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ASSESSING THE LONG TERM EFFECTS OF CHANGES IN FISHING EFFORT AND MESH SIZE FROM LENGTH COMPOSITION DATA

by

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Introduction

Because the length of fish can be regarded as a function of age, it should be possible in principle, to analyse length composition data, using techniques that have been developed for the analysis of age composition data. The "Cohort Analysis" is a technique that makes use of data related to specified time intervals. Although it is customary to use age composition data, there should be no objection in principle to using length composition data provided differences in length can be validly related to differences in time.

For some species, the growth of individual fish can be investigated using back calculations of length from the scales. For haddock, the results suggest that much of the individual variation in length with age is due to variation in the first year of life; ie individuals tend to be above or below average size for the whole of their lives. To a first approximation, individual growth curves appear as a set of curves, that differ mainly with respect to their intercepts on the age axis. The situation is illustrated diagrammatically in Figure 1.

The results suggest that although there may be a relatively large variation in the age of fish at a particular length, there appears to be relatively smaller variation in the length of time required for a fish to grow from one length to another. This suggests that it should be possible to apply a virtual population or "cohort analysis" technique to length composition, as well as to age composition data.

This paper deals with its application for Faroe haddock length composition data.

The cohort analysis technique

The cohort analysis (Pope 1972) estimates mortality rates and provides a way of determining how many fish there must be in the sea, in order to account for a given number of fish caught. The basic equation is:-

$$N_t = N_{t+1}\, e^{M} + C_t\, e^{M/2} \qquad \text{....1}$$

where N_t is the number in the sea aged t years

N_{t+1} is the number in the sea aged t+1 years

C_t is the catch of fish aged between t and t+1 years

M is the instantaneous rate of natural mortality.

It is not necessary for the time period involved to be exactly equal to one year, or indeed to remain constant in successive applications of equation (1). Thus for greater generality, (1) may be replaced by

$$N_t = N_{t+\Delta t}\, e^{M\,\Delta t} + C_t\, e^{M\,\Delta t/2} \qquad \ldots.2$$

where Δt refers to the time interval between the ages t and $t+\Delta t$. In this form, the equation can be adapted for application to length composition data.

Thus consider two groups of fish of lengths L_1 and L_2 cm respectively. It will first be supposed that length can be related to age by the von Bertalanffy equation

$$\text{ie } L = L_\infty (1 - e^{-K(t-to)})$$

$$\text{so that } t = to - \frac{1}{K} \ln \left(1 - \frac{L}{L_\infty}\right) \qquad \ldots.3$$

From (3) it follows that fish of length L_1 cm should have an average age given by

$$t_1 = to - 1/K \ln (1 - L_1/L_\infty) \text{ years} \qquad \ldots.4$$

Similarly fish of length L_2 cm should have an average age

$$t_2 = to - 1/K \ln (1 - L_2/L_\infty) \text{ years} \qquad \ldots.5$$

The average time required to grow from L_1 to L_2 cm should therefore be given by the difference between (4) and (5):-

$$\text{ie } (t_2 - t_1) = (1/K) \ln \frac{(L_\infty - L_1)}{L_\infty - L_2} \text{ years} \qquad \ldots.6$$

Unlike equations (4) and (5) which contain 3 constants (L_∞, K and to), equation (6) only contains 2 constants (L_∞ and K). This is one reason why variations in the age interval $(t_2 - t_1)$ for a given length interval $(L_2 - L_1)$, might be expected to be less than the variations in the age for a given length.

With reference to equation (2), let N_1 represent the number of fish that attain a length L_1 cm during any one year and let N_2 represent the number that attain L_2 cm. Let $(t_2 - t_1)$ in equation (6) represent Δt in equation (2).

Substitution of (6) into (2) then gives:-

$$N_1 = N_2 \left\{\frac{L_\infty - L_1}{L_\infty - L_2}\right\}^{M/K} + C_{1/2} \left\{\frac{L_\infty - L_1}{L_\infty - L_2}\right\}^{M/2K} \qquad \ldots.7$$

where $C_{1/2}$ is the number of fish caught during a year with lengths between L_1 and L_2 cm.
Inspection of equation (7) shows that it should be possible to carry out a modified cohort analysis on length composition data for various assumptions about M/K and L_∞.
For computational convenience, the equation can be transformed to the alternative form shown in equation (8).

$$N_1 = [N_2 X_L + C_{1/2}] X_L \qquad \ldots.8$$

$$\text{where } X_L = \left\{\frac{L_\infty - L_1}{L_\infty - L_2}\right\}^{M/2K} \qquad \ldots.9$$

Having estimated a value for N_L for the largest fish, successive applications of equation (8) should then lead to estimates of N_L for the smaller fish.

The rate of exploitation (F/Z) for each length group can then be determined from the relationship:-

$$F/Z = (\text{number caught})/(\text{number dying})$$

Comparison of results from length and age composition

For comparative purposes, Faroe haddock data used by the Working Group on the Fish Stocks at the Faroes were analysed. In the analysis values of L_∞ and K of 83 cm and 0.15 respectively, as used by the Working Group (Anon 1974) were first adopted. A value of M of 0.2 was used for the cohort analysis of the age composition data. In order to make the results obtained from the two sets of data comparable, a value of M/K of 0.2/0.15 = 1.333 was used in the analysis of the length composition data. It was assumed that the value of F/Z was 0.7 for the largest and oldest fish in each analysis.

Table 1 gives details of the analysis of the length composition data using a value of L_∞ = 83 cm (equation (8) was used with X_L as defined in equation (9)). Table 2 gives the corresponding data for a conventional cohort analysis applied to the age composition data.

Each method provides estimates of F/Z, in one case corresponding to various length groups and in the other corresponding to various age groups.

In addition, similar analyses to the one in Table 1 were carried out using different values of L_∞ and different values of M/K.

The various values of F/Z obtained are compared in Tables 3 and 4. Age groups have been aligned to correspond as closely as possible with the length groups.

Comparison of the results shows that:-

1. The values of F/Z obtained from the length composition data, with M/K = 1.333 and L_∞ = 83 cm, were lower than the corresponding values of F/Z obtained from age composition data.
2. By increasing the value of L_∞, with M/K constant at 1.333, reasonably good agreement between the values of F/Z obtained by the two methods was obtained when L_∞ = 93 cm.
3. Alternatively, by decreasing the value of M/K with L_∞ constant at 83 cm gave reasonably good agreement of values of F/Z obtained by the two methods when M/K = 1.1.

Discussion

The results in Tables 3 and 4 show that in order to make the values of F/Z from the age and length composition data similar, it is necessary to use a value of L_∞ greater than 83 cm or a value of M/K less than 1.333.

This is an interesting result and one that might be explained by noting that the values of L_∞ and K of 83 cm and 0.15 were obtained from the observed relationship between mean length and age. However, for the length composition analysis it would have been more appropriate to have used values obtained from an observed relationship between mean age and length. The two relationships need not necessarily be the same and one implication of the results is that in fact they are not.

One way of improving the agreement between the results from the two sets of data was by increasing the value of L_∞ from 83 to 93 cm. One way of explaining this is by supposing that the larger individuals sampled consist of individuals that happen to be growing faster than would be expected from the curve of mean length on age. Thus, consider a group of fish for which the value of L_∞, calculated from the relationship between mean length and age, happens to be 100 cm. If equation (6) is used with L_∞ = 100 cm the time required for a fish to grow from 95-100 cm should be infinitely great (since an infinitely long time is required for a fish to attain 100 cm). In practice however, any individuals with lengths in the range 95-100 cm, are likely to be individuals that are growing faster than the "average". The time for these individuals to grow from 95-100 cm is therefore likely to be very much less than the time estimated using average values of L_∞ and K.

There is no reason too, why in practice, there might not be individuals with lengths greater than the average value of L_∞, and for these the application of equation (6) using an average value of L_∞ would lead to meaningless results. From these considerations it is suggested that the curve of mean age on length might deviate from the curve of mean length on age and that the difference between the two might be greater for the larger (and older) fish.

Estimates of numbers in the sea

In addition to estimates of mortality rate, the cohort analysis provides estimates of the numbers in the sea needed to account for the numbers landed at each age or size. The values obtained from the analysis of the age and length composition data for the two smallest length groups and for the two youngest age groups are compared in Table 5.

Comparison of results is not direct, since the two methods do not necessarily estimate the same quantities. The estimate of the number of fish of 30 cm for example, is an estimate of the number of fish in the sea that first attain this length. This they will do over a range of ages.

To a first approximation however, it is expected that the number of Faroe haddock of 30 cm should be similar to the number at the beginning of age group 2.

Comparison of results shows that the various estimates are not as sensitive as the value of F/Z to the assumptions made about L_∞ or M/K.

The estimate of the number of fish in the sea at the beginning of age group 2 using age composition data, is 32.6 million fish. Comparison with the results obtained from the various analyses of the length composition data show that in the example when L_∞ was 93 cm and M/K was 1.333 the number in the sea at a length of 30 cms was estimated at 31.4 million fish. Alternatively, when L_∞ was 83 cm and M/K was 1.1, the value was 32.4 million fish. The agreement appears to be quite good.

Mortality rates

Survival and mortality rates can also be calculated from the estimates of N_L. Thus, the survival rate $(S\,\Delta t) = e^{-Z\,\Delta t}$ during the period in which fish grow from length L_1 cm to length L_2 cm is given by:-

$$e^{-Z\,\Delta t} = N_2/N_1 \quad \text{....10}$$

The corresponding total mortality rate is $Z\,\Delta t$. It is related to $S\,\Delta t$ by:-

$$Z\,\Delta t = -\ln\,(S\,\Delta t) \quad \text{....11}$$

Note that the mortality rates $Z\Delta t$ are not annual values. They relate to mortalities during the time periods required to grow from one specified length to the next.

A value of $F\Delta t$ for each length interval can be obtained from the relationship:

$$F\Delta t = (F/Z)\ Z\Delta t$$

Values of $F\Delta t$ and $Z\Delta t$ are given in the example in Table 1.

Finally, by assuming a value for M or for K, annual values of Z can be obtained. Thus, given a value of M, Z can be estimated from:-

$$Z = M/[1 - (F/Z)] \qquad \ldots .12$$

Alternatively, given a value of K, an estimate may first be obtained for Δt by using equation (6).
Then given Δt, Z may be determined from:-

$$Z = Z\Delta t / \Delta t \qquad \ldots .13$$

It should be noted that these alternatives are equivalent, and apart from rounding errors lead to identical results.
Values of Z determined using equation (12) are given in the example in Table 1. A value of M = 0.2 has been assumed.

Estimating the effect of a change in fishing effort

A method of estimating the long term effect of changes in fishing effort using fishing mortality rates at various ages has been described by Jones (1961). The principle of the method is that conversion factors for estimating the long term effects of changes in fishing effort or mesh size can be derived for each age group separately. These factors are based on cumulative fishing mortality rates, and can be estimated directly from the values of $F\Delta t$ shown in Table 1. For example, suppose that there is an increase in fishing effort that causes a proportionate change in the fishing mortality rate at each age by the same amount. The formula for (C_t) the conversion factor at age t given by Jones (1961) can then be simplified and written in the form:-

$$C_t = (1 + X/100) \exp - (X/100 \sum^{t} F\Delta t) \qquad \ldots .14$$

where X is the percentage change in fishing mortality rate at each age and this can be positive or negative. $\sum^{t} F\Delta t$, is the sum of the instantaneous mortality rates (multiplied by the respective time periods Δt) up to age t. When dealing with age or length groups, a first approximation is to sum the values of $F\Delta t$ to the middle of each age or length group.

Since the method is not necessarily dependent on the grouping interval, there is no reason, in principle, why it should not be applicable, to the data in Table 1.

As an example, the long term effects of a 20% increase in fishing effort have been worked out in Table 6 using the values of $F\Delta t$ determined in Table 1. Columns A - D show the steps for converting numbers landed at each length to weights landed at each length, using the weight at length factors in column A.

Column E gives the values of $F\Delta t$ for each length group taken from Table 1. Column G shows the sum of the values of $F\Delta t$ up to the middle of each length group.

The following estimates are obtained:
For a 20% increase in fishing effort, the new equilibrium yield is given by 18.39×10^3 tons. Compared with the existing yield of 18.64×10^3 tons, this represents a 1.3% decrease in landings, which is not very different from the result obtained from a comparable analysis of the age composition data with M = 0.2 (Anon 1974).

It should be noted that constant recruitment has been assumed in these calculations.

The estimates in Table 6 have been based on the values of $F\Delta t$ calculated in Table 1 in order to illustrate the method. It might have been more appropriate to have carried out the original analysis using a value of $L_\infty = 93$ cm (or a value of M/K = 1.1) in view of the results obtained in Tables 3 and 4. This has been tried, but it was found that the effect on the final estimates of the effect of a 20% increase in fishing effort were insignificant.

Estimating the effect of change in mesh size

Given the values of $F\Delta t$ for each length group, the methods described by Jones (1961) can also be adapted for dealing with the situation where there is a change in mesh size and also for the more general situation in which there is a change in both mesh size and fishing effort. In each instance a conversion factor for each length group can be calculated by an appropriate manipulation of the values of $F\Delta t$.

Summary and Conclusions

An investigation of the growth of individual haddock, based on back calculations from the scales, suggests that individuals tend to be above or below average size for the whole of their lives. Individual growth curves appear to be superficially similar in shape, and differ mainly in having different intercepts on the age axis. For this reason, it is suggested that "age directed" techniques such as virtual population or cohort analysis techniques ought to be just as applicable to length composition data as to age composition data.

To investigate this possibility, a cohort analysis has been attempted for Faroe haddock using both length and age composition data.

It was found possible, by an appropriate choice of the basic parameters to obtain reasonably comparable estimates of the rate of exploitation (F/Z) by both methods. An example of the method is given in Table 1. Of interest was the discovery that one way of getting good agreement was by assuming values of L_∞ and K consistent with individual growth curves that tended towards a higher asymptote than the curve of mean length on age.

The minimum assumptions required for the analysis of length composition data are a value of M/K, a value of L_∞, and a value of the rate of exploitation (F/Z) for the largest fish. Given these it is possible to determine the rate of exploitation (F/Z) for each length group.

Without making further assumptions, it is also possible to make assessments of the long term effects on yield-per-recruit of changes in fishing effort and/or mesh size.

Although one more assumption is required than in a conventional cohort analysis, it could be argued that setting limits to L_∞ and the ratio of M/K is not necessarily any more difficult than setting limits to M.

For example, for some species, values of M/K might be inferred from data given by Beverton and Holt (1959).

By further assuming a value for either M or K, estimates of the annual values of F and Z at various lengths can also be obtained.

For species which cannot be aged the method should enable a range of estimates to be obtained for various assumptions about M/K and L_∞. For species that can be aged, the analysis of length composition data should provide information to supplement that obtained from the analysis of age composition data. This may provide indirect evidence about individual growth curves that might otherwise be obscured by working with mean length at age data. Also, in a situation where fishing mortality varies with age (or length) it may be just as important to examine the relationship between F and length directly, as to examine the relationship between F and age. Disadvantages of the method are that:-

a. more assumptions have to be made than when dealing with age composition data;

b. in order to eliminate the effect of variations in year class strength it is necessary to use an average length composition based on a number of years sampling. The effect of year class fluctuations on age composition data on the other hand can be eliminated if samples are available for only two years.

This objection should not be too serious however, for those species, in which year class variation is relatively small.

References

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Table 1

Cohort analysis using Faroe haddock length composition data for the period 1959-1972

L_∞ = 83 cm M/K = 1.333 final F/Z = 0.7

Length	$L_\infty - L$	A $\left(\frac{L_\infty - L_1}{L_\infty - L_2}\right)$	X_L $(A)^{0.667}$	C_L No. landed (millions)	N_L (1) No. in Sea (millions)	F/Z	$e^{-Z\Delta t}$	$Z\Delta t$	$F\Delta t$	Z
25	58	1.0943	1.062	0.30	41.54	0.060	0.878	0.128	0.008	0.21
30	53				36.55					
		1.1042	1.068	2.49		0.363	0.813	0.208	0.075	0.31
35	48				29.70					
		1.1163	1.076	3.92		0.510	0.741	0.300	0.153	0.41
40	43				22.00					
		1.1316	1.086	4.17		0.581	0.673	0.395	0.229	0.48
45	38				14.82					
		1.1515	1.099	3.80		0.633	0.595	0.519	0.329	0.54
50	33				8,82					
		1.1786	1.116	2.59		0.638	0.540	0.616	0.393	0.55
55	28				4.76					
		1.2174	1.140	1.46		0.614	0.500	0.692	0.424	0.52
60	23				2.39					
		1.2778	1.178	0.87		0.620	0.408	0.888	0.550	0.53
65	18				0.98					
		1.3846	1.242	0.40		0.599	0.320	1.139	0.683	0.50
70	13				0.31					
>70				0.22		0.7				
Total				20.22						

Examples for 35-40 cm length group:-

col. A 1.1163 = 48/43

X_L 1.076 = $(1.1163)^{0.667}$

N_L 29.70 = [22.00(1.076) + 3.92] 1.076 - see text equation (8)

F/Z 0.510 = 3.92/(29.71 - 22.00)

$e^{-Z\Delta t}$ 0.741 = 22.00/29.70

$Z\Delta t$ 0.300 = $-l_n$ (0.741)

$F\Delta t$ 0.153 = (0.300)(0.510)

Z 0.41 = (0.2)/(1-0.510) - see text equation (12). A value of M = 0.2 has been assumed.

(1) Estimated from data supplied by members of the "Working Group on the fish stocks at the Faroes", February 1974.

Table 2

Cohort analysis using Faroe haddock age composition data for the period 1957 - 1972

$M = 0.2 \quad e^{M/2} = 1.105 \quad \text{final } F/Z = 0.7$

Age	No. landed(C_L)	No. in sea(N_L)[1]	F/Z	e^{-Z}	Z
1		40.13			
	0.25		0.033	0.813	0.21
2		32.64			
	4.13		0.428	0.704	0.35
3		22.99			
	6.33		0.640	0.570	0.56
4		13.10			
	4.92		0.721	0.479	0.74
5		6.28			
	2.09		0.690	0.518	0.66
6		3.25			
	1.29		0.733	0.458	0.78
7		1.49			
	0.80		0.808	0.336	1.09
8		0.50			
	0.30		0.833	0.280	1.27
9		0.14			
	0.08		0.800	0.286	1.25
10		0.04			
≥10	0.03		0.7		
Total	20.22				

(1) Estimated from data supplied by members of the 'Working Group on the fish stocks at the Faroes', February 1974.

Table 3

Comparison of values of F/Z obtained from the analysis of Faroe haddock length and age composition data

Effect of varying L_∞ with M/K = 1.333

From Age Composition		Length group \ L_∞	From Length Composition					
Age Group	M = 0.2		83	90	93	95	97	100
1	0.033	25-30	0.060	0.075	0.081	0.085	0.089	0.097
2	0.43	30-35	0.36	0.42	0.44	0.46	0.47	0.48
		35-40	0.51	0.57	0.59	0.61	0.62	0.63
3	0.64	40-45	0.58	0.64	0.66	0.68	0.69	0.70
4	0.72	45-50	0.63	0.70	0.72	0.73	0.74	0.76
5	0.69	50-55	0.64	0.71	0.73	0.74	0.76	0.77
6	0.73	55-60	0.61	0.70	0.72	0.74	0.75	0.77

Table 4

Comparison of values of F/Z obtained from the analysis of Faroe haddock length and age composition data

Effect of varying M/K with L_∞ = 83 cm

From Age Composition		Length group \ M/K	From Length Composition					
Age Group	M = 0.2		0.8	0.9	1.0	1.1	1.2	1.3
1	0.03	25-30	0.12	0.11	0.09	0.081	0.07	0.06
2	0.43	30-35	0.55	0.51	0.47	0.44	0.40	0.37
		35-40	0.68	0.65	0.62	0.58	0.55	0.52
3	0.64	40-45	0.74	0.71	0.68	0.65	0.62	0.59
4	0.72	45-50	0.78	0.75	0.72	0.70	0.67	0.64
5	0.69	50-55	0.78	0.75	0.73	0.70	0.67	0.65
6	0.73	55-60	0.76	0.73	0.70	0.68	0.65	0.62

Table 5

Comparison of numbers in the sea (millions) obtained from the analysis of length and age composition data

Effect of varying L_∞ with M/K = 1.333

From Age Composition		Length group \ L_∞	From Length Composition					
Age Group	M = 0.2		83	90	93	95	97	100
1	40.1	25	41.5	36.6	35.1	34.3	33.6	32.6
2	32.6	30	36.6	32.6	31.4	30.8	30.2	29.5

Effect of varying M/K with L_∞ = 83 cm

From Age Composition		Length group \ M/K	From Length Composition					
Age Group	M = 0.2		0.8	0.9	1.0	1.1	1.2	1.3
1	40.1	25	30.5	32.2	34.1	36.1	38.3	40.7
2	32.6	30	28.0	29.4	30.8	32.4	34.1	35.9

Table 6

Worksheet for predicting the effect on landings of a 20% increase in effort

A Av weight kg	B Length group cm	C Numbers landed (millions)	D Catch (tonsx10^{-3})	E FΔt	G ΣFΔt(2)	0.2 ΣFΔt	exp-0.2ΣFΔt
0.19	25-30	0.30	0.06	0.008	0.004	0.001	0.999
0.31	30-35	2.49	0.77	0.075	0.045	0.009	0.991
0.47	35-40	3.92	1.84	0.153	0.159	0.032	0.969
0.69	40-45	4.17	2.88	0.229	0.350	0.070	0.932
0.96	45-50	3.80	3.65	0.329	0.628	0.126	0.862
1.30	50-55	2.59	3.37	0.393	0.990	0.198	0.820
1.71	55-60	1.46	2.50	0.424	1.398	0.280	0.756
1.94	60-65	0.87	1.69	0.550	1.885	0.377	0.686
2.77	65-70	0.40	1.11	0.683(1)	2.501	0.500	0.607
3.5	≥70	0.22	0.77	0.700(1)	3.193	0.639	0.528
Total		20.22	18.64				

(1). Assumed value
(2) Summed to the middle of each length group eg for the 35-40 cm group
0.159 = (0.008 + 0.075 + 0.153/2)

New equilibrium yield(3)
= 1.20 [(0.06)(0.999) + (0.77)(0.991) + ... (0.77)(0.528)] = 18.39 x 10^3 tons

Old equilibrium yield
= 18.64 x 10^3 tons

% change in yield $= \left(\frac{18.39 - 18.64}{18.64}\right)100 = -1.3\%$

(3) Calculated from formula:-

$$(1 + X/100) \left\{(\Sigma \text{Catch})(\exp - [X/100 \, \Sigma F\Delta t])\right\}$$

where X = % change in effort

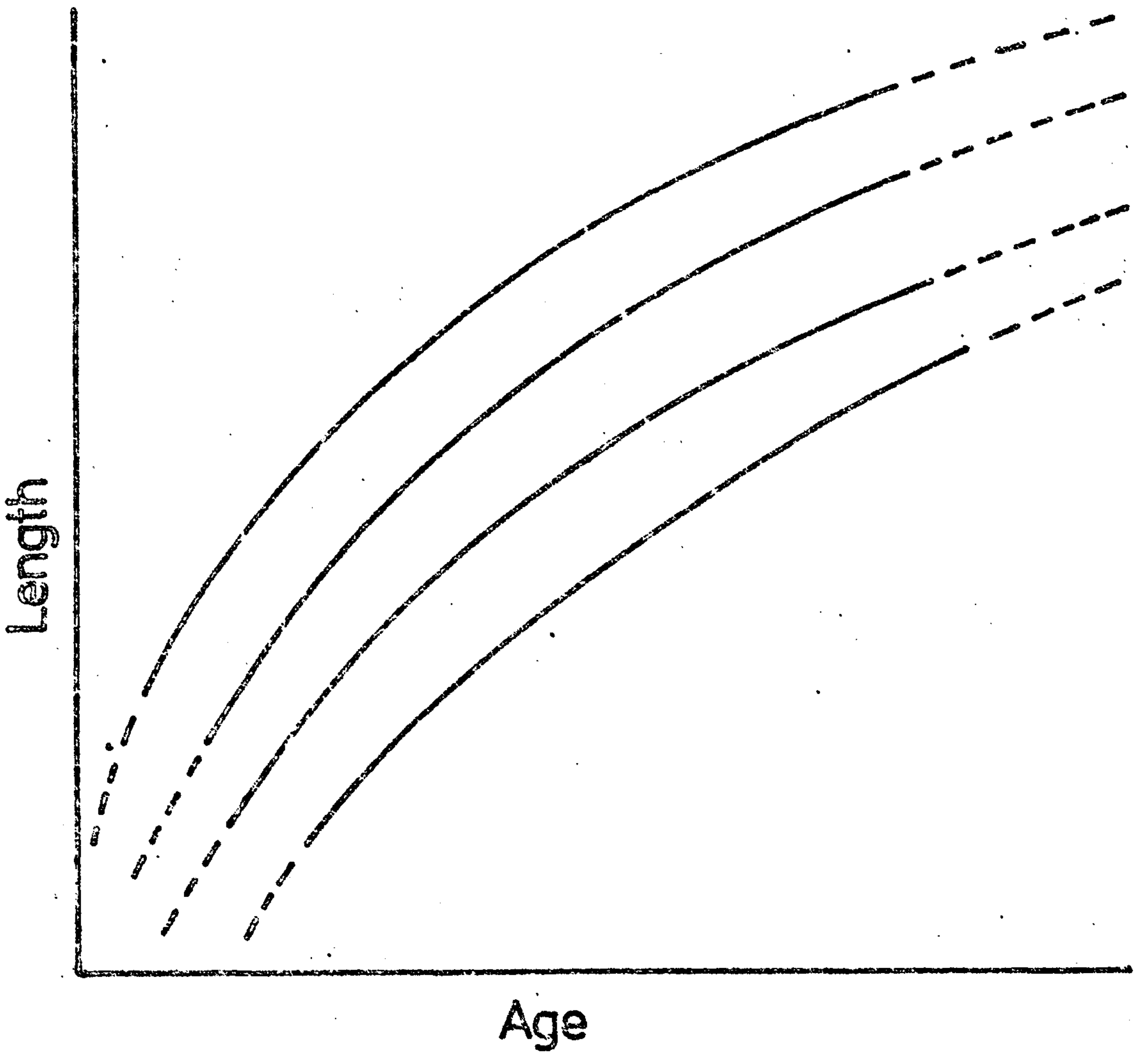

Figure 1 Showing diagrammatically, the relationship between the growth curves of individual haddock as deduced from back calculations on the scales.