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MODERN THEORY OF EXPLOITING A FISHERY, AND APPLICATION TO NORTH SEA TRAWLING

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Modern Theory of Exploiting a Fishery, and Application to North Sea Trawling.

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THERE have recently been three important papers on the theory of most effective fishing. Russell's of 1931[1]) laid the theoretical foundation. Hjort, Jahn and Ottestad[2]), in 1933, detected the significance of the point of inflexion in a sigmoid population curve. To Thompson and Bell, 1934[3]), belongs the credit for emphasizing the importance of the rate of fishing, from which follows the peculiar attraction of the modern theory, that the benefit of efficient exploitation lies more in *economy of effort* than in increase of yield, or preservation of future stocks, though both of these purposes may also be served. Thus Thompson and Bell's argument has been put into practice, and has in fact led to a progressive economy of effort during three years, in which the yield of the Pacific halibut has been artificially stabilized at a somewhat low level, which it had reached during the depression of 1931[4]). Their theory, however, is incomplete. The present work has had a double aim, that of correcting and continuing the theory, and of applying it to the North Sea fisheries.

There are three ways of approaching the problem. They all use data, different data in each case, and they all lead to the same conclusion, that an economy of effort is desirable in the North Sea, that is, *that a certain proportion of the time and money of the fishermen is at present devoted to reducing their catch, or is at least wasted.* It also follows that in unrestricted fishing, proceeding as it usually does at ever increasing intensity, as grounds and habits become better and better known and gear more and more improved, there must come a time when new inventions are harmful. Nevertheless, once the new

[1]) Journ. Cons. Int. Expl. de la Mer. VI. Copenhagen.
[2]) Hvalrådets Skr. 7. Oslo.
[3]) Rep. Int. Fish. Comm. 8. Seattle.
[4]) *Loc. cit.* p. 12.

invention has done its harm in reducing the productivity of the stock, its use must be continued, because the old gear will not pay expenses on the less productive stock. So the fishermen are left with the expense of the invention, with no compensating increase in yield.

It is tempting to suggest practical ways of making the improvement in exploitation, because the peculiar virtue of the modern theory is that the measures needed involve Economy and Leisure, both of which are intrinsically good, whereas measures we have thought of before were devoid of any attraction in themselves. However, it would be altogether premature to discuss practical measures, whilst the theory and evidence of its applicability have not stood the test of criticism.

If the theory is sound there are many practical implications, but they are not the concern of this paper.

The essentials of the theory are two. **A.** If the rate of mortality be reduced, as by reducing the rate of fishing (hence increasing economy and leisure), the average age of the population will be raised, and *vice versa.* **B.** There is a most profitable age to harvest any growing crop. For example, the hay crop, of species maturing in different weeks, must yet be cut at a certain age which takes advantage of as much growth as possible and avoids as much "mortality" by seeding as possible. The pasture should carry only a certain number of sheep, neither too many nor too few for the best yield; that is, there is an optimum rate of cropping. A growing steer must theoretically be sold at a certain most profitable age, depending on rate of growth and rate of food consumption.[1] It should be noted that none of these cases takes account of the necessity of leaving sufficient adults for reproduction, with which indeed this paper does not deal, except inclusively under (3) below. But we note that anything we do for better exploitation in the North Sea should be helpful also as regards reproduction.

It follows from these two considerations, A and B, that all we have to do, to be satisfied that economy and leisure are available, is to demonstrate that the present age of our stock is below the most profitable age. Actually it seems that, near its maximum, the yield of the North Sea is comparatively stable for quite considerable changes in rate; it is expressed by a rather flattish topped curve, and it is therefore most practical to say that it will pay to reduce fishing so long as the yield is not thereby reduced. Also, the maximum yield is not exactly the most profitable. Some further economy can still be made by reducing fishing, depending on the ratio of overhead costs (requiring a certain turnover) to running costs per ton of fish.

We shall now apply the theory enunciated in A and B, above, to the North Sea Fisheries, in three independent ways.

Our three solutions use varying amounts of the theory, and each has its share of approximations and assumptions. No. 2 seems the best founded.

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[1]) James Wilson. The Principles of Stockfeeding. London 1927.

1. Evidence of General Statistics.

In this section we take it as an accepted fact that the stock in 1928—1932 consisted of smaller fish than in 1909—1913. There are statistics which support this, but they are open to some objection and I prefer to take this fact to be generally admitted. Now, we find that the total yield in 1909—1913 was fully as great as in 1928—1932. But, if the fish were larger, then it is legitimate to think that they were older; so an older stock gave, for five years within which we know of no great change in fishing rate, as great a yield as did a younger stock for another five years, within which we also know of no great change in fishing intensity. We use the landings of all North Sea species, except herring, by all fishermen, in metric tons (000 omitted)[1]:

1909—1913:	419,	416,	440,	463,	433.	Mean: 434
1928—1932:	413,	431,	458,	428,	411.	Mean: 428

Actually the *catches* in the earlier period were certainly higher than in the later, because fish were then rejected at sea which are now landed. The evidence of these figures simply is that the catch *was* no less before the introduction of the Vigneron-Dahl trawl and other changes of which the nett result has been to lower the age of the stocks.

So far as it goes, the evidence of general statistics is, therefore, that the yield would not be less if the stock were stabilized at a lower fishing rate.

2. From Growth and Age-Census Data.

a. Argument.

According to Russell's equation a stock will be in equilibrium with fishing when the "logarithmic" rates (r in compound interest equations, such as $w_2 = w_1 . e^{rt}$) tending to increase it are equal to those tending to decrease it, or

$C = A + G - M$ where C is capture,
A is recruitment,
G is growth,
M is natural mortality;

say

$C = V$, calling V the "rate of natural increase." .... (1)

Consider a stock N_1W_1, where N stands for number and W for average weight, becoming N_2W_2 at a year older.

Then

$$N_2W_2 = e^{V} N_1W_1 \qquad \text{..........} \quad (2)$$

Now, in equilibrium, the yield is Y in

$$Y = NWC$$
$$= NWV$$

[1]) Bulls. Stats. Cons. Int. Copenhagen.

So

$$\frac{Y_2}{Y_1} = \frac{N_2W_2C_2}{N_1W_1C_1} = \frac{e^{V}N_1W_1V_2}{N_1W_1V_1} = \frac{e^{V}V_2}{V_1} \qquad \ldots\ldots\ldots\ldots (3)$$

So

$Y_2 - Y_1$ will be positive

so long as

$e^{V}V_2 - V_1$ is positive

or, *a fortiori,* since V_1, V and V_2 must be in descending order of magnitude, as

$e^{V_2}V_2 - V_1$ is positive,

which, expanding e^{V_2}, discarding minor necessarily positive terms, substituting the constituents of V, and putting in numerical values for A and G from the data (which will be described later) reduces, for the North Sea cod, to the statement that

$Y_2 - Y_1$ will be positive, so long as

0.456 at least equals $(M_2 - M_1) + 1.516\ M_2 - M_2^2$ .... (4)

in which $(M_2 - M_1)$ and M_2 are considered to be unknown.

If we put in trial values for these unknowns we find graphically that either the change in natural mortality rate or the new natural mortality rate has to be quite ridiculous, from the information we have, for the right half of equation (4) to be equal to 0.456. We therefore conclude that there is no doubt that the new yield will at least equal the old, and that there is plenty of margin for error in the approximations we have used as to A and G. The values obtained are as follows.

If $M_2 - M_1$ were (%)	M_2 would have to exceed (%)
40	3
30	11
20	19
10	29
0	41

Now, from our census data, we know that we are only proposing to raise the average age from $2^1/_2$ to $3^1/_2$, in a fish which is first mature at about 5 years of age, and it is really very unlikely that in these young fish the natural mortality rate would thereby be raised. In fact we would expect it to fall. Yet if we make the change only zero, we find that the new mortality rate has to be as high as 41 per cent., which is quite impossible from what information we have, and even from consideration of the natural span of life, which is about 8 years even under fishing, and likely to be about 20 without fishing. But if we make M_2 something reasonable, as 11 per cent. or less, we would have to believe that the change was positive by the absurd amount of 30 per cent. or more. We see from inspection that continuation of the series of the trial values in either direction can only result in more ridiculous values, either of one unknown or the other.

Similar results are obtained from the data on North Sea haddock and plaice. The three species, cod, haddock, and plaice, together make up more than 60 per cent. of the North Sea trawl catch, whether by weight or value[1]). There is no reason to believe that the other species would show compensating changes, sufficient to prevent the conclusion applying to the total. It is therefore concluded that the yield would be no less, were the fishing effort reduced so as to allow the fish to become one year older.

b. Data and Approximations.

The data have all been published elsewhere. For the cod I have used those of this laboratory[1a]), the haddock data are from the work of Harold Thompson of the Scottish investigations[2]). For the plaice we use Bückmann's data[3]). The general method was to calculate "logarithmic" rates of growth at various ages by applying the compound interest law to the data given. Where interpolation was necessary this was done graphically. It is hoped that the footnotes will enable the computations to be repeated. Table 1 is the calculation sheet for the cod, using the census of September[4]). Another, using the annual census, gives similar results. Little letters are used for rates, etc. at a given age.

Table 1.

	Age 1½	2½	3½	4½	5½	6½	7½	Total
g	1.89	1.01	0.60	0.44	0.39	0.29		
w[5])	250	950	2000	3350	5010	7180		
wg	472	960	1200	1474	1954	2082		
n_1[6])	47	32	8	9	3	1	1	$101 = N_1$
$n_1wg/100$	222	307	96	133	59	21		$838 = N_1W_1G_1$
$n_1w/100$	118	304	160	302	150	72		$1106 = N_1W_1$
								$\therefore G_1 = 0.758$
								$A_1 = 118/1106 = 0.107$
m	0.20	0.13	0.08	0.05	0.05	0.05		
n_2[7])	47[8])	40	29	8	9	3		$136 = N_2$
$n_2wg/100$	222	384	348	118	176	62		$1310 = N_2W_2G_2$
$n_2w/100$	118	380	580	268	451	215		$2012 = N_2W_2$
								$\therefore G_2 = 0.651$

1) Bull. Stat. 1932 (1934) p. 18 Mean 1912—1932.
1a) Graham, Sea Fish. Invest. XIII. 4. London 1934.
2) Rapp. Cons. Int. LIV. Copenhagen 1929.
3) Rapp. Cons. Int. LXXX. Copenhagen 1932.
4) Graham 1934, p. 139.
5) By interpolation. Weights at whole years from Graham, 1934, p. 137, March, and Russell, Sea Fish. Invest. V. 1. 1922. p. 75. Also, for age 1, length from Graham 1934, pp. 42 and 67, and weight from Russell, 1922, by integrating length cubed with respect to length from average length at 0 to average length at 1 year old and so on, and multiplying by a condition factor. A simpler method would have served for the present purpose.

Lines g, w and n_1 are from the data. The calculation as far as G_1 is simple multiplication, addition and division. The line m requires explanation. Strictly speaking we only know the order of magnitude of the natural mortality rate, not any values as accurate as those given. We do, however, only use these values for weights in the calculation of G_2, and we rely on the experience that errors in weights are of minor importance in calculating an average. As to our knowledge of the order of magnitude, we have the total mortality rate for haddock from Thompson's census of age[1]), and we have the fishing mortality rate for plaice from large-scale marking experiments. Thus Borley reported that something like 30 per cent. per annum of marketable plaice were returned in the years before the war[2]). If we subtract fishing mortality rate from total mortality rate we are left with natural mortality rate. With these data in mind, I have simply written in some probable values for cod. The remainder of the calculation can be followed from the notes, but there are two more approximations that should be pointed out. Firstly it has been assumed that the same number of recruits would be found in the line n_2. Secondly, it has been taken as a first approximation that g and w would be unchanged in the older stock. It will be remembered that the defence of these approximations is that there is ample room in the final conclusion for error that they may have introduced[3]).

The conclusion of this digest of the results of fishery research is also that a lower fishing rate would give as great a yield, when the stock became stabilized at that rate.

3. From Consideration of the Effect of the War on Landings.

(i) The principal assumption of this section is that V, the "logarithmic" rate of natural increase of the stock at a given moment, including rate of reproduction, is directly proportional to the difference between the weight of the stock at that moment and the maximum weight the area will support. We can be pretty sure that V is some positive function of that difference in weight, but the assumption of direct proportion may, of course, be too simple. It is, however, a reasonable first approximation.

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[6]) Graham 1934, p. 139.

[7]) $n_2 = n_1 . e^{-r}$, where r is the assumed rate of natural mortality at a given age in whole years.

[8]) Assuming new entry unchanged.

[1]) *loc. cit.* p. 157.

[2]) Sea Fish. Invest. III. 3. London 1916. p. 66.

[3]) Some further notes will be necessary for repeating the calculations for cod (annual census), for haddock and for plaice. In the cod calculation it was necessary arbitrarily to repeat n_2 at 2½, owing to disturbance by net selection. It can be shown for all three species, that disregard of net selection has probably caused an underestimate. For haddock I used Thompson, 1929, p. 146, and Russell, Sea Fish. Invest. I, 1914, Pt. I, p. 130 and integrated. For plaice I used Bückmann's figures, p. 13. Stock A.

(ii) From the *Bulletins Statistiques* we can express the landings of all bottom species (that is excluding herring) as percentages of the average of 1909—1913. We obtain

1919	1920	1921	1922	1923	1924	1925
105	128	115	117	88	89	100

That is, the drain of 1920—1922, namely 28, 15 and 17 per cent. above the pre-war average could not be sustained, although the stock was augmented by the war respite.

(iii) We have unpublished figures for the landing in each month by 1st class British steam trawlers landing their own catch in England. We also have the corresponding number of days absence. The earliest period in 1919 in which the number of days absence approached the pre-war figure was at the end of the year, from October to December. The data are

	Days absence (00 omitted)		Landing (cwts; 000 omitted)	
	1913	1919	1913	1919
Oct.	137	106	177	348
Nov.	119	100	162	266
Dec.	131	113	172	262
Total	387	319	511	876

These figures are not accurate indices of the relative weights of the stock, but they can be used as a rough guide. Thus 876/511 is 1.71. Alternatively, (876/319): (511/387) is 2.08. We conclude that the stock at the end of 1919 was rather less than double the weight of the pre-war stock.

(iv) From (iii) we make the assumption that the upper limit of stock is not less than twice the pre-war weight.

(v) We have all in our minds the idea that the stocks had considerable respite during the war. I try to estimate this by saying that it was equivalent to so much time of complete cessation of fishing. The working has to be crude. Foreign fishing was not so much curtailed as English fishing. Also English fishing was more curtailed than the number of days absence indicates. The statistics are:

	1913	1914	1915	1916	1917	1918	1919
Eng. days absence (000 omitted) ..	147	124	76	41	37	56	92

Because of information collected soon after the end of the war as to war-time interference with even the reduced fishing, I think a more comparable series would be as follows.

Corrected Eng. days absence	147	120	60	30	30	50	85

(This correction is not necessary to the conclusion).

If we multiply each of these figures by the corresponding ratio of the total landing to the English landing, we obtain another series, which seems the best we can achieve, as an index of intensity of fishing.

	1913	1914	1915	1916	1917	1918	1919
Relative intensity	346	335	191	157	109	141	230

Finally, I call the respite of 1914 $\frac{346-335}{346}$ of a year, and so on. Adding up the series of such fractions we obtain about two and two-thirds years. This gives some numerical idea of how much respite the fish had, but obviously one wishes it were better.

(vi) Knowing that many marks are shed or not sent in, we use the information from Borley[1]) to assume that the pre-war rate of natural increase (equals fishing rate in a stable stock) was more than 30 but distinctly less than 50 per cent. per annum in 1913 and is 50 per cent. now.

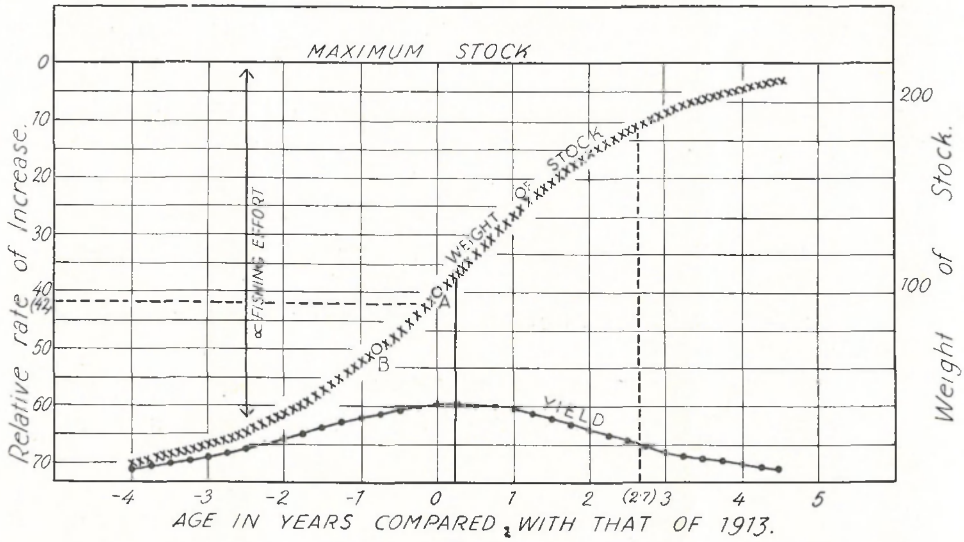

Fig. 1.

(vii) Under (1) we have seen that the landing of recent years is hardly less than in 1909—1913, the difference in catches being only what we can allow for rejected fish in pre-war days. So we assume that the pre-war catch was not more than 20 per cent. greater than the present catch.

Thus Fig. 1 was drawn. Starting at A with stock of weight 100 we chose a rate of 40 per cent. per annum and a maximum stock of 220. One tenth of the chosen rate was applied at simple interest to give the stock one tenth of a year later. The rate was then changed in proportion to the new vertical distance from the maximum and the

[1]) *loc. cit.*

next point was found. So proceeding upwards and downwards the whole curve of weight of stock was drawn. It clearly resembles the sigmoid curves of Hjort, Jahn and Ottestad and of earlier writers. Judging by the difficulty encountered in drawing the trial attempts at Fig. 1, very little latitude has been introduced by the graphical method. This is the only curve encountered that would fulfil the numbered requirements already given.

Fig. 1 gives a complete representation of the theory, although, as we have been at some pains to show in our arrangement of this paper, the basis for action does not rest alone on the fundamental assumption as to rate of increase. The main curve AB in the figure traces the natural growth of a stock, starting from a low value and not subject to fishing. At any point the stock may be stabilized by a fishing effort which is proportional to the vertical distance between the point on the curve and the maximum. The yield under the condition of stability is given by the lower curve, of which the ordinates are differential coefficients of the stock function, that is, they measure the slope of the main curve.

Taking the stock at A as the pre-war stock and that at B as the present stock and numbering the conclusions of the curve according to the requirements, we have:

(ii) that the maximum stable catch is only a little above that of the stock at A, so that the drain of 1920—1933 could not be maintained.

(iii) and (v) that the stock increased to 1.9 times its pre-war weight in 2.7 years.

(iv) that the maximum stock is 2.2 times the pre-war, or about 3 times the present stock.

(vi) that the pre-war rate was 40 per cent. per annum.

(vii) that the pre-war stock could maintain a catch 14 per cent. greater than could the present stock.

These fulfil the requirements.

If we accept these calculations as a rough approximation, we find that the maximum stable yield is 15 per cent. greater than the present yield and that this yield would be obtained by 75 per cent. of the present effort.

Such as it is then, the estimate is that about one quarter of the fishermen's time and expense is at present devoted to reducing their catch.

By way of illustration we finally work out what would be the yield in successive years as a result of reducing fishing time by one-sixth. The present rate of natural increase is assumed to be 50 per cent., balanced by a fishing rate of 50 per cent. In the new circumstances the stock would start to increase at 50—42 or 8 per cent. per annum. As the stock increased it would have a new rate of natural increase, less than 50, until finally the weight increased to the amount shown in Fig. 1 for the rate of 42.

The calculation is carried out in steps of one-tenth of a year:

Table 2. Abridged.

Time	Stock	Rate of Increase	Catch 0.042 of Stock
0	70		2.94
		0.50 — 0.42 = 0.08	
0.1	70.5		2.96
		0.08	
0.2	71.0		2.98
		0.08	
0.3	71.5		3.00
		0.49[1]— 0.42 = 0.07	
0.4	72.0	.	3.02
.	.	.	.
.	.	.	.
.	.	0.07	.
.	.		.
0.9	74.5		3.13
	Yield in 1st year	=	30.35
1.0	75	0.48[1]— 0.42 = 0.06	3.15
.	.	.	.
.	.	.	.
.	.	0.05	.
.	.		.
1.9	79		3.32
	Yield in 2nd year	=	32.43
	Yield in 3rd year	=	34.13
	Yield in 4th year	=	35.48
	Final yield[1]	=	39.50
	Present yield	=	35.00

Against our saving of about 16 per cent. in coal and some other expenses, we have therefore to debit a loss in turnover of 13½ per cent. in the first year, 7½ per cent. in the 2nd, 2½ per cent. in the 3rd, and thereafter no loss, but finally a gain of 13 per cent.

It is to be noted that growth is assumed to take place equally throughout the year. This is not so. To ensure as little loss in turnover as possible such an operation should begin in March or April.

Statistics of the war-time respite therefore agree with the other two sources of data, in showing that a reduction of fishing-rate would not harm the yield. They also provide an estimate of the benefit.

Conclusion and Acknowledgement.

This paper is an attempt at more precise formulation of the opinion, that has been long held by many fishermen and scientists, that it would pay to give the fish a chance to grow. Most fishermen and some scientists would also add "and a better chance to breed." I am

[1]) From Fig. 1.

particularly indebted to Mr. Wollaston, among the colleagues who have been so helpful in discussing this paper, for his emphasis on the possibility that the stocks of some species are not in equilibrium with fishing, but, owing to shortage of eggs, may be in a state of decline, a subject which he is investigating further. Much might be written as to pros and cons in this matter, but a decision is hampered by lack of crucial evidence. In this paper it is only necessary to point out: (i) that even a stock declining in numbers can be better fished, from the point of view of economy, leisure, and yield, if the fish are allowed to grow; (ii) that any reduction of fishing rate would slow down the decline; (iii) that, for all we know, a reduction of, say, 16 per cent. in the fishing rate might indeed be sufficient to arrest the decline altogether. Only this should be made clear, that if the stock be in such a state of decline, one must not be too sanguine as to increase of yield over the present yield, but should rather think of it in terms of the yield that would be taken if the fishing rate were not reduced.

Finally, the correction proposed to the theory, as developed by Thompson and Bell, may be put into words: It will pay to reduce the fishing rate at any rate so long as the stock will thereby grow in weight sufficiently for the product of the new reduced fishing-rate multiplied by the new augmented stock to be no less than the product of the old higher rate and the old smaller stock.

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