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The stock and recruitment relationship in Arcto-Norwegian cod

by

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INTRODUCTION

The progressive depletion of spawning stocks in many areas and the associated risk to long-term yield through reduced recruitment is causing increasing concern. It is this risk that has stimulated the present management strategy for Georges Bank herring, aimed at permitting this stock to recover to a specific biomass level. However, whilst it is expected that no long-term benefit in yield would derive from a further reduction of herring stocks (and many others), it is by no means certain that this would in fact cause lasting damage to the resource, nor is it clear what level of spawning stock should be considered adequate.

In considering this same problem in relation to management of the Arcto-Norwegian cod stock, NEAFC requested ICES 'to consider the possibility of an estimation of the optimum size of the spawning stock of Arcto-Norwegian cod'. This has been attempted by a modification of existing techniques which still deals with the problem only at an empirical level but which may be of more general interest. The analysis recognizes the interaction of the age of maturity in the stock with the effect of fishing from recruitment to spawning, and so gives expression to the events at all phases of the life-cycle which may influence the size of the spawning stock and hence the number of recruits it can produce.

THE STOCK AND RECRUITMENT RELATIONSHIP

Estimates of parent stock in each year have been derived as follows:

1 The age composition of the stock was derived for the beginning of each year from Virtual Population Analysis.

2 The mature stock at 1 January was then calculated, assuming that 50% of seven-year-old fish, and all fish of eight years or older, were mature. From this the annual catch in the Norway Coast spring fishery was deducted, on the assumption that the majority of these fish are actually caught in pre-spawning condition and are therefore effectively lost to the spawning stock.

3 The biomass of the mature stock was estimated by multiplying the number of mature fish of each age group by the average weight at each age and summing for all age groups.

4 The mature biomass was then converted into eggs, assuming a production of 400 eggs per g of mature biomass (based on Botros, 1962).

5 The number of resultant three-year-old recruits was taken from the Virtual Population Analysis and is therefore estimated independently from the estimates of mature stock size.

A Ricker stock and recruitment curve was fitted to the resultant data for the years 1942-68. The equation of the curve used was

$$R = aSe^{-bS} , \tag{1}$$

where R = number of recruits,

S = parent stock size,

a = coefficient of density independent mortality,

b = coefficient of density dependent mortality.

The curve was fitted by the method of least squares to minimize $\Sigma(R - aSe^{-bS})^2$. The calculated curve, with its 95% confidence limits, is shown in Figure 1. The parameters of the curve are

$$a = 3.8981, \quad b = 0.1122,$$

where R is measured as numbers x 10^{-8} of three-year-old recruits and S as eggs x 10^{-14}.

This is the conventional relationship between stock and recruitment, which is in practice difficult to interpret unless the effect of fishing upon the recruits is superimposed to establish the link between them and the spawning stock which they generate. The essential criterion of stability is that the stock should replace itself over its entire life-cycle; a given spawning stock should generate an equivalent spawning stock in the filial generation. This suggests a transformation of the data to give the potential egg production, S_2, of filial recruits, assuming that they are subject only to natural mortality. The ratio S_2/S_1 is then a measure of the proportion of the new generation which is surplus with regard to the criterion of replacement. In the context of the fishery and the mortality it generates it is more relevant to express this ratio in its inverse form, as the proportion of S_2 which must survive to replace S_1. Thus since $S_2 = S_1e^x$, $S_1/S_2 = e^{-x}$, and since the estimation of S_2 incorporates the effect of natural mortality, e^{-x} approximates to e^{-F} summed from recruitment to the mean age of the spawning stock. From expression 1, then,

$$\log_e S_1/S_2 = \log_e 1/a + bS_1 \ . \qquad (2)$$

The plot $\log_e S_1/S_2$ against S_1 is given in Figure 2, from which the fitted line may be retransformed to the Ricker-type stock and recruitment curve $S_2 = 12.164\ S_1e^{-0.1122S_1}$, shown in Figure 3.

Also plotted in Figure 2 is the $\log_e$ reduction in potential egg production per unit of fishing mortality plotted against annual fishing mortality on fully exploited age groups. It can be shown that $\log_e$ reduction in potential egg production per unit of F is equivalent to ΣF up to mean age of mature stock. Thus by relating the two lines plotted in Figure 2 it is a simple matter to determine the level of annual fishing mortality required to harvest the surplus production at any stock level. At the point at which the stock just replaces itself in the absence of fishing, $\log_e(S_1/S_2) = 0$ and $S_2 = S_1 = 22.3 \times 10^{14}$ eggs, and this is indicated by the broken line. In the absence of fishing the stock will tend to stabilize at this level under the influence of natural mortality only. At stock levels below the replacement level there is surplus production of recruits. If, for any size of stock, the whole surplus is removed by fishing the stock will remain in equilibrium. Using Figure 2 the amount of fishing mortality which has to be applied to remove the surplus production can be determined as follows:

For any given stock size read the value of $\log_e(S_1/S_2)$ from the graph of $\log_e(S_1/S_2)/S_1$. This value is numerically equal to $-\Sigma F$ (or the log reduction in potential egg production per F), and the annual value of F on the fully recruited age groups is read from the graph of $-\Sigma F/F$. For example, for a stock size of 10×10^{14}

eggs the value of $\log_e(S_1/S_2) = -1.38$ can be read from the graph of $\log_e(S_1/S_2)/S_1$. Then from the graph of $-\Sigma F/F$, $-\Sigma F = -1.38$ can be seen to be equivalent to an annual $F = 0.205$. This value of annual F is based on the pattern of recruitment to the exploited stock as in recent years.

The following conclusions can be made from Figure 2:

(i) At each stock size up to the replacement point there is an appropriate level of fishing mortality which will remove surplus production and maintain the stock in equilibrium. This value of F is greatest at low stock levels, where density-dependent mortality of pre-recruits is least, and decreases to zero at the replacement point.

(ii) If ΣF is greater than 2.5, the stock will inevitably tend to extinction because losses by fishing exceed the surplus generated when density-dependent mortality is at a minimum. In this stock $\Sigma F\, 2.5$ = annual $F = 0.43$, owing to the time of exposure to fishing between recruitment and spawning.

(iii) There is a clear increase in variance about the stock and recruitment curve at low levels ($< 6 \times 10^{14}$ eggs).

(iv) Within this area of instability in recruitment at very low stock levels, only the largest year-classes contain enough recruits to offset the level of exploitation which has been characteristic of recent years.

INTERPRETATION OF THE STOCK AND RECRUITMENT CURVES

In Figures 1 and 3 the points for each year are identified. The curve has been fitted to the points for 1942-68, for which estimates of three-year-old recruits are available from Virtual Population Analysis. In Figure 1 points are also plotted for the years 1969-71, using recruitment data estimated from pre-recruit surveys. Also indicated in Figure 1 are the estimates of mature stock size for the years 1972-77. It will be seen that the present very low size of the mature stock is expected to decline still further, probably reaching a minimum level in 1975-76.

The stock and recruitment curve is more easily interpreted when stock and recruitment are plotted in equivalent units, as in Figure 3.

In this figure the 45° replacement line is drawn. Recruitment above this line under the dome of the stock and recruitment curve is recruitment in excess of that required to provide a replacement stock, and this represents the amount which can be harvested if the stock is maintained in equilibrium. Where the lines intersect, at a stock size of 22.3×10^{14} eggs, the stock will just replace itself in the absence of fishing. To the right of this point recruitment is less than the parent stock and there is no surplus production of recruits. The maximum number of recruits is produced from a stock size of 8.9×10^{14} eggs. Maximum surplus production is obtained with a stock size of 7.3×10^{14} eggs (indicated by the arrow in Figure 2), when the number of recruits produced is equivalent to 39.2×10^{14} eggs, of which 31.9×10^{14} are surplus to that required for replacement. The optimum stock size of 7.3×10^{14} eggs is equivalent to the observed stock size in the early 1950s.

In Figure 4 the annual fishing mortality appropriate to maintain the stock in equilibrium is plotted against stock size. The resultant equilibrium catch is also plotted in the figure. Exploited at the optimum level the Arcto-Norwegian cod stock would give an annual yield of over 800 000 tons.

This curve represents the yield under equilibrium conditions and should not lead to the conclusion that catches will decrease dramatically as soon as fishing mortality exceeds $F = 0.3$, or the stock is depleted below 7.3×10^{14} eggs. In fact, catches of Arcto-Norwegian cod have averaged close to 800 000 tons throughout the post-war period, when fishing mortality has averaged $F = 0.5$–0.6. This has resulted in a gradual depletion of the resource over a long period, the catch being maintained by the surplus, as defined here, plus a portion of the replacement stock level. The rate of decline will vary - depending on the degree of excess fishing mortality - until finally, as now in the Arcto-Norwegian cod, stock reserves reach a very low level.

SUMMARY

1 A Ricker-type stock and recruitment curve has been fitted to observed data of parent stock size and the size of the resultant recruitment. The data covered the period 1942-68.

2 A relationship was derived between stock size and the level of annual fishing mortality required to harvest the production in excess of that required to maintain the stock in equilibrium, assuming that the selection pattern would be the same as at present.

3 The optimum size of the mature stock, in the units used, would be 7.3×10^{14} eggs. This corresponds to the observed size of the mature stock in the early 1950s. At this stock size, and with the present selection pattern, the optimum level of annual fishing mortality would be $F = 0.26$, when an average annual yield of over 800 000 tons could be expected. It is possible that by changing the selection pattern an even greater yield might be obtainable.

4 The conclusions in this paper are based on the assumption that the size of recruiting year-classes would be determined from the spawning stock according to the calculated stock and recruitment relationship. The stock and recruitment curve would be expected to represent the average relationship between stock and recruitment, but individual annual values would be expected to show the same variance about the curve as has been the case for the observed data for past years.

REFERENCE

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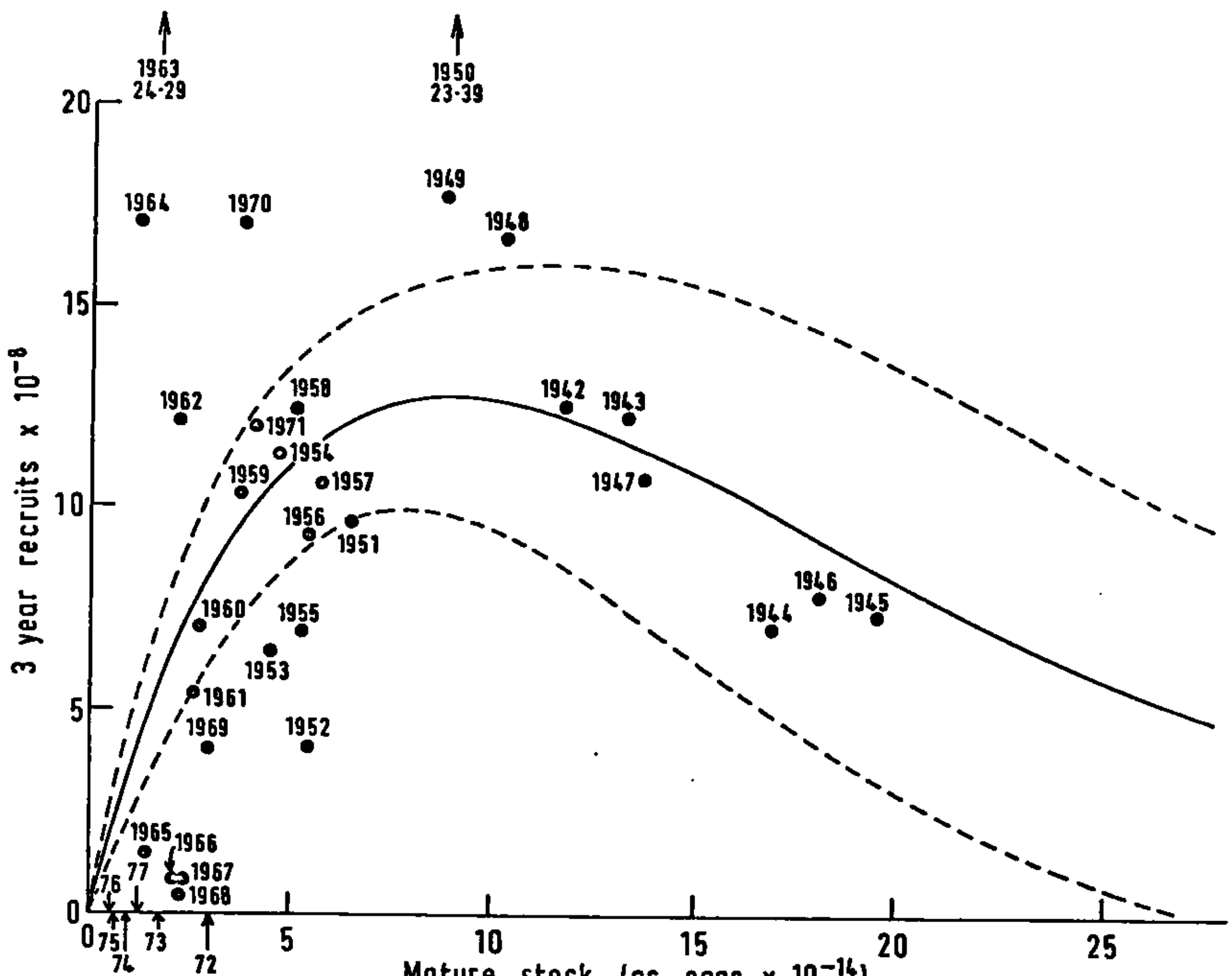

Figure 1 Stock-recruitment curve for the Arcto-Norwegian cod. $R = 3.8981\,S e^{-0.1122S}$. The curve is fitted to the points for 1942-68. The broken lines indicate 95% confidence limits of the curve.

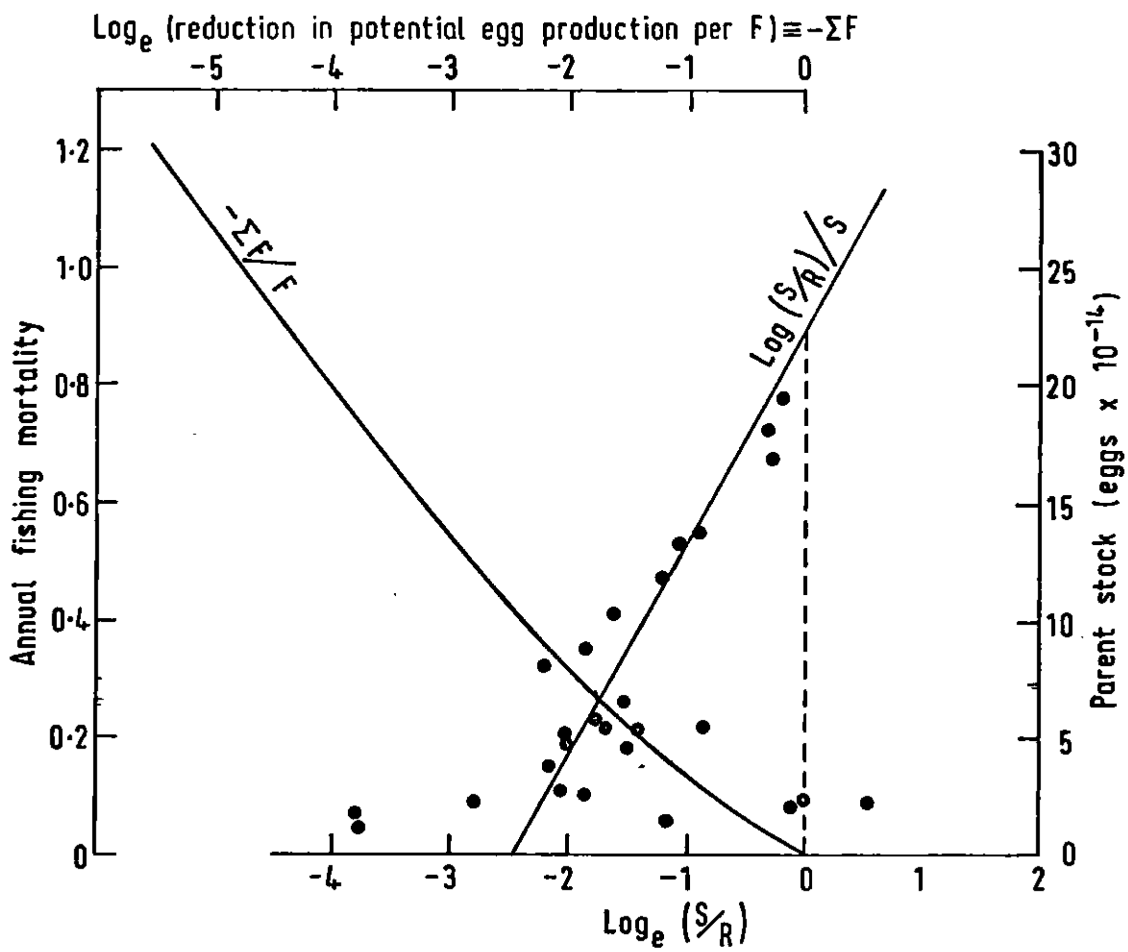

Figure 2. Plot of log$_e$ (Stock/Recruit) against Stock. The observed points for years 1942-68 are shown and the line represents the fitted stock-recruitment curve. Plot of cumulative fishing mortality on mean age in mature stock against annual fishing mortality coefficient.

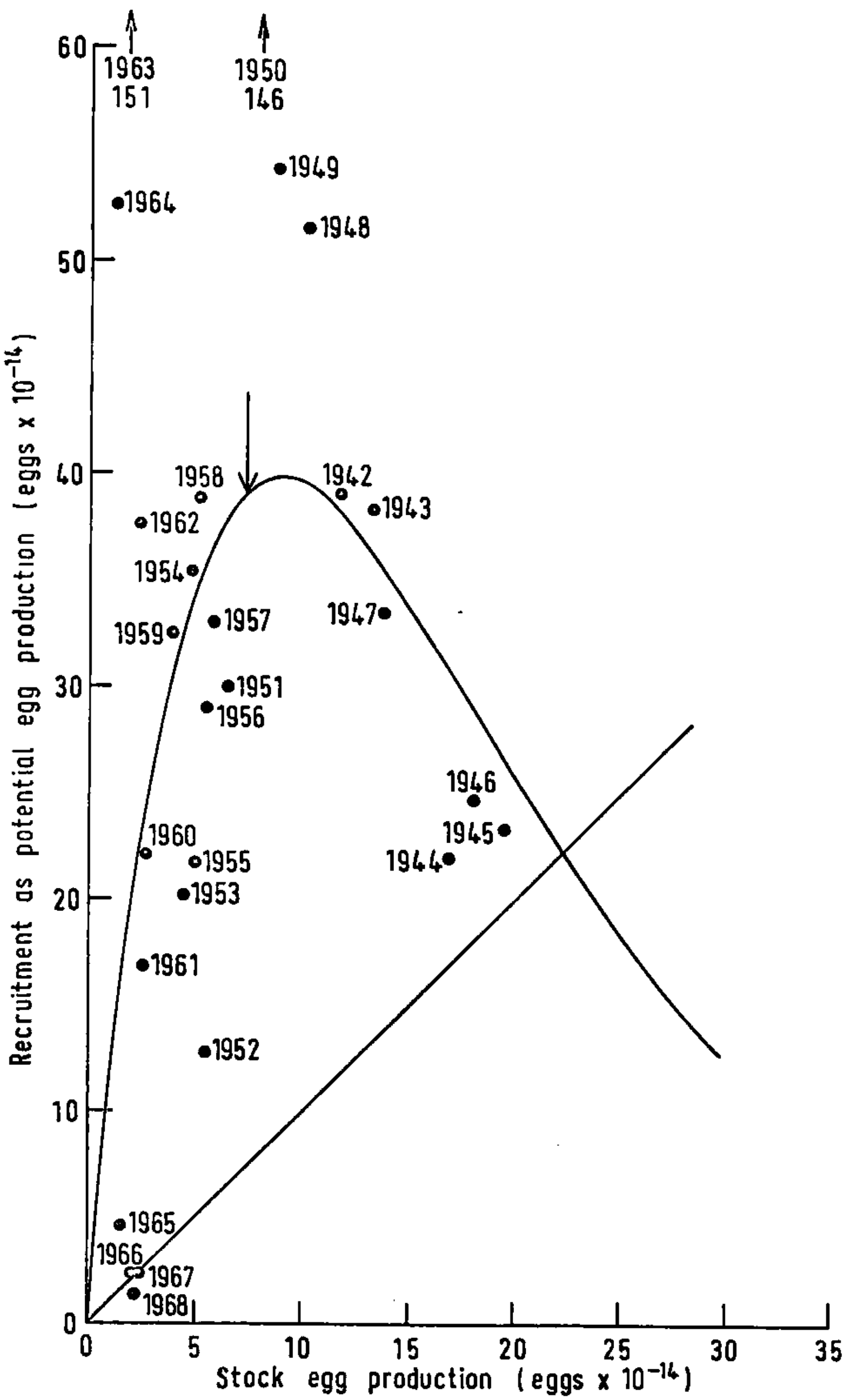

Figure 3 Stock-recruitment curve for Arcto-Norwegian cod. Recruits and stock measured in the same units. $R = 12.164 S e^{-0.1122S}$. The arrow indicates the point of maximum surplus production.

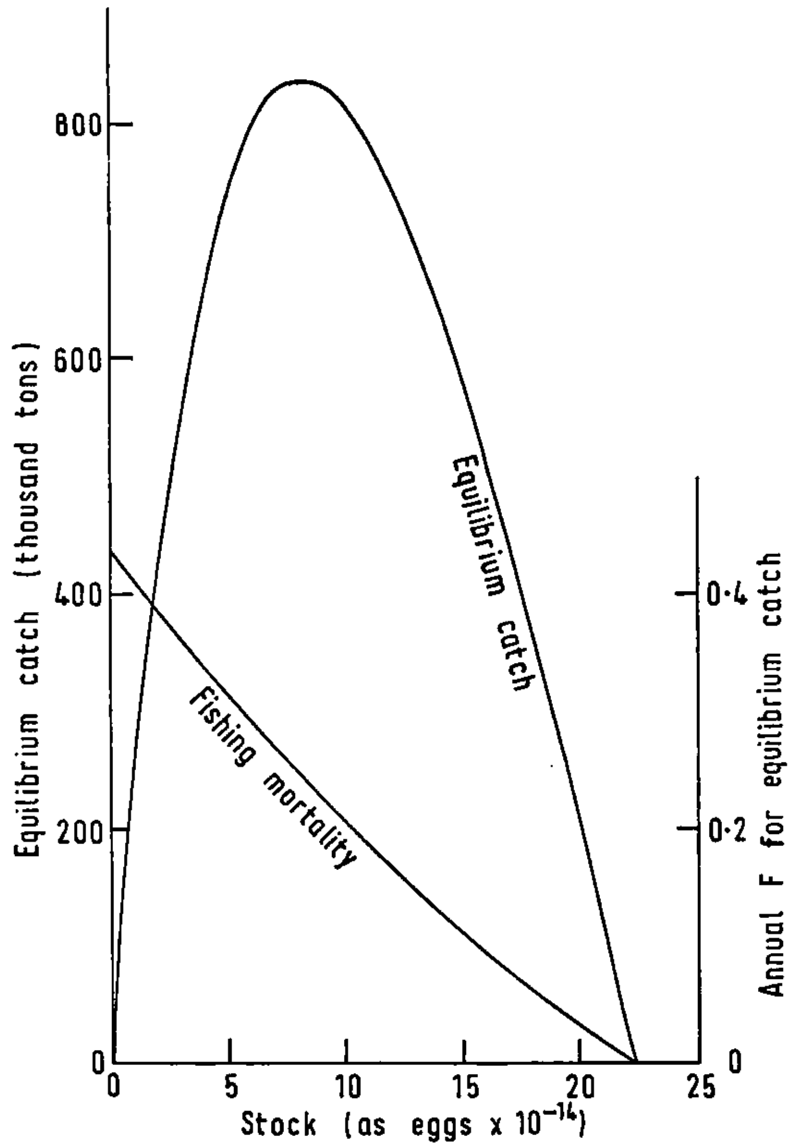

Figure 4 Equilibrium catch against stock size, and the annual fishing mortality required to achieve equilibrium catch.