J. Cons. int. Explor. Mer, 36(1): 35–41. Novembre 1974.

Stock and recruitment relationship in the Northeast Arctic cod stock and the implications for management of the stock

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The Ricker stock and recruitment equation has been fitted to data for the northeast Arctic cod stock covering the period 1942–1968. From this relationship the mature stock size which produces the maximum equilibrium harvestable catch has been determined. A relationship has been derived between stock size and the annual fishing mortality required to harvest production in excess of that required to replace the parent stock. The implications of these relationships on the management of the stock have been discussed and a computer simulation technique has been used to study the effects, over a 25 year period, of fishing at various stabilized levels of fishing mortality. A level of fishing mortality much lower than at present would be required to allow the spawning stock size to build up from the very low level expected in the mid 1970s and thereby reduce the risk of recruitment failure.

Introduction

Since 1969 the annual reports of the ICES Northeast Arctic Fisheries Working Group (ICES 1970, and subsequent annual reports) have expressed concern at the declining size of the spawning stock of Arcto-Norwegian cod. In its 1972 report the Group pointed out that the spawning stock would become very small indeed by the mid-1970s. The Working Group considered that at low levels of spawning stock the risk of poor recruitment was increased. In this paper we have calculated a stock and recruitment relationship for the Arcto-Norwegian cod stock. Using this relationship we have shown what size of catch can be expected at any equilibrium level of stock size, and the level of fishing mortality required to take this catch has been estimated. Using this stock and recruitment relationship the optimum stock size has been calculated, together with the yield that can be expected from it. Using a computer simulation, the trend in catches to be expected over the next 25 years has been calculated if the stock is exploited at a range of constant values of fishing mortality with the present mesh size of 130 mm. Similar catch trends have been calculated at the same levels of fishing mortality, assuming exploitation with minimum trawl cod-end mesh sizes of 145 mm and 160 mm.

The stock and recruitment relationship

Data for 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 was then calculated, assuming that 50% of seven-year-old fish were mature and all fish of eight years or older were mature. From this the annual catch from ICES Division IIa was deducted, on the assumption that the majority of fish in the IIa catch are taken in the pre-spawning fishery and are therefore effectively lost to the spawning stock.
3. Mature stock biomass 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. The weight/age measure used was the average weight at age in the English catches from Division IIa.
4. The mature biomass was then converted into eggs, assuming a production of 400 eggs per g of mature biomass (based on Botros, 1962) to give an index of spawning stock in terms of egg production.
5. The number of resultant three-year-old recruits was taken from the Virtual Population Analysis. Estimates of the number of recruits are independent of estimates of mature stock size.

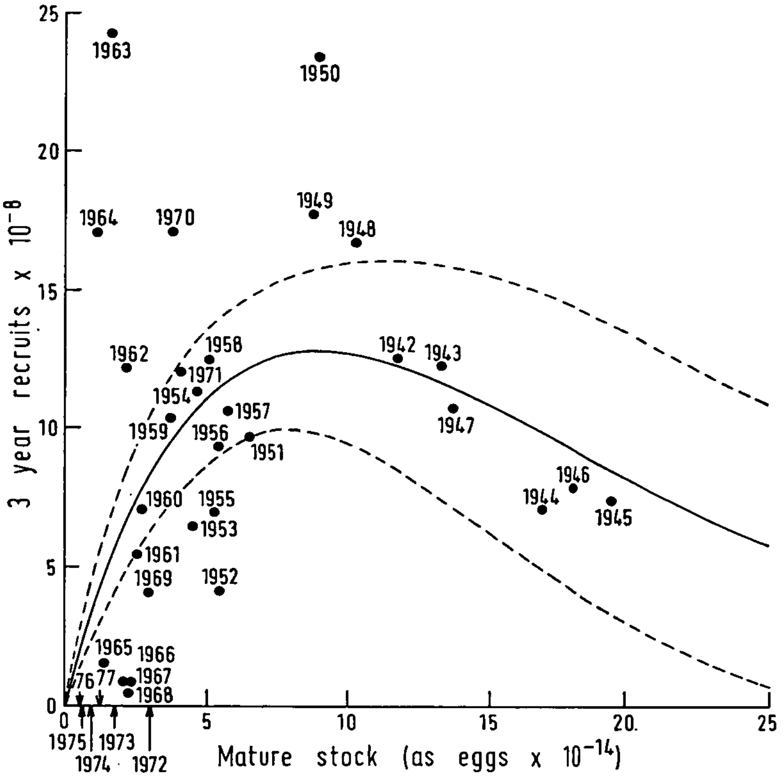

Figure 1. Stock and recruitment curve for the Arcto-Norwegian cod $R = 3{\cdot}8981S\exp(-0{\cdot}1122S)$ fitted to the points for 1942–68. The broken lines indicate 95% confidence limits of the curve.

A Ricker stock and recruitment curve was fitted to the resultant data for the years 1942–1968. The equation of the curve used was:

$$R = a\,S\,e^{-bS} \quad\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

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 $\Sigma[R - aS\exp(-bS)]^2$. The calculated curve, with its 95% confidence limits, is shown in Figure 1; the parameters are: $a = 3{\cdot}8981$ and $b = 0{\cdot}1122$, where R is measured as numbers $\times\ 10^{-8}$ of three-year-old recruits and S as eggs $\times\ 10^{-14}$.

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 (10^8 three-year-old recruits = $3{\cdot}12 \times 10^{14}$ eggs). The stock and recruitment curve transformed in this way is plotted in Figure 2 and is defined by $S_2 = 12{\cdot}1640\ S_1\exp(-0{\cdot}1122S_1)$ where S_1 and S_2 are both measured as eggs $\times\ 10^{-14}$.

If parent stock and recruits are measured in the same units the stock will replace itself when $S_2 = S_1$. If $S_2 > S_1$, recruits are produced in excess of the number required to replace the stock and the surplus can be harvested. The degree of surplus can be expressed as the ratio S_2/S_1 or in the inverse form S_1/S_2, it represents the extent to which S_2 can be depleted and still provide replacement of the parent stock. Thus if $S_2 = 100$ and $S_1 = 10$, $S_1/S_2 = 0{\cdot}1$ and 90% of S_2 can be removed, leaving $S_2 = S_1$. The logarithm of this ratio, $\log_e(S_1/S_2)$, is plotted against stock (S_1) as the points in Figure 3. The fitted line is that given by the Ricker stock-recruitment curve $S_2 = 12{\cdot}1640S_1\exp(-0{\cdot}1122S_1)$. Also plotted in Figure 3 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 3 it is a simple matter to determine the level of annual fishing mortality required to harvest the surplus production at any stock level. (For the purposes of this paper, recruitment to the exploited stock is considered complete at six years of age. Proportional recruitment for younger age-groups has been taken as 3 years = 0·3, 4 years = 0·6, and 5 years = 0·9, as adopted at the 1972 meeting of the Northeast Arctic Working Group.)

Interpretation of the stock and recruitment curves

In Figures 1 and 2 the points for each year are identified. The curve has been fitted to the points for 1942–1968, 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 1972–1977. 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 1975–1976.

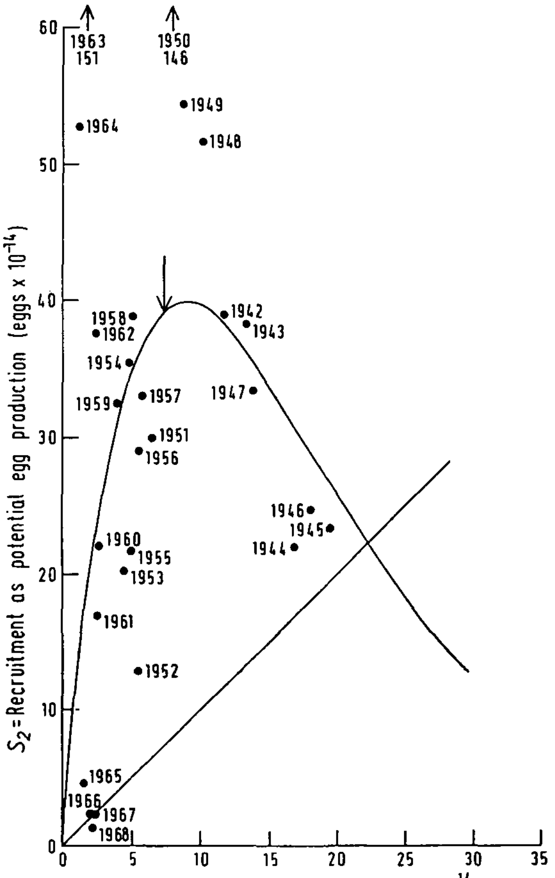

Figure 2. Stock and recruitment curve for Arcto-Norwegian cod. Recruits and stock are measured in the same units. $S_2 = 12{\cdot}164 S_1 \exp(-0{\cdot}1122 S_1)$. The arrow indicates the point of maximum surplus production.

The stock and recruitment curve is more easily interpreted when stock and recruitment are plotted in equivalent units, as in Figure 2. 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 $22{\cdot}3 \times 10^{14}$ 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 $8{\cdot}9 \times 10^{14}$ eggs. Maximum surplus production is obtained with a stock size of $7{\cdot}3 \times 10^{14}$ eggs (indicated by the arrow in Fig. 2) when the number of recruits produced is equivalent to $39{\cdot}2 \times 10^{14}$ eggs, of which $31{\cdot}9 \times 10^{14}$ are surplus to that required for replacement. The optimum stock size of $7{\cdot}3 \times 10^{14}$ eggs is equivalent to the observed stock size in the early 1950s.

In the alternative plot in Figure 3 the stock and recruitment curve has been plotted as $\log (S_1/S_2)$ against S_1 and in this form it is a straight line. At the point at which the stock just replaces itself in the absence of fishing, $\log (S_1/S_2) = 0$ and $S_2 = S_1 = 22{\cdot}3 \times 10^{14}$ 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 3 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 $\log (S_1/S_2)$ from the graph of $\log (S_1/S_2)S_1$. 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 $S_1 = 10 \times 10^{14}$ eggs the value of $\log (S_1/S_2) = -1{\cdot}38$ can be read from the graph of $\log (S_1/S_2)S_1$.

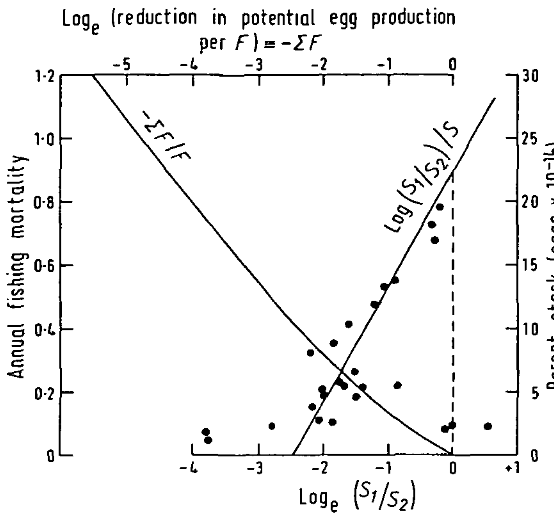

Figure 3. Plot of log$_e$ (stock/recruit) against stock. The observed points for years 1942–68 are shown and the line represents the fitted stock and recruitment curve. Plot of cumulative fishing mortality on mean age in mature stock against annual fishing mortality coefficient.

Then from the graph of $-\Sigma F/F$, the value of $-\Sigma F = -1{\cdot}38$ can be seen to be equivalent to an annual $F = 0{\cdot}205$. This value of annual F is based on the pattern of recruitment to the exploited stock as defined above.

The following conclusions can be made from Figure 3.

(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 and decreases to zero at the replacement point.

(ii) If ΣF is greater than 2·5, equivalent to an annual F of 0·43, the stock will inevitably tend to extinction because losses by fishing exceed the surplus generated when density-dependent mortality is at a minimum.

(iii) The maximum catch is obtained with a stock size of $7{\cdot}3 \times 10^{14}$ eggs, exploited with an annual fishing mortality of 0·26.

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

(v) 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.

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 with the present pattern of selection.

Computer simulation

A version of the computer simulation program described by Clayden (1972) was used to predict catch trends from the Arcto-Norwegian cod stock if, starting from the stock situation as in 1971, the stock was exploited over a period of 25 years at a range of values of fishing mortality which remained constant over the whole period. Three runs were made, the first with the selection pattern as at present and the other two with selection patterns equivalent to the use of 145 mm and 160 mm mesh sizes. Comparisons of the yields given by runs 1 and 2, and 1 and

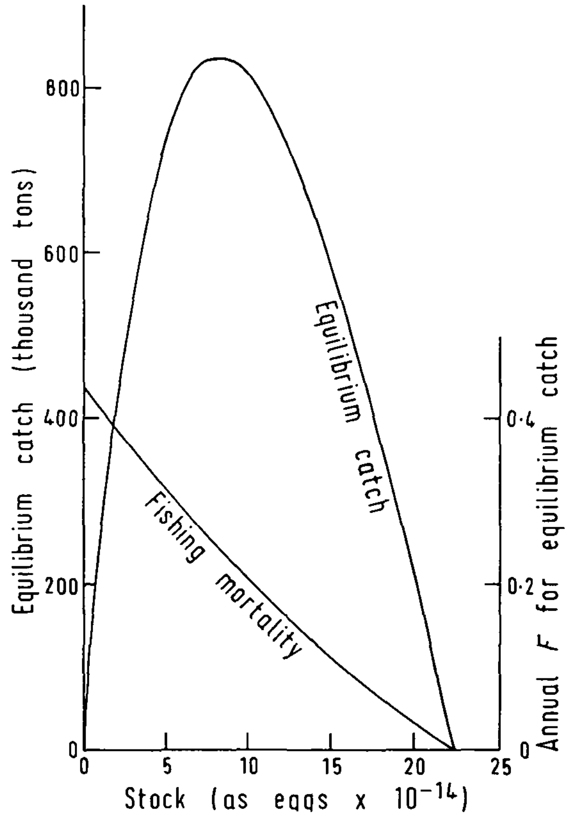

Figure 4. Equilibrium catch against stock size, and the annual fishing mortality required to achieve equilibrium catch.

3 provide estimates of the benefits to be derived from the introduction of larger minimum mesh sizes.

The computer model works as follows. The initial stock is subjected to natural and fishing mortality. The numbers at each age removed from the stock by fishing mortality are multiplied by the appropriate weight at age and the products summed to give the catch for the year. The survivors at the end of

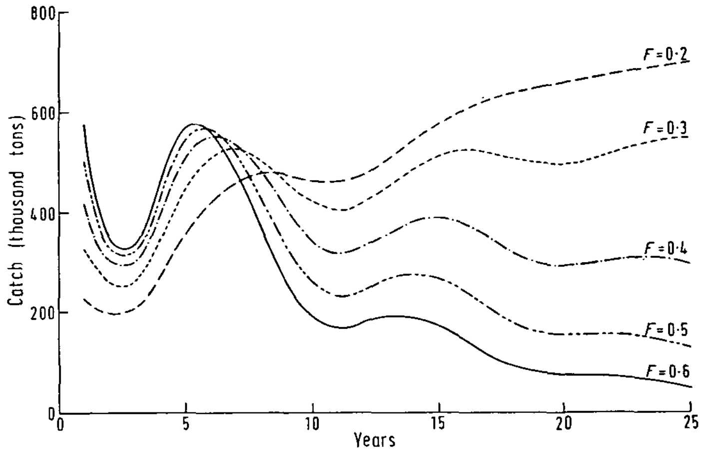

Figure 5. Catch predictions for exploitation at constant levels of fishing mortality. 1971 stock composition used as initial stock.

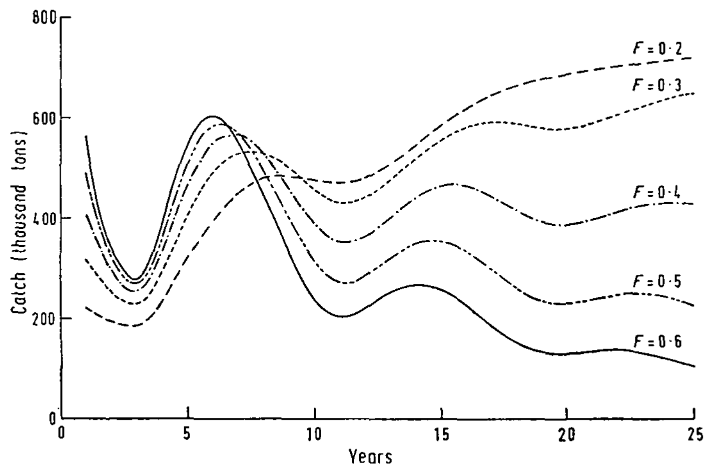

Figure 6. Catch predictions as in Figure 5 but allowing for the use of a 145 mm mesh size throughout.

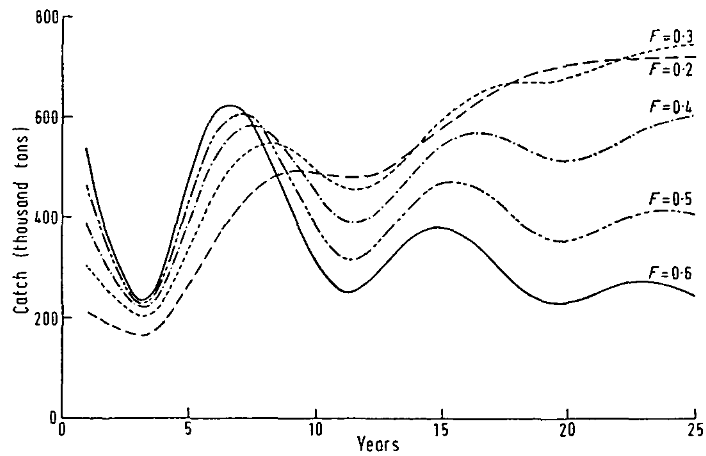

Figure 7. Catch predictions as for Figure 5 but allowing for the use of a 160 mm mesh size throughout.

the year are carried forward as the stock for the next year and their ages are incremented by 1. The estimates of 0-group recruits are added to this stock. Recruitment is calculated from the size of the mature stock in the previous year and the stock and recruitment relationship. This cycle is then repeated 25 times to simulate 25 years' fishing. The data used in the model are summarized in Appendix 1.

This approach excludes the effects of variation in the density-independent component of the mechanism determining recruitment. However, presuming this to vary without trend, the long-term simulation is expected to indicate the probable trend in catches under different fishing conditions.

The results of the three runs are given in Figures 5–7. The initial fluctuations result from the year-class strengths as estimated from Virtual Population Analysis or 0-group surveys up to 1971. The initial decline in catches is due to the strong 1963 and 1964 year-classes fading out of the fishery. The subsequent upsurge results from the recruitment of the good year-classes of 1969–1971. After the 1971 year-class, recruitment is determined by the stock and recruitment relationship and the fluctuations are gradually damped out. Figure 8 provides a comparison of yields at selected values of fishing mortality for changes of mesh to 145 mm and 160 mm.

Conclusions from the computer simulation

With the present mesh size and selection pattern (Fig. 5) it can be seen that a constant level of F greater than $F = 0{\cdot}3$ results in a trend of declining catches. If larger mesh sizes were to be used (Figs. 6 and 7), fishing mortality could be increased to about $F = 0{\cdot}4$ (145 mm mesh) or $F = 0{\cdot}5$ (160 mm mesh) without causing a long-term downward trend. Figures 5–7 also provide some indication of the rate at which the fishery might be expected to recover if fishing mortality was to be stabilized at adequately low levels. From Figure 8 it is clear that mesh-size increases up to at least 160 mm would give a long-term improvement in yields for all levels of F above $F = 0{\cdot}2$, after an initial period of reduced yields.

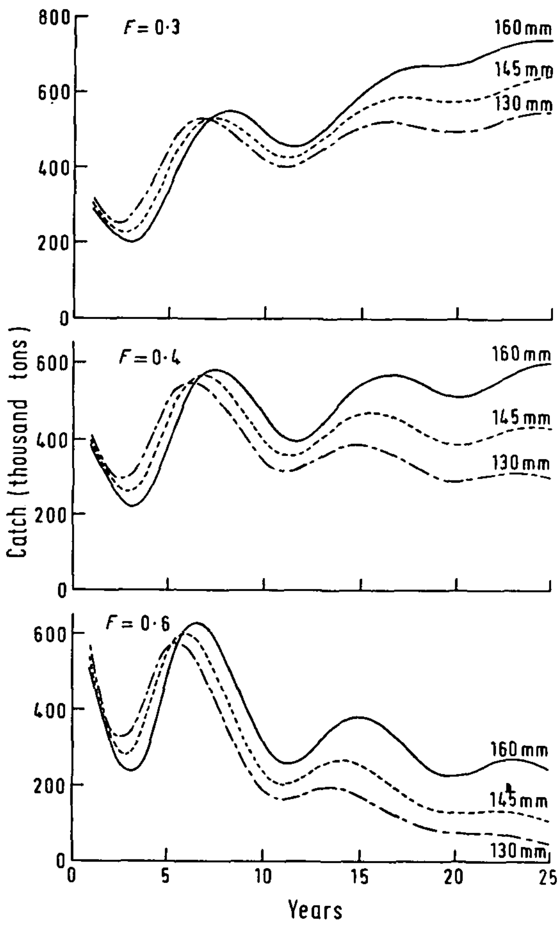

Figure 8. Comparison of yields for minimum mesh sizes of 130, 145 and 160 mm, at selected constant values of fishing mortality.

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 1942–1968.
2. A relationship was derived between stock size and the level of annual fishing mortality required to harvest the prodution 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 $7{\cdot}3 \times 10^{14}$ 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 fishing mortality would be $F = 0{\cdot}26$, 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 size of the mature stock is presently at a very low level and is expected to decline still further

before showing some recovery after the mid 1970s. The present management strategy for the immediate future should be to reduce fishing to a level where the harvest is less than the surplus production, allowing the difference to go towards building up the size of the mature stock to the optimum level.

5. The computer model gives an indication of how the fishery could be expected to recover if fishing mortality was to be stabilized, assuming a selection pattern as at present or for modified selection patterns as might result from the adoption of larger minimum mesh sizes. It is not intended to suggest that a constant low level of fishing mortality would give the most rapid rate of recovery, or that it would give the greatest possible yield during the period required for the stock to build up to its optimum size. It would be more efficient to vary fishing mortality according to the size of the year-classes in the fishery, with the aim of producing each year a spawning stock of optimum size but no larger or smaller. This would be very difficult or impossible to achieve in practice.
6. 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.

References

Botros, A. G. 1962. Die Fruchtbarkeit des Dorsches (*Gadus morhua* L.) in der westlichen Ostsee und den westnorwegischen Gewässern. Kieler Meeresforsch., 18 (1): 67–80.

Clayden, A. D., 1972. Simulation of the changes in abundance of the cod (*Gadus morhua* L.) and the distribution of fishing in the North Atlantic. Fishery Invest., Lond., Ser. 2, 27 (1): 58 pp.

ICES, 1970. Northeast Arctic Fisheries Working Group. Report of the 1969 Meeting. Co-op. Res. Rep., Ser. A, (16): 60 pp.

Appendix 1

Data used in computer model

1. Age composition of stock: 1971 stock as estimated at the 1972 Northeast Arctic Working Group meeting. This includes estimates of recruitment for the 1969–71 year-classes based on 0-group and pre-recruit surveys. The capacity of the model permits only age-groups 0–11 to be used in the calculations. When older age-groups constitute a significant proportion of the stock, the model will tend to give an underestimate of the catch and of the mature stock size.
2. Age/maturity relationship: 0% mature up to age 7, seven-year-olds 50% mature, 8 and older 100% mature. No allowance has been made for the deduction of each year's IIa catch from the mature biomass, estimated as at the beginning of each year, as was done in fitting the stock and recruitment curve. A correction was made for this in some later computer runs but the difference in the results was quite small.
3. Selection pattern: the values of F referred to are those relating to fully exploited part of the stock. The proportion of the given value of F acting on partially selected age-groups are as follows:

Age (years)	Proportion of F		
	Present mesh	145 mm mesh	160 mm mesh
3	0·30	0·14	0·04
4	0·60	0·43	0·24
5	0·90	0·76	0·56
6	1·00	0·94	0·82
7		0·96	0·89
8		1·00	0·96

The proportions for the 145 mm and 160 mm mesh sizes were calculated from selection ratios for each age for 130/145 mm and 130/160 mm mesh changes, based on a selection factor of 3·6.

4. Weight at age: as given in the 1971 Report of the Northeast Arctic Working Group.
5. Instantaneous coefficient of natural mortality: $M = 0·3$.
6. Stock and recruitment relationship: as developed in this paper.