annual estimates of overall Div. 2J3KL proportion mature at age in the fall for the period 1973-91, the proportions mature were analysed using PROBIT analysis with a logit link function (SAS Institute Inc. 1989) such that

$$\hat{p}_{jkl}^{m'} = \frac{1}{(1 + \exp(-x))}$$

and

$$x = \tau + \alpha \,\text{age}\, j + \beta_k \,\text{year}\, k + \gamma_l \,\text{season}\, l + \varepsilon$$

where $\hat{p}_{jkl}^{m'}$ = predicted proportion mature at age j in year k and season l

α = age effect

β = year effect

γ = season effect

ε = error term

τ = intercept

All terms in the model were significant. From the parameterized model, the proportion mature at age j=3 to 14 in fall for year k=1973 to 1991 were predicted (Fig. 1).

Weights at age on January 1 determined from sampling the commercial fishery (Fig. 2) were used together with the PROBIT estimates of proportion mature at age and ADAPT estimates of numbers at age (Bishop et al. 1993) to calculate spawner biomass for each year between 1973 and 1992. The estimated spawner biomass using the proportion mature at age is generally higher than that estimated using 7+ (Fig. 3), although both show a similar pattern. SSB reached lows in 1977 and 1991-92. The estimate of SSB for 1992 is 60 000 tons greater using the proportion mature at age than for the 7+ estimate.

Replacement and spawner per recruit

Replacement of the spawner stock is necessary for a population to persist. The risk of not achieving replacement may be expected to increase as fishing and natural mortality increase and as weight at age, proportion mature at age and weight specific fecundity decrease. Weights at age and proportion mature at age are routinely measured for many fish stocks and have been shown to vary over time. In the case of Div. 2J3KL cod stock, proportions mature at age were quite variable in the 1970s; values for 5, 6 and 7 year olds declined in the early 1980s while in more recent years this trend has reversed (Fig. 1). Weights at age for the Div. 2J3KL cod stock demonstrate strong cohort effects as well as nonrandom year effects (Fig. 2). ADAPT estimates of fishing mortality at age demonstrate a declining trend in the late 1970s following extension of jurisdiction, followed by an increasing trend throughout the 1980s and early 1990s with a sharp decline coinciding with the introduction of the moratorium on the fishery in 1992 (Fig. 4). We demonstrate that the calculation of replacement recruitment based on averages are misleading when these patterns exist.

Replacement recruitment R^* is that recruitment which is required to produce the same biomass of spawners as the biomass of spawners that gave rise to it. Replacement does not take place instantaneously. As a cohort ages, it makes annual contributions to the current year's spawner biomass over it's lifetime, the magnitude of which depends on natural and fishing mortality rates, weights at age and proportion mature at age. R^* is therefore an artificial construct which requires careful definition. Assuming vectors of fishing mortality at age, weights at age and proportion mature at age, the spawner biomass resulting from a cohort can be calculated as

$$S = \sum_{i=r}^{I} (N_i w_i p_i) \qquad (1)$$

where

$$N_{i+1} = N_i e^{-(F_i + M)} \qquad (2)$$

and where

S = spawner biomass

N_i = the number alive in a cohort at age i ($N_i = R$ when $i=r$)

w_i = the weight of an individual fish at age i

p_i = the proportion mature at age i

r = the age at recruitment

I = terminal age class

F_i = the annual instantaneous fishing mortality rate on age i

M = the annual instantaneous natural mortality rate

From (1) and (2) replacement recruitment R^* can be computed as

$$R^* = \frac{S}{\sum_{i=r}^{I} (\gamma_i w_i p_i)} \qquad (3)$$

where

$$\gamma_i = 1 \quad \text{for } i=r$$

and

$$\gamma_i = \prod_{k=r+1}^{i} (e^{-(F_{k-1}+M)}) \qquad \text{for } i>r \qquad (4)$$

It is common practice (e.g. Sissenwine and Shepherd, 1986; Gabriel et al. 1989; Mace and Sissenwine, 1993) to assume vectors of w and p which represent average values for several years and to compute replacement or *SPR* for specific values of F (such as average F) and a constant partial recruitment vector. We refer to these quantities as "average replacement recruitment" and "average *SPR*". In a historic analysis, for which annual estimates of fishing mortality and annual vectors of w and p are available, and where these values are varying nonrandomly, we favour the calculation of "annual replacement recruitment" in which the replacement recruitment in year j, R^*_j, corresponding to S_j, is calculated from the F_j, w_j and p_j vectors. The two approaches are compared below for cod in Div. 2J3KL for the period 1973-88.

Average replacement recruitment for the period 1973-88 calculated using weights, maturities and fishing mortalities at age averaged over the period 1984-88 (from data in Baird et al. 1992) is equivalent to *Fmed*, an estimator of *Frep* or replacement fishing mortality (Mace and Sissenwine (1993) (Fig.5). The implication is that fishing mortality was not excessive over this period. However, the trajectory of annual replacement reveals that the level of recruitment required to meet replacement increased sharply over the period 1980-88. The different perspectives obtained from examining average replacement and annual replacement, and the causes for these differences, are considered further below, using data from the 1993 assessment of the Div. 2J3KL cod stock (Bishop et al. 1993).

By plotting average replacement and annual replacement recruitment against year, together with annual recruitment values, it can be seen that, although recruitment from 1983 onwards appears to have been below both annual and average replacement levels, the trends in these levels differ (Fig. 6). Annual replacement appears to have increased steadily over the period 1978-89 whereas average replacement has declined fairly steadily from 1981 onwards. By removing the *SSB* effect in the calculation of replacement, and plotting annual replacement per spawner and average replacement per spawner, it can be seen that the trend in the annual replacement recruitment persists, indicating that it has become progressively harder for recruitment to exceed replacement in recent years (Fig. 7) as a result of trends in fishing mortality, weights at age and proportions mature at age.

The dramatic decline in annual replacement per spawner in 1992 is a result of reduced fishing mortality brought about by the moratorium on the commercial fishery within the 200 mile zone imposed in that year. Annual replacement per spawner for F=0 (Fig. 8) removes the effect of fishing and shows that replacement stopped increasing after 1987. The only two variables in this calculation are weights at age and proportion mature at age. Although weights at age have been declining over the 1980s, proportions mature at the lower ages increased in the late 1980s (Fig. 9), arresting the decline in annual replacement per spawner. A plot of annual replacement recruitment per spawner at F=0 together with the estimated recruit per spawner data points, indicates that recruitment in the late 1980s has come close to the replacement level (Fig. 10), i.e. close to the level at which the stock will continue to decline even in the absence of fishing.

The calculation of annual replacement and annual replacement per spawner has been demonstrated to be much more informative regarding the status of the stock than average replacement. Both methods attempt to simplify a complete age structured model to provide a useful reference to indicate whether or not population size is likely to grow or decline under different levels of fishing mortality. However, when there are time trends in the inputs to the calculations, using averages is less useful. Further, analyses of properties such as stability and depensation below replacement are unlikely to be informative if they are based on an *S-R* analysis using average replacement rather than annual replacement or, preferably, a full age structured model.

Annual replacement per spawner can be calculated for the most recent year for which there are data on weights and proportions mature at age. This can be useful for determining the appropriate level of *F* for the current year. If estimates of spawner biomass are available for the most recent years and an *S-R* relationship has been demonstrated, then recruitment can be predicted for the most recent years and compared with the replacement level. We demonstrate below the usefulness of nonparametric analysis in estimating the probability of failing to meet replacement recruitment.

Spawner-recruit relationship

The stock-recruit scatter for Div. 2J3KL cod for the period 1973-89 (Fig. 11) shows considerable variability in recruitment with spawner stock size, particularly at intermediate spawner biomass. A non-linear fit of the standard Ricker model

$$R_j = S_j e^{(a - b S_j)} + \varepsilon_j$$

gives estimates of a and b which are not significantly different from zero (a=0.1360, lower (1-α)%=-1.458, upper (1-α)%=1.216; b=0.132E-5, lower (1-α)%=-0.23E-5, upper (1-α)%=0.419E-5; α=0.05).

A nonparametric analysis of recruitment, following the general approach of Evans and Rice (1988), Rice and Evans (1986,1988) may be more useful. This approach benefits from not requiring the assumption of a specific model. Ignoring *SSB* for the time being, the recruitment data can be plotted as a frequency distribution, and as a cumulative plot of the probability of recruitment (ordinate) being less than or equal to a specified value (abscissa) (Fig. 12). Note that because the frequency distribution and the cumulative probability plots only reflect the 17 estimated recruitments between 1973 and 1989, they are irregular in appearance. Given no further information, we can predict from the cumulative frequency distribution that, based on past data, there is a probability of 0.5 that recruitment in the next year will be approximately 240 million 3 year old fish or less. The question can now be asked 'Can we make a better prediction if we pay more attention to previous recruitment that occurred at biomass levels similar to that biomass at which we wish to predict recruitment, rather than treating recruitment at all biomass levels equally?'

In order to examine this, we can weight a recruitment data point that corresponds to a spawner biomass that is close in magnitude to the spawner biomass at which we want to make the prediction, more than a recruitment data point that corresponds to a spawner biomass that is not as close. A 'kernel' is a probability density function used to weight the contribution of surrounding data to the estimate at the point of interest. We selected a Gaussian kernel and used a 'jackknife' approach (more correctly, cross-validation, e.g. as in Rice and Evans 1988) to estimate the appropriate standard deviation (σ) for the pdf from the 17 *S-R* pairs. The performance measure used for comparison was the jackknifed prediction sums of squares using the weighted mean recruitment as the predicted recruitment (note, several alternative performance measures could be considered). The Gaussian kernel estimator performed better (ss=17.6E10) than both the jackknifed unweighted mean recruitment (ss=19.5E10) and the commonly used geometric mean recruitment (ss=20.1E10), with a minimum ss at $\sigma = 66.8 \times 10^3$ (Fig. 13).

The improvement in predictive ability of the Gaussian kernel estimator over the unweighted mean indicates that there is potentially some information in the spawner stock size with respect to recruitment. The probability that the resulting reduction in the prediction sums of squares was obtained due to chance alone can be estimated by an appropriate randomization test. The Gaussian kernel estimator was applied 180 times on randomly shuffled recruitment data (i.e. each recruitment value randomly assigned to each spawner stock value for the 17 years). In 28 cases the jackknifed prediction sums of squares from the randomly shuffled data was less than or equal to that obtained from the correctly sequenced recruitment data, implying that there is a p=0.16 that the observed reduction in prediction sums of squares could be due to chance alone. Although this probability is larger than that which would normally be considered acceptable in a hypothesis test, the use of spawner biomass to predict recruitment may nevertheless have some utility in an assessment that incorporates a probability distribution for recruitment in a prognosis, rather than a single value such as the geometric mean of past recruitments.

Using the estimated minimum prediction ss value of σ for the Gaussian kernel, the cumulative probability of recruitment at different spawner stock sizes can be computed (Fig. 14). This can be used to determine the probability of obtaining a recruitment of less than or equal to some value at different spawner stock sizes. Although there is a substantial shift to the right in the cumulative probability for an *SSB* of 500 000 tons compared to 100 000 tons, the cumulative curve for a *SSB* of 300 000 tons crosses over the cumulative curve for 100 000 tons as a result of several low recruitment values at intermediate *SSB*.

The low recruitment values at intermediate *SSB* are of considerable interest, particularly when the time sequence of the data are examined (see Fig. 11). During the decline in *SSB* in the mid-1970s and the subsequent recovery in the late-1970s and early 1980s recruitment was substantially higher than that estimated for the period over the mid to late 1980s. This change in *RPS* with time (nonstationarity in the *S-R* relationship) may invalidate the application of estimators that do not take the temporal pattern of the data into account. Similar temporal patterns in *RPS* have been observed in several other groundfish stocks in the northwest Atlantic (DFO, unpublished data).

To examine this further, a non-parametric analysis was carried out with a weighting factor based on the time difference in years between the value to be predicted and the other values in the data set. Results using a Gaussian kernel indicate a substantial decrease (factor of 3) in the jackknifed prediction sums of squares by taking temporal pattern into account (ss=6.18E10). The standard deviation that minimizes the prediction ss is small (σ=0.58), giving all the weight to the year before and the year after the year to be predicted (equivalent to giving the year before and the year after a weighting of 1 and all other years a weighting of 0) (Fig. 15). The probability of observing a ss value this small or smaller due to chance alone was estimated to be 0.11 in 180 randomizations using a test similar to the one described above for biomass. Although it might be appropriate to use both the year before and the year after to estimate the appropriate weighting parameter, the prediction sums of squares is substantially higher using only the previous year's recruitment in the estimator (ss=13.1E10, compared to 16.8E10 for the unweighted mean) indicating that large uncertainty in predicting future recruitment persists. Using the value of recruitment in the year before as a predictor of recruitment in the current year is unlikely to be robust with respect to a decline in spawner biomass, and a predictor incorporating both spawner biomass and temporal pattern in recruitment may be more reliable.

Based on the nonparametric analysis with spawner biomass, the probability of achieving replacement recruitment was examined for 1990-92 - years for which no recruitment estimate currently exists (Fig 16). At estimated values of F it is estimated that there is a p=1 that recruitment was less than that required to meet replacement in both 1990 and 1991 whereas, as a consequence of the moratorium, this drops to p=0 in 1992. The decreased probability of good recruitment with the decline in the spawner biomass over the period 1990-92 is indicated by the shift in the cumulative frequency for recruitment values of 200 to 400 million. There is a considerable improvement in the probability of achieving replacement with a 50% reduction in F for both 1991 and 92 indicating that lower fishing mortality in these years might have begun to arrest the decline in spawner biomass. Because annual replacement is an approximation to true replacement which takes place over the lifetime of a cohort, the effect would not be as immediate as indicated, but would depend on F in subsequent years.

Discussion

Both annual replacement and average replacement are quantities calculated by simplifying a complete age structured model in an attempt to provide useful references to indicate whether or not population size is likely to grow or decline under different levels of F. The disadvantage of average replacement recruitment and reference points such as *Frep* is that they do not reflect important year-to-year changes in weights and proportions mature at age. Annual replacement is sensitive to these changes. Calculation of annual R^* per spawner or annual *SPR* at F=0 are also useful steps in the assessment of stock status because they clarify the causes for changes in the level of recruitment required to meet replacement. Calculations of annual R^* per spawner at F=0 demonstrated that the time trends in weights and maturities at age in the Div. 2J3KL cod stock have resulted in a substantial increase in the recruitment per spawner required to meet replacement over the period 1980-87, as a consequence of changes in weights and maturities at age.

Nonparametric analysis of *S-R* data can provide a probabilistic prediction of recruitment in the most recent years for which recruitment estimates are not available. These predictions can be used, together with calculations of replacement level at current weights and maturities at age to determine the probability of meeting replacement at different levels of F.

The analyses conducted in this paper suggest that biological reference points and management targets for the Div. 2J3KL cod stock, and perhaps for other groundfish stocks, should incorporate annual estimates of weights at age and proportions mature at age when trends in these values are found to occur. The use of averages to calculate quantities such as replacement for such stocks is likely to be misleading.

Acknowledgements

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References

Baird, J.W., C.A. Bishop, W.B. Brodie and E.F. Murphy. 1992. An assessment of the cod stock in NAFO Divisions 2J3KL. CAFSAC Res. Doc. 92/75, 76p.

Bishop, C.A., E.F. Murphy, M.B. Davis, J.W. Baird and G.A. Rose. 1993. An assessment of the cod stock in NAFO Divisions 2J+3KL. NAFO SCR Doc. 93/86, 51p.

Evans, G.T. and J.C. Rice. 1988. Predicting recruitment from stock size without the mediation of a functional relation. J. Cons. Int. Explor. Mer, 44:111-122.

Fowler, F.G. and H.W. Fowler. 1934. The Pocket Oxford Dictionary of Current

English. Oxford University Press, Oxford, p980.

Gabriel, W.L., M.P. Sissenwine and W.J. Overholtz. 1989. Analysis of spawning stock biomass per recruit: an example for Georges Bank Haddock. N. Am. J. Fish. Man. 9:383-391.

Morgan, M.J and J.M. Hoenig. 1993. Maturity at age from length stratified sampling. ICES C.M. 1993/ D:55, 11p.
Mace, P.M. and M.P. Sissenwine. In press. How much spawning per recruit is enough? In Smith, Hunt and Rivard (eds.) Halifax Risk Workshop.

Noakes, D.J. 1989. A nonparametric approach to generating inseason forecasts of salmon returns. Can. J. Fish. Aquat. Sci. 46:2046-2055.

Rice, J.C. and G.T. Evans. 1986. Non-parameteric prediction of recruitment from stock and the relationship of the residuals to water temperature for cod in NAFO Divsions 2J+3KL and 3M. NAFO SCR Doc. 86/106, 13p.

Rice, J.C. and G.T. Evans. 1988. Tools for embracing uncertainty in the management of the cod fishery in NAFO division 2J+3KL. J. Cons. int. Explor. Mer. 45:73-81.

Ricker, W.E. 1954. Stock and recruitment. J. Fish. Res. Bd Can., 11:559-623.

SAS Institute Inc. 1989. SAS/STAT User's Guide, p1686.

Sissenwine, M.P. and J.G. Shepherd. 1987. An alternative perspective on recruitment overfishing and biological reference points. Can. J. Fish. Aquat. Sci. 44:913-918.

Smith, S.J. and G.D. Somerton. 1981. STRAP: A user-orientated computer analysis system for groundfish research trawl survey data. Can. Tech. Rep. Fish. Aquat. Sci. 1030: iv + 66p.

Templeman, W., V. M. Hodder, and R. Wells. 1978. Sexual maturity and spawning in haddock, Melanogrammus aeglefinus, of the southern Grand Bank. ICNAF Research Bull. 13:53-65.

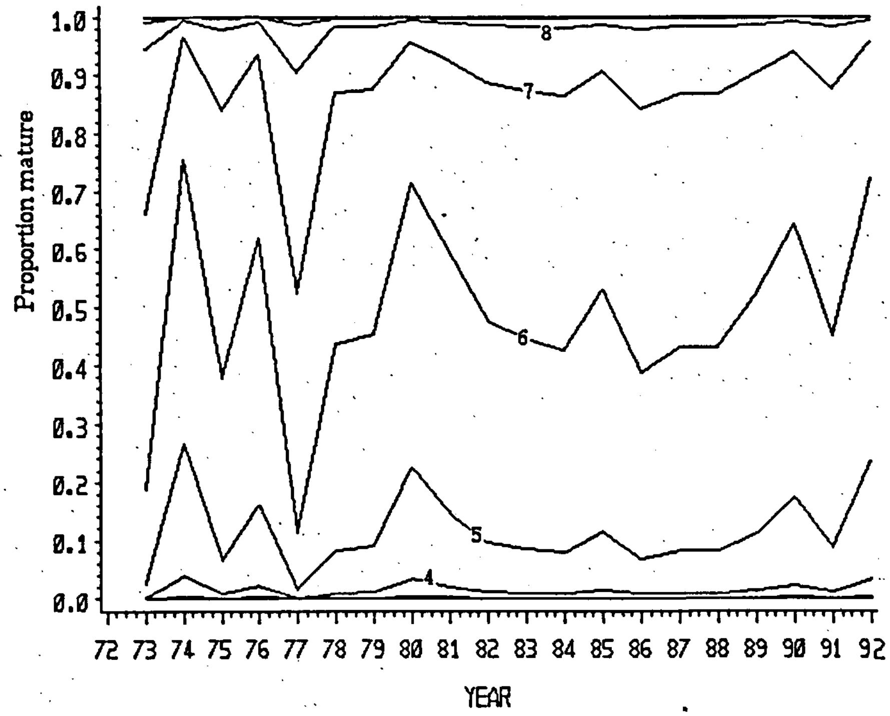


Fig. 1. PROBIT estimates of proportion mature at age for the NAFO Div. 2J3KL cod stock for the period 1972-92 based on survey data.

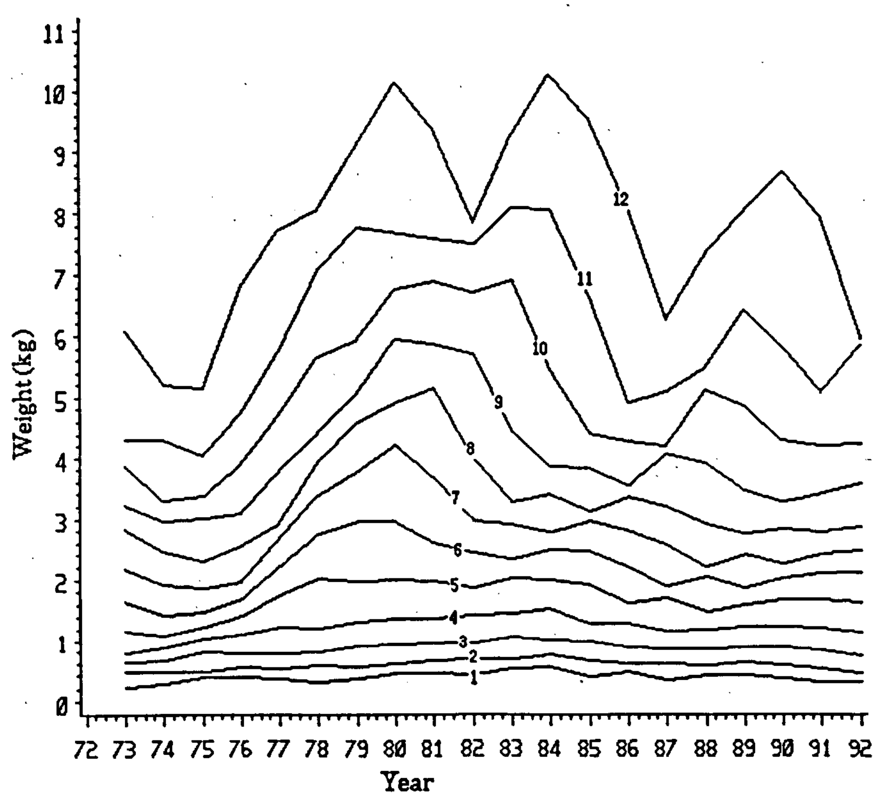


Fig. 2. Weights at age on January 1 in each year estimated from the commercial fishery.

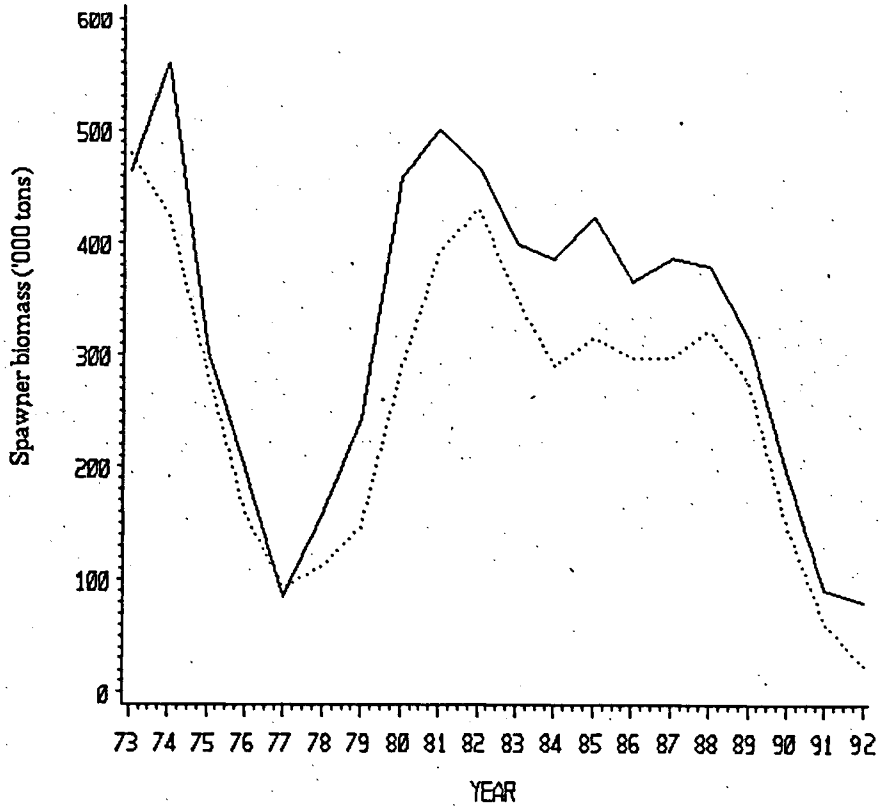


Fig. 3. Spawner biomass from ADAPT estimates of numbers at age and weights at age on January 1, calculated using estimated proportions mature at age from survey data (solid line) and by assuming all fish 7+ are mature (broken line).

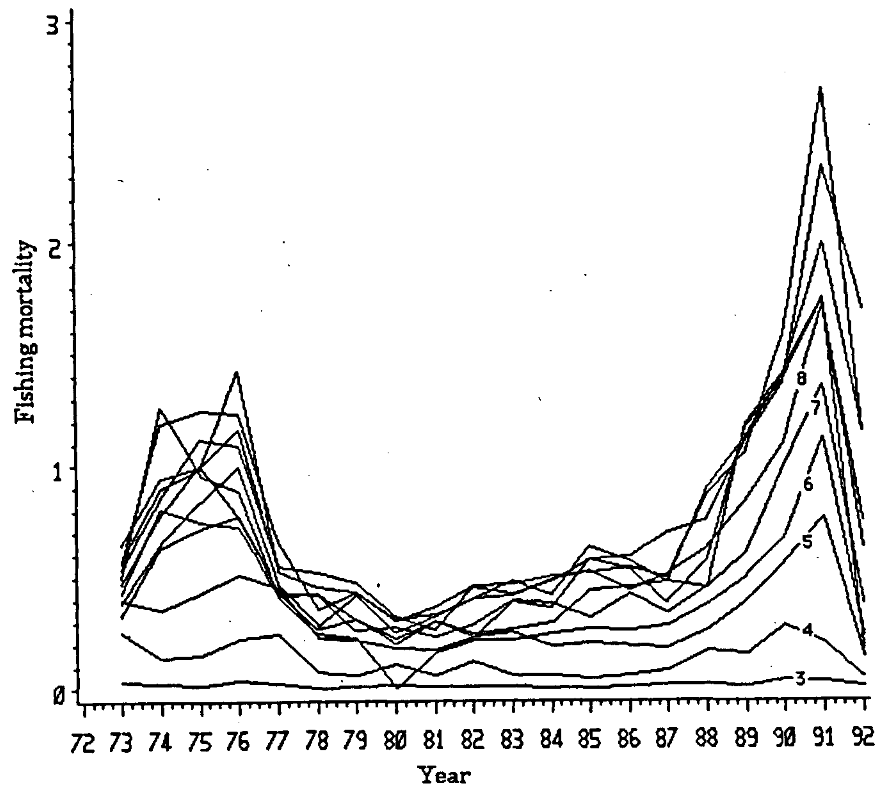


Fig. 4. ADAPT estimates of fishing mortality at age by year for the period 1973-92.

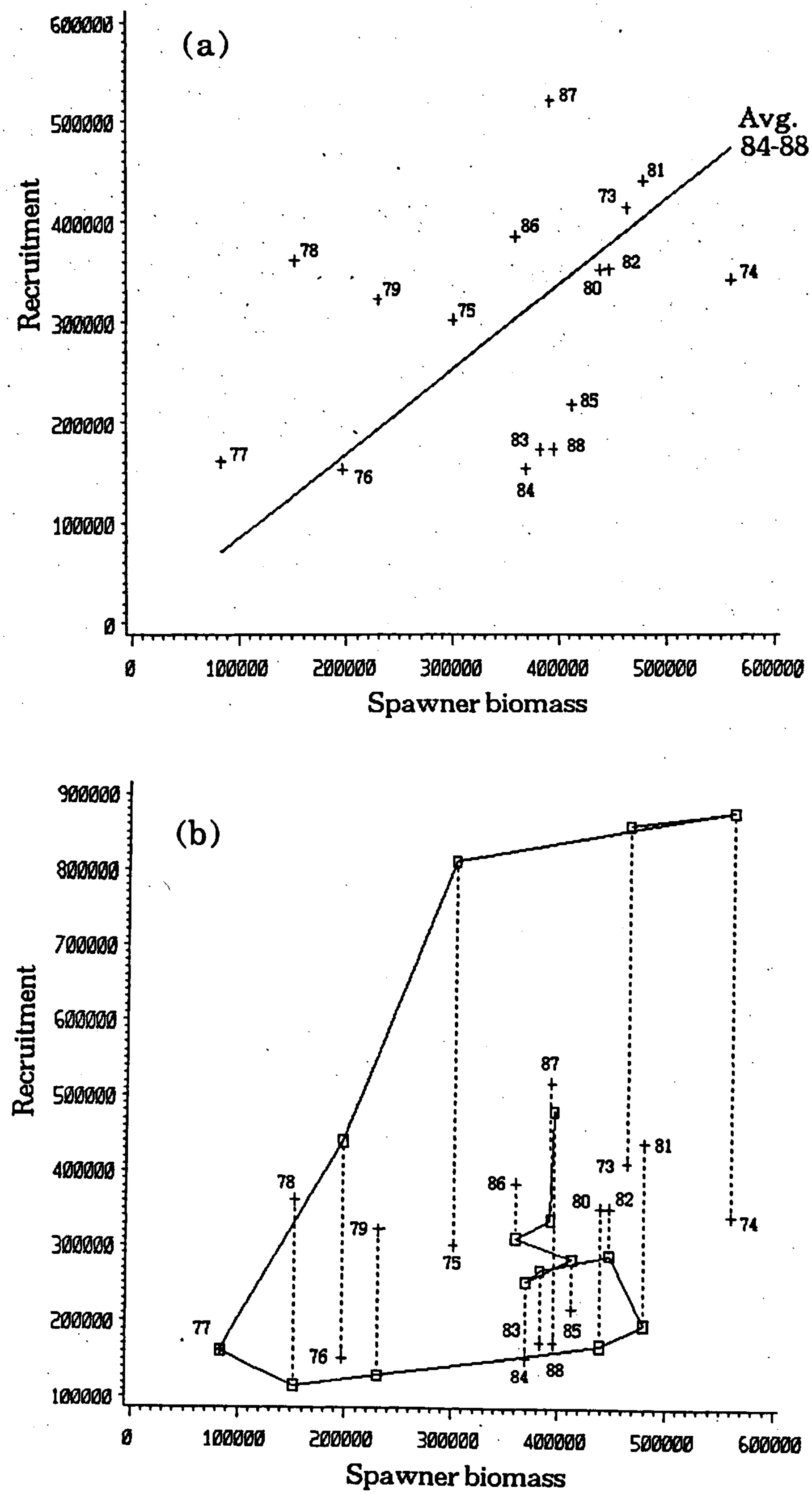


Fig. 5. (a) Stock-recruit data from ADAPT estimates for the period 1973-91 together with replacement calculated using average weights, maturities and fishing mortalities for the period 1984-88. (b) As in (a) but with an annual replacement trajectory. The relative position of recruitment data points with respect to annual level of replacement is indicated by a vertical broken line.

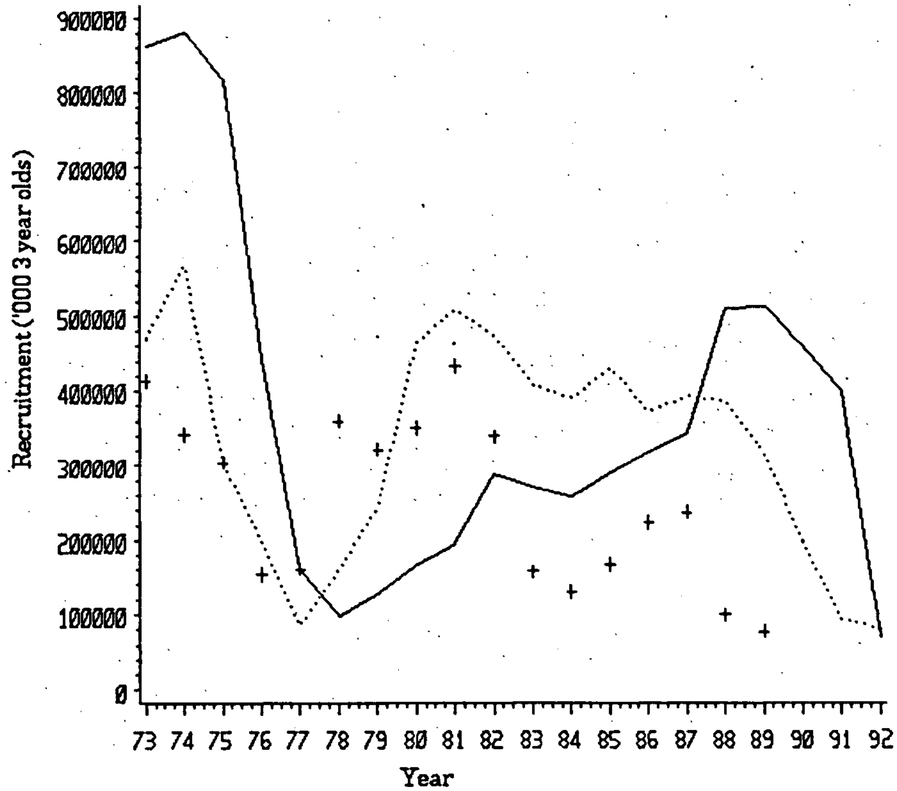


Fig. 6. Average (broken line) and annual (solid line) replacement recruitment levels together with estimates of annual recruitment (+) for the period 1973-92.

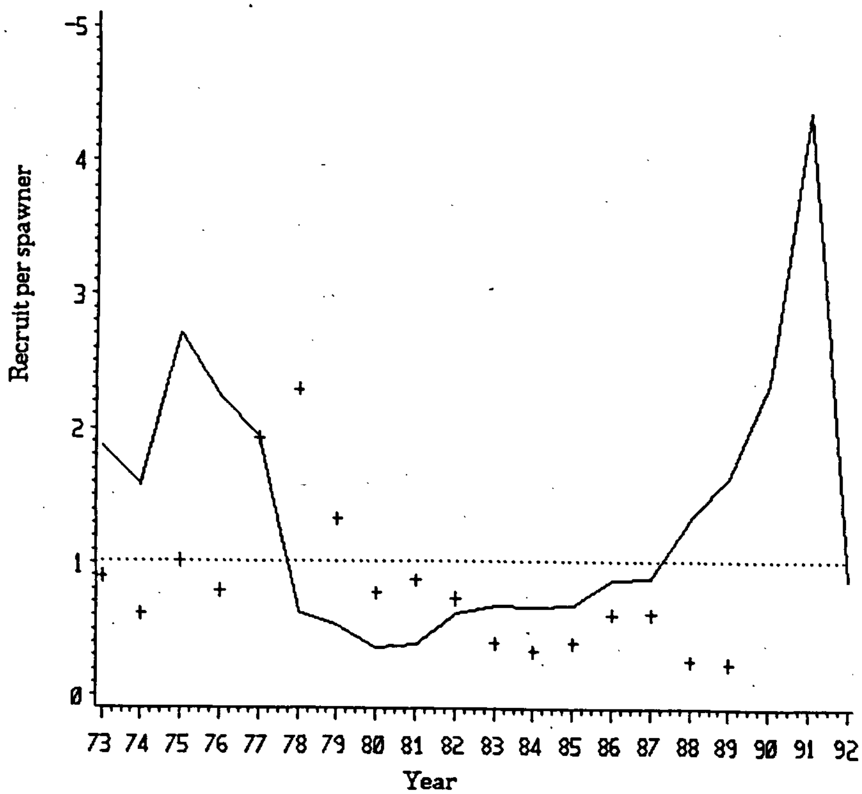


Fig. 7. Average (broken line) and annual (solid line) replacement recruitment per spawner together with estimates of annual recruitment (+) for the period 1973-92.

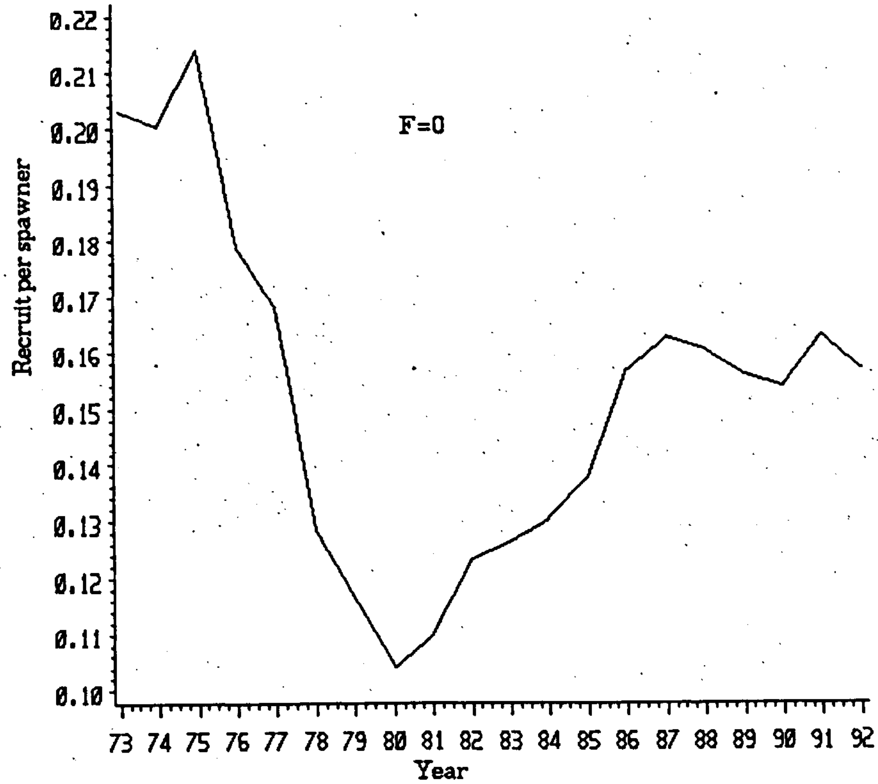


Fig. 8. Annual replacement recruitment per spawner at F=0 for the period 1973-92.

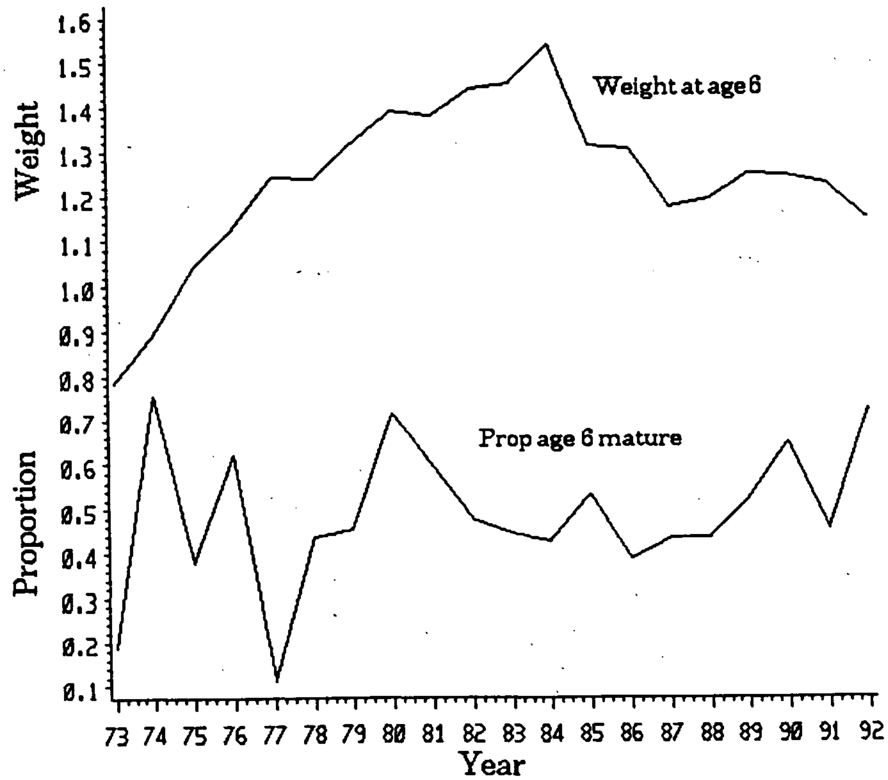


Fig. 9. Trends in weight and proportion mature at age 6 extracted from Figs. 1 and 2.

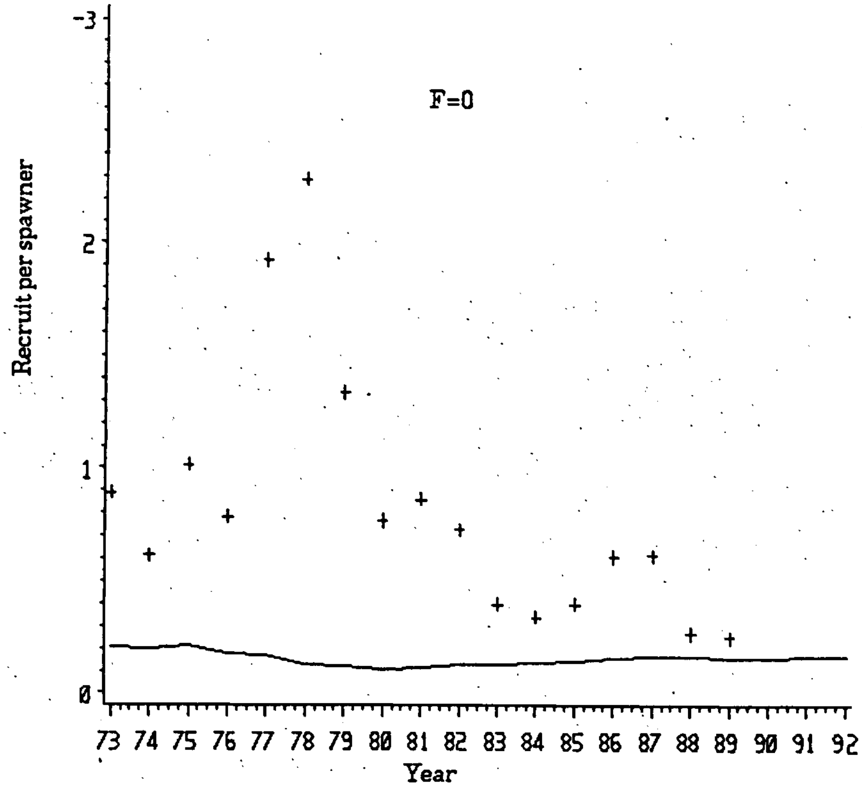


Fig. 10. Annual replacement recruitment per spawner at F=0 together with estimates of annual recruitment per spawner.

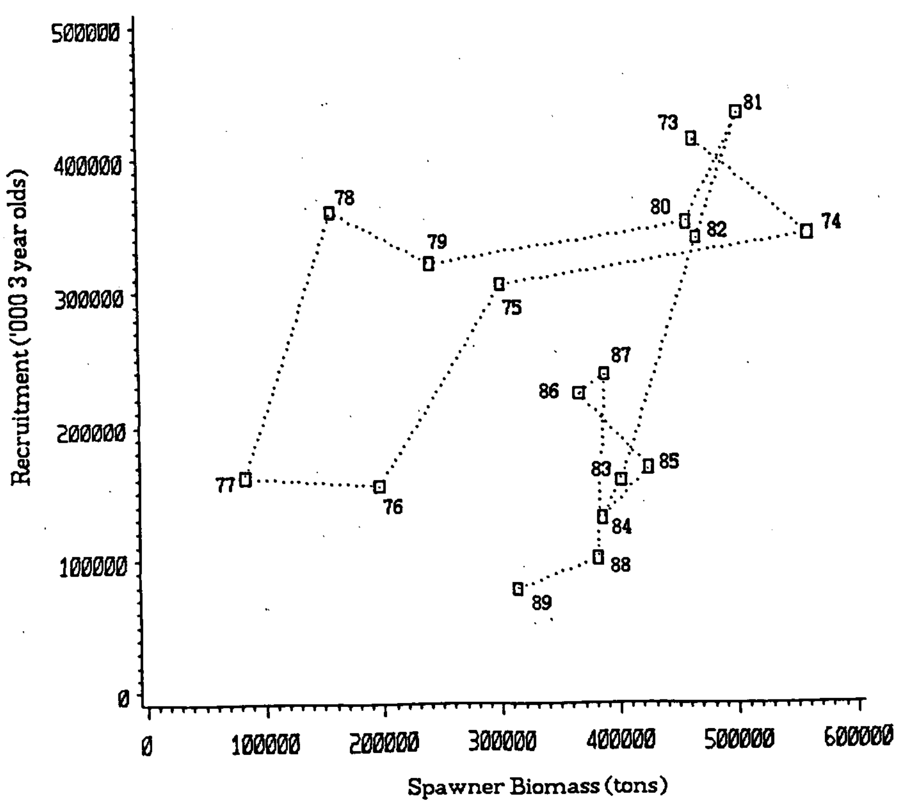
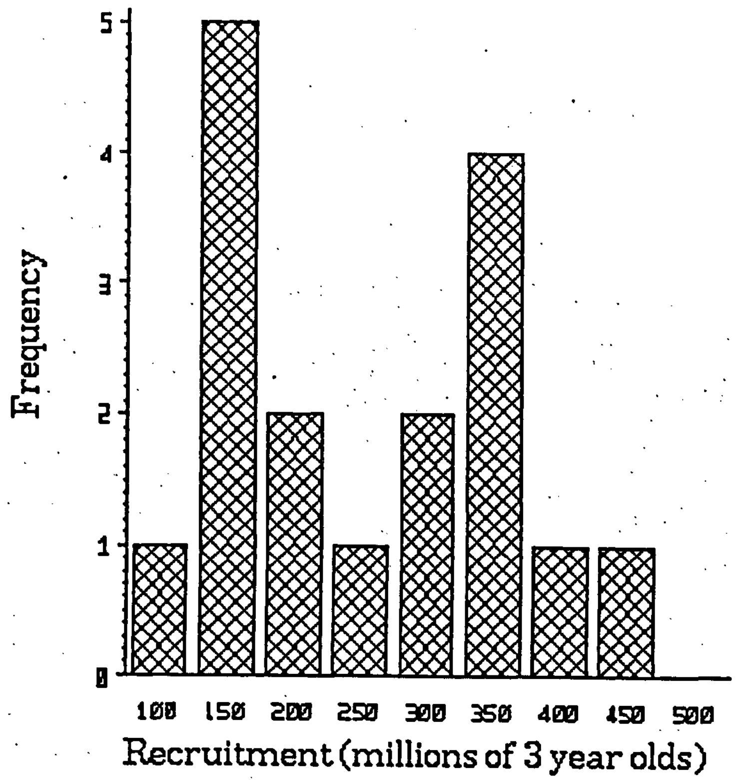


Fig. 11. Stock-recruit scatter for the period 1973-89. Data points are connected to show temporal sequence.



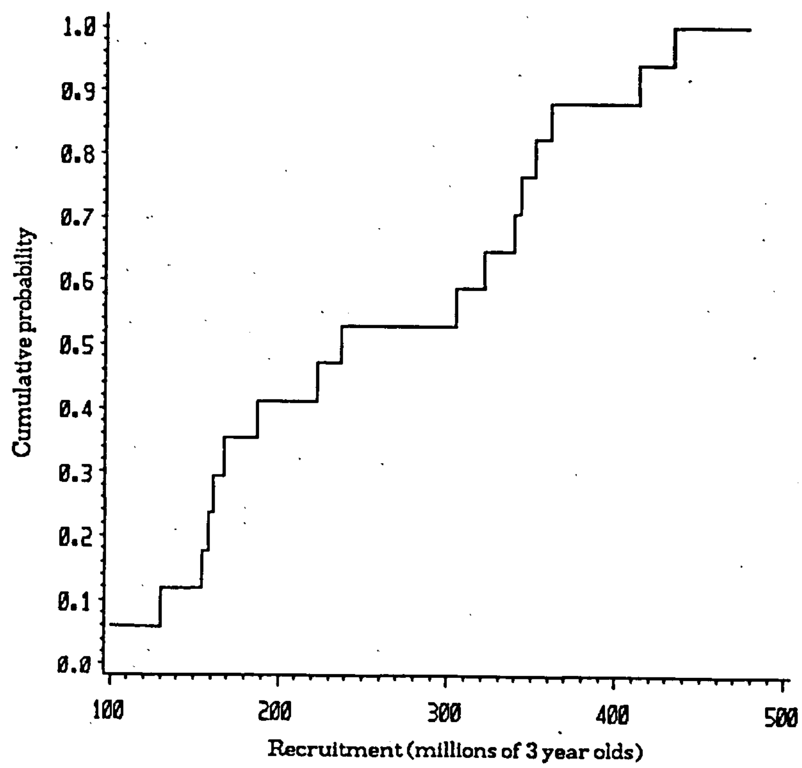


Fig. 12. Frequency distribution and cumulative probability plot for recruitment (millions of 3 year old fish) for the period 1973-89.

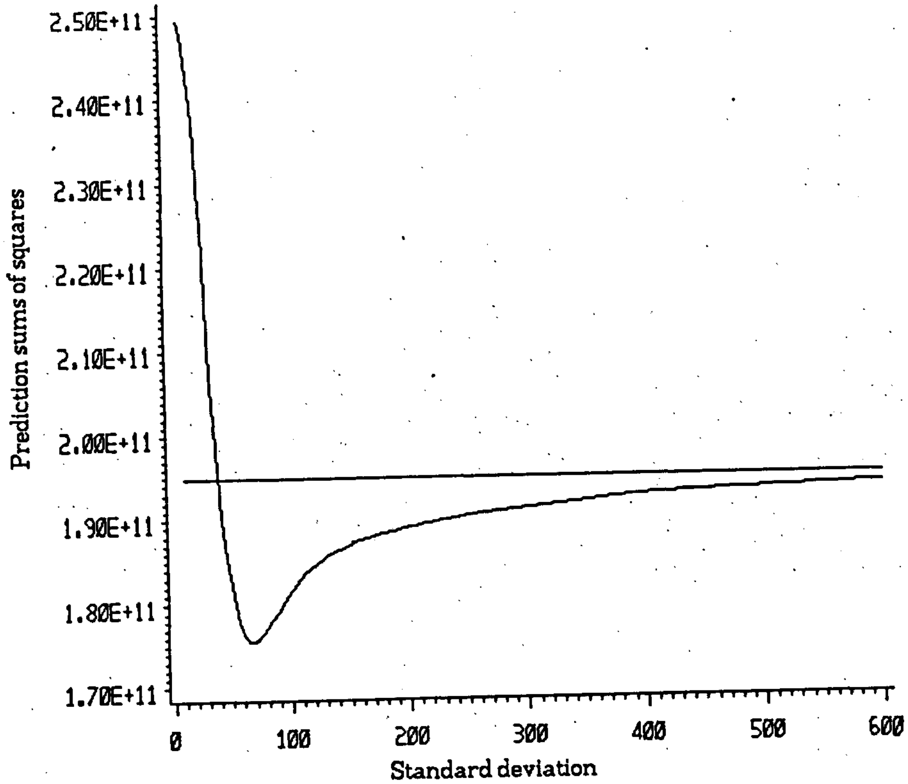


Fig. 13. Jackknifed prediction sums of squares for the Gaussian kernel estimator applied to spawner biomass at different values of the shape parameter σ. The horizontal line gives the jackknifed prediction ss for the unweighted data.

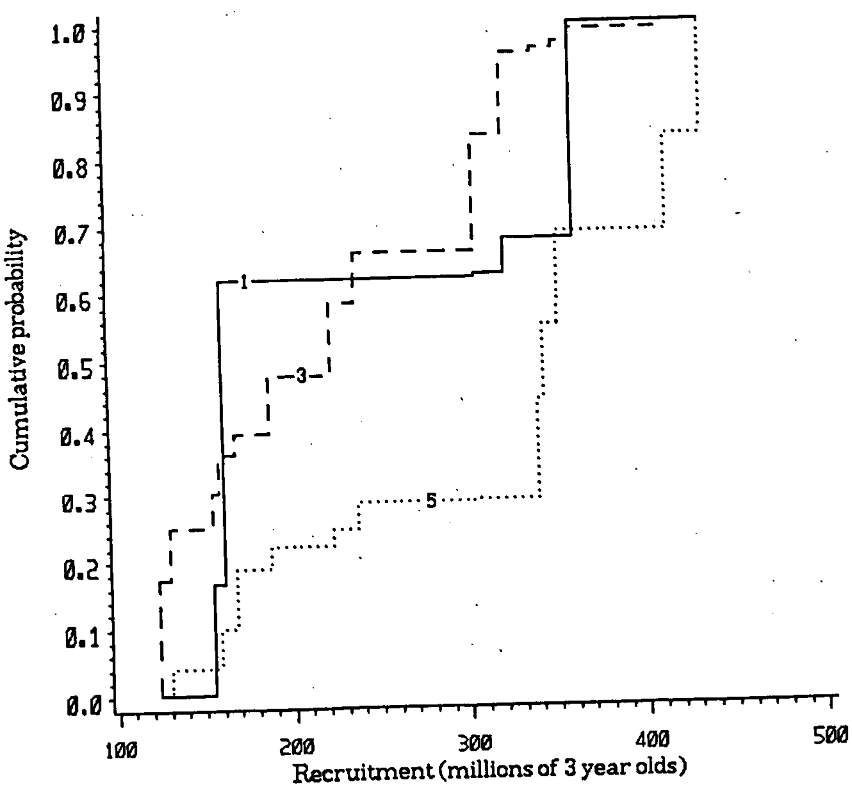


Fig. 14. The cumulative probability of recruitment at different spawner stock biomass levels (1=100 000 tons spawner biomass, 3=300 000 tons, 5=500 000 tons).

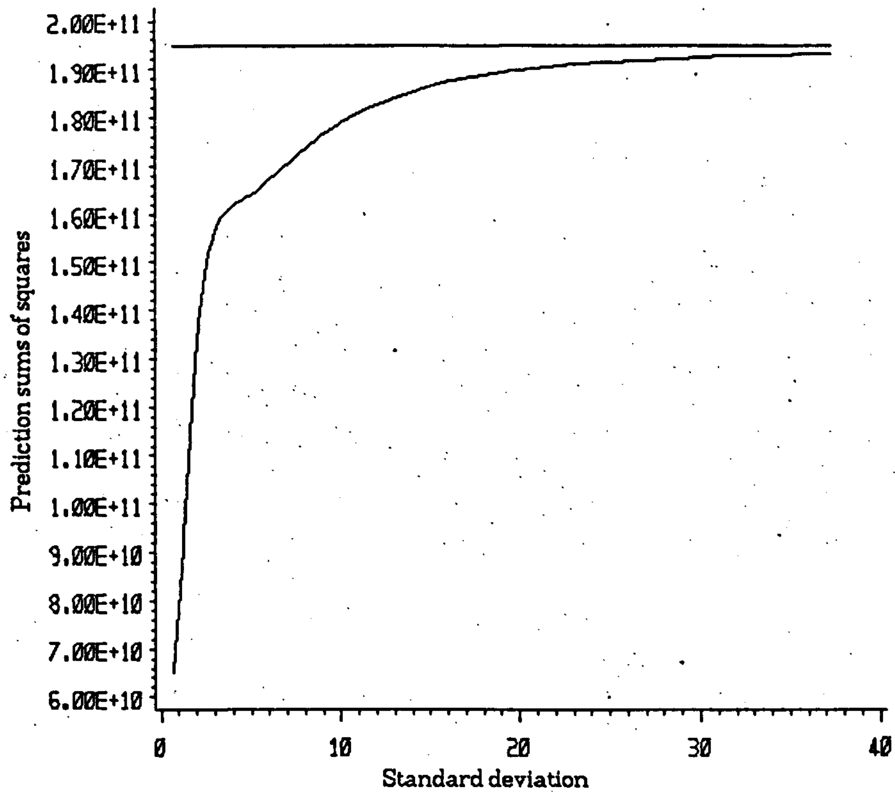


Fig. 15. Jackknifed prediction sums of squares for the Gaussian kernel estimator applied to the temporal pattern (difference in years) at different values of the shape parameter σ. The horizontal line gives the jackknifed prediction ss for the unweighted data.

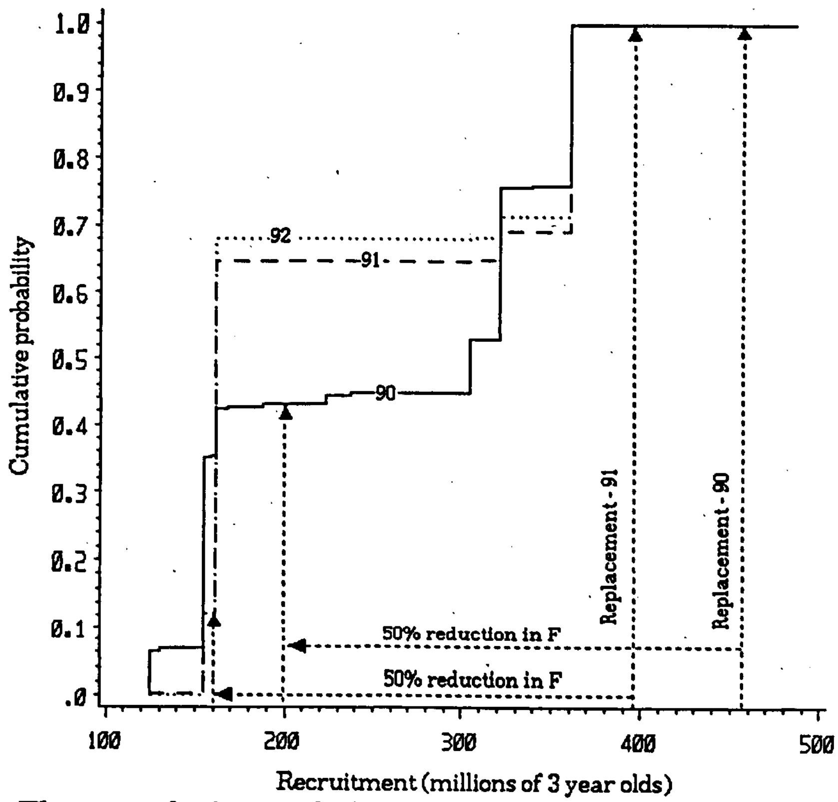


Fig. 16. The cumulative probability of recruitment corresponding to the biomass levels in 1990-92. Vertical broken lines indicate the position of the 1990 and 1991 replacement levels (the 1992 level is off the plot to the left). The horizontal broken lines indicate the decreased probability of failing to meet replacement which could have been expected with a reduction in fishing mortality.