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The Estimation of Natural Mortality for the Harp Seal (*Pagophilus groenlandicus*)

by

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THE CALCULATION OF TOTAL EFFECTIVE HUNTING EFFORT REMOVING BIASES DUE TO ICE CONDITION CATCHABILITY, AND QUOTA INTRODUCTION.

(A) The calculation of hunting effort unit.

A number of techniques are used to hunt harp seals in the western Atlantic, however, the largest proportion of effort comes from large Norwegian and Newfoundland vessels. The unit effort to which all others were adjusted was a man-day from one of these vessels. The amount of effort expended hunting seals aged one and older (1+), was calculated by multiplying the effort by the ratio of the catch of seals aged one and older to the catch resulting from the large vessel hunt. The results of these calculations appear in Table 1, column a.

(B) The calculation of effective effort (E/N)

The density of harp seals does not change as the population contracts. Thus, a unit of effort does not result in the same fraction of the population being exploited. This change in the catchability, q, of seals is a problem of considerable importance. Fortunately, independent estimates of harp seal production are available (Lett and Lavigne 1975, Fig. 8). The continual decline in population size allows for the regression of time (1950 equals year one) on pup production. By making the assumption that pup production is broadly related to population size, a correction can be made for changes in the catchability by dividing effort by the population index since $q \alpha \frac{1}{N}$, producing an estimate of effective effort (E/N). The regression provides estimates of pup production in years when no aerial sensing was carried out. The results of this manipulation appears in Table 1, column b.

their paper in some detail to discover what actully has happened through all the manipulations Lett and Lavigne have carried out.

One problem in doing this is that gross errors occur in their basic input data. (This is documented in Working Documents by T. BENJAMINSEN, Ø. ULLTANG and T. ØRITSLAND presented to the Special meeting of Scientific Advisers to Panel A (Seals), Ottawa, November 1975 and Bergen, December 1975), and it is difficult to judge what effect these errors have had on the results without repeating all the calculations with corrected data. This problem, however, may be disregarded for the purpose of the present paper by assuming that the data used by Lett and Lavigne represent a hypothetical harp seal population.

The first suspecious feature of the method used by Lett and Lavigne is that a population size (or population index) had to be assumed for each of the different years in the period studied in order to use the effort data. The assumed population sizes, shown in Fig. 8 of their first paper (Lett and Lavigne, 1975 a) are mainly based on aerial surveys. Lett and Lavigne's "effective effort" is given by $E/N_{assumed}$ where $N_{assumed}$ denotes the assumed population size. Equation (3) then gives

(4) $$C/(E/N_{assumed}) = k\,N_{assumed}$$

The catch per unit of "effective effort" therefore simply is proportional to the assumed stock size.

In Fig. 4 of their paper (Lett and Lavigne, MS 1975 b) mortalities are estimated for the yearclasses 1951-1962 by regression of the logarithm of catch per unit of "effective effort" against age.

Equation (4) gives

$$\frac{\text{catch per unit "effective effort" in year } t}{\text{catch per unit "effective effort" in year } t+1} = \frac{N_{assumed} \text{ in year } t}{N_{assumed} \text{ in year } t+1}$$

If the catch and effort data had fitted the basic assumption in equation (1) the regressions in their Fig. 4 therefore simply would have given the mortalities inherent in the assumed stock sizes.

This, however, is not what their Fig. 4 gives because a series of manipulations were made with the "effective effort" data before the regressions were calculated. In order to discover what the regressions in their Fig. 4 really give the different steps in the manipulations must be looked at.

In Fig. 1 in Lett and Lavigne's paper (MS 1975 b) fishing mortalities from cohort analysis (Lett and Lavigne, MS 1975 a) are plotted against "effective effort". Lett and Lavigne concluded from this figure that catchability had changed from 1966 onwards and they explained this as result of the introduction of catch quotas. The possibility of a change in catchability from 1966 onwards (a change in k in equation (1)) can not be disregarded, but the reason for the change can not be catch quota regulations because overall quotas

(E) <u>The modification of total effective effort to account for changing ice conditions.</u>

The relationship between catch/unit total effective effort (E/N) and the population size from cohort analysis was severely autocorrelated. Since the error was systematic, and magnified as the population increased, it was hypothesized that cyclical environmental conditions were responsible. Sargeant and Fisher (1960) noted "large fluctuations occur in catch per unit effort from year to year, as a result of variable ice conditions". An index of the ice conditions is the percentage adults in the catch, since when ice conditions are poor there will be more hunting of adults and when ice conditions are good there will be more hunting of pups. The intense hunting of adults, of course, causes the average catch/unit effective effort to fall. The cyclic nature of this variable was removed using the following multivariate equation;

$$(2)\quad CUE = 29298(POP^2/I)-211250(POP^2/I^2)+108138(POP/I^2) -472(POP^2)-40(I)-643.467.$$

VARIABLE	COEFF	ST. ERROR	T. VALUE
POP^2/I	29298	6770	4.33[a]
POP^2/I^2	-211250	59380	3.56[a]
POP/I^2	108138	33939	3.19[a]
POP^2	- 472	157	3.00[a]
I^2	40	17	2.40[a]

The coefficient of multiple determination (R^2) is 0.82 while the F for regression is 14.06[a] ($F'_{5,16}/2.85$).

[a] significant at $P \geq 0.05$.

where POP is the population $x10^{-6}$ from the cohort analysis Table 2, and I is the percent age adults in the catch. The percentage adults in the catch were as follows:

Year	%	Year	%	Year	%	Year	%	Year	%	Year	%
1952	42.2	1956	10.9	1960	65.7	1964	23.4	1968	29.5	1972	2.0
53	33.0	57	50.6	61	6.9	65	31.9	69	21.2	73	20.8
54	51.2	58	91.7	62	48.9	66	26.7	70	14.8		
55	29.1	59	26.9	63	20.6	67	16.7	71	8.5		

By using the mean percentage catch of adults (30.6%) CUE were subsequently predicted. The residual catch/unit effective efforts were added onto these predicted values to illustrate the natural variation in the data (Table 2), which is effectively an analysis of covariance. The catch /unit efforts, after removal of the variability in ice condition were plotted and appear in Fig. 2. The relationship between CUE and population size from cohort analysis is clearly positive and goes through the origin when the 1954 value is ignored.

The best estimate of effort is obtained by dividing the estimated CUE's (Table 2) into the total catches. *No information on natural mortality used in the cohort analysis is transferred into the predicted CUE's* since the population sizes from the cohort analysis are independent of any time series in this regression. No matter what value of natural mortality had been used in the cohort analysis, the predicted CUE's in each given year would be the same. Thus, equation 2 is merely an additional data purification and does not mediate any a priori assumptions about natural mortality. These predicted values of effective effort were plotted against the weighted hunting mortalities generated from the cohort analysis (Table 3, Fig. 3). The amount of variation in hunting mortality explained by the effective effort is 95%. Therefore, the effective efforts in Table 1, column e are an excellent index of real hunting effort.

THE DETERMINATION OF TOTAL MORTALITY FOR INDIVIDUAL COHORTS.

Since a reliable estimate of effective hunting effort was now available, the catch rates of individual cohorts in each year were now calculated by dividing the effort in column e, Table 1 into the catch at ages from Lett and Lavigne (1975) Table 1. The result of this manipulation is in Table 4. The regression of age on the logarithm of CUE yields an estimate of total mortality, for ages I to XIV.

The regression lines appear in Fig. 4 for the 1951 to 1962 cohorts. All the regressions were highly significant with 91% of the variation in CUE being explained on average by the variations in age. The mean total mortality, Z, for these cohorts is 0.24±0.03(2.2SE). Thus, there is only a 5% chance that total mortality is above 0.27 or below 0.21. Cohort analysis yields average estimates of hunting mortality. With natural mortality in the cohort analysis being M_C0.21, the average value is 0.047±0.011(2.2SE). This value subtracted from 0.24 yields an estimate of natural mortality of 0.19.

Paloheimo's linear formula was also used to try and estimate mortality, however, there is more variation in the catch composition than in hunting mortality, making a significant regression between total mortality and hunting effort impossible. This is unfortunate since the method removes the effects of shifts in recruitment as well as changes in hunting mortality, however, the mean value using this method confounded with hunting effort is 0.24±0.07(2.2SE). Thus, total mortality varies between 0.31 and 0.17 using Paloheimo's linear formula. Clearly, the values obtained following cohorts gives a 63% increase in precision of the estimate of the mean total mortality.

An alternative method was tried to determine the relationship between effort and total mortality, by accumulating the effort that the cohort experiences in each year, and dividing by the total number times the cohort experienced hunting over the number of years analysed. Thus, a weighted mean effort is obtained, representing the average effort experienced by the cohort over the years analysed. The fishing mortality was assumed to be proportional to this weighted mean. The problem with this method is that variations in the weighted efforts are small. Values for effort for reliable estimates of mortality ranged between 26.27 and 50.38 man-days. The results are plotted in Fig. 5. The regression line is not significant, however, it is the best estimate of natural mortality available. The intercept value, M, is 0.225. If this graph says nothing else, it shows that values of hunting mortalities are low since a two-fold change in effort resulted in almost no change in Z, and the estimates of Z are extremely reliable (Fig. 4). Given the reliability of the effort estimates and total mortality, together, variations in hunting mortality must be small, since a substantial increase in the covariance is required for a significant slope on the regression of effort on total mortality.

DISCUSSION

One of the obvious questions is, why hunting mortality from the cohort analysis is so well correlated with effective hunting effort, but no significant correlation can be determined between effective effort and total mortality; with both regressions being based on the same data. Cohort analysis is based on the formula:

$$(3)\quad N_i = C_i\ \mathrm{EXP}(M/2) + N_{i+1}\ \mathrm{EXP}(M)$$

where N_i is the population of a year-class at the ith birthday, C_i is the catch of a cohort at age i, and M is the instantaneous coefficient of natural mortality. Therefore, the calculation of each successive year class relies on all the estimates of year-class size afterwards, therefore, the analysis improves with the number of iteration of equation 3. In Pope's (1972) words "errors in F and by sampling error of catch data, converge to fairly small values" within a few iterations. The rate of convergence, is to some degree dependent on the amount of error in the starting values of hunting effort. The F values in 1952 then have cumulative information in them from 24 years of data in comparison to the two years of information in the calculation of Z from Paloheimo's linear formula. Consulting, Figure 3 and table 3 indicates that as early in the analysis as 1970, predicted hunting mortalities were extremely reliable, an indication that the starting F value of 0.033 was a reliable one. It also indicates that during the first few years the sampling error of the catch data is small.

The hunting mortality on pups is extremely high, whereas the hunting mortality on 1+ seals is low. Therefore, the calculation of population numbers of 1+ seals are much more susceptible to changes in natural mortality than the abundance level of pups. It is therefore worth noting *that an M of 0.21 is the lowest possible value of M that can be put into the cohort analysis to produce enough adults to give the observed or predicted pup* *production*, even in the earlier years. As previously stated, pup production remains rather invariate in relation to M. This is possibly the best check on cohort analysis as well as providing a rather realistic minimum value of M. It is acknowledged that this value of M is elevated by the small unreported catches of 1+ seals by Eskimos and by wounded seals which sink and are unreported, however, a higher M in the cohort analysis may produce more realistic population estimates.

The estimate of natural mortality used by Lett and Lavigne (1975) was 0.21. This estimate is the mean of all the known estimates of natural mortality for other pinnipeds (Lett and Lavigne 1975). In addition, the best correspondence was achieved between the cohort analysis and the values generated from the simulation using an M of 0.21 (Lett and Lavigne 1975, Fig. 5). Furthermore, pup production generated by the cohort analysis compared very well with values from aerial sensing and tagging using this same value of natural mortality (Lett and Lavigne 1975, Fig. 8).

In summary: (1) the level of hunting mortality is low and probably resides between 0.03 and 0.08.

(2) the estimates of effective hunting efforts are reliable.

(3) the estimates of total mortality, Z, are reliable, and rather invariate for individual cohorts.

(4) the catch/unit efforts are well correlated with the cohort analysis population sizes.

(5) a doubling of hunting effort results in almost no change in total mortality.

(6) natural mortality resides somewhere near 0.225 and a minimum estimate would be 0.21 when the effects of sinkage are confounded into the analysis.

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Table 1. The metamorphosis of hunting effort. Column (e) is considered the best index of hunting effort.

YEAR	EFFORT (LARGE NOR. AND NEWF. VESSELS)	EFFECTIVE EFFORT (EFFORT/POPULATION INDEX)	EFFECTIVE EFFORT OF TOTAL CATCH	EFFECTIVE EFFORT ADJUSTED FOR QUOTA	EFFECTIVE EFFORT ADJUSTED FOR AN INDEX OF ICE CONDITION
1952	232.2[a]	41.46[b]	49.53[c]	49.53[d]	19.09[e]
53	119.8	22.19	26.10	26.10	15.07
54	103.8	19.58	21.93	21.93	19.63
1955	58.2	11.45	14.63	14.63	18.60
56	19.0	3.88	6.17	6.17	13.14
57	306.0	65.11	68.98	68.98	25.84
58	321.0	69.78	89.73	89.73	52.06
59	88.6	20.14	24.40	24.40	34.35
1960	411.1	97.60	118.20	118.20	57.26
61	34.8	8.70	15.01	15.01	8.77
62	177.6	45.54	59.00	59.00	65.37
63	75.0	20.27	33.73	33.73	40.28
64	135.7	38.77	57.01	57.01	55.16
1965	154.6	46.85	80.49	80.49	44.41
66	95.9	29.97	46.95	109.81	66.51
67	79.9	26.63	41.28	97.21	58.80
68	38.2	13.64	18.97	48.02	40.42
69	73.2	28.15	34.99	93.41	61.87
1970	35.6	14.83	23.76	52.13	47.47
71	12.4	5.39	8.21	16.26	25.54
72	3.4	1.60	14.01	27.74	17.19
73	20.0	10.50	18.86	37.34	32.84
74	18.8	11.06	19.35	38.31	43.38

a Effort for large Norwegian and Newfoundland vessels only.

b Effective effort is (a) divided by a population index from aerial sensing to remove the effects of changing catchability.

c Effective effort (b) has been magnified to represent the entire catch of harp seals one and older.

d Effective effort (c) has been modified after 1966 to include the increase in efficiency related to hunting adults on the molting patches.

e Effective effort (d) has been modified to remove the autocorrelation due to changing ice conditions.

Table 2. Catch/unit effective efforts, before and after the removal of autocorrelation due to ice condition, and population size from the cohort analysis of seals one and older.

YEAR	CUE BEFORE	CUE AFTER	POPULATION SIZE x 10^{-6}
1952	2172	4694	4.21
53	2870	3413	3.92
54	4078	6821	3.73
1955	5281	4984	3.49
56	7298	3904	3.13
57	1158	2555	2.89
58	1700	2991	2.76
59	3298	2985	2.42
1960	1008	1436	2.22
61	1076	1394	1.99
62	1913	2118	1.92
63	1812	1416	1.72
64	1285	1145	1.52
1965	640	635	1.32
66	656	786	1.21
67	572	694	1.02
68	754	983	0.93
69	594	905	0.92
1970	765	972	0.82
71	1254	1221	0.74
72	471	780	0.67
73	668	886	0.66

$\overline{CUE}_B = 1878 \pm 371(SE)$ $\overline{CUE}_A = 2169 \pm 361(SE)$ $\overline{P} = 2.01 \pm 0.25(SE)$.

Table 3. Weighted hunting mortalities (F) from the cohort analysis using an M of 0.21, and hunting efforts.

YEAR	HUNTING MORTALITY (F)	EFFORT (E/N)
1952	0.031	19.09
53	0.024	15.07
54	0.030	19.63
1955	0.026	18.60
56	0.015	13.14
57	0.036	25.84
58	0.063	52.06
59	0.042	34.35
1960	0.067	57.26
61	0.010	8.77
62	0.070	65.37
63	0.042	40.28
64	0.060	55.16
1965	0.049	44.41
66	0.074	66.51
67	0.065	58.80
68	0.045	40.42
69	0.083	61.87
1970	0.056	47.47

$\bar{F}$ = 0.047±0.005(SE) $\overline{E/N}$ = 39.160±4.451(SE)

Table 4. Catch/unit effective effort using catch at age data from Lett and Lavigne (1975) Table 1 and effective effort from column e, Table 1 (this paper).

	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
I	79	1737	1734	399	69	136	167	81	103	269	238	100	73	54	133	115	111	222	88	164	67	164
II	276	511	685	643	308	204	108	199	353	193	323	165	102	54	133	77	69	50	102	72	51	72
III	371	427	187	809	325	267	269	211	581	242	157	158	171	112	85	42	78	81	65	90	51	90
IV	439	253	401	332	274	309	389	164	187	304	188	114	139	165	90	43	52	77	62	52	135	52
V	540	253	132	477	206	161	298	199	145	98	162	99	134	161	95	75	43	74	67	57	51	57
VI	607	199	178	270	223	136	272	222	187	126	59	90	122	146	102	85	50	55	38	41	56	41
VII	461	174	155	229	274	203	175	211	125	112	78	68	82	83	82	79	59	60	30	30	73	30
VIII	461	199	87	311	223	203	181	187	62	70	83	71	58	68	51	55	62	66	46	30	51	30
IX	366	194	96	104	171	148	135	176	42	70	62	62	49	32	34	45	41	53	46	42	33	42
X	366	139	150	104	120	148	146	129	62	79	42	71	53	27	27	35	41	48	51	39	33	39
XI	366	134	46	83	154	204	129	82	42	48	33	70	42	104	35	40	31	41	34	20	23	20
XII	359	99	132	103	69	136	114	59	31	44	33	52	38	34	23	27	27	29	29	28	28	28
XIII	242	84	132	21	103	136	91	47	25	39	29	50	37	31	23	26	22	29	24	24	11	24
XIV	169	65	69	21	69	161	79	82	42	26	31	56	34	28	25	33	28	30	19	15	5	15
XV	163	50	91	42	103	96	61	47	21	26	59	47	21	30	21	30	25	26	24	16	23	16
XVI	180	79	118	21	68	80	50	23	31	20	22	50	21	19	23	21	23	20	22	13	17	13
XVII	134	65	50	42	51	68	44	35	21	141	26	38	28	15	15	21	22	24	19	10	11	10
XVIII	118	45	14	1	34	68	15	23	21	7	21	23	26	13	21	22	25	16	14	10	11	10
XIX	84	40	59	1	17	56	21	35	8	6	12	21	24	17	13	22	22	19	14	10	1	10
XX	84	65	32	21	17	56	44	12	21	18	26	24	11	7	13	18	15	13	15	7	17	7
XXI	84	40	14	35	34	12	21	1	4	1	4	18	8	9	7	10	10	10	8	5	1	5
XXII	45	15	14	1	51	28	26	1	10	4	16	17	8	5	5	8	13	6	6	4	5	3
XXIII	45	10	37	1	34	46	23	12	1	4	4	15	9	2	9	7	6	7	5	4	1	3
XXIV	6	15	9	1	34	12	32	1	1	2	4	11	7	5	4	8	5	4	3	1	1	1
XXV	40	10	37	1	34	1	15	12	1	9	7	5	11	5	8	4	3	3	3	2	1	2

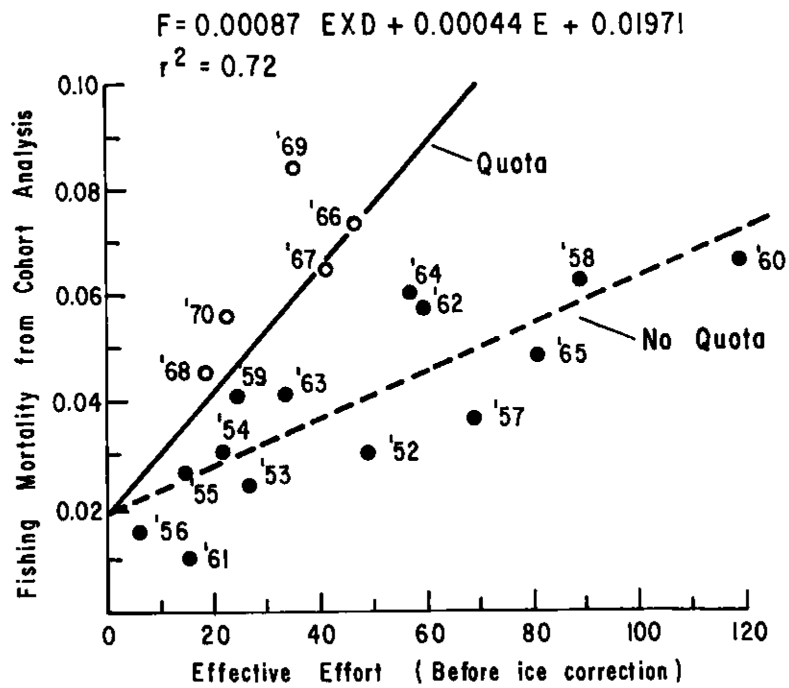

Figure 1. The effect of the quota on the catchability of 1+ harp seals. The upper line represents the effects of quota management while the lower line shows the relationship between hunting mortality with no quota. As can be seen, closing dates instituted in 1961 had no effect on catchability.

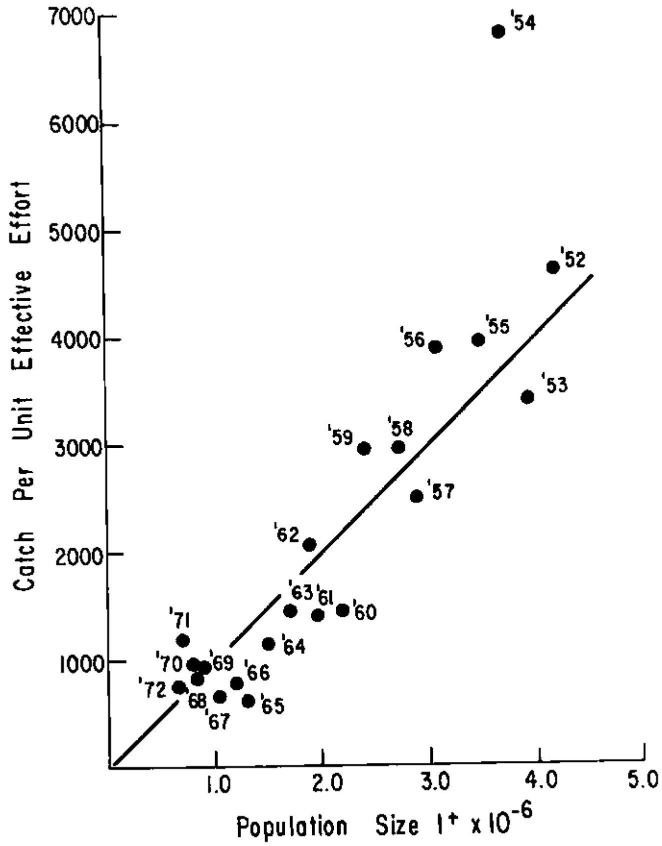

Figure 2. The relationship between the population sizes of 1+ harp seals and catch/unit effective effort after the removal of the effects of ice condition and quota management.

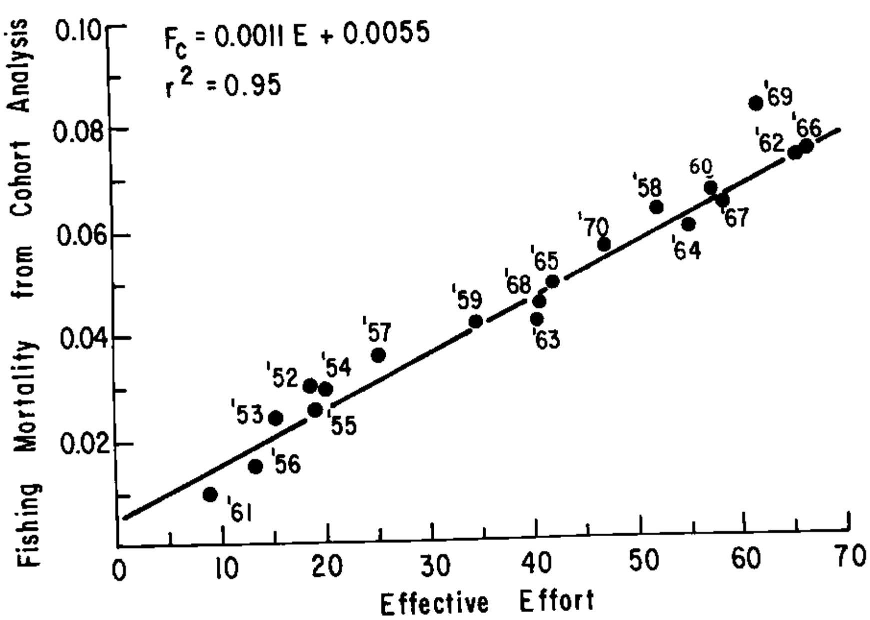

Figure 3. The regression of effective effort (Table 3) on fishing mortality from cohort analysis.

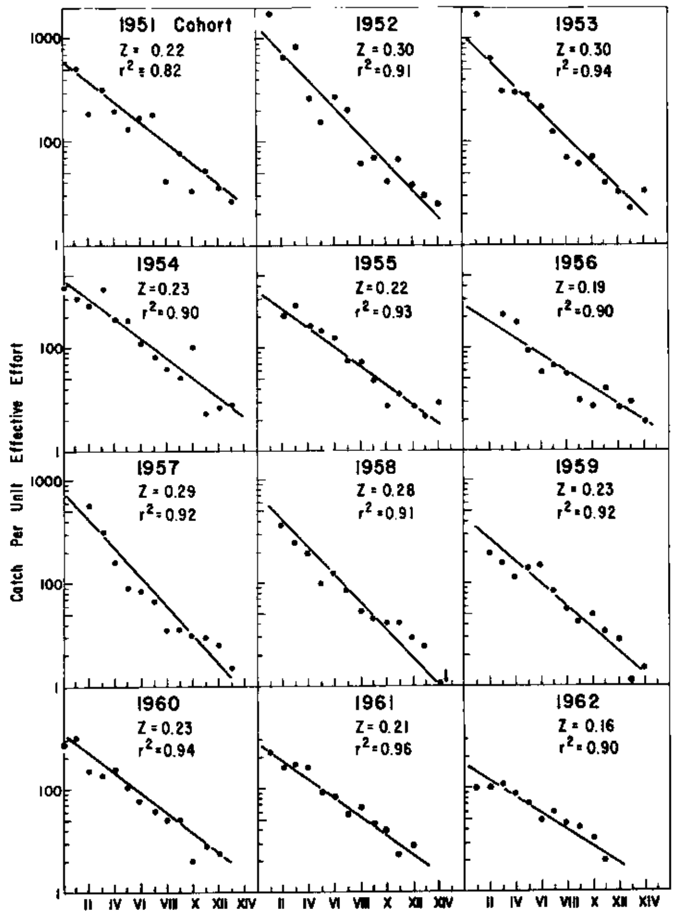

Figure 4. The regressions of age on the natural logarithms of CUE determined from (Table 4). The slopes of the lines represent the instantaneous rates of total mortality independent of recruitment effects for cohorts 1951-1962.

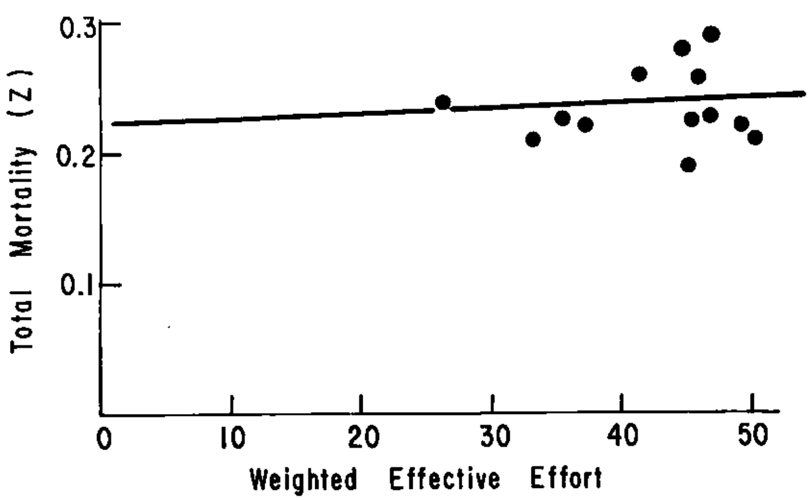

Figure 5. The regression of different levels of weighted effective effort on total mortality for individual cohorts. The weighted effective effort is the summation of all the effort experienced by the cohort in each year divided by the addition of the consecutive integers to maximum age analysed.