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An Analysis of NAFO Division 2J3KL Cod Spawner Biomass and Recruitment

by

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Abstract

Spawner stock biomass is calculated from maturity data for cod in NAFO Division 2J3KL using a PROBIT model. A non-parametric analysis of the effect of spawner biomass and temporal pattern on the probability distribution of expected recruitment is carried out. Replacement recruitment is defined and annual replacement recruitment is compared with the more commonly calculated average replacement recruitment. It is suggested that biological reference points based on annual replacement recruitment incorporating non-parametric stock-recruit relationships may play a useful role in the assessment of conservation status of groundfish stocks.

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. Biological reference points can be derived from these quantities and relationships and used to define conservation and overfishing. In this paper we examine these quantities and relationships for the cod stock in NAFO Division 2J3KL.

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. However, because the sex ratio of cod in Div. 2J3KL does not appear to be significantly different 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 population 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.

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 Hoenig and Morgan (in prep) was used:

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

where N_i = estimated population number in length class i

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

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

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

n = the number of length classes

The estimated population number in length class i (N_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 corrected 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). There appears to be a trend in recent years for increasing proportion mature at ages 5, 6 and 7 and a decline in proportion mature at these ages in the early 1980s. The model estimates exhibit considerable interannual variability prior to 1978 and much less variability after that period.

The PROBIT estimates of proportion mature at age were used together with numbers at age from ADAPT and weights at age on January 1 determined from sampling of the commercial fishery 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. 2), 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.

Spawner-recruit relationship

The stock-recruit scatter (Fig. 3) shows considerable variability in recruitment with spawner stock size, particularly at intermediate spawner biomass. Potential *S-R* relationships, with *SSB* calculated as above using maturity data and *R* equal to the ADAPT estimate of numbers at age 3 (C. Bishop, DFO St John's, unpublished analysis), were examined using both parametric and non-parametric analyses. A non-linear fit of the standard Ricker model

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

passed through the scatter of points (Fig. 4) but gave estimates of a and b which were 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) was applied. This approach benefits from not requiring a specific model structure to be assumed. 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. 6). 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 230 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 at a similar spawner biomass?'

In order to examine this question, 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 the jackknifed unweighted mean recruitment (ss=19.5E10) with a minimum ss at $\sigma = 66.8 \times 10^3$ (Fig. 6).

The fact that the Gaussian kernel estimator provide better predictions of recruitment than 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 250 times on randomly shuffled recruitment data (i.e. each recruitment value randomly assigned to each spawner stock value for the 17 years). In 50 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=0.2 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. 7). 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. 3). 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 (i.e. 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).

In a preliminary examination of the temporal pattern, a non-parametric analysis was carried out by adding a further weighting factor to the estimator for the time difference in years between the value to be predicted and the other values in the data set. Both weightings were based on a Gaussian pdf. Preliminary results indicate a substantial decrease (factor of 3) in the jackknifed prediction sums of squares (ss=6.4E10) by taking temporal pattern into account, although the significance of this has yet to be tested by applying an approximate randomization test. For the time kernel, the standard deviation that minimizes the prediction ss is small (σ=0.58), giving almost all the weight to the year before and the year after the year to be predicted. The standard deviation for the *SSB* kernel decreases compared to the estimator with *SSB* alone, giving weight only to those *SSB* values that are very close to the *SSB* at which recruitment is to be predicted. Using time alone gives an even lower prediction sums of squares (ss=6.2E10) suggesting that the temporal effect swamps the *SSB* effect, however an estimator which does not incorporate *SSB* may not be robust and this needs to be examined. 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 *SSB* together with only the previous year's recruitment in the estimator (ss=12.2E10) indicating that large uncertainty in predicting future recruitment persists.

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. Biological reference points based on average values will be misleading when there are temporal patterns to the variability. We analysed data for NAFO Div. 2J3KL cod for the period 1973-88 to demonstrate this.

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, to some extent, 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, in press) to assume vectors of w and p which represent average values for several years and to compute replacement for specific values of F and a constant partial recruitment vector or, conversely, to calculate SPR. We refer to these 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, we favour calculating "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.

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. 8). Annual replacement appears to have increased steadily over the period 1978-89. By removing the *SSB* effect in the calculation of replacement, and plotting annual replacement per spawner and average replacement per spawner, it can be see 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. 9). The dramatic decline in annual replacement per spawner in the last year is a result of reduced fishing mortality brought about by the moratorium. Annual replacement per spawner for F=0 (Fig. 10) removes the effect of fishing. Annual replacement per spawner for F=0 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. 11), arresting the decline in annual replacement per spawner. However, 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 this level (Fig. 12), i.e. the level at which the stock will continue to decline even in the absence of fishing.

Discussion

Both annual replacement and average replacement are quantities calculated by simplifying a complete Leslie model to provide a useful reference to indicate whether or not population size is likely to grow or decline. The disadvantage of average replacement recruitment is that it may underestimate or overestimate the recruitment required to meet replacement when there are time trends in weights or proportions mature at age.

The effect of spawner biomass and fishing mortality obscures the effects of weights and proportions mature at age on replacement recruitment, and we advocate calculation of annual R^* per spawner or annual *SPR* at F=0 as one of the steps in the assessment of stock status. Calculations of annual R^* per spawner at F=0 demonstrate 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.

It is common practice in the assessment of northwest Atlantic fish stocks to use all fish over some specific age in the calculation of spawner stock biomass. Where sufficient maturity at age sample data exist we advocate that this data be used, and present a method using a PROBIT model to estimate year and age effects. It is also common practise to use geometric mean recruitment in the prognosis of stock status under different management options. Non-parametric analysis of the *SSB* effect and temporal patterns in recruitment data may be useful in providing cumulative probability distributions of the expected recruitment at a specific *SSB* in the next year.

The analyses conducted in this paper suggest that the definition of biological reference points for groundfish stocks in the northwest Atlantic should incorporate current data on weights at age and proportions mature at age when trends in these values occur. Non-parametric analysis of the effect of *SSB* and temporal patterns on recruitment may also be useful in this regard.

Acknowledgements

This paper is based on data collected and processed by the Gadoids Section of the Groundfish Division, Science Branch, Department of Fisheries and Oceans in St John's. We are indebted to the Section, and particularly Claude Bishop, for making the data available and for encouraging this study.

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Probit model estimates of fall proportions mature

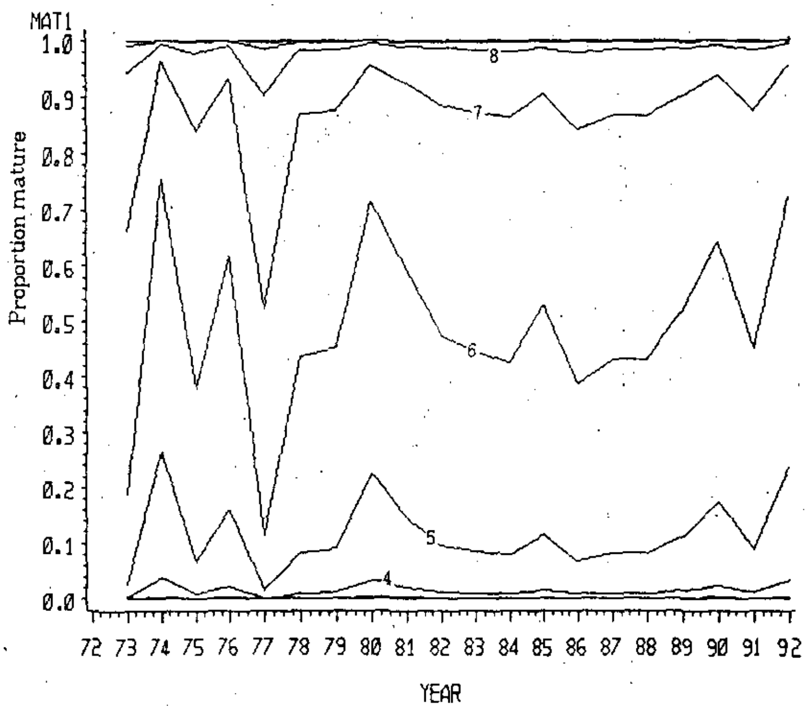


Fig. 1. PROBIT estimates of proportion mature at age for the NAFO Div. 2J3KL cod stock for the period 1972-92 based on survey data.

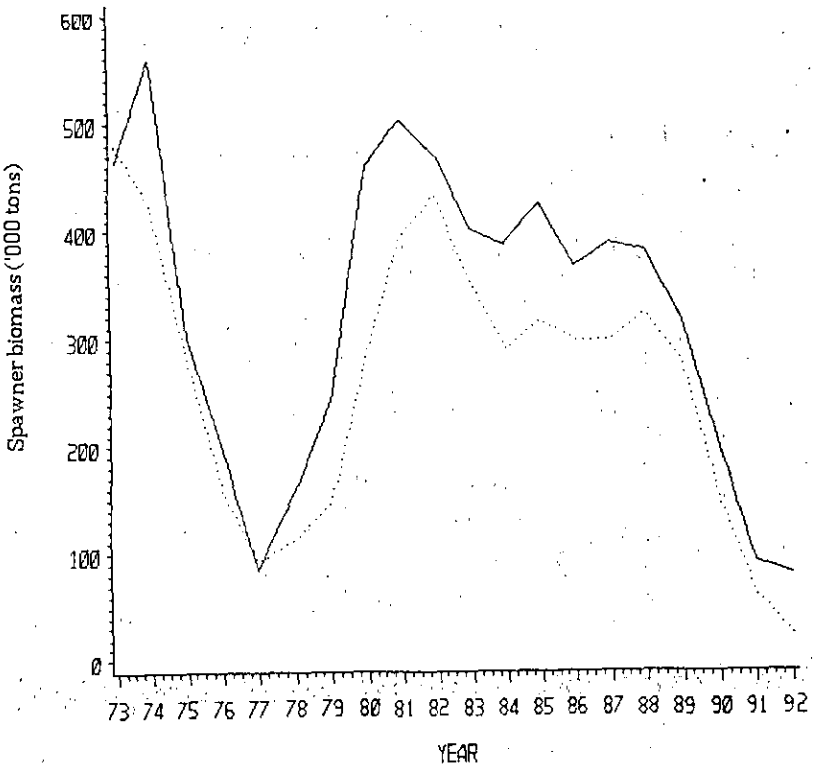


Fig. 2. Spawner biomass calculated using estimated proportions mature at age from survey data (solid line) and by assuming all fish 7+ are mature (broken line).

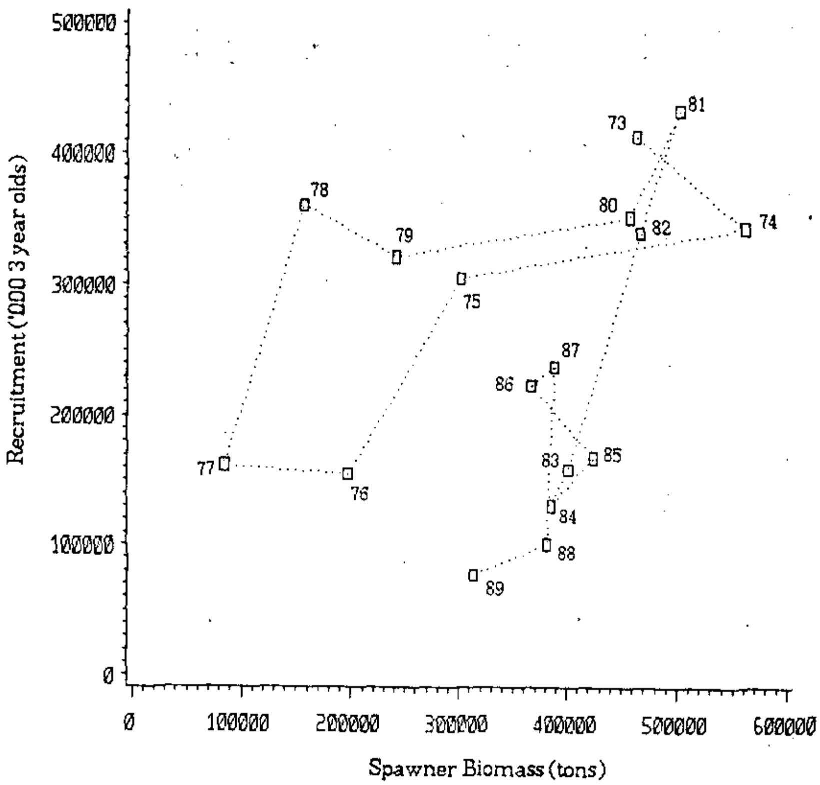
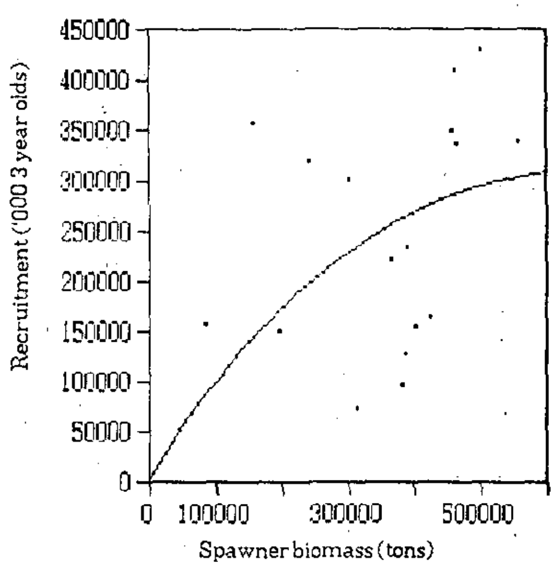


Fig. 3. Stock-recruit scatter from ADAPT estimates and maturity data from surveys.



Fig, 4. A nonlinear fit of the Ricker model to the stock-recruit data for the period 1972-89.

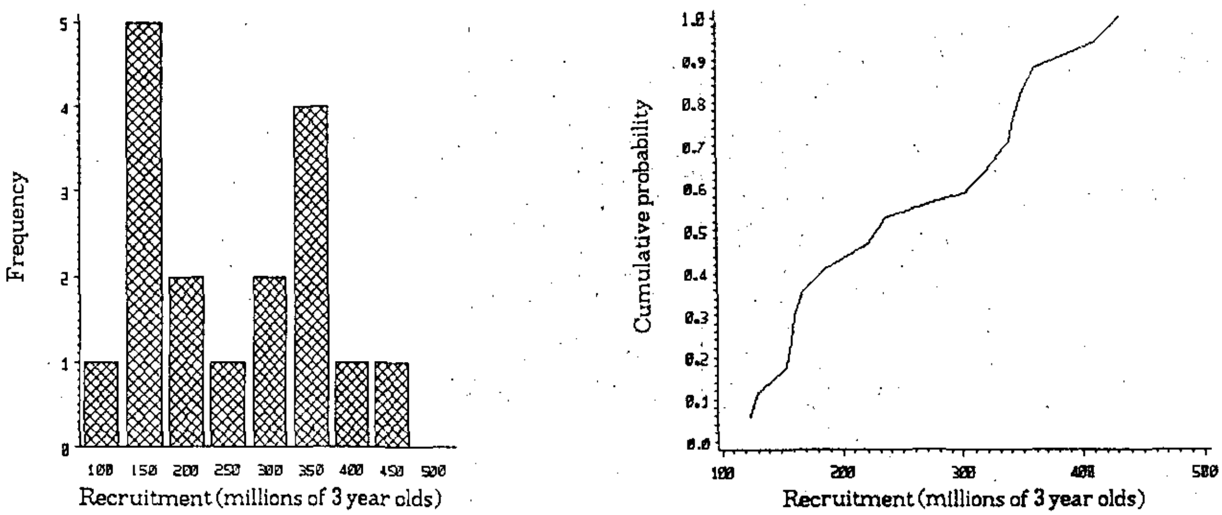


Fig. 5. Frequency distribution and cumulative probability plot for recruitment (millions of 3 year old fish) for the period 1973-89.

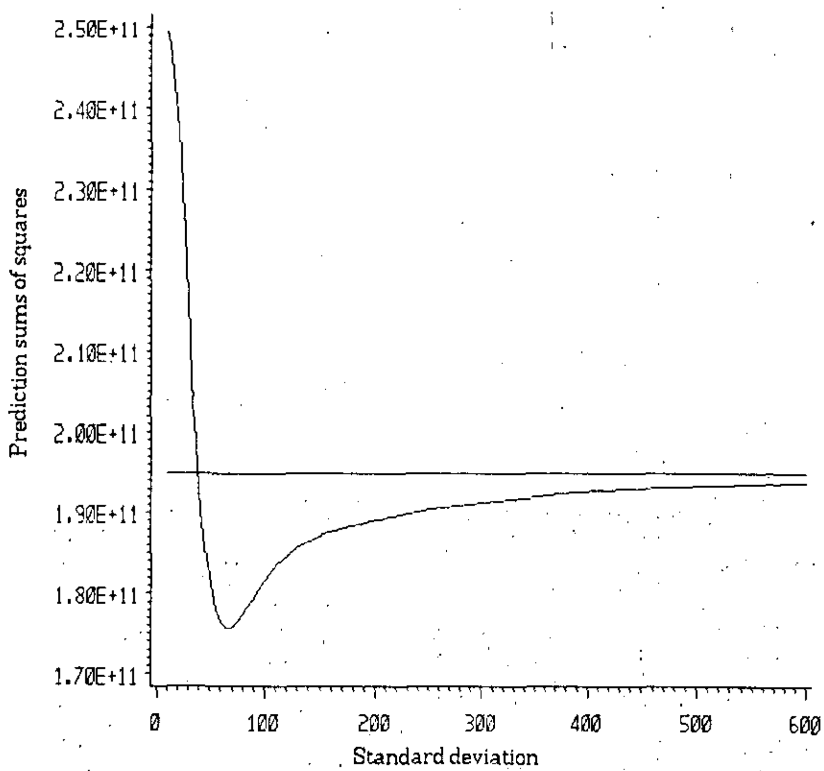


Fig. 6. Jackknifed prediction sums of squares for the Gaussian kernel estimator at different values of the shape parameter σ. The horizontal line gives the jackknifed prediction ss for the unweighted data.

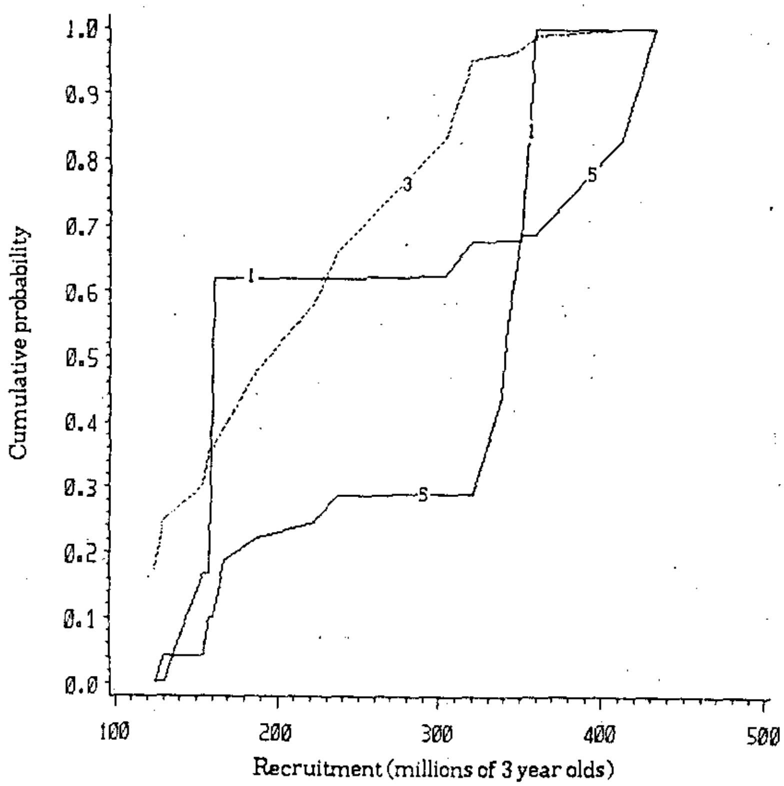


Fig. 7. The cumulative probability of recruitment at different spawner stock biomass levels (1=100 000 tons spawner biomass, 3=300 000 tons, 5=500 000 tons).

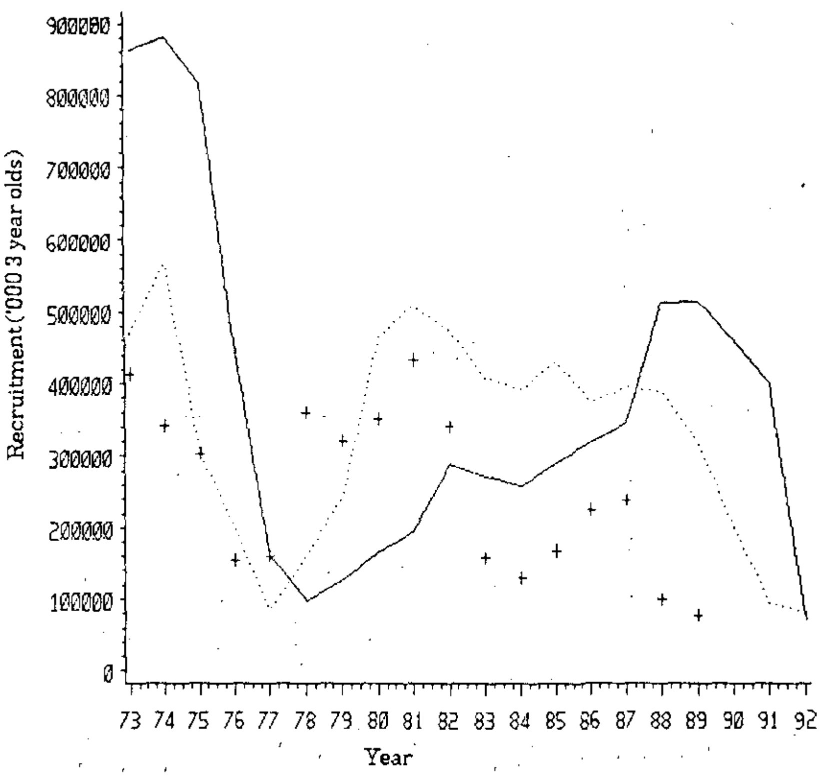


Fig. 8. Average (broken line) and annual (solid line) replacement recruitment levels together with estimates of annual recruitment (+).

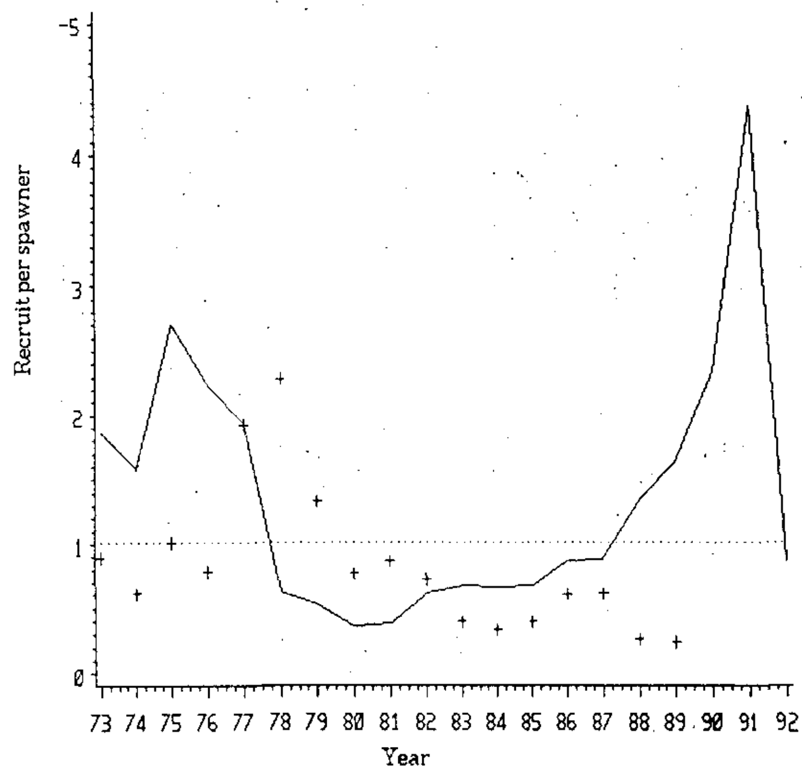


Fig. 9. Average (broken line) and annual (solid line) replacement recruitment per spawner together with estimates of annual recruitment (+).

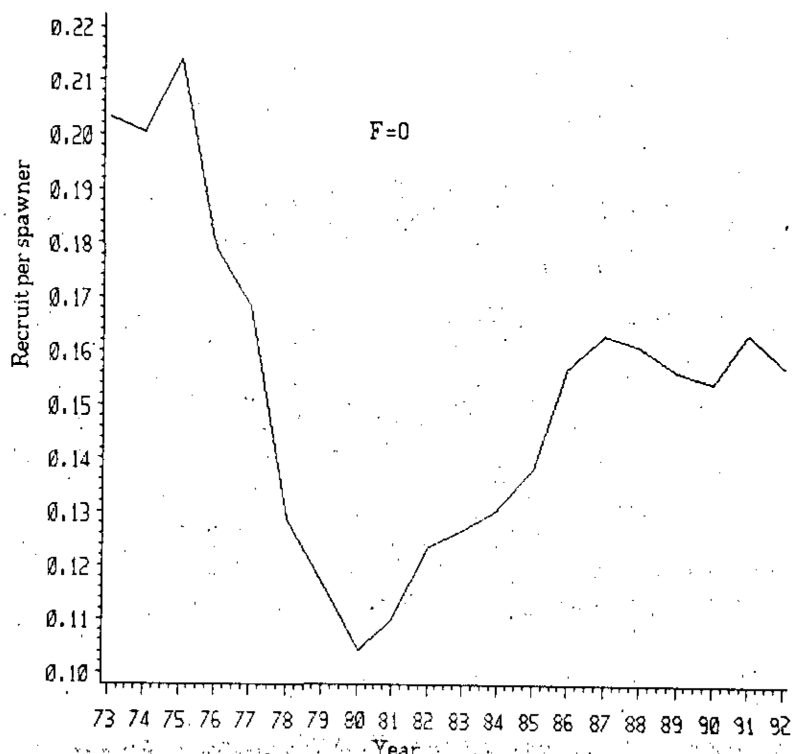


Fig. 10. Annual replacement recruitment per spawner at F=0.

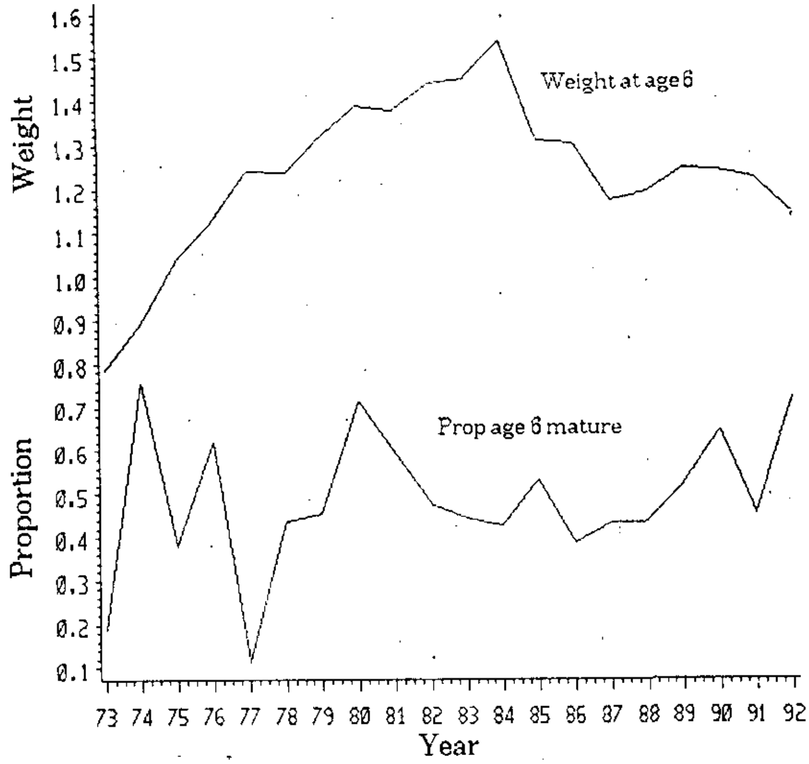


Fig. 11. Trends in weight and proportion mature at age 6.

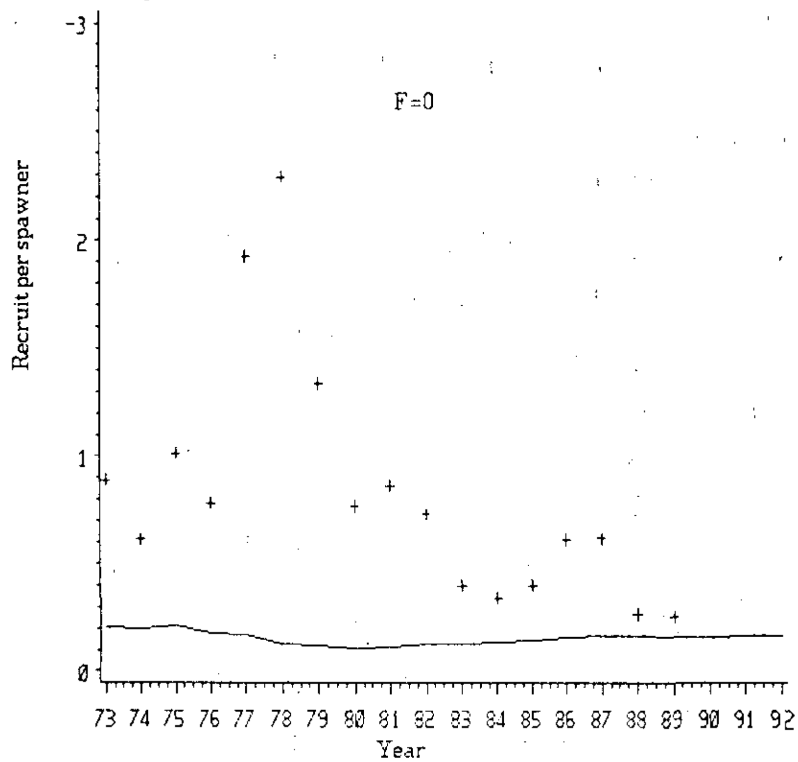


Fig. 12. Annual replacement recruitment per spawner at *F*=0 together with estimates of annual recruitment.