

# YIELD ISOPLETHS OF THE HALIBUT, *HIPPOGLOSSUS* *HIPPOGLOSSUS*, IN NORTHERN NORWAY<sup>1</sup>

By

OLE A. MATHISEN

College of Fisheries, University of Washington, Seattle.

and

STEINAR OLSEN

Institute of Marine Research, Bergen

## INTRODUCTION

In late autumn and early winter halibut congregate to spawn in certain localities of the deep Norwegian fjords. Since the 1936—1937 spawning season these concentrations of fish have been exploited annually with large-meshed gill nets. These nets are usually set on the bottom between depths of 400 and 600 meters. Since the gear is highly efficient, regulations establishing a closed season and a minimum mesh size have been enforced since 1937 to conserve the stocks. There have been changes in mesh size and length of closed period, but there has never been any limitation of effort or catch.

Catches increased greatly when the gill-net fishery commenced in 1936, but they declined severely after a few years (Fig. 1). Clearly, the catches in the years 1936—1940 were in excess of the normal yield of the stocks (THOMPSON 1950) and were provided by an accumulation of large and old fish. Hostilities in 1940 to 1945 resulted in a new accumulation of fish on the grounds, and when the war ended, fishing both with gill nets and in particular with long lines was resumed on an expanded scale. Catches and stock abundance soon declined again and then stabilized. During the last 10 years they have remained at a relatively low level, and the annual yield is slightly less than 1,900 metric tons, with a value at landing of 7—8 million Norwegian kroner. This pattern of stock abundance and catches was observed in the halibut fisheries of all three counties of Northern Norway, Finnmark, Troms and Nordland.

The Institute of Marine Research in Bergen, Norway, has on two occasions sponsored research on halibut. The first investigations commenced in 1936 and were stopped because of war hostilities. DEVOLD (1938 and 1943) gave the first data on catch, age composition, growth

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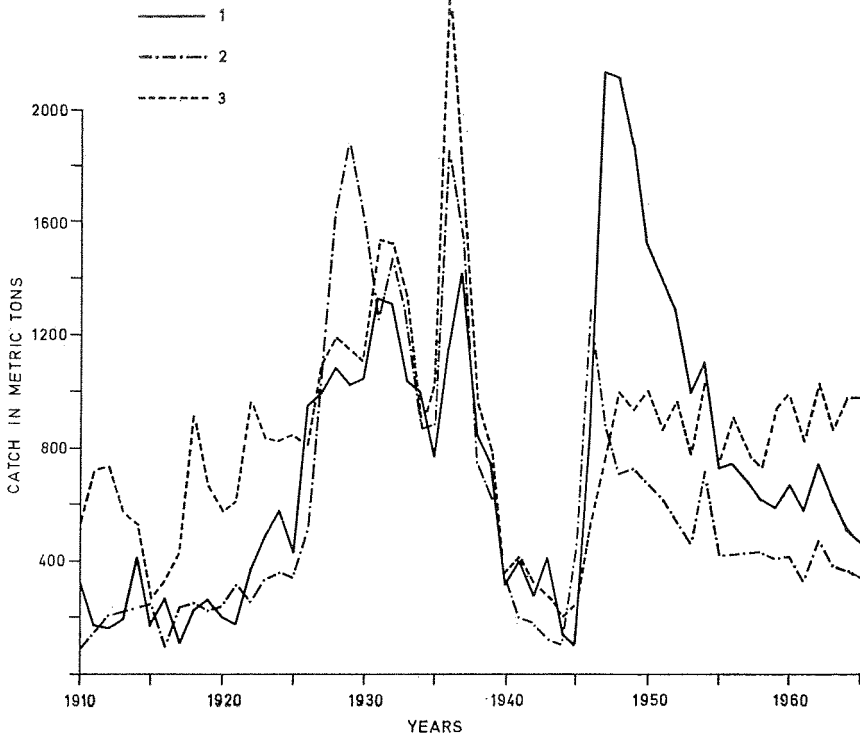


Fig. 1. Catch of halibut in Northern Norway by counties. 1) Finmark, 2) Troms, 3) Nordland.

rate and migration. In 1955 these studies were resumed and continued through 1960. Additional information was obtained by the use of experimental gill nets of varying mesh size, fished throughout the season closed to commercial fishing. The results have, in part, been published by OLSEN and TJEMSLAND (1963); but the most comprehensive account is a thesis report by TJEMSLAND (1960) in which the author attempts to establish the mesh size which will provide for the best utilization of the stocks.

The present report utilizes the same basic data. There are two reasons for conducting a further analysis of the data. First, recently developed computer programs greatly facilitate the determination of growth rate and yield of a stock of fish and eliminate the previous necessity for some assumptions. Second, precise determination of the natural and fishing mortality rate, the growth rate, and above all, changes in stock abundance is not possible from existing data. These parameters are necessary to formulate a definite program for management of these fisheries so as to maintain maximum sustainable yield. A useful approach seems to be to calculate a series of yield isopleths where age at entry and fishing

effort can be varied to determine intervals within which these parameters should be set to obtain a maximum yield per recruit. Another important objective is to point out areas in which further research is needed.

Analysis was performed at the Norwegian Computer Center with a Univac 1107 by the senior author, originally in preparation for a course in computer technique given at the Institute of Marine Biology at the University of Oslo, 1965—1966.

#### METHODS AND RESULTS

Three basic parameters are needed for any yield calculation, viz., the coefficients of the weight-length relationship for males and females; growth curves, either of length or weight, as a function of age; and mortality rates, both of natural and fishing mortality.

##### *WEIGHT—LENGTH RELATIONSHIP*

In the classical yield model developed by BEVERTON and HOLT (1957), weight is considered a cubic function of length, primarily to facilitate manual integration. This restriction is eliminated with the use of computers. The exponent in the equation

$$W = q \cdot L^{\delta}$$

may not only be different from three, but it may also vary between male and female or between mature and immature fish.

Data on mature halibut were largely derived from catches taken with nets of 16 in. mesh. The selection range of these nets, i. e., the interval between the two «50 % selection lengths,» does not cover the size range of mature halibut. It is, therefore, reasonable to assume that the size and age composition of the catches taken with 16 in. mesh gill nets, which was the only net size used commercially prior to 1960, were biased in regard to the number of small and large fish.

The majority of the immature halibut were captured with long line. They originated from different localities in Northern Norway (Fig. 2). However, gear selection is of minor consequence since most of the size groups were represented.

Weight of the immature fish was recorded as dressed weight with the head to the nearest 10 grams, and weight of mature halibut as dressed weight without the head and to the nearest kg. Since the weight of the head represents a small fraction of total body weight in immature fish and does not influence subsequent yield calculations, the inconsi-

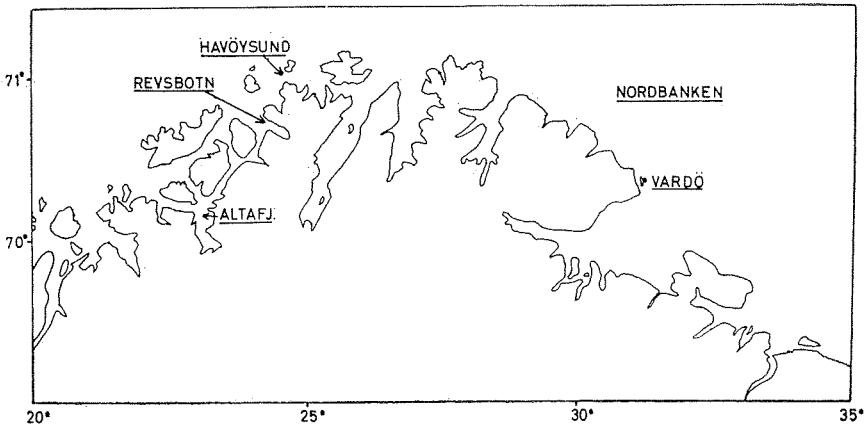


Fig. 2. Sampling localities.

stency may not be serious. Total length (distance from the tip of the head to the end of the tail) was measured to the nearest centimeter.

Table 1. Account of weight/length observations<sup>1</sup> on halibut, *Hippoglossus hippoglossus*, in Northern Norway.

	Location	Month	Year	Sample size	
				♂	♀
A. Immature halibut	Nordbanken	March/April	1938	65	53
	Tromsø	October	1939	383	319
	Havøysund	April	1955	59	42
	Revsbotn	May	1955	64	49
B. Mature halibut	Altafjord	Jan./Feb.	1957	990	258
	Altafjord	Jan./Feb.	1958	89	141
	Altafjord	Jan./Feb.	1959	150	162
	Altafjord	Jan./Feb.	1960	188	125

<sup>1</sup> An additional 744 length measurements of mature males and 93 length measurements of mature females taken at Altafjord in 1956 were used to determine growth in length.

For each of the sixteen groups of halibut in Table 1, the two coefficients,  $q$  and  $\delta$ , of the equation  $W = q \cdot L^\delta$  were determined on the log-transformed data by linear regression. BMD program 01R (DIXON, 1965), which also permits an analysis of covariance, was used. Two hypotheses were tested: all groups have a common regression line,  $H_A$ ; the different groups in the comparison have a common slope of their regression lines but with individual intercepts,  $H_B$ .

The appropriate test for hypothesis  $H_A$  is

$$F = \frac{(S_T - S_S)/(c - 1)}{S_S/(N - c - 1)}$$

where  $S_T$  is the total sum of squares around the common regression line,  $S_S$  is the sum of squares of deviations from the regression lines with common slopes,  $N$  refers to the total sample size, and  $c$  denotes the number of groups in the comparison.

For hypothesis  $H_B$ , the test is

$$F = \frac{(S_S - S_E)/(c - 1)}{S_E/(N - 2c)}$$

where  $S_E$  is the combined sum of squared deviations from individual regression lines within each group.

The results are summarized in Table 2. Hypothesis  $H_A$  was rejected consistently for all groups. Hypothesis  $H_B$  was sustained for immature males and females as well as for all mature fish combined. Although it was rejected for the mature females on the 1 % significance level, it was sustained on the 1 %/00 level. This was not possible for the mature males. At present it is difficult to determine whether the difference is real or whether it is an artifact caused by heterogeneity of the material and observation technique. The heterogeneity in the case of the males apparently

Table 2. Comparison of the regression lines of log weight/log length for different groups of halibut

Grouping	Sample size N	Regression coefficient $\delta$	F-tests			
			Hyp. A	D.f.	Hyp. B	D.f.
All samples	3,137	3.0013	53.53**	(15, 3,120)	58.87**	(15, 3,105)
All males	1,988	2.9473	57.06**	(7, 1,979)	3.92**	(7, 1,972)
All females	1,149	3.0221	15.50**	(7, 1,140)	3.78**	(7, 1,133)
All immature halibut	1,034	3.0058	77.77**	(7, 1,025)	53.40**	(7, 1,018)
All immature males	571	2.9883	123.77**	(3, 566)	3.58	(3, 563)
All immature females	463	3.0278	57.13**	(3, 458)	0.07	(3, 455)
All mature halibut	2,103	3.2183	26.18**	(15, 2,094)	0.38	(15, 2,071)
All mature males	1,417	3.2485	40.55**	(3, 1,412)	43.39**	(3, 1,409)
All mature females	686	2.9532	11.37**	(3, 681)	4.23**	(3, 678)

\*\* Rejection of hypothesis on the 1 % level.

arises from the 1958 data, which yielded a lower value than the common value given in Table 2, while the coefficients for the three other remaining years were nearly equal.

For the time being it is necessary to use the regression coefficients for mature males and females determined from all data in the subsequent

calculations with the reservation that later they may be modified somewhat. If one accepts hypothesis  $H_B$ , the common regression coefficient for either group can be calculated from

$$b_s = \frac{\sum_{i=1}^c \left[ \sum_{j=1}^{n_i} X_{ij} Y_{ij} - \frac{T_i^x \cdot T_i^y}{n_i} \right]}{\sum_{i=1}^c \left[ \sum_{j=1}^{n_i} X_{ij}^2 - \frac{(T_i^x)^2}{n_i} \right]}$$

On this basis one can determine a weight-length curve for the mature males and females. By taking the logarithm on both sides of  $W = q \cdot L^\delta$ , one obtains  $\log q = \log W - \delta \log L$ . Substitution of values for  $\log L$  and  $\log W$  yielded the results shown in Table 3.

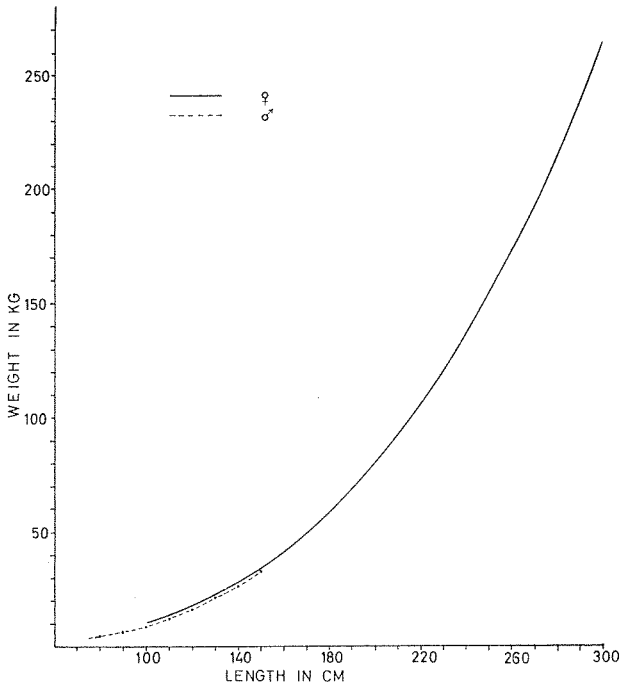


Fig. 3. Weight/length relationship of mature halibut.

Fig. 3 illustrates that despite the tremendous difference in maximal weight or length between males and females, weight as a function of length is nearly the same for males and females over the common length range, which simplifies the setting of a common lower selection size for the gill nets.

Table 3. Calculation of weight-length coefficients for mature halibut.

Sex	$\delta$	Log $\bar{W}$	Log $\bar{L}$	$W = q \cdot L^\delta$
♂	3.2485	3.766	2.253	$1.295 \cdot 10^{-3} L^{3.2485}$
♀	2.9532	3.182	2.075	$2.762 \cdot 10^{-4} L^{2.9532}$

#### GROWTH IN LENGTH AND IN WEIGHT

A number of growth equations describe the growth of a fish as a function of age. Generally, they are derived either from the absolute or from the specific growth rate of individual fish. In observations used in this analysis age was determined from the otoliths. No backcalculations were attempted of the annual growth increments because of the great ages of the fish, which were more than 40 years for the females. Therefore, in this analysis the growth curves were derived from composite data.

SOUTHWARD and CHAPMAN (1965) applied VON BERTALANFFY'S growth-in-length curve to the Pacific halibut, *Hippoglossus stenolepis*, and found generally a very satisfactory correspondence between calculated growth increments and increments predicted from the curve itself for individual fish; but they point out that it is not certain that the average of individual growth curves will yield the same result as that derived from composite data. This condition was assumed in this analysis.

Two classes of growth curves were explored:

##### 1. Simple von Bertalanffy Growth-in-length Curve.

VON BERTALANFFY (1934) first proposed the following equation to describe growth:

$$L_t = L_\infty (1 - e^{-K(t-t_0)})$$

ABRAMSON'S (1965) computer program was used to estimate the parameters in the equation by a least-square technique. The method is vastly superior to methods based on the linear relationship between  $L_{t-1}$  and  $L_t$ , where errors in both variables and autocorrelation render interpretation of the results open to question. Further, all three parameters are estimated simultaneously, and the same number of observations are not necessitated for each age class. Since in this instance length at a given age was determined from actual data and not from backcalculated length data for individual fish, the method is particularly suitable.

Immature and mature fish as well as males and females were analyzed separately. The results are shown in Table 4.

Table 4. Estimated parameters for Von Bertalanffy's growth-in-length and growth-in-weight curves

Grouping	Year(s)	Sample size N	$L_{\infty}$ (cm)	St. error	K	St. error	$t_0$	St. error
<i>A. Length data</i>								
Male, mature	1956	756	130.76	1.65	.16	.021	2.00	1.044
Male, mature	1957	1,253	131.44	1.44	.17	.019	1.85	.941
Male, mature	1956—1960	2,437	130.81	.74	.20	.012	3.68	.388
Male, mature	1957—1960	1,681	131.21	.84	.21	.014	4.21	.399
Female, mature	1956		No solution for $Z = e^{-kq}$ between .001 and .999					
Female, mature	1957		No solution for $Z = e^{-kq}$ between .001 and .999					
Female, mature	1956—1960	760	302.77	22.92	.03	.001	16.34	2.008
Female, mature	1957—1960	668	298.43	23.09	.04	.008	15.77	2.063
Male, immature	All years	—	No solution for $Z = e^{-kq}$ between .001 and .999					
Female, immature	All years	—	No solution for $Z = e^{-kq}$ between .001 and .999					
<i>B. Weight data</i>								
			$W_{\infty}$ (kg)					
Male, mature	1957—1960	1,660	37.52	8.01	.047	.018	4.44	1.211
Female, mature	1957—1960	657	249.97	57.99	.025	.008	-2.63	.724



Mature males measured included fish from age 8 through age 31. Parameters were calculated in every case regardless of whether observations for all years were combined or observations for individual years were considered alone. Age readings are highly comparable between years; age determinations in 1956 and 1957 were made by two different people, yet the final curves for these two years are almost identical.

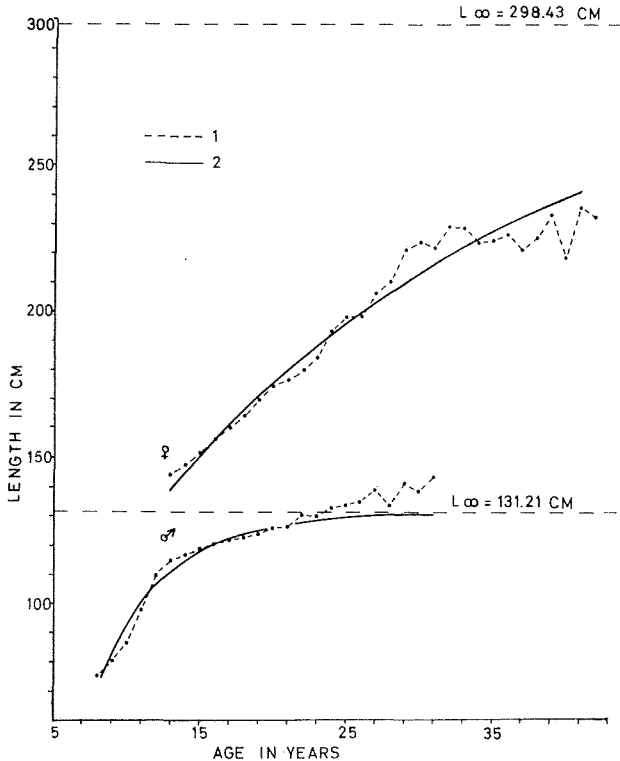


Fig. 4. VON BERTALANFFY'S growth-in-length curves for mature halibut: female (top), and male (bottom). 1) Observed growth curve 1957—1960, 2) Estimated growth curve 1957—1960.

The estimated curve fits observed data on the males (Fig. 4, bottom), but the value of  $L_{\infty}$  obtained for the females is much higher than even the highest value recorded in the material examined (Fig. 4, top). The growth pattern of the two sexes differs decidedly. Mature males attain their maximum size relatively early, their growth rate retards drastically after age 12 or age 13. Mature females maintain their initial growth rate for a much longer period and retardation of their growth rate is less. The physiological difference manifested is worthy of intensive future studies.

The question remains as to the validity of the high value determined for  $L_{\infty}$  for the females. The recruitment of mature females into the fishery commences at age 11 to age 13 and apparently terminates before age 20. Since only the faster growing individuals are available for exploitation at first and the samples are representative only of a restricted number of age classes, the left limb of the growth curve is inflated. The discrepancy between the calculated maximum size and the observed maximum size may be due to the females not living long enough to attain such size or the selectivity of the nets.

It is important that no solution of the equation was possible for the females when the years 1956 and 1957 were considered alone, nor for the immatures, both males and females. The latter could have been anticipated since only age classes 2 through 11 were represented, ages with a rapid, almost exponential growth pattern.

A more general form of VON BERTALANFFY's growth-in-length curve was calculated and plotted to incorporate data on both immature and mature halibut.

## 2. *Extended von Bertalanffy Growth Curve*

As discussed by RICHARDS (1959) and CHAPMAN (1960), a four-parameter growth equation may be obtained by starting from the general differential equation

$$\frac{dw}{dt} = H \cdot w^m - k \cdot w$$

where  $H$  and  $k$  are coefficients of anabolism and catabolism, respectively, and  $m$  is the rate of change between metabolic rate and weight. Integration of this equation with a weight-length relationship of the form  $W = q \cdot L^{\delta}$  will lead to a VON BERTALANFFY equation of the following form (CHAPMAN, 1960):

$$L_t^{1-m} = L_{\infty}^{1-m} - (L_{\infty}^{1-m} - L_0^{1-m})e^{-K(1-m)t}$$

To estimate the four parameters  $L_{\infty}$ ,  $L_0$ ,  $K$ , and  $m$  by minimizing the sum of squared deviations of observed points from estimated points is indeed a formidable task by manual methods. However, a recently developed computer program by K. J. TURNBULL (1964) achieves this in a rather short time provided the growth data over the entire life span conforms to a sigmoid pattern. The solution is of the form

$$L_t = A \cdot (1.0 + B e^{-Kt})^{\frac{1}{1-m}}$$

Table 5. Mean lengths and weights of immature and mature halibut combined, males and females.

Time scale t:	True age (years)	Number observations	♂ Mean length (cm)	Number observations	♀ Mean length (cm)	Number observations	♂ Mean weight (kg)	Number observations	♀ Mean weight (kg)
1	2.5	357	43.6	305	43.9	358	.82	305	.84
2	4.5	87	53.5	67	54.9	34	1.50	22	1.96
3	6.5	214	63.3	205	65.2	114	2.72	106	2.94
4	8.5	89	77.9	43	80.6	75	4.49	32	5.68
5	10.5	86	94.1	7	107.7	67	7.32	4	19.68
6	12.5	228	111.3	30	143.3	167	13.14	26	29.92
7	14.5	264	116.5	72	149.0	214	14.89	68	33.99
8	16.5	372	120.2	98	159.0	253	16.32	87	41.08
9	18.5	520	122.5	92	165.0	357	17.86	74	48.67
10	20.5	483	125.0	108	174.3	313	19.06	86	56.97
11	22.5	271	129.1	114	180.7	178	21.64	102	64.54
12	24.5	128	131.2	82	196.4	88	24.69	78	79.05
13	26.5	41	133.4	50	202.8	22	24.23	47	91.55
14	28.5	11	131.5	32	213.2	6	26.00	30	97.59
15	30.5	13	130.6	26	222.8	6	26.00	25	115.12
16	32.5			17	229.1			16	118.62
17	34.5			20	224.1			18	115.95
18	36.5			8	217.8			6	109.33
19	38.5			8	230.0			7	129.85
20	40.5			9	227.8			7	109.42

Table 6. Parameter values for CHAPMAN-RICHARD's general growth equation, rescaled.

	Scale factor	$L_{\infty}$	B	K	m	K/m	$K/(2m+2)$	Rescales growth equation
A. Length data	1/6	21.800	30.724	.634	3.505	.181	.070	$l_t = 130.80 [1.0 + 30.72e^{-.63t}]^{\frac{1}{1-.351}}$
	1/10	23.810	-.095	.206	.956	.215	.063	$l_t = 238.10 [1.0 - .095e^{-.22t}]^{\frac{1}{1-.96}}$
B. Weight data		$W_{\infty}$ (kg)						
	1/1	29.388	-1.028	.222	.674	.33	.66	$W_t = 29.39 [1.0 - 1.03e^{-.22t}]^{\frac{1}{1-.67}}$
	1/4	34.665	-.655	.186	.866	.21	.49	$W_t = 138.67 [1.0 + .66e^{-.19t}]^{\frac{1}{1-.87}}$

The procedure consisted of finding the mean length within each of age classes 2 through 31. Because of program limitation, it became necessary to scale the lengths of the males by multiplication with a factor  $k = 1/6$  and to average the lengths of two and two adjacent year classes. Thus the time unit  $t$  corresponds to the true age of 2.5 years with an increment of 2 years. Essentially the same was done for the females except that the timespan ranged from age 2 through age 41 and the scale factor used was  $k = 1/10$ .

The basic length data are presented in Table 5 and the parameter values are summarized in Table 6, rescaled to original values (Fig. 5). The curve for the male halibut almost follows a pure GOMPertz growth curve and that of the female halibut is related more to a logistic curve. Nevertheless, the mean relative growth rate,  $K/m$ , and the weighted mean growth rate,  $K/(2m + 2)$ , after the interpretation by RICHARDS (1959), are nearly the same for the sexes.

The main interest lies in asymptotic lengths. In the case of the males there is hardly any difference from the value obtained by fitting the

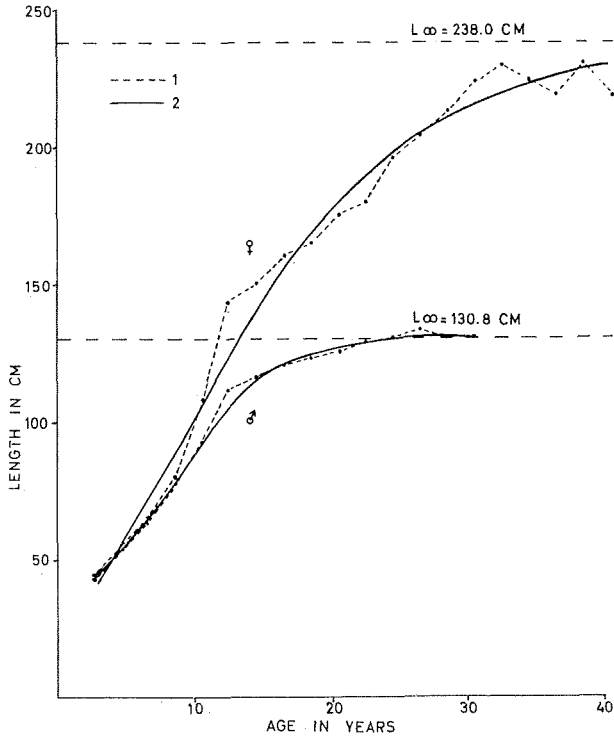


Fig. 5. CHAPMAN-RICHARD'S growth-in-length curve for mature halibut: female (top), and male (bottom). 1) Observed growth curve 1956—1960, 2) Estimated growth curve 1956—1960.

classical VON BERTALANFFY curve to the data, but in the case of the females  $L_{\infty}$  is about 60 cm less than the value estimated earlier. The choice between these two values can be facilitated by considering the weight data.

### Growth-in-weight Curves

Since very few weight measurements were taken in 1956, the growth curve was based on data for the years 1957—1960. For the males the year classes 8 through 31 and for the females the age classes from 13 through 24 were well enough represented for the data to fit a standard VON BERTALANFFY growth-in-weight curve. The results are summarized at the bottom of Table 4 and illustrated in Fig 6.

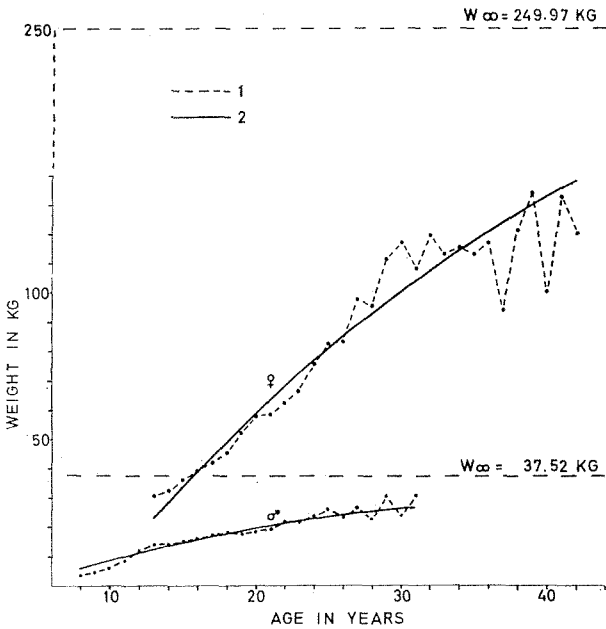


Fig. 6. VON BERTALANFFY's growth-in-weight curve for mature halibut: female (top), and male (bottom), 1) Observed growth curve 1957—1960, 2) Estimated growth curve 1957—1960.

The value of  $W_{\infty}$  for the males accords with the observed weight of the largest and oldest male halibut; but, as was the case with length, the value for the females approaches the highest weight recorded of single, exceptional individuals. It was, therefore, natural to determine the same parameter values by means of CHAPMAN-RICHARD's version of the growth-in-weight curve. The results are summarized at the bottom of Table 6 and illustrated in Fig. 7.

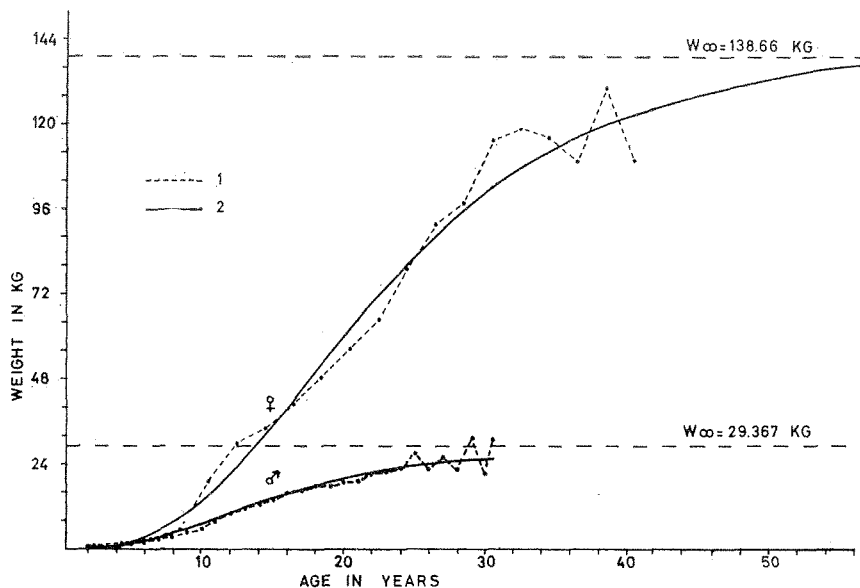


Fig. 7. CHAPMAN-RICHARD'S growth-in-weight curve for mature halibut: female (top), and male (bottom). 1) Observed, 2) Estimated.

The value of  $m$  for the males equals almost  $2/3$ , as suggested by VON BERTALANFFY (1934). The mean absolute growth rate,  $K/m$ , and mean relative growth rate,  $K/2(m-1)$ , fall within the ranges given by SOUTHWARD and CHAPMAN (1965) for the Pacific halibut. Thus the two species of halibut conform to the same pattern of growth despite their widely separated ranges. The identity of the patterns is especially striking since SOUTHWARD and CHAPMAN derived their parameter estimates from backcalculated data for individual fish.

On the strength of this similarity, the values of  $L_{\infty}$  and  $W_{\infty}$  for the Finmark halibut derived from the generalized CHAPMAN-RICHARD'S growth equation and based on average length or weight data within a year class were used in the subsequent yield calculations. The asymptotic values then conform more closely to the maximum values for length and weight usually observed. Greater precision can hardly be expected until backcalculated growth data are available for individual fish.

#### MORTALITY RATES

The reliability of any yield calculation depends greatly on the accurate assessment of the instantaneous natural mortality rate,  $M$ , and the applied instantaneous fishing mortality rate,  $F$ , throughout the lifespan of the fish. Very few tagging experiments have been conducted, and the observations are of little value in a separation of  $F$  and  $M$ .

The only recourse is to estimate the total instantaneous mortality,  $Z = F + M$ , from the composite catch curve interpreted with some caution. It is inconceivable that recruitment would remain constant in the examined halibut stock with about 30 year classes represented. However, constant recruitment is a necessary condition in any estimate of mortality from the age distribution of the total catch in one year. As an alternative one could examine changes in abundance of the same year class over the period 1956—1960 provided that the effort remained constant.

The situation is commonly encountered in practical fisheries investigations. However, with modern computer techniques yield computations can be made over a wide range of assumed values within which the true parameter values in all probability will fall. Hence, one can define an area on the yield surface encompassing the true parameter value. Frequently this suffices as a basis in formulating a rational management scheme.

The combined catch curves for males or females for the years 1956 to 1960 were analyzed in different ways by relaxing certain assumptions, as discussed by CHAPMAN and ROBSON (1960) and ROBSON and CHAPMAN

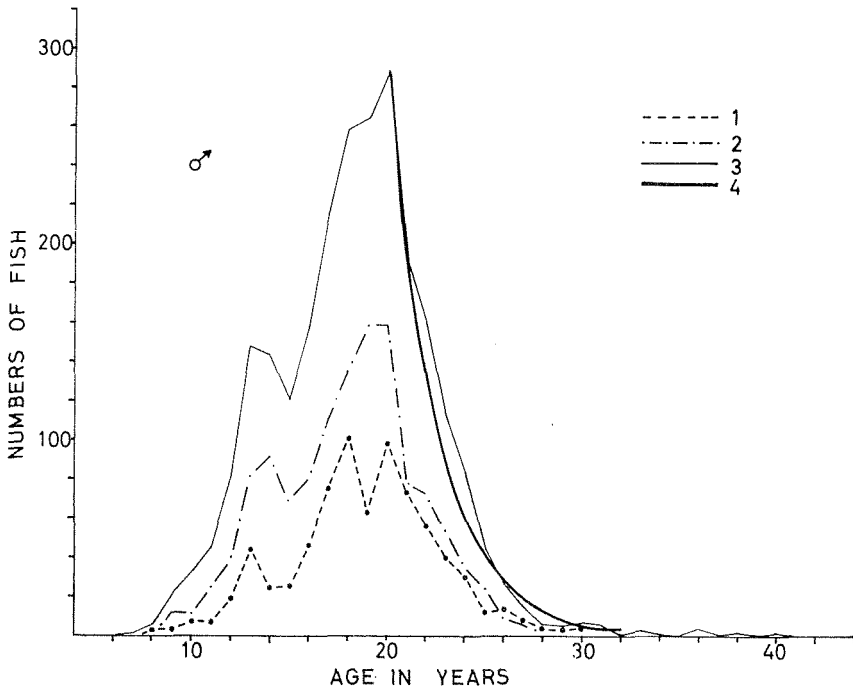


Fig. 8. Catch curves for male halibut. 1) Catch curve 1956, 2) Catch curve 1957, 3) Catch curve 1956—1960, 4) Estimated survival curve.



(1961). GALES' (1964a) computer program was used to study four alternatives:

1. calculation of total instantaneous mortality from the observed total catch curve using an age of full recruitment to the left of the peak of the catch curve,
2. testing by means of a chi-square test if the assumed age of full recruitment can be sustained, and if not, at which age this took place,
3. telescoping of the older age groups on the assumption that age determination may become progressively more difficult with increasing age,
4. exploration of segments of the catch curve to include sections with fully recruited age groups exposed to the same fishing mortality.

The catch data are depicted in Figs. 8 and 9 and the obtained Z-values listed in Table 7.

Recruitment of the males into the fishery begins in the eighth year of life, when length is about 75 cm and terminates before the twentieth year, when length ranges from 123 to 126 cm. At this age growth-in-length has been largely completed and the effect of mesh selection will not change materially with increasing age. Hence, a reasonable estimate of total mortality can be derived from the catches from age 20 on.

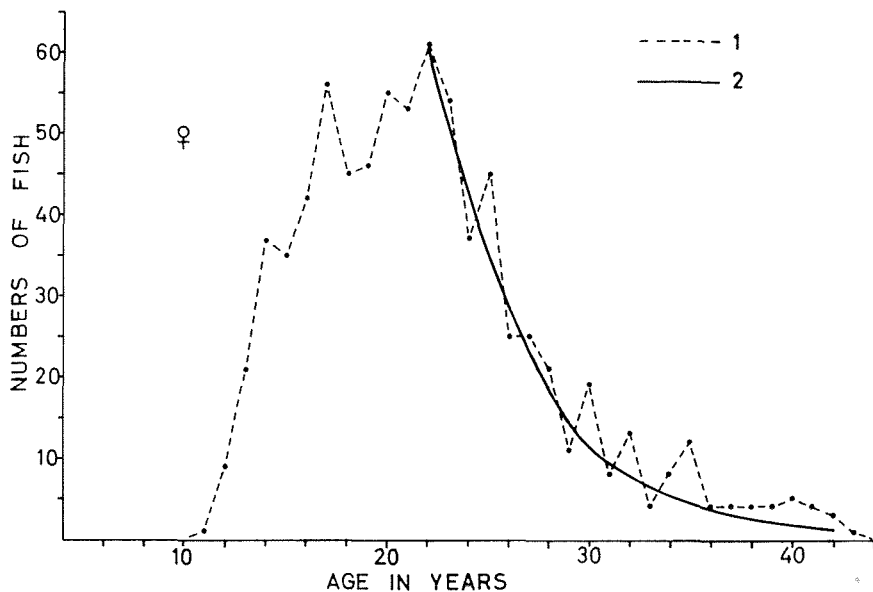


Fig. 9. Catch curve for female halibut. 1) Catch curve 1956—1960, 2) Estimated survival curve.

Table 7. Estimated total instantaneous mortality coefficients for halibut, from the original catch data and from catch data adjusted for the effect of mesh selection.

Years	Source	Z	95 % confidence interval of Z	
<i>A. Original catch data ♂</i>				
1956—60	Age at full recruitment 18 years . . . . .	.30	.287	— .319
1956—60	Age at full recruitment determined to be 20 years	.39	.364	— .415
1956—60	Ages $\geq$ 31 combined . . . . .	.39	.365	— .417
1956—60	Ages 20—28 only . . . . .	.38	.349	— .415
1956	Age at full recruitment 20 years . . . . .	.38	.337	— .420
1957	Age at full recruitment 20 years . . . . .	.45	.404	— .490
<i>B. Adjusted catch data ♂</i>				
1956—60	Age at full recruitment 18 years . . . . .	.38	.350	— .415
1956—60	Age at full recruitment determined to be 20 years	.39	.364	— .415
<i>C. Original catch data ♀</i>				
1956—60	Age at full recruitment 17 years . . . . .	.14	.128	— .150
1956—60	Age at full recruitment determined to be 22 years	.18	.165	— .204
1956—60	Ages $\geq$ 31 combined	.18	.160	— .202
1956—60	Ages 20—22 . . . . .	.23	.056	— .464
1956—60	Ages 25—29 . . . . .	.29	.169	— .436
1956—60	Ages 25—31 . . . . .	.24	.156	— .330
<i>D. Adjusted catch data ♀</i>				
1956—60	Age at full recruitment 22 years . . . . .	.16	.161	— .163
1956—60	Age at full recruitment determined to be 28 years	.18	.175	— .180

This was done, first, by setting the full recruitment age a little lower, at age 18; second, by combining the catches of all fish 31 years or more, and, third, by using only the catch vector from age 20 through age 28. In all cases the total instantaneous mortality was found to be of the same magnitude and the value of Z about .39 (Table 7).

The situation was less clear for the females. Apparently full recruitment is completed from ages 17 to 22 years, during which length ranges from 160 to 180 cm, which is in the upper selection range of the 16-in. gill nets.

The right limb of the female catch curve was first examined. With initial full recruitment at age 17, the total instantaneous mortality, Z,

was calculated and the value found to be .14 (Table 7). Application of the chi-square test established the age of full recruitment at 22 years with  $Z = .18$ . The same result was obtained by telescoping all ages from age 31. Various segments of the catch curve, viz., ages 20—22, ages 25—29, and ages 25—31, yielded somewhat higher estimates, but with an associated higher variance, and broader confidence intervals (Table 7).

An attempt was made to adjust for the bias introduced by the selectivity of the gill nets. From the data on number of fish caught per length interval, OLSEN and TJEMSLAND (1963) established a set of selection curves for halibut gill nets. These were used to adjust the catch curve according to the procedure used by OLSEN (1959) for herring in Newfoundland waters. The mortality estimates derived from the adjusted data are given in Table 7. For both males and females the adjustments resulted in reduced estimates of  $Z$ , but the differences were rather small in all cases. Thus, there is a suggestion that the slope of the right-hand portions of the catch curves is too abrupt. Because of the small magnitude of this bias, the scantiness of the material from which the selection curves were derived, and the variance in the mortality estimates introduced by the adjustments, there is little reason to prefer these estimates to those derived from the original data.

In this event the total instantaneous mortality of the males may be set tentatively equal to .39; and of the females equal to .18. Assuming further that the natural mortality,  $M$ , during the exploited phase is the same for both sexes and constant from year to year, we have  $F\delta + M = .39$ ,  $F\text{♀} + M = .18$ , which gives the relationship  $F\delta = .21 + F\text{♀}$ , or that the instantaneous fishing mortality rate of males with the gear combination utilized was .21 higher than that for the females. It further places an upper limit of .18 on the natural instantaneous mortality.

This difference could stem from two causes. Since  $F = c \cdot f$ , with  $c$  as the catchability coefficient and  $f$  equal to the number of effort units, a real difference exists. But the magnitude of this difference allows for a difference in vulnerability to the gill nets between males and females caused by differences in behavior.

The right limbs of the examined catch curves represent the numbers of halibut twenty years of age or more in the catches. However, certain age groups, especially among the females, were subjected to a low fishing mortality during the years 1940—1945. Throughout their fishable life-span these groups must have been overrepresented in the catches in relation to the younger year classes for the years studied; the younger year classes were heavily exploited by long lines after 1945. The net effect is a flattening of the right limbs of the age curves in Figs. 8 and 9. Hence, the calculated mortality rates should be considered minimum

values. In the absence of suitable data for establishment of an upper bound for total mortality rate, an approximation is made in the subsequent chapter by comparing rates obtained for other stocks of halibut.

#### YIELD ISOPLETHS

BEVERTON and HOLT (1957) divide the life of a fish into two principal periods. One covers recruitment to the fishing grounds and extends from time  $t_p$  to  $t_{p'}$ . The other includes the fishable lifespan from time  $t_{p'}$  to  $t_x$ , when the fish either die or reach a size outside the selection range of commercial gear. Throughout both periods natural mortality,  $M$ , operates and decreases the original number of recruits,  $R$ , in an exponential manner. A variable fishing mortality,  $F$ , applied either throughout the entire fishable lifespan or within preset time intervals further reduces the number of recruits.

The harvestable yield is further determined by the parameters  $W_\infty$ ,  $K$ , and  $t_0$  of VON BERTALANFFY'S growth equation and the exponent  $\delta$  of the weight-length relationship. On these premises and with the notation given above, the yield from  $R$  recruits may be calculated from

$$Y_w = \int_{t_{p'}}^{t_x} FR e^{-M(t_p - t_p')} e^{-(F+M)(t - t_{p'})} q L_\infty^\delta (1 - e^{-K(t - t_0)})^\delta dt$$

JONES (1957) and, later, PAULIK and GALES (1964) have transformed this equation into an incomplete beta function and prepared a computer program to solve the BEVERTON and HOLT yield equation (GALES 1963). After the appropriate transformation, the equation will be

$$Y_w = (F/K) RW_\infty e^{-M(t_p - t_{p'})} e^{(F+M)(t_{p'} - t_0)} \int_{e^{-K(t_x - t_0)}}^{e^{-K(t_{p'} - t_0)}} X^{\frac{F+M}{K} - 1} (1-X)^\delta dx$$

This program was utilized to construct yield isopleths for males and females individually where both  $t_{p'}$ , and  $F$  can be varied.

The parameter values utilized are:

$t_p = 6$  years

$t_{p'} =$  range 6—31 years with increments of one year

$t_x = 35$  years for the males and 45 years for the females

$F =$  range 0.0—2.0 with increments of 0.1

$R = 1$

$M = 0.05, 0.10, 0.15$

The remaining parameter values were taken from the CHAPMAN-RICHARD'S growth-in-weight function, some of which were substituted with data from Table 6 (Table 8). From the calculated yields, Figs. 10—11 were prepared.

Table 8. Parameter values used for yield calculation with CHAPMAN-RICHARD'S growth-in-weight function

Parameter	♂	♀
$\delta = \frac{1}{1-m}$ .....	$\frac{1}{1-0.674} = 3.10$	$\frac{1}{1-0.866} = 7.48$
K .....	0.222	0.186
$t_0 = \frac{\ln B}{K}$ .....	$\frac{0.0276}{0.222} = 0.124$	$\frac{-0.424}{0.186} = -2.279$
$W_\infty$ .....	29.388	138.67

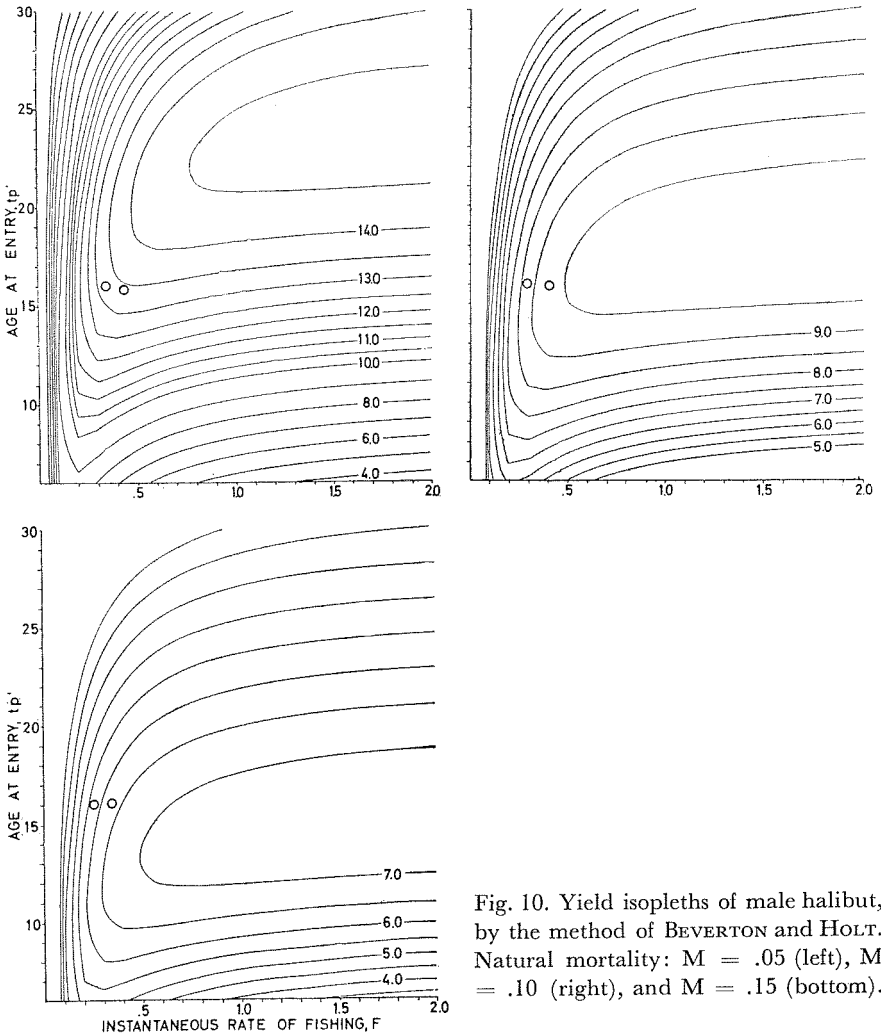


Fig. 10. Yield isopleths of male halibut, by the method of BEVERTON and HOLT. Natural mortality:  $M = .05$  (left),  $M = .10$  (right), and  $M = .15$  (bottom).

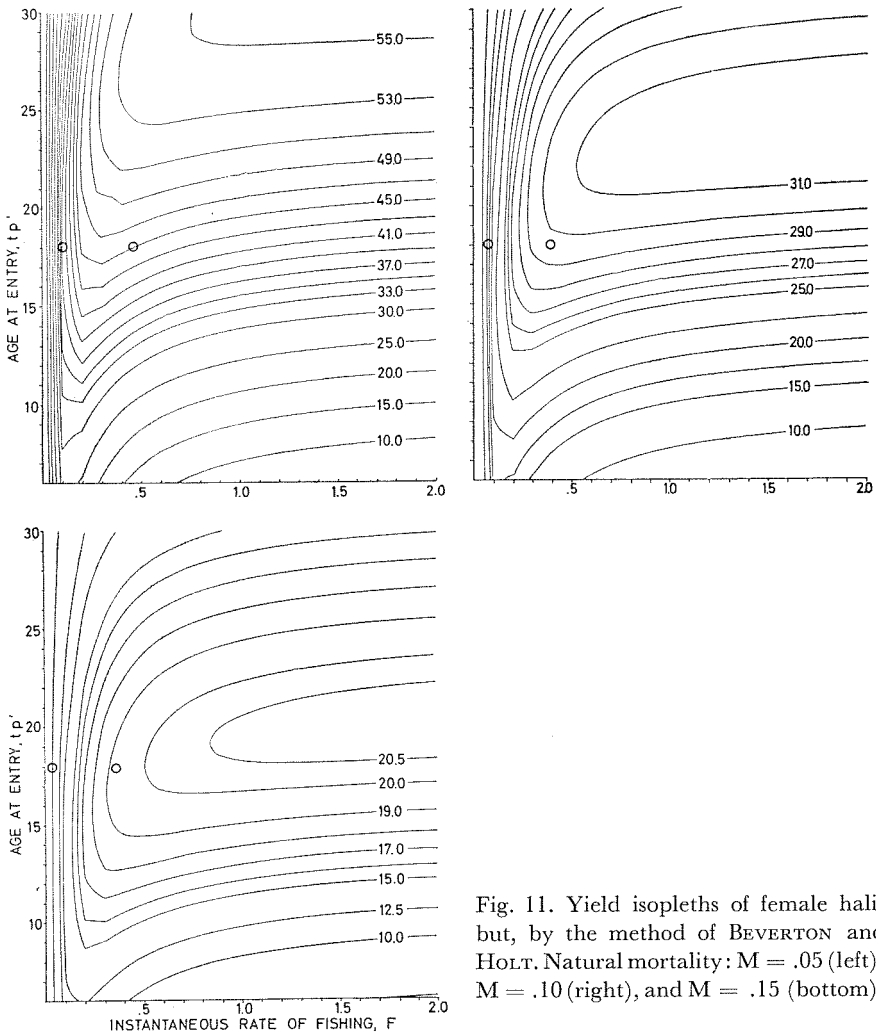


Fig. 11. Yield isopleths of female halibut, by the method of BEVERTON and HOLT. Natural mortality:  $M = .05$  (left),  $M = .10$  (right), and  $M = .15$  (bottom).

The yield isopleths have in common a very steep gradient of response surface for low fishing intensities. They all conform to the usual pattern, with the maximum yield reached at a higher age of entry,  $t_p$ , and higher instantaneous fishing rate,  $F$ , as the natural mortality decreases. The areas of maximal yields are broad and domeshaped and vary between males and females. Therefore, they do not afford a sharp definition of optimum fishing strategy. Ideally, isopleths should be constructed for the combined yield of males and females. Since at present it is not certain that natural mortality is identical for the sexes and since the same amount of gear will not generate the same instantaneous rate of fishing

on males and females, their construction must be deferred until the necessary data are available. If one assumes that males and females are recruited into the fishery in the same proportion, fishing should be adjusted largely to maximize the yield of the females.

The effect of the fishery as it is conducted today can be evaluated by assuming more than 50 % recruitment at an age of 16 years for the males and 18 years for the females, and a total instantaneous mortality,  $Z$ , of .39 for the males and .18 for the females. These lattice points are indicated by circles in Figs. 10—11.

A second set of lattice points has been drawn corresponding to a total mortality of  $Z = .5$ , approximately the rate estimated for the Pacific halibut (ANON., 1960). The best estimate of natural mortality,  $M$ , in the principal areas, Area 2 and Area 3, was .20. In Area 2 the best estimate of current fishing mortality,  $F$ , was .30, while in Area 3 the estimate from age composition was .25, and from catch statistics .60.

In all probability one can assume that the natural mortality is less for the halibut stock in Altafjord than for the halibut stock on the Pacific Coast of North America because of the presence of a substantial number of very old fish.

With these two points as the upper and lower bounds for total mortality, a doubling or tripling of the fishing effort will bring about only a slight increase in the yield per male recruit (Fig. 10).

The yield per female recruit increases rapidly from the lower to the upper bound of total mortality,  $Z$ . This is true for all three levels of natural mortality considered here. Beyond the upper bound an increase in fishing mortality has minor effect on the yield per recruit.

Should the natural mortality,  $M$ , be as low as .05, then the present age of entry into the fishery would be decidedly too low and a substantial increase in yield would materialize from increasing both  $t_p$ , and  $F$ . The same would be true for the yield per male recruit although to a lesser extent.

Thus, the proper evaluation of a management program depends on the precision of the estimates of natural and fishing mortality. This is illustrated for the natural mortality in Fig. 12, where the yield is drawn as a function of  $t_p$ , for four different values of  $M$ . Fishing mortality has been adjusted to give a total mortality of  $Z = 0.39$  for the males and  $Z = 0.18$  for the females. All these curves are rather flat, and a wide range of values for  $t_p$ , around the peak will result in yields of about the same magnitude. If it is assumed that the total mortality is a precise estimate, then the yield is primarily a function of natural mortality.

It is also possible that the natural mortality rate differs between males and females; less for the females and probably decreasing with age. An

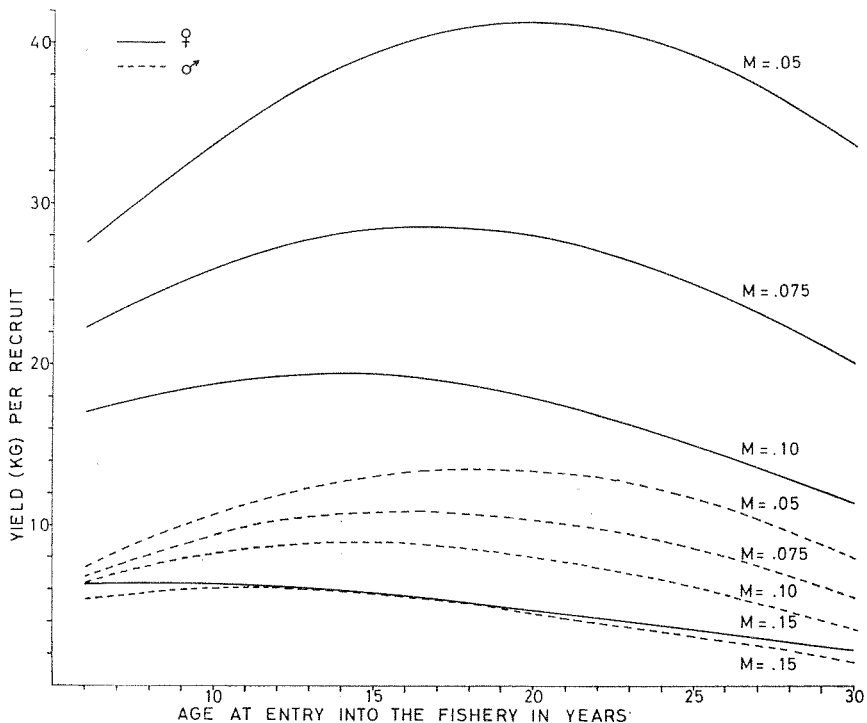


Fig. 12. Yield per female and male halibut recruit with different age at entry into fishery.

accurate assessment of this parameter should be undertaken in future investigations of these stocks of halibut. These tentative estimates serve to define the range of total mortality within which isopleths are most useful to management yield.

The preceding calculations were based on parameters obtained from a growth-in-length or growth-in-weight function fitted to observed length or weight data. A knife-edged selection of the stock was assumed despite the nature of the gear and the body proportions of the fish.

A different set of yield isopleths can be constructed after a method suggested by RICKER (1958) whereby yield is computed from the arithmetic mean of the observed weight at the beginning and at the end of each year throughout the fishable lifespan of a fish. Thus, a series of linear interpolations are made over the relatively short period of one year.

A computer program was prepared by PAULIK and BAYLIFF (1967) and GALES (1964b) for this purpose. Provisions are made for introducing multipliers so that yield can be computed for any desired fishing mortality



Table 9. Mean weights and fishing rates<sup>1</sup> of halibut, used for computation of yield isopleths

Age	♂		♀	
	Mean weight (kg)	Instantaneous rate of fishing	Mean weight (kg)	Instantaneous rate of fishing
7	3.31	.04	5.01	.04
8	4.01	.12	6.96	.07
9	5.15	.22	7.35	.14
10	6.02	.36	32.00	.26
11	8.20	.58	28.00	.42
12	12.17	.67	30.78	.59
13	13.72	.81	32.22	.76
14	14.53	.89	35.99	.87
15	15.34	.95	39.56	.93
16	15.94	1.00	42.19	.96
17	16.62	1.00	45.14	.99
18	18.01	1.00	51.88	1.00
19	17.79	1.00	56.86	1.00
20	18.85	1.00	57.09	1.00
21	19.39	1.00	62.59	1.00
22	21.71	1.00	66.58	1.00
23	21.53	1.00	77.26	1.00
24	23.32	1.00	80.51	1.00
25	27.09	1.00	84.54	1.00
26	23.27	1.00	97.72	1.00
27	26.29	1.00	90.55	1.00
28	23.50	1.00	111.70	1.00
29	31.00	1.00	117.60	1.00
30	21.33	1.00	108.70	1.00
31	30.67	1.00	120.30	1.00
32			120.30	1.00
33			115.00	.9
34			116.50	.8
35			117.00	.7
36			101.70	.6
37			121.30	.5
38			134.30	.4
39			100.00	.3
40			138.50	.2
41			120.50	.1

<sup>1</sup> Multipliers for the basic instantaneous rate of fishing,  $F = 1.0$ , were initially 1. with increments of .1 to a maximum of 2.0.

for each year in the fishable lifespan of the fish. In this manner the actual recruitment curve is simulated.

The observed mean weights for males and females are listed in

Table 9. Recruitment curves were approximated from the catch curves in Figs. 8 and 9 and also from selection curves constructed from the catches of the three sizes of experimental gill nets.

For the males, recruitment into the fishery was assumed to commence at age 7 and to terminate at age 16. This was simulated by increasing the efficiency of the basic instantaneous rate of fishing,  $F = 1.0$ , in the manner indicated in Table 9. For the females, recruitment was assumed to commence at age 8 and to terminate at age 18. The increase in the efficiency of the fishing gear during this period simulates this prolonged recruitment.

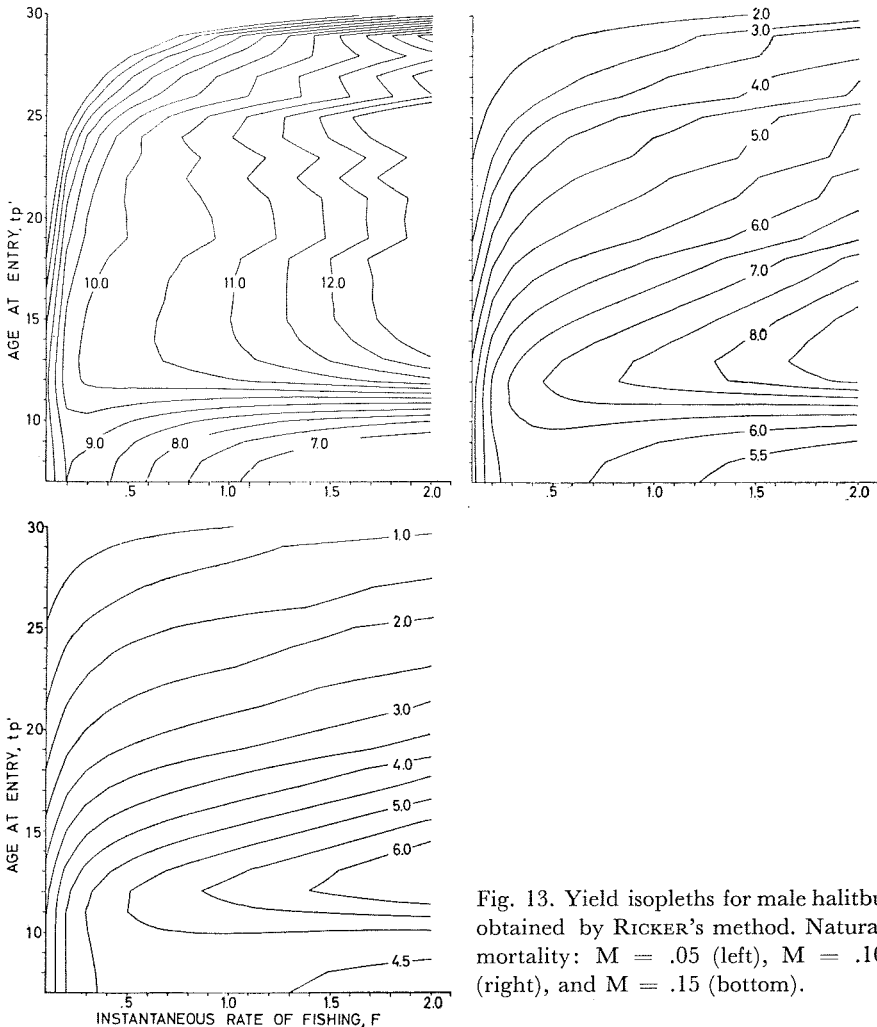


Fig. 13. Yield isopleths for male halibut obtained by RICKER's method. Natural mortality:  $M = .05$  (left),  $M = .10$  (right), and  $M = .15$  (bottom).

Gill nets place also an upper selection curve or recruitment away from the fishery. This was shown by a linear decrease in effective fishing power from age 28 to age 41 for the females, and exclusion from the fishable stock of any succeeding age classes.

The instantaneous rate of fishing at full efficiency was varied in steps from  $F = .1$  to  $F = 2.0$  with even increments of  $.1$ .

The age at entry into the fishery was likewise varied with even increments of one year, commencing at age 7 and ending at age 30 for the males. For the females the corresponding ages were ages 8 and 34.

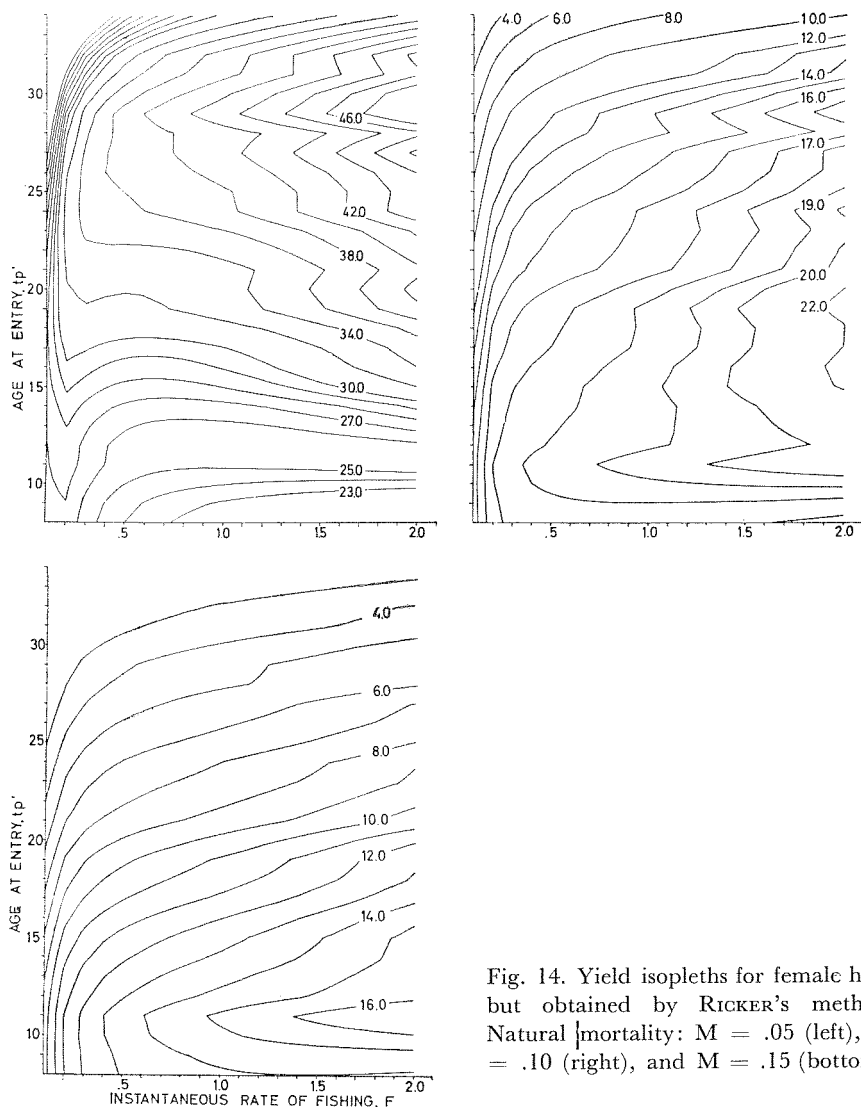


Fig. 14. Yield isopleths for female halibut obtained by RICKER'S method. Natural mortality:  $M = .05$  (left),  $M = .10$  (right), and  $M = .15$  (bottom).

The results are depicted in Figs. 13—14. The irregularities of the contour lines, which are especially sharp in the instance of low natural mortality, are caused by inaccuracies in observed weights. On several occasions there were recorded decreases in average weight from one year to the next, which would disappear with a larger number of observations.

The yield curves show lower over-all values than those seen in Figs. 10—11 because of the adjustment of effective fishing effort during the recruitment phase, and, in case of the females, because also of the withdrawal from the fishable stocks of the very old and large females. The response surfaces emerging in this case are somewhat different from that of the previous yield calculations. If the natural mortality,  $M$ , were in the range .10 to .15, a higher yield would be realized from both male and female recruits by increasing the fishing effort many times over the presumed present effort. The same would be true, particularly in regard to yield per female recruit, if the natural mortality were as low as .05 provided the age of entry were delayed.

#### DISCUSSION

The formulation of a definite strategy for management of the halibut fishery in Northern Norway should await corroborative evidence from changes in stock size as measured in catch per unit of effort. But the available material allows one to explore different possibilities.

A more precise definition of  $W_{\infty}$  is needed. The two computed values, one derived from VON BERTALANFFY's equation and the other from CHAPMAN-RICHARD's formula, differ substantially. Although the latter seems to be more precise than the former on the basis of the present material, it may only hold true for the exploited stock.

There are other reasons to believe that a  $W_{\infty}$  of about 163 kg dressed weight is too low for the females, even if about 15 % is added to compensate for undressed weights. Larger females are frequently caught, and weights up to 333 kg have been recorded (EHRENBAUM, 1936). However, a higher value for  $W_{\infty}$ , which only enters into the yield calculations as a multiplying factor, will only raise the values of the contour lines.

More troublesome is the uncertainty connected with the value assigned to natural mortality. The data for the present analysis were collected at a time when the fishery was intensifying, and when it was operating on stocks that had accumulated over five years. The total mortality determined from catch curves may therefore represent transitional rather than stable values. Because of the high age at entry into the fishery and

the long lifespan of the halibut in Northern Norway, the period of transition must have been rather extended.

Collection of field data terminated in 1960. There is need for a re-assessment of the catch curve now that the recruitment is derived from a parent population which has been fully exposed to a more even fishing pressure. At the same time a study should be made of the efficiency of different types of gill nets converted to standard units of effort. Only then can relative estimates of changes in stock size be obtained.

The present study has shown considerations essential to the rational management of the halibut stocks in Northern Norway. One is the need for a continuous set of observations on age composition and effort to obtain measure of changes in stock size. The expense involved would be relatively small compared to the possible gains. The halibut stocks in Northern Norway are to a greater extent than other stocks of fish in this area exploited by one nation only. Hence it can be regulated relatively efficiently compared with those fisheries involving many nations. Experience has demonstrated that international regulation is difficult to achieve under such conditions.

#### SUMMARY

1. Data on age composition, growth, and mortality rates of the halibut, *Hippoglossus hippoglossus*, collected in Finmark, 1956—1960, supplemented with data on immature halibut from various localities in Northern Norway were examined.
2. A weight-length relationship was determined separately for males and females.
3. Total instantaneous mortality rate was determined for males and females based on age composition data.
4. Yield isopleths were calculated based on a knife-edged selection curve into the fishery and also on prolonged recruitment. In the latter case variable fishing effort was applied to the age groups to simulate the recruitment into the fishery and withdrawal away from the fishable stock of the large females.
5. A precise determination of maximum length or weight, natural and fishing mortality rate were not achieved. Hence the change in yield per recruit could only be suggested as a function of age at entry into the fishery and fishing mortality.

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