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GEAR SELECTIVITY AND THE VARIATION OF YIELD

by

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SUMMARY

For constant fishing effort, the variation of yield is driven by largely unpredictable changes in the annual recruitment. Given the statistics of recruitment fluctuations, the yield variability depends on the level of effort and the selection parameters of the gear. This paper examines the significance of the latter effect, with particular reference to the shape of the selection ogive.

An age-structured population model is used to develop the theory of yield variation. Gears are selective on fish length and the model includes stochastic length-at-age distributions.

The model is applied to the North Sea haddock fishery using data from quarterly trawl surveys in 1991. The catch analysis is performed in quarterly steps to take account of the within-year growth of young fish. The results show that the yield is least variable when the selection range is of the order of the 50% retention length. Thus "knife edge" selection (zero selection range) is not the optimal harvest strategy when the objective is to minimise the yield variability.

INTRODUCTION

The variability of the yield from a fishery is driven in most cases by the fluctuating level of recruitment. The extent to which these changes affect the yield depends on the exploitation level and other characteristics of the fishery, notably the selectivity of the fishing gear.

MacLennan *et al.* (1992) have shown how the yield variability depends on the fishing effort through the number of year-classes contributing to the fishery. In this paper, the age-structured model is further developed to take account of the selectivity of the gear, in particular the shape of the selection ogive which determines the relative mortality of different sizes of fish.

THEORY

Following the terminology of MacLennan *et al.* (1992), the variability of yield is described by the factors H_1 and H_2 which determine the effect of stochastic recruitment fluctuations on the annual yield. In the age-structured model, these factors are functions of the catch coefficients C_n at age n which are

$$C_n = W_n (1-M_n/Z_n) \exp(-\sum_{n=1}^{j-1} Z_j) [1-\exp(-Z_n)] \tag{1}$$

M_n and Z_n are respectively the annual natural and total mortality rates at age n. W_n is the weight per fish and the fishing mortality rate is $F_n = Z_n - M_n$. H_1 is the year-on-mean variability factor which relates to changes in the long term.

$$H_1 = \sum C_n^2/(\sum C_n)^2 \tag{2}$$

H_2 is the year-on-year variability factor which relates to changes from one year to the next.

$$H_2 = \sum (C_n - C_{n-1})^2/(\sum C_n)^2 \tag{3}$$

In these equations, the summations are taken over all ages in the fishery. It is assumed that the smallest fish escape capture so that $C_0 = 0$.

The selectivity of towed fishing gear depends primarily on the size of the fish, and is normally expressed in terms of the length of the fish, L, through an ogive function. If S(L) is the proportion of fish of length L entering the gear which are caught, one form of the ogive is

$$S(L) = 1/(1 + \exp[\ln(9)(L - L_{50})/SR]). \tag{4}$$

Where L_{50} is the length at which 50% of the fish are caught, and SR is the selection range, the length difference between the 25% and 75% retention points on the ogive. For a given species, L_{50} and SR are determined only by the type of gear used in the fishery.

In any natural population, there will be a range of sizes for a given age since some fish grow faster than others. The size distribution at age n may be described by a probability density function, $\rho_n(L)$. Thus $\rho_n(L)\,\Delta L$ is the proportion of age-n fish with lengths in the range L to (L + ΔL). The gear selectivity may now be expressed as a function of age through the convolution of S(L) and $\rho_n(L)$.

$$S_n = \int_0^\infty \rho_n(L)\, S(L)\, dL \tag{5}$$

Thus S_n is the proportion of age-n fish entering the gear which are caught. The next problem is how to relate S_n to the fishing mortality rate F_n. Clearly F_n is proportional to S_n. The factor of proportionality depends on the fishing effort and the accessibility of the various ages to capture. Suppose for the present that all ages are equally accessible to the fishery. We then have

$$F_n = E\, S_n \tag{6}$$

Where the factor E depends on the fishing effort but is the same for all *n*. Substituting equations (4-6) into (1) allows us to calculate the variability factors H_1 and H_2 as functions of the fishing effort, given the selectivity characteristics of the gear and the biological parameters (natural mortalities, size distributions etc) of the target stock.

In order to consider the effect of selectivity changes, through a new gear being introduced to the fishery for example, or a different mesh size, we need to specify some condition on the fishing effort before and after the change occurred. If E were constant, this would imply the same amount of fishing time, or the same size of fleet fishing without restriction.

However, in the case of a fishery controlled by a quota on the catch, aimed at the fishing mortality rate being held constant, the effort cannot remain constant when the selectivity function S_n is changed. Suppose the fishery is managed so that the fishing mortality of mature fish is constant, $\bar{F}$ say. $\bar{F}$ will be an appropriate average of the F_n for the mature ages. When S_n changes, it is only necessary to find the new value of E which gives the same $\bar{F}$. The implication in this scenario is that the fleet must adjust the time spent fishing since the catch is limited by quota, not by the available effort.

APPLICATION TO NORTH SEA HADDOCK

To apply the above theory, it is first necessary to have a growth model which includes the length-at-age as a stochastic parameter. This has been done using catch data from British groundfish surveys in 1991. During that year, one or two surveys were conducted in each quarter - first, second and third by RV *Scotia* (A W Newton, pers. comm.) and second, third and fourth by RV *Cirolana* (C T Macer, pers. comm.).

The present study uses length and age data from samples of haddock *Melanogrammus aeglefinus*. The numbers of fish caught in the age range 0-6 years were sufficient to give a good indication of the growth pattern in that period. Furthermore, the growth can be studied in quarterly increments by combining samples from the various surveys. Few fish older than six years were caught and they have been excluded from the analysis.

For the second and third quarters, the *Scotia* and *Cirolana* data have been combined as though from the one survey, to give a single data set for each quarter.

Biological Data

Figure 1 shows the mean length for each age in quarterly increments. The points aligned with the marks on the age axis are from the survey in the first quarter, the points next to the right are for the second quarter and so on. The 0-group is shown for the third and fourth quarters only, since few of these fish were caught in the earlier surveys.

A von Bertalanffy growth curve has been fitted to the mean lengths as shown in Figure 1. The fitting procedure was to minimise the proportional sum of squares, defined as follows. If L_t is the observed length at age t, and $\hat{L}(t)$ is the fitted value, the sumsquare to be minimised is

$$SS = \sum_t \left[\frac{\hat{L}(t) - L_t}{L_t}\right]^2 \tag{7}$$

With t in years and $\hat{L}$ in cm, the fitted growth curve is

$$\hat{L}(t) = 42.92\ [1-\exp\ (-0.529\ [t + 0.0589])] \tag{8}$$

While the fit is reasonably good, it is interesting to note the seasonal changes in growth rate which have not been included in the present model. At age 2 for example, the positions of the quarterly points relative to the fitted curve show the much faster growth in the second and third quarters compared to other times of year.

Figure 2 shows the standard deviation (SD) of the lengths of fish sampled from each year-class, again with the results of the various surveys spaced along the age-axis as quarterly increments. There appears to be a trend of SD increasing with age, although the results for age 4 and older fish are scattered, probably due to the small sample sizes (Table 1).

For the purposes of the present study, it has been assumed that the length SD increases linearly with age. There is no clear biological basis for this assumption, but it is as good as any other and is reasonably supported by the data in Figure 2. A linear regression on these data gives the result (for SD in cm, t in years)

$$SD = 1.07 + 0.95t \tag{9}$$

The weight-length relationship has been taken from Coull *et al.* (1988). For haddock, the total weight w in grammes for a fish of length L cm is

$$W = 0.0182\ L^{2.8268} \tag{10}$$

Some seasonal variation of the weight-length relationship was noted by Coull *et al.* The above formula is the mean annual relationship which is considered to be good enough for present purposes.

Finally, natural mortality rates are required for the evaluation of the catch coefficients. In the case of haddock, M is believed to be very high for the youngest fish (Anon., 1993). Since the youngest fish are also fast growing, it is necessary to consider the natural and fishing mortalities over time intervals rather less than a year, especially when the exploitation rate is high. The present model is therefore based on a quarterly analysis. Values of M quoted in the literature (or assumed by working groups) are annual averages, however, it may be supposed that there is a progressive decrease over each year. On this assumption, quarterly values of M have been interpolated from the annual rates in Anon. (1993). For the 0-group, Anon. (1987) suggests that the mortality is mostly in the second half of the year, and this has been taken into account in the values of M by quarter shown in Table 2.

RESULTS AND DISCUSSION

Using the above theory and reference biological data for the North Sea haddock fishery, the variability factors can be evaluated as functions of L_{50} and the selection range, given one condition on the fishing mortality or effort. For the present study, it was decided to specify the mortality of fish at age 2 or older, most of which are mature. This avoids the complication of the very high natural mortality on the younger fish, but more importantly the mature mortality is most relevant to the future of the spawning stock, and for that reason it may be controlled as a management objective. Conditions of high and low fishing mortality have been compared in the present study, for which F_{2+} has been set at 1.0 and 0.3 respectively.

Figure 3 shows a set of graphs of the variability factors against selection range, supposing that the latter could be changed while L_{50} remained fixed. In each graph there are three curves, one for each value of L_{50}. The graphs for H_1 and H_2 are on the left and right respectively, while the high and low mortality rates are shown above and below respectively.

All the curves in Figure 3 show the same general features. In particular, the variability factors are always highest when SR is zero. As SR increases, both H_1 and H_2 drop to a minimum and then increase slowly towards an asymptotic value when SR is very large. There is little difference in the shape of the curves between H_1 and H_2, but the proportional changes in H_2 are greater. This implies that optimising SR to reduce the variability of yield will be more effective in smoothing year-on-year changes. It is also noted that the value of SR for minimum variability is less for H_2 than for H_1.

The selection ranges of the trawls and series currently used in the fishery are generally less than 10 cm and thus would be well to the left of the minima in Figure 3 (Robertson and Ferro, 1988; Robertson and Stewart, 1988).

Comparing the high and low fishing mortality conditions, it is seen that the minimum variability occurs at smaller values of SR in the former case. Also, the proportional change in H between SR = 0 and the minimum is greater when F_{2+} is higher. Therefore, when the exploitation rate is high, gears with the optimum selectivity are more likely to be beneficial in reducing the variability of yield.

Changes in L_{50} have little effect when SR is large, although it has to be remembered that the condition of constant F_{2+} means that an increase of L_{50} would be accompanied by greater effort to maintain the catch. When SR is small, however, L_{50} appears to have a larger effect which is not consistent inasmuch as the 20, 25 and 30 cm curves are not always in the same relative positions. The reason for this anomaly is not clear.

The effect of changing the mortality and growth parameters has been investigated. Figure 4 shows the results for M = 0.2 for all ages, other data remaining the same as for Figure 3. There is little difference between the two sets of curves when SR is less than 15 cm. But at large values of SR, the curves in Figure 4 are much flatter and the minimum position is less well defined. It seems therefore that the sharp minima in Figure 3 are associated with the high natural mortality of the youngest fish.

In Figure 5, the distribution of length-at-age has been narrowed so that the SD of length is about half the previous value. M is still 0.2 for all ages. There is little difference between the curves in Figures 4 and 5, suggesting that the results are not sensitive to the variance of the length distribution.

CONCLUSIONS

A model has been developed which shows how the variability of the yield depends on the selectivity of the fishing gear. This model has been applied to biological data from the North Sea haddock fishery. As well as the usual von Bertalanffy growth curve describing mean lengths, the model requires the variance of lengths-at-age. These data have been obtained from the quarterly surveys conducted by British Research Vessels in 1991. It is shown that a linear relationship between the SD of length and age is a satisfactory basis for the model.

The variability factors H_1 and H_2 have been examined as functions of the selection range of the fishing gear. The yield has minimum variability when SR is around 20-30 cm, the same order as the 50% retention length. Similar results were obtained for cases of low and high exploitation of the stock. However, an important conclusion is that the condition SR = 0, sometimes referred to as "knife-edge selection", is not optimum when the aim is to reduce the variability of yield. H_2 can change by a factor of three or more between SR = 0 and SR = 20 cm. The proportional change in H_1 is much less, so this effect is more important when it is year-on-year changes that are being considered.

The well-defined minima of the variability curves seem to be controlled by the natural mortality of the youngest fish which is particularly large in the case of haddock. When M is constrained to a constant 0.2, the minimum is poorly defined or non-existent. However, it remains the case that knife-edge selection is not the optimum, and considerable reduction of yield variability is achieved when SR is around 20 cm. The SR of gears currently used in the fishery is 10 cm or less, well below the optimum value.

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TABLE 1

Length-at-age data for haddock sampled during *Scotia* and *Cirolana* groundfish surveys in the North Sea during 1991. Integer ages refer to the survey in the first quarter, plus 0.25 for the second quarter and so on

Age (years)	Length (cm)		No of fish measured	Age (years)	Length (cm)		No of fish measured
	Mean	SD			Mean	SD	
0.50	11.4	1.7	5,427	3.25	35.8	4.1	169
0.75	14.2	2.2	7,491	3.50	36.6	4.2	34
1.00	18.0	2.4	7,177	3.75	38.5	5.5	63
1.25	21.4	2.2	9,791	4.00	36.4	2.7	16
1.50	25.3	2.3	2,615	4.25	39.9	5.8	39
1.75	27.3	2.7	4,333	4.50	39.4	6.5	5
2.00	27.3	2.5	1,494	4.75	41.1	6.3	20
2.25	30.0	3.2	988	5.00	38.3	4.6	93
2.50	32.6	3.3	238	5.25	39.4	6.2	120
2.75	33.7	3.8	425	5.50	38.0	5.8	27
3.00	33.4	3.3	271	5.75	44.6	7.4	45

TABLE 2

Annual natural mortality rates of haddock for each age and quarter. M = 0.2 is assumed for all ages greater than four years

Age (years)	M	Age (years)	M
0.5	4.77	2.50	0.36
0.75	3.42	2.75	0.29
1.00	2.47	3.00	0.25
1.25	1.92	3.25	0.25
1.5	1.37	3.50	0.25
1.75	0.82	3.75	0.25
2.00	0.51	4.00	0.20
2.25	0.44		

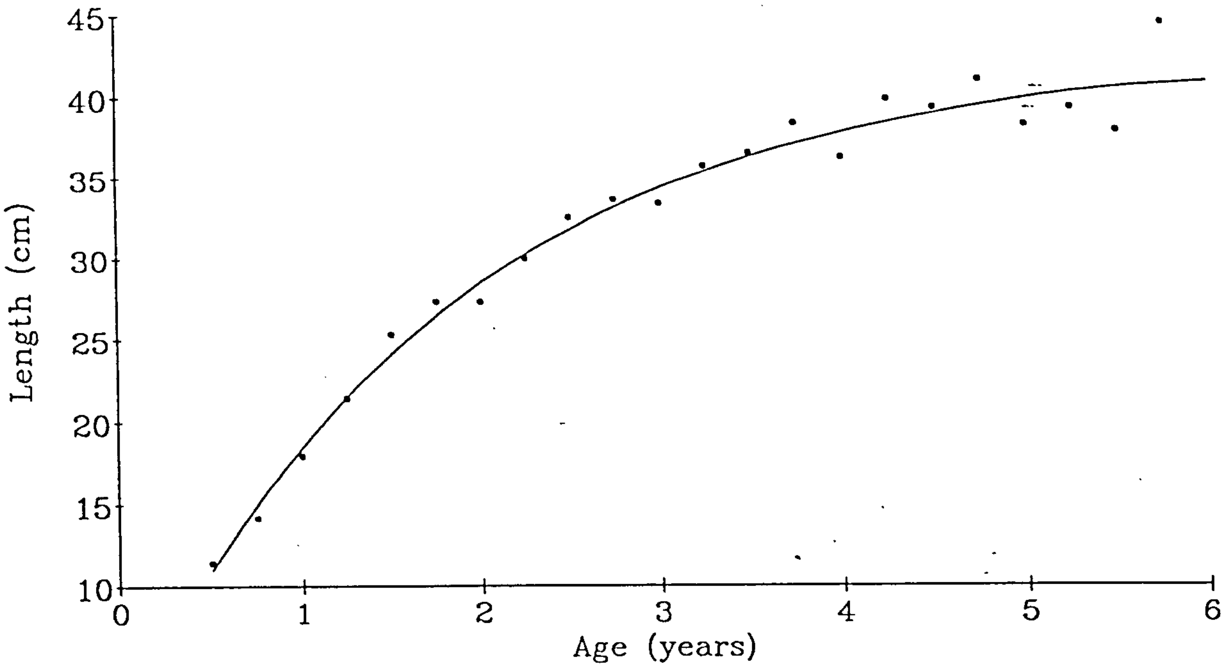

Figure 1 North Sea haddock, length vs age from quarterly groundfish surveys in 1991. The fitted curve is Length = 42.92 [1-exp (-0.529 [Age + 0.0589])].

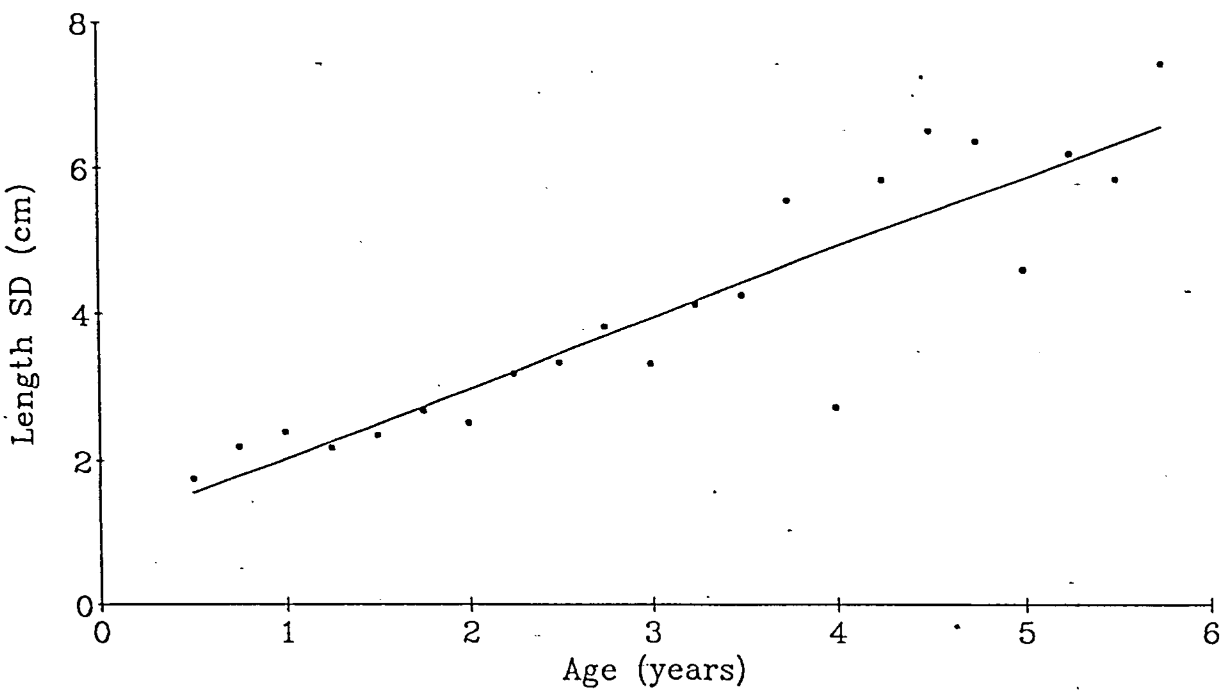

Figure 2 North Sea haddock, standard deviation of length vs age from quarterly groundfish surveys in 1991. The linear regression line is SD = (1.07 + 0.95 x Age).

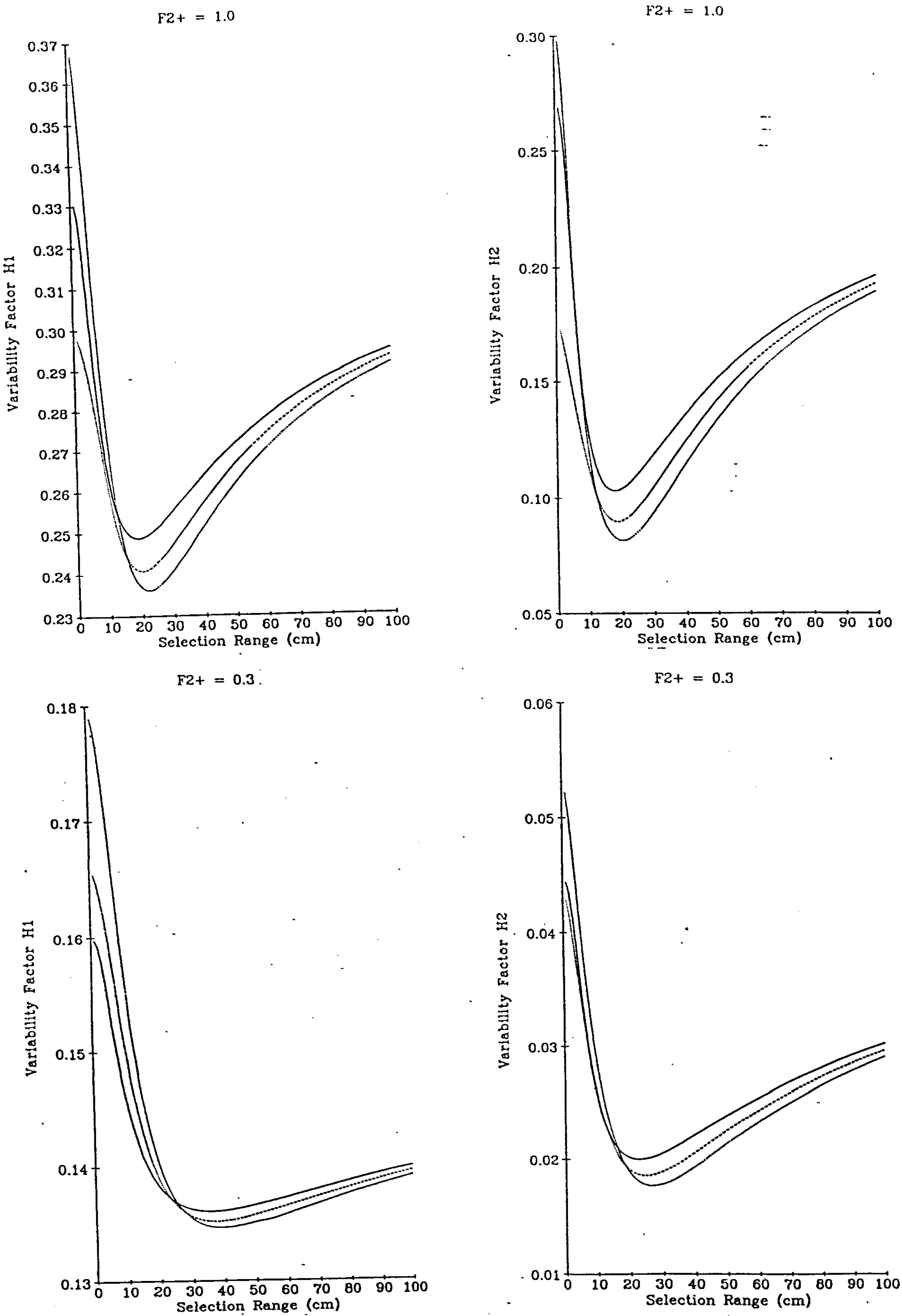

Figure 3 Variability factors H_1 and H_2 vs selection range for two fishing mortality rates on 2+ fish and three values of L_{50}; —— 20 cm; - - - - 25 cm; ..... 30 cm. Based on data for the North Sea haddock stock.

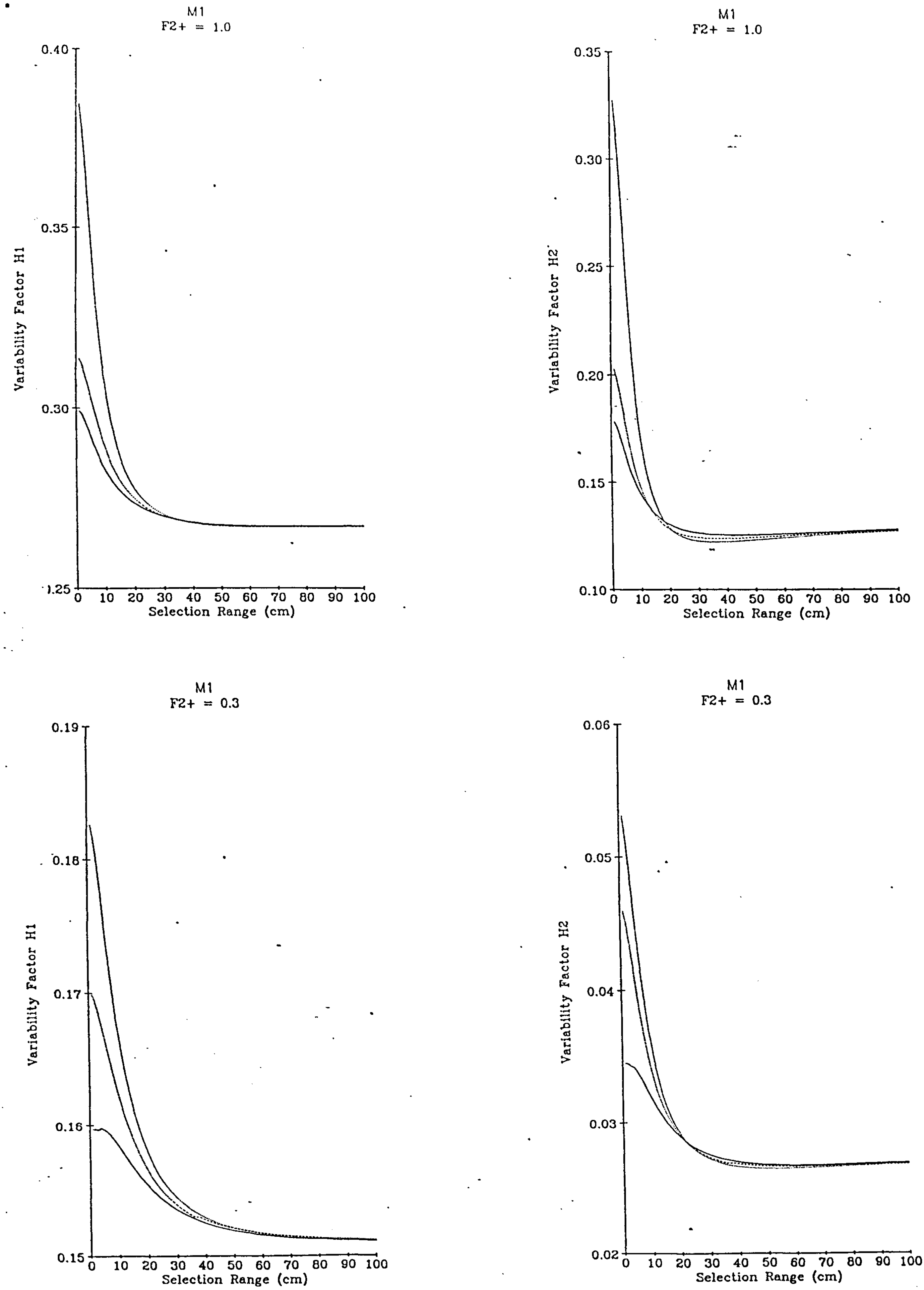

Figure 4 Variability factors H_1 and H_2 vs selection range for two fishing mortality rates on 2+ fish and three values of L_{50}; —— 20 cm; - - - - 25 cm; ..... 30 cm. M = 0.2, other data as in Figure 3.

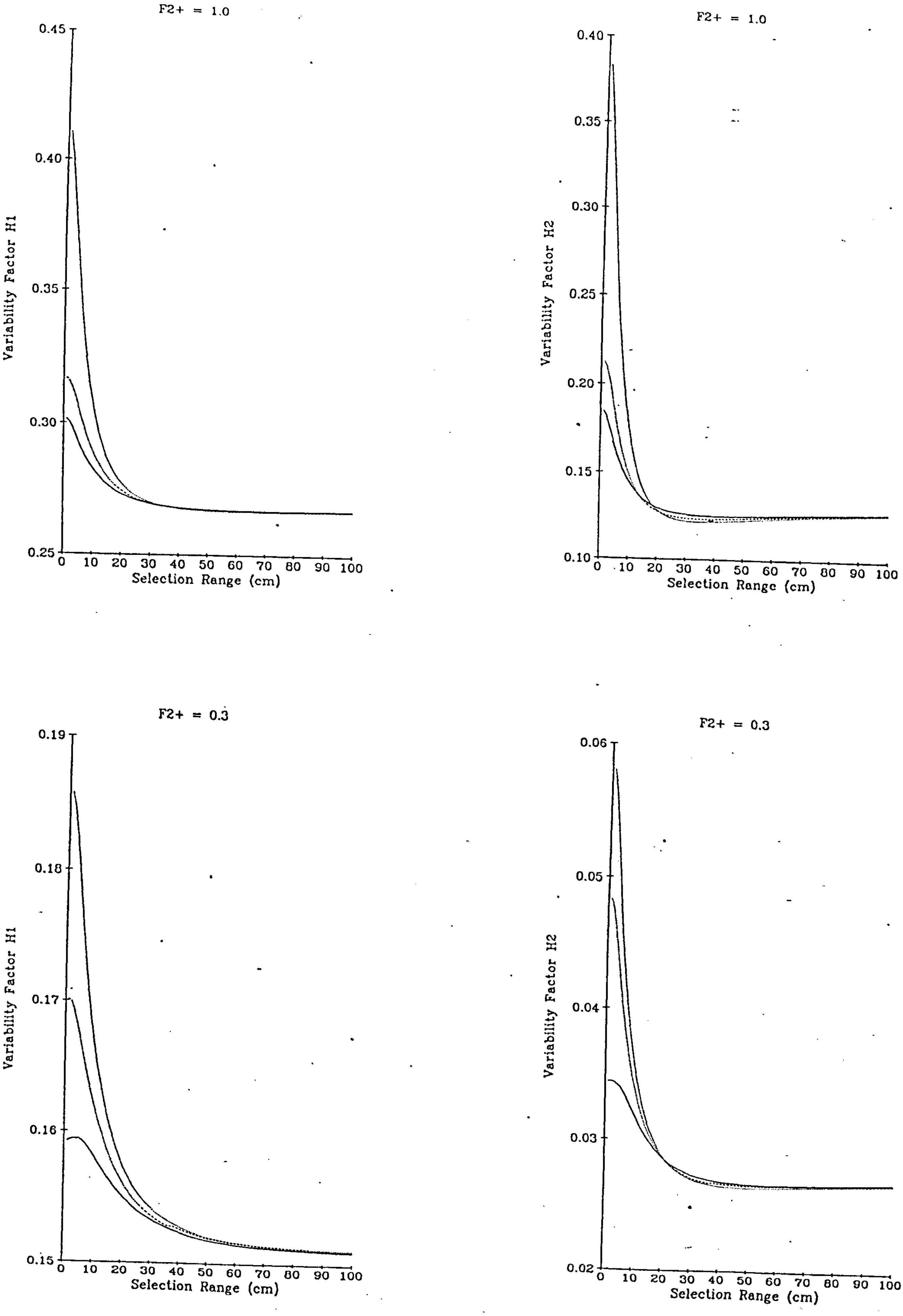

Figure 5 Variability factors H_1 and H_2 vs selection range for two fishing mortality rates on 2+ fish and three values of L_{50}; — 20 cm; - - - - 25 cm; ..... 30 cm. M = 0.2 and SD of length = (0.5 + 0.5 x Age), other data as in Figure 3.