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The Estimation of Fishing Mortality Rate for Bank Spawners, from Larval Abundance Data

by

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1. Introduction

Much of the current uncertainty about the factors governing the postwar decline in the North Sea herring fisheries, especially in the southern North Sea, is due to the lack of reliable estimates of the magnitude of the fishing and natural mortality rates for the exploited herring stocks. Attempts to estimate them for the southern North Sea "Downs" spawning group have been made by Cushing (1959) and Postuma (1961), using a variety of data and methods. Cushing's estimates give an average value for natural mortality rate (M) of rather less than 0.2, while Postuma's give a lower value, in the region of 0.1. For the period since 1951, when total mortality rates (F + M) have been high, these estimates point to a relatively high fishing mortality rate (F), greater than 0.5, and an F/F + M ratio in excess of 0.7.

Hitherto, no attempts have been made to arrive at precise estimates of these rates for the northern and central North Sea "Bank" stock, due mainly to difficulties in obtaining reliable measures of the fishing effort exerted on this stock from year to year, and in obtaining unbiassed estimates of abundance of its exploited age groups during the spawning period. However, from an analysis of the available Scottish data from the north-western North Sea, during postwar years, Parrish and Craig (1961) postulated a relatively low fishing mortality rate and high apparent natural mortality rate for this stock, in contrast to Cushing's conclusions for the Downs stock.

As a basis for estimating the fishing mortality rate directly, use has been made for a number of species of estimates of total spawning stock size, derived from egg production, fecundity and sex ratio data. An example of the use of this method, for southern North Sea plaice is given by Beverton and Holt (1956). While quantitative egg surveys of the Pacific herring, Clupea pallasii, have been widely used for estimating spawning stock size (Stevenson and Outram 1953, Taylor 1961), quantitative sampling of eggs of the Atlantic herring, Clupea harengus L. has been confined to studies of Atlanto-Scandian (Runnström 1941) and Clyde (Parrish et al. 1959) spring spawning stocks; no comprehensive data for North Sea autumn spawners are available. However, for a number of years, quantitative sampling of larvae has been undertaken over the main spawning areas in the North Sea, and although larval production data cannot provide accurate estimates of spawning stock size, due to mortality during incubation and after hatching, they can give underestimates of it. This paper deals with the estimation of spawning stock size, and fishing mortality rate for the "Bank" herring stock, using larval abundance data.

2. Method of Estimation

The annual catch, in numbers (C_n) from fish present in an exploited stock at the beginning of a year is given by the expression:-

$$C_n = \frac{F}{Z} R(1 - e^{-Z})$$

where F = instantaneous fishing mortality rate

Z = instantaneous total mortality rate

This can be rearranged in terms of F, as follows:-

$$F = \frac{C_n \cdot Z}{R(1 - e^{-Z})}$$

Thus, an estimate of F can be made from annual catch (in numbers) data, and estimates of the exploited stock size at the beginning of the year (R), or alternatively at the end of the year (Re^{-Z}), and the instantaneous total mortality rate (Z).

3. Estimation of Stock Size.

In 1951 Scottish workers began a regular programme to investigate the distribution and abundance of autumn spawned herring larvae in the north-western North Sea. It was initially intended to cover the area from 56°N to 59°45'N and from the Scottish coast to the prime meridian, as this embraces all of the major spawning areas within Scottish waters (Wood 1930, Clark 1933). Normally four or more cruises were carried out to sample this area within the period mid August to mid December. Until 1957 all sampling was by timed, oblique hauls from bottom to surface with a 1 metre net of bolting silk, with 60 threads per inch. In 1957 the Gulf III sampler (Bridger 1958) - now widely accepted as the standard sampling instrument for herring larvae by European workers - was introduced. In that year, so as to give a basis for comparison with earlier material, at each station on all cruises a sample was taken with both the Gulf III and 1 metre oblique net. A full account of the material collected during this investigation will be published elsewhere.

For the present purpose, only material relevant to the problem of assessing the annual production of herring larvae within the area is of interest. Unfortunately, owing to the size of the area to be covered, and the limited resources available to do this, in some years the available data are inadequate to provide a satisfactory assessment of production because a major area of larval production was not sampled at the critical time. Of the years during which this sampling was carried out, and for which larval data, are so far available, only 1951, 1953, 1954 and 1958 are considered to have been well enough sampled to give an adequate assessment of larval production.

Larvae taken on these surveys were grouped into three size intervals: less than 10 mm, 10-15 mm, and over 15 mm. Only the first two of these groupings will be considered here as being relevant to the measurement of larval production. For Gulf III hauls the numbers of a size group in a sample were converted to the numbers below a square metre of surface from a knowledge of the volume of water filtered and the depth of the water column through which the net fished. For the earlier material taken with a 1 metre silk net the sample numbers were also converted to this basis using the conversion factors from 1 metre net to Gulf III calculated from the large numbers of paired hauls made with the two gears in 1957.

Subsequent calculation of the numbers of larvae in the sampled area on each cruise were made by contouring at levels of 1, 5, 10, 50 and 250 larvae/sq metre, measuring the area within each contour in square metres, raising these areas by the contour level and summing the values so obtained. To arrive at an estimate of larval production over the season these cruise values were plotted against the mid-point of the cruise date on a time scale and the area within the resulting curve measured to give an estimate of seasonal abundance. This would also be a measure of larval production if one could assume that all larvae within any of the size groupings represented one day's production, and if the cruise total was representative of the mean production for the inter-cruise period. The size at hatching of herring larvae is not accurately known. Bowers (1952) for Manx autumn spawners gives a range of 6-9 mm and Blaxter (1956) for Buchan autumn spawners gives a mean size at hatching of about 6.5 mm. The subsequent rate of growth is even less well known although at least up to absorption of the yolk-sac it is probably fairly rapid. On this basis, by taking larvae of less than 10 mm as representative of the cruise production one covers the size range at hatching, and is unlikely to include many larvae which are more than a few days old. Unfortunately, it is quite clear from the frequency distribution of millimetre size groups that the youngest stages are not sampled in terms of their true abundance. The reasons for this are not clear; in their earliest stages the larvae may be concentrated too close to the bottom to be sampled efficiently. More probably, the distribution of larvae of this size range in dense aggregations of limited spatial extent, results in their seldom being sampled by station grids with stations spaced 15 miles apart. It is, however, clear that by taking numbers of herring larvae less than 9.5 mm the production of larvae is seriously underestimated.

For this reason the numbers in the size category 10-15 mm are also given. Taking all larvae up to 15 mm as indicative of larval production raises the possibility of resampling the same batch of larvae, and so overestimating production. It is unlikely, however, that this source of estimation outweighs the other factors which cause underestimation discussed below.

There are several sources of error in utilising any figure of larval abundance as an index of spawning stock size, most of which are likely to result in underestimation of the desired parameter. Perhaps the most serious of these is the mortality occurring between recently spawned eggs and any subsequent larval stage.

No estimates are available of the magnitude of the mortality over the egg phase but losses are likely from the following several sources:-

(a) eggs unfertilised or unviable

(b) predation on eggs,

(c) eggs not developing due to being too heavily over-laid by subsequent spawning etc.

A figure of 50% loss during the egg stage is probably not unreasonable.

Repeated sampling at daily intervals over a known spawning ground during the period of hatching both in the North Sea and in the Clyde have shown that the hatching rate rises to its peak value very quickly, is maintained at this value for only a few days and falls off again equally quickly. Thus the estimated hatching rate at its peak may be as much as ten times that estimated on the previous day. Moreover, this peak production of larvae appears to take place over only very limited areas about 4-9 square miles in extent with quite low levels of larval abundance outside them. As a result such peaks of abundance are very liable to be missed by cruises 2-3 weeks apart in time and by stations spaced at 10-15 mile intervals. Under these conditions the chances are that in most years the magnitude of the cruise and station spacings will result in a serious underestimation of the abundance of small larvae. It is true that these larvae will be subsequently sampled on succeeding cruises when they have diffused out to give a more widespread and even distribution. By this time they will be considerably older and have undergone a heavy larval mortality.

For these reasons it is believed that to take the abundance of larvae less than 10 mm as the basic material for calculation the spawning stock size would result in a gross underestimate of it; taking larvae up to 15 mm in length may give some degree of overestimation due to resampling but it is thought that this is more than compensated by the other factors leading to underestimation discussed above and that on balance some underestimation will still be present. Both sets of values of estimated larval abundance are given in Table 1 from which two values of spawning stock size are subsequently derived.

Table 1

Estimated production of herring larvae in the N.W. North Sea 1951-58.

Year	<10 mm	10-15 mm	$\leqslant 15$ mm
1951	76×10^{12}	330×10^{12}	406×10^{12}
1953	152×10^{12}	430×10^{12}	582×10^{12}
1954	60×10^{12}	65×10^{12}	125×10^{12}
1958	104×10^{12}	180×10^{12}	284×10^{12}

The values given in Table 1 refer only to the abundance of larvae in the north-western North Sea, that is, on the Shetland and Buchan spawning grounds. Other areas of considerable importance as spawning grounds for "Bank" herring are known on the Dogger Bank and off the English east coast (Whitby). Spawning also takes place, in some years at least, in the eastern North Sea (Jutland Bank). No detailed information is available regarding the size of the larval production in these areas in the years under consideration, but from Dutch data (unpub. see Report of N.Sea Herring Working Group) it would appear that the production of larvae on the Dogger is of about the same order of size as in the north-western North Sea. Therefore, for the present purpose and in the absence of better information, the production of larvae in these areas combined has been assumed to be the same as in the north-western North Sea. Total production has therefore been taken to be twice the values given in Table 1.

The other information required to derive an estimate of spawning stock size from an assessment of larval production is the fecundity of the stock and the ratio of the sexes in the spawning population. Baxter (1959) gives the relationship between length and fecundity of northern North Sea spawners as being $F = 0.198L^{3.8417}$. From this equation, knowing the size distribution of the spawning population an accurate mean fecundity for it could be calculated. However, in view of the other sources of error in the data it seems adequate to take a mean size of the spawning females as

27 cm and assess the fecundity of the whole population on this basis. This gives the mean fecundity of a "Bank" spawner as 60,000 eggs. This, applied to the whole of the "Bank" stock, will tend to overestimate fecundity, and thus underestimate stock size, owing to the rather smaller mean size and lower fecundity per unit length of Dogger spawners. The sex rate has been taken as equal for the two sexes.

On the basis of these figures the stock sizes of all "Bank" spawners in the four years considered are given in Table 2. Two estimates are given for each year, one based on the abundance of larvae less than 10 mm and one on larvae less than 15 mm.

Table 2.

Estimates of spawning stock size of "Bank" spawners 1951-58

Year	From larvae <10 mm	From larvae ≤ 15 mm
1951	50.7×10^8	270.7×10^8
1953	101.4×10^8	388.0×10^8
1954	40.0×10^8	83.3×10^8
1958	69.3×10^8	189.3×10^8

It is our belief that for the reasons discussed above the smaller of these estimates (based on larvae below 10 mm) is a gross underestimate and that the larger may still to some degree be below the true abundance of "Bank" spawners. Therefore, for the present purpose, the higher of the two sets of values have been taken, as the best available estimates of spawning stock size.

4. Estimates of Adult "Bank" Herring Catches.

In the years in question, the greater part of the fishery on "Bank" spawners took place before and during the spawning season, in the period January-October. The fisheries for spent herring in the late autumn and winter contributed only a small fraction of the total. In estimating the fishing mortality rate, therefore, the catches for the years in which the spawning stock sizes have been estimated are taken, and the spawning stock sizes refer to the end of the year (i.e. Re^{-Z}). The part of the total catch taken after the spawning season in the year in question is assumed to be the same as in the preceding year.[1] The further advantage of using the estimate of stock size for the end rather than the beginning of the year of exploitation is that it avoids the necessity to estimate recruitment during the succeeding year.

The catches (in tons) of the North Sea and English Channel herring fisheries as a whole, excluding those taken in the Norwegian fishery and in the industrial fisheries for small, immature herring, for the years in which stock estimates have been made, were as follows:-[2]

1951 = 704, 641
1953 = 770, 058
1954 = 647, 097
1958 = 567, 152

In the absence of accurate information as to the relative contributions to this total catch of "Bank" and "Downs" autumn spawners and of other spawning groups (e.g. Downs, Atlanto-Scandian, coastal spring spawners, etc.), due principally to uncertainty about the mixing rates of "Bank" and "Downs" herring in the northern North Sea pre-spawning fisheries, estimates of "Bank" herring catch have been made as follows:-

1) Strictly speaking, the relevant catch data are from the post spawning months in one year to the end of the spawning season in the next.

2) These data are taken from Bull.Stat. and represent landings from the North Sea and English Channel, minus the Norwegian and Danish catches. It is assumed that the Norwegian catches are composed of Atlanto-Scandian herring, and the Danish of immature, industrial fish.

(a) All herring caught in the Southern Bight and English Channel have been taken to be non "Bank" spawners.

(b) 25% of the catch from the remainder of the North Sea (i.e.Dogger, Gut, English N.E. coast, Fladen, north-western North Sea, north-eastern North Sea) are taken to be members of spawning groups other than the "Bank" group[1] (e.g. Downs, and Atlanto-Scandian and other spring spawners) or immature members of the "Bank" group, not contributing to the adult stock in the year in question.

The resulting estimates of adult "Bank" herring catches in weight and numbers,[2] in the years in question are given in Table 3.

Table 3.

Estimates of catches of adult "Bank" herring

Year	A Total North Sea minus Norway-Denmark (tons)	B Southern Bight[3] and Channel + 25% of remainder	C Estimated "Bank" catch (tons) (A-B)	D Estimated "Bank" catch (numbers)
1951	704,641	351,135	353,506	247.5×10^7
1953	770,058	393,377	376,681	263.7×10^7
1954	647,097	321,512	325,585	227.9×10^7
1958	567,152	234,566	332,568	232.8×10^7

It is considered that these values tend to overestimate the numbers of adult "Bank" fish caught, for the following reasons:-

(a) 25% is probably an underestimate of the non "Bank" fish caught in the central and northern North Sea fisheries, especially in the earlier years. For example, Scottish data for the north-western North Sea (Ann. Biol. Vols.VIII, X, XI, and XV) show that spring spawners and immatures together constitute up to 20% of the catches in some years. Scottish and German data for the Fladen and north-eastern North Sea also point to similar values. Also, the total statistics includes catches of the Scottish immature "halflin" fishery, and of immature herring in the Dogger area. (See, for example, German data in Ann. Biol. Vol. XV (1958))

(b) the value of 7,000 herring per ton is probably an overestimate of the average count for adult "Bank" herring. (cf. Scottish data in Stat. News Letter No. 7),which gives a mean count/cran of 1061, which is equivalent to a count/ton of approximately 6,000. The average size of herring taken in the trawl fisheries in the north-eastern North Sea and at Fladen is greater than in the Scottish fisheries; however, the average size of herring in the Dogger catches tends to be lower than of those to the north.

5. Estimates of Fishing Mortality Rate.

In addition to the estimates of catch and spawning stock size, values are also required of the total mortality rate Z, for each of the years. The appropriate estimates for the "Bank" spawning stock as a whole, are not accurately known, but, for the present purpose, estimates obtained from Scottish data for the north-western North Sea prespawning fishery (Parrish and Craig: in press) have been taken.

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1) The problem of estimating the proportions of "Downs" and "Bank" spawners in the northern North Sea prespawning stock is currently under consideration by the North Sea Working Group (see "Progress" and"Second" reports of this Group).

2) An estimate of 7,000 fish per ton has been used throughout. This is based on counts/cran taken in the Scottish fisheries in the north-western North Sea (see, for example, Stat. News Letter No.7 for 1958).

3) Data for Southern Bight and Channel taken from "Past Time Statistics" Stat. News Letters Nos. 11A and 11B, and national Statistical journals.

Owing to the wide year to year variations in these estimates, during the period 1950-1958, a value of Z = 0.6, has been used for all years.[1)]

The estimates of F, using the stock abundance estimates, based on $\leqslant$15 mm larvae in Table 2, the catches in Table 3 and a value of Z = 0.6, are as follows:-

1951 - 0.06
1953 - 0.05
1954 - 0.20
1958 - 0.09

Unfortunately, it is not possible, with the data available and our current knowledge of the biology and population dynamics of the North Sea herring stocks, and especially of the early spawning products, to gauge the accuracy of these estimates, but, as mentioned above, the data used are likely to overestimate rather than underestimate the parameter; therefore, it seems that, in all the years considered, the average F was small, with an upper limit of 0.1-0.2. Even if only the larval production data for the north-western North Sea were used to estimate spawning stock size, the F values would not exceed 0.2, in any of the years except 1954.

Further, since the total catch of herring was at a peak during the period 1952-1958, it is unlikely that the rates exceeded this level in any of the years after 1950.

Although the estimated total mortality rates for the "Bank" stock are not accurately known, the values obtained from Scottish data suggest that in the postwar period they averaged about 0.5-0.6. This suggests that the value of the natural mortality rate (M) during this period was about 0.3-0.4, and the rate of exploitation ($\frac{F}{Z}$), about 0.2-0.4.

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1) The estimates of F are not influenced critically by the values of Z used, since it appears in both the numerator and denominator of the equation. For example, the estimates for 1953, for values of Z = 0.2, 0.6 and 1.0 are 0.07, 0.05, and 0.04 respectively.

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