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DETERMINATION OF NATURAL AND FISHING MORTALITIES: ANALYSIS OF TAG RECORDS OFF WESTERN NOVA SCOTIA

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Abstract

A tagging programme carried out by Dr. F.D. McCracken has been analysed. The time-distribution of returns indicates that effort expended on the tagged population fluctuates considerably. This cannot be explained by the distribution of total effort or catch. More refined analyses can be made by considering short time intervals during which fishing is assumed constant. Given an arbitrary value for combined instantaneous natural and tagging mortality rate the fishing mortality rate for each interval can be estimated from the number of returns. Totalling the rates over all time intervals gives a total fishing mortality corresponding to the assumed natural and tagging mortalities. A range of all possible combinations of mortalities is obtained by considering all possible natural and tagging mortality rates. Constant values of the combined mortalities give a relation between the instantaneous mortality rates. For calculation the exact formulae are given with two approximations at different accuracy levels. The data are analysed by assuming constant values for combined natural and tagging mortality rates and results are compared with those from the methods of Ketchen and of Beverton and Holt. Both appear to over-estimate the natural and tagging mortality rate.

Introduction

In the summer of 1953, 1,800 cod and 580 haddock were tagged off western Nova Scotia (off Lockeport). From those fish, about 800 cod and 150 haddock were recaptured in 1953 to 1956. The tagging program was planned by Dr. F. D. McCracken and carried out under his supervision.

Four types of tags - hydrostatic, Peterson red and white disks, Peterson yellow disks, and strap tags - were used. In general, the disk types of tag gave almost the same percentage recoveries, while the percentage recoveries for hydrostatic and strap tags were lower than those of Peterson disks. The difference between hydrostatic and disk tags was great enough to be significant for cod but not necessarily for haddock. The percentage recoveries of strap tags were so low compared with the other tags that we have not used them in the analysis.

The tag returns provide us with valuable information about fishing and natural mortalities. From the study of the distribution of returns in time it is obvious that the effort expended on the population of tagged fish fluctuates considerably, being high in spring and summer and low in fall and winter. This fluctuation cannot be explained on the basis of the distribution of total effort or catch. For this reason none of the standard methods previously used is strictly applicable.

More refined analyses can be made by considering short time intervals during which the fishing can be assumed to be constant. If an arbitrary value is given for combined instantaneous natural and tagging mortality rate, an estimate of the fishing mortality rate for each time interval can be calculated from the known number of returns. By totalling the instantaneous rates over all time intervals the total instantaneous fishing mortality rate is obtained which corresponds to the assumed natural and tagging mortalities. If all possible values of instantaneous natural and tagging mortality rates are considered then a range of all possible combinations of mortalities is obtained. A more usual while less satisfactory procedure is to assume that the combined natural and tagging mortalities are constant or vary in a known pattern. In this case a relationship (a curve) between the instantaneous fishing mortality rates and the combined natural and tagging mortality rates is obtained.

The Lockeport tagging data are analysed by assuming constant values for combined instantaneous natural and tagging mortality rates. This restriction to constant values has been primarily due to lack of time.

The results of the analysis of haddock data are then compared with the values obtained by two previously established methods. One is described by Ketchen[1)] and the other one is the method of Beverton and Holt. The method of Ketchen appears to give a better estimate than that of Beverton and Holt while both of them probably over-estimate the natural and tagging mortality rate.

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1) The way Ketchen uses his data is actually a modification of the method which was first described by Leslie and Davies (1939). The popularity of their method in fisheries studies is probably attributable to D. B. DeLury who, working independently, derived the same equations in 1947. The reference to the work by Leslie and Davies was obtained from W. E. Ricker, personal communication.

Method

Let N_v denote the population size of tagged fish at the beginning of the v^{th} unit time interval (e.g. a month, a quarter) and let X_v, F_v and M_v be the number of returns, the instantaneous fishing mortality, and the instantaneous natural mortality, respectively, during the course of the v^{th} time interval. The time unit is assumed to be small enough so that F_v and M_v can be regarded as constants. We have

$$(1) \qquad X_v = \frac{F_v}{M_v + F_v} N_v \left(1 - \exp. - (F_v + M_v)\right)$$

and the recursive equation for N_v is given by

$$(2) \qquad N_v = N_{v-1} \exp. - (F_{v-1} + M_{v-1})$$

If N_v and M_v are given (N_v follows from (2)) then (1) admits a solution of F_v. However, when the equations (1) and (2) have to be used repeatedly the procedure tends to be slow. We will therefore give two alternative approximations.

If F_v and M_v are very small (e.g. when the unit time interval is short) then the equations (1) and (2) may be written

$$(1)' \qquad F_v = \frac{X_v}{N_v}$$

$$(2)' \qquad N_v = N_{v-1} - X_{v-1} - M_{v-1} N_{v-1}$$

It was found that the approximations (1)' and (2)' were sufficient (for two digit accuracy of F_v) when F_v and $M_v \leq .10$. To study the accuracy in each individual case the exact formulas (1) and (2) or the more refined estimates (1)'' and (2)'', given below, may be used.

For the case when F_v and M_v are outside the range suitable for (1)' and (2)' more accurate approximations can easily be given. For this purpose we write, on the basis of (1)

$$X_v = F_v N_v \left(1 - \frac{F_v + M_v}{2}\right)$$

This, for all practical purposes, may be written

$$(1)'' \qquad F = \frac{X_v}{N_v} \div \left(1 - \frac{\frac{X_v}{N_v} + M_v}{2}\right)$$

N_v is calculated rapidly from (2) by using the table of exponential functions, i.e.

$$(2)'' \qquad = (2)$$

This approximation has been found sufficient in all cases used ($F_v + M_v \leq .40$), giving in general two digit accuracy.

Because the modification of the Leslie and Davies method by Ketchen is not so well known and has not been used to estimate the natural mortality we will give a short account of it.

Leaving out the subscripts of F_v and M_v in (1) and replacing N_v by N_o and denoting the accumulated catch of tagged fish by C_t we get

$$(3) \qquad C_t = \frac{F}{F + M} N_o - \frac{(C/F)_t}{F + M}$$

where (C/F) is the catch per unit of effort, i.e.

$$(C/F)_t = F N_o \text{ exp.} - (F + M)$$

The equation (3) can be written

$$(4) \qquad (C/F)_t = F N_o - (F + M) C_t$$

By plotting the catch per unit of effort against accumulated catch we get a straight line providing that the natural and tagging mortality (or rate of immigration) is constant (in relation to fishing effort). In practice the line is fitted by the least squares method. The intersection of the line with the axis of accumulated catches gives the estimate of the total number of returns to be caught. If this estimate is N_E then from (4)

$$(5) \qquad \frac{N_E}{N_O} = \frac{F}{F + M}$$

where F + M is the slope of the fitted line. When N_O (the number of fish tagged, or the estimated number of fish in the water at the beginning of the study period) is known F can be calculated from (5).

This method has not been applied in the case when the fishing and natural or tagging mortalities are not constant. However, there is no reason why it could not be modified.

Cod

As the first application of the type of the analysis proposed we consider the cod tagging in the summer of 1953 off western Nova Scotia (Lockeport). The percentage recoveries of cod were in general quite high. In Table I the number of fish tagged the numbers recovered in 1953, 1954, 1955 and 1956, along with the estimated numbers left in the water on the 1st of November 1953, are recorded for each type of tag. The last figures are obtained by discarding the returns before November and assuming alternatively .05, .16 and .29 instantaneous natural mortality rates. The monthly recoveries from November 1953 to October 1954 are given in the fourth column of

Table II for disk tags. The number of returns reflects the effort expended on the tagged population. The total effort over the whole area does not follow the same pattern.

A month has been selected as a unit time interval. Using the formulae (1)' and (2)' successively Table II is constructed for disk tags. Corresponding to each hypothetical natural mortality rate the Table gives the estimated population size at the beginning of each month and the instantaneous fishing mortality rates during each month. The monthly instantaneous fishing mortality rates are then summarized to give the total instantaneous rate. The results including the two additional relationships, the one representing the hydrostatic tags and the other representing disk and hydrostatic tags combined, are plotted in Figure 1.

The two types of tags give strikingly different results. For instance, at the total instantaneous mortality rate .60 the corresponding natural mortalities for hydrostatic and disk tags are .32 and .07 respectively. The higher estimated natural mortality for hydrostatic tags is probably attributable to the higher tagging mortality or direct loss of tags. The results of other cod taggings in our waters exhibit the same phenomenon.

The total instantaneous mortality rate for the Lockeport cod population is estimated to be about .60 (45%) for the summer seasons. From Figure 1 we get a value .07 for the instantaneous natural mortality rate for disk tags (.24 for hydrostatic and disk tags combined). The corresponding instantaneous fishing mortality rate is .53. If the total mortality rate, on account of the possible tagging mortality, is, say .70, then the value for combined instantaneous natural and tagging mortality is .14, true natural mortality rate being .04. In general the existence of the tagging mortality implies a value for natural mortality even lower than .07.

There are no confidence limits available for the total instantaneous mortality rate of .60. If we place them completely arbitrarily at .43, .80 (35%, 55%), which are quite high, then the corresponding values for instantaneous natural mortality rates are 0, .20 (0%, 18%).

Using the estimate .07 for the natural mortality rate, the fishing mortality rate (effort) can be obtained following the pattern of Table II. The values are plotted in Figure 3. The fishing mortality is high during the months of May-August and comparatively low during the rest of the year. While the total catch is rather steady over the year, it indicates that the fishery must be concentrated on at least two semi-discrete populations; we may call them the summer and winter populations. During the winter, fishermen move to deeper water where the population is only partly mixed with the population fished during the summer.

In the second and third years after the tagging (i.e. in 1955 and 1956) the number of recaptures dropped considerably. By using the rate M = .07 together with the known fishing mortality, the number of tags in the water at the beginning of the years 1954 and 1955 can be estimated. In 1954 about 38% of the estimated number of disk tags in the water at the beginning of the year were recovered, in 1955 only 5% were recovered. This phenomenon is associated both with the almost complete absence of older cod (8 - 9 years old) in age frequencies and with the loss of tags due to growth.

<u>Haddock</u>

All haddock were tagged in the vicinity of Lockeport. From the total number of returns in 1954, about 54% of the tags came from the inshore grounds close to the tagging area, 42% came from the adjacent LaHave and Browns Banks, and 2% from more remote grounds. In general, the movement took place in an easterly direction along the shore or to the nearby offshore banks.

In contrast to cod, haddock tag returns did not exhibit any unusually high percentage recoveries during and immediately after the tagging period. This may be attributable to the fact that haddock move around more, mixing rapidly with the rest of the population. Under those circumstances the total effort might apply to the population of tagged fish and we might put

$$(6) \qquad F_1 N_1 : F_2 N_2 : \ldots = X_1 : X_2 \ldots$$

where F_1 and N_1 are the fishing effort expended, and the average number of tags in the first area; X_1 the number of returns from the first area; F_2, N_2 and X_2 the corresponding figures for the second area; etc., during any one season. We would have to assume in (6) that the unit gear has the same fishing efficiency in all areas. However, because of the seasonal pattern of the fishery the proportions of tagged fish present at any one bank can hardly be estimated. This implies again that we do not have any index of effort expended on the population of tagged fish, even if the total effort by areas is known.

In the absence of a better substitute we will assume that the natural mortality is the same constant for all areas. Apart from the work involved in calculations this restriction to constant values is not essential.

In Table III the number of fish tagged by type of tag, the number of hydrostatic and disk tags recovered, and the estimated number of hydrostatic and disk tags left in the water on the 1st of November 1953, are given. In estimating the numbers left in the water .20, .30, .40 and .50, combined instantaneous natural and tagging mortality rates are assumed. Table IV, the sixth column, gives the number of recoveries of hydrostatic and disk tags combined, by seasons. In constructing Table IV we have used the more refined approximations (1)'' and (2)''. It gives the instantaneous fishing mortality rates for both season and year, and the average instantaneous fishing mortality rates corresponding to four different instantaneous natural mortality rates. Table IV is summarized in Figure 2.

There have been no big changes in the total fishing effort from 1953-56. However, if we assume the instantaneous natural and tagging mortality rate, M = .30, then the fishing mortality rate decreases from F = .20 in 1954 to F = .16 in 1956; at the rate M = .40 it increases from F = .23 to F = .31. Providing that there has been no increase in the tagging or natural mortality and providing that the effort has been constant, the combined instantaneous natural mortality rate is apparently between M = .30 and M = .40, the instantaneous average fishing mortality being between F = .20 and F = .29. The total mortality is around .40 (from age frequencies) and from the above estimates of fishing mortality we get the range from .11 to .20 for instantaneous natural mortality rate.

From Figure 2, assuming the total instantaneous mortality rate .40, we get a range of possible values from the natural mortality rate. The maximum natural mortality is realized when there is no tagging mortality, which implies that the total mortality of tagged and untagged fish is equal. Corresponding to the value .40 of total mortality, we get a value of .24 for the instantaneous natural mortality rate. This is the very maximum, providing .40 is the true total mortality rate, which, on the basis of previous consideration, is quite likely too high.

By combining all the returns during three seasons beginning with the last season of 1953, we can smooth out some of the seasonal variations. Assuming the effort to be constant we can calculate F + M and F by the Beverton and Holt method. This gives the values F + M = .76 and F = .25, and consequently M = .51. On the basis of Table IV this value of M = .51 appears to be unreasonably high. Almost the same results are obtained whatever grouping of seasons is used.

By using the method of Ketchen we get the values F + M = .60 and F = .20, and consequently M = .40. From Table IV the average fishing mortality corresponding to M = .40 is F = .29. Presumably the value F = .20 is therefore too low, and consequently M = .40 too high. From Figure 2, corresponding to F + M = .60, we get F = .25 and M = .35. This gives the value .15 for the instantaneous natural mortality rate alone.

Acknowledgement

The data for the analysis was given by Dr. F. D. McCracken who was in charge of the tagging program. His views and his knowledge of the fishery have helped greatly in choosing the type of analysis employed.

Literature

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DeLury, D.B. 1947. On the estimation of biological populations Biometrics, 3: 145-167.

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Table I

Cod Tags

Type of Tag	No. Tagged	No. of returns in 1953	1954	1955	1956	No. of returns from November 1, 1953-October 30, 1954
Hydrostatic	932	206	148	12	8	176
Disk	605	229	91	4	1	148
Strap	263					48

	No. left in the water November 1, 1953, assuming different natural mortality rates		
	M = .05	M = .16	M = .29
Hydrostatic	765	748	712
Disk	434	411	396
Strap	240	237	230

Table III

Haddock Tags

Type of Tag	No. Tagged	No. of returns in 1953	1954	1955	1956
Hydrostatic	276	13	30	16	6
Disk	185	14	26	19	9
Strap	119				

	No. left in the water Nov.1, 1953, assuming different natural and tagging mortality rate				
	M = .20	M = .30	M = .40	M = .50	M = .60
Hydrostatic	248	241	233	234	214
Disk	163	158	152	148	144

Table II

Cod - Disk Tags

	No. of tagged fish for 3 different natural mortalities			No. of returns	Loss for natural mortality			Estimated fishing mortality for 3 different natural mortalities		
	M = .05	= .16	= .29		M = .05	= .16	= .29	M = .05	= .16	= .29
1953 Nov.	434	416	396	24	2	5	8	.055	.058	.061
Dec.	408	387	364	14	2	5	7	.034	.036	.038
1954 Jan.	392	368	343	7	2	5	7	.018	.019	.020
Feb.	383	356	329	7	2	4	7	.018	.020	.021
March	374	345	315	6	2	4	6	.016	.017	.019
April	366	335	303	9	2	4	6	.025	.027	.030
May	355	322	288	36	1	4	6	.101	.112	.125
June	319	282	246	35	1	3	5	.110	.124	.142
July	283	234	206	20	1	3	4	.071	.085	.097
Aug.	262	211	182	9	1	3	4	.034	.043	.049
Sept.	252	199	169	9	1	2	3	.036	.045	.053
Oct.	242	188	157	0	1	2	3	0	0	0
Dec.	241	186	154	Total instantaneous fishing mortality rate =				.518	.586	.655

Table IV

Haddock - combined hydrostatic and disk tags

Season[1)]	No. of tagged fish for 4 different natural mortalities				No. of returns	Estimated fishing mortality for 4 different natural mortalities			
	M = .20	M = .30	M = .40	M = .50					
1953 IV	411	399	385	372	14	.04	.04	.04	.04
1954 I	375	347	324	302	26	.07	.08	.09	.10
II	329	290	259	254	13	.04	.05	.05	.06
III	300	249	208	208	11	.04	.05	.06	.06
IV	274	214	172	160	5	.02	.02	.03	.03
1955 I	255	190	146	131	21	.09	.12	.16	.19
II	221	152	109	91	8	.04	.06	.08	.10
III	202	130	88	69	3	.01	.02	.04	.05
IV	190	115	74	55	4	.02	.04	.06	.08
1956 I	177	100	61	43	6	.04	.06	.11	.16
II	162	85	48	31	11	.01	.01	.02	.04
III	152	76	41	25	4	.03	.06	.11	.19
IV	140	65	32	17	2	.01	.03	.07	.14
1957 I	132	57	26						

1) I : February, March April; II : May, June, July

III : August, September, October; IV : November, December, January.

Table IV (cont.)

	Fishing mortalities by year			
	M = .20	M = .30	M = .40	M = .50
1954	F = .17	F = .20	F = .23	F = .25
1955	F = .16	F = .24	F = .34	F = .42
1956	F = .09	F = .16	F = .31	F = .53
	Average instantaneous fishing mortality rate			
	F = .14	F = .20	F = .29	F = .40

Figure 1

Cod - Relation between instantaneous combined natural and tagging, and total mortality rates based on 1953 Lockeport tagging.

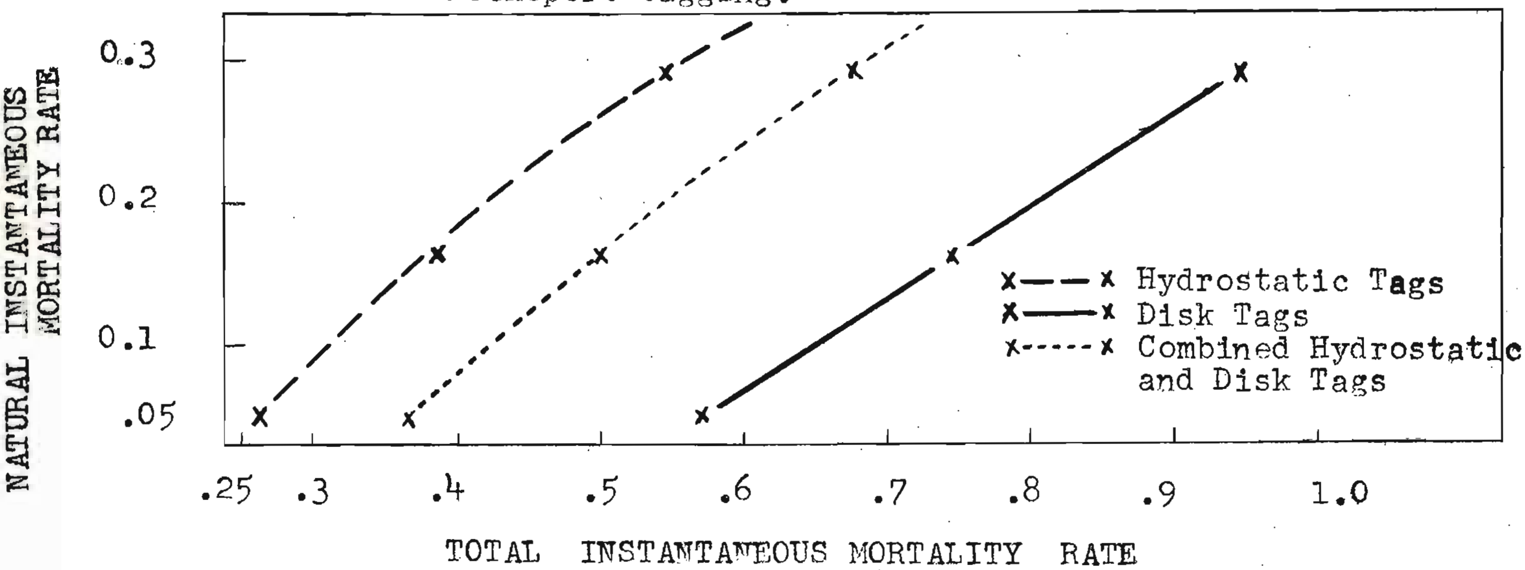

Figure 2

Haddock - Relation between instantaneous combined natural and tagging, and total mortality rates based on 1953 Lockeport tagging.

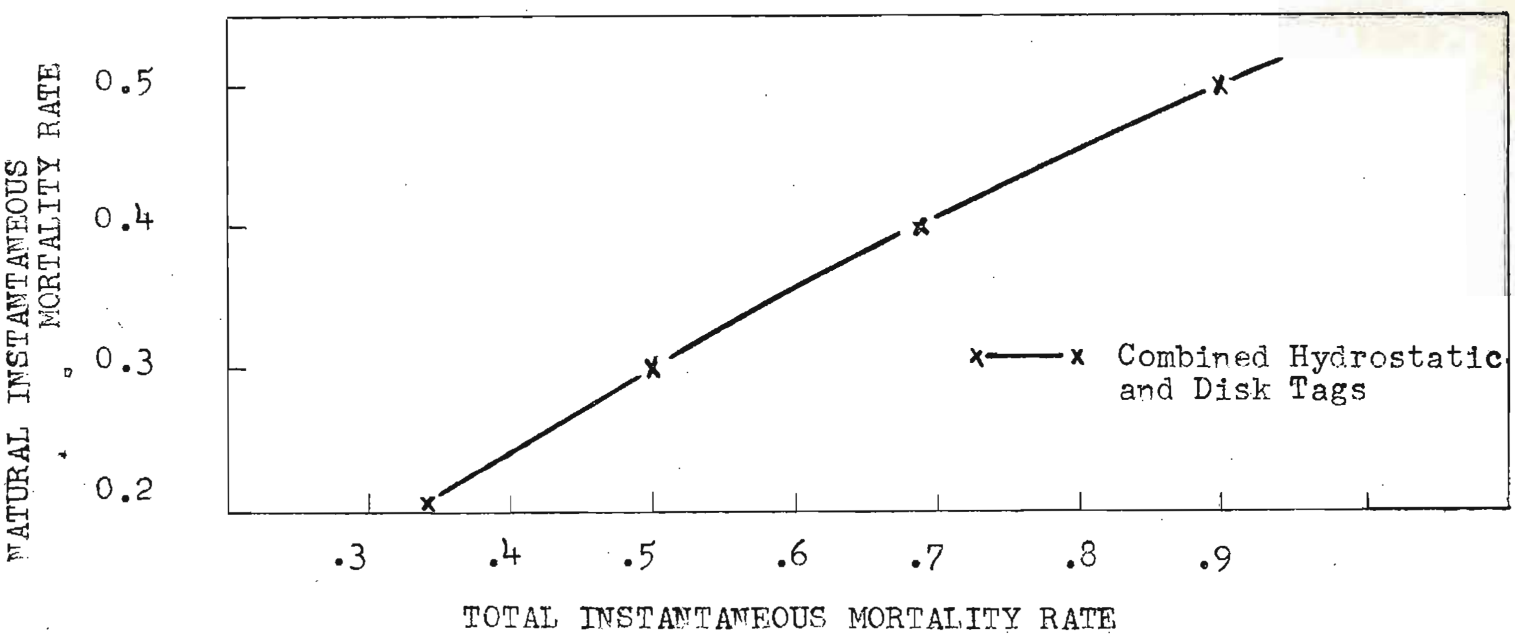

Figure 3

Cod - The distribution of effort expended on the summer populations as estimated from tag returns.