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A SIMULATION STUDY OF THE METHOD OF DERIVING NATURAL MORTALITY RATE USING DATA FOR *CHAMPSOCEPHALUS GUNNARI* IN SUBAREA 48.3

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Abstract

A method of determining the rate of natural mortality, based on the construction of a regression between the rate of annual fishing mortality (determined by VPA) and fishing effort, is described. The intersect of this regression must be equal to zero if the natural mortality rate has been correctly identified and something other than zero if it has not been correctly chosen. Data for *Champsocephalus gunnari* in Subarea 48.3 are used to show that the described method is sound. When a mistake is made in the choice of natural mortality coefficient, the estimate of the intercept of the regression is other than zero. A bias in the intercept will be positive if the assumed natural mortality coefficient is less than the "true" value and close to zero or slightly greater than zero if the assumed value is greater than the "true" one.

Résumé

Description d'une méthode permettant de déterminer le taux de mortalité naturelle à partir de la construction d'une régression entre le taux de mortalité par pêche annuel (établi par VPA) et l'effort de pêche. Le point d'intersection de cette régression doit être égal à zéro si le taux de mortalité naturelle a été identifié correctement, et, s'il est différent de zéro, celui-ci est incorrect. Les données sur *Champsocephalus gunnari* de la sous-zone 48.3 sont utilisées pour prouver que la méthode décrite est fiable. Si le taux de mortalité naturelle n'est pas correctement choisi, l'estimation du point d'intersection de la régression est différente de zéro. Tout biais dans le point d'intersection sera positif si le taux présumé de mortalité naturelle est inférieur à la valeur "réelle".

Резюме

Описан метод расчета коэффициента естественной смертности, основанный на построении регрессии между коэффициентом ежегодной промысловой смертности (определенным при помощи VPA) и промысловым усилием. Свободный член этой регрессии должен равняться нулю, в случае если коэффициент естественной смертности определен правильно, и быть отличным от нуля, в случае ошибки. Данные по *Champsocephalus gunnari* в Подрайоне 48.3 использованы для подтверждения целесообразности описанного метода. При совершении ошибки в выборе коэффициента естественной смертности, свободный член этой регрессии будет отличен от нуля. Наклон пересечения будет положительным, если предположенный коэффициент естественной смертности меньше чем "истинное" значение.

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Resumen

Se describe un método para determinar el índice de mortalidad natural basado en la construcción de una regresión entre el índice de mortalidad por pesca anual (determinado por el VPA) y el esfuerzo pesquero. Si el índice de mortalidad natural se ha identificado correctamente, la intersección de esta regresión deberá ser igual a cero. Se emplearon los datos de *Champsocephalus gunnari* de la Subárea 48.3 para demostrar que el método descrito está correcto. Cuando la selección del índice de la mortalidad natural es errónea, la estimación de la intersección de la regresión es diferente a cero. El sesgo de la intersección será positivo si el índice de mortalidad natural supuesto es menor que el valor "real".

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1. INTRODUCTION

In 1989, in the papers by Shlibanov (1989) and Sparre (1989) natural mortality rates for *Patagonotothen guntheri* estimated by different methods were calculated as 0.48, 0.63, 0.72, 0.83, 0.94 and 1.06. The values were so obviously scattered that they gave rise to extreme uncertainty in assessment of this commercial species. In a special study of this species, Gasyukov and Dorovskikh (1990) suggested a new approach to the determination of natural mortality. They concluded that the natural mortality rate of 0.9 was the most likely value for *P. guntheri* in Subarea 48.3.

A similar situation arose regarding estimation of the natural mortality rate for *Champsocephalus gunnari* in Subarea 48.3. A value of 0.56 obtained by Frolkina and Dorovskikh (1989) differed from the value of 0.35 used by the Working Group on Fish Stock Assessment (WG-FSA) in previous years. In 1990 the same authors confirmed the natural mortality rate of 0.56 by using a large amount of original data and the approach outlined in Gasyukov and Dorovskikh (1990).

A discussion of this approach for verifying the natural mortality rate calculation held at the meeting of the WG-FSA (CCAMLR, 1990) indicated that the scientific justification for using the method of Gasyukov and Dorovskikh (1990) would be improved if its behaviour and performance were to be studied by means of mathematical simulation.

2. METHODS FOR REFINING NATURAL MORTALITY RATE CALCULATIONS

The method of Gasyukov and Dorovskikh, (1990) is very close to Paloheimo method (Ricker, 1975). It is based on the construction of a regression between the rate of annual fishing mortality and fishing effort and the premise that the intersect of this regression should be equal to zero when the value of natural mortality chosen is correct (see Frolkina and Dorovskikh, 1990). Age composition of the catches, $C_{a,y}$, for a series of years and standardised values of fishing effort E_y, $y = 1,2 \,.....n$ were used as the initial data. A set of possible values of natural mortality M_i, $i = 1,2, \,.....j$ is assumed to be known. Then the algorithm for the determination of natural mortality consists of the following steps:

Mortality Algorithm

(i) a specific value of natural mortality M_i is selected from the set of its possible values;

(ii) a VPA is run, tuned to fishing effort data by one of the methods of Pope and Shepherd (1985). The tuning method which would correspond studies of a given fish species is preferable;

(iii) the VPA is used to compute the annual fishing mortality $\mathbf{F}_{a,y}$, and abundance $\mathbf{N}_{a,y}$ rates by age and fishing year, where terminal fishing mortality rates and fishing mortality rates for the oldest age group by fishing year are estimated by the tuning algorithm;

(iv) mean weighted values of annual fishing mortality, $\mathbf{F}_y$, for all age groups fully represented in the catch beginning from age $\mathbf{a}_f$ is:

$$\mathbf{F}_y = \sum_{a=a_f}^{a_k} w_{a,y} \times \mathbf{F}_{a,y} \tag{1}$$

where $w_{a,y}$ are weight factors.

(v) regression equation parameters $\mathbf{a}_i$, $\mathbf{a}_d$ and $\mathbf{b}_i$ are found from:

$$\mathbf{F}_y = \mathbf{a}_i + \mathbf{b}_i \, \mathbf{E}_y \tag{2}$$

where the index ***i*** corresponds to selected natural mortality rate;

(vi) steps 2 to 5 are then repeated for a range of values of natural mortality.

The main principle of the natural mortality rate verification is based on an assumption that if the selected natural mortality rate **M** is correct, then the factor **a** in regression equation (2) will be equal to zero (fishing effort is proportional to fishing mortality). In practical calculations, with regard for the random pattern of the initial data and the final sample amount it will be reasonable to apply the statistical null hypotheses that this factor is equal to zero.

It should be noted that steps (iv) and (v) can be accomplished by a number of methods. Mean weighted fishing mortality rates in particular, can be estimated using corresponding age group abundance values,

$$w_{a,y} = \frac{\mathbf{N}_{a,y}}{\Sigma \, \mathbf{N}_{a,y}} \tag{3}$$

or using factors recommended by Shepherd (1982):

$$w_{a,y} = \frac{\mathbf{F}_{a,y} \, e^{-\mathbf{Z}_{a,y}} \left[1 - e^{-\mathbf{Z}_{a,y}}\right]}{\mathbf{Z}_{a,y}} \tag{4}$$

For determination of regression equation parameters (2) both the algorithm of simple and that of functional regressions can be used (Ricker, 1975).

3. SIMULATION DESCRIPTION

The method of simulation has been widely used, especially recently, for resolving various problems and a description can be found in Butterworth (1988). This method has been used in CCAMLR by Basson and Beddington (1989), Kock (1989), De la Mare and Constable (1990).

A model proposed by Butterworth (ICSEAF, 1989) and simplified for our modelling study seems to be most consistent with our objectives.

The basic relationships in the Butterworth (1988) model are:

Simulation model

(i) Main relationships of abundance dynamics

$$\mathbf{N}_{a+1,y+1} = \mathbf{N}_{a,y} e^{\left(-\mathbf{Z}_{a,y}\right)} \tag{5}$$

$$\mathbf{Z}_{a,y} = \mathbf{M} + \mathbf{S}_{a,y}\,\mathbf{F}_y \tag{6}$$

$$\mathbf{S}_{a,y} = \mathbf{S}_a \tag{7}$$

where $\mathbf{S}_a$ is selectivity at age $\boldsymbol{a}$;

$\mathbf{F}_y$ is total fishing mortality at year $\boldsymbol{y}$;

$a = 1,2,\ \ldots.,\ a_k$;

$y = 1,2,\ \ldots.,\ y_k$.

(ii) "Stock recruitment" ratio:

$$N_{0,y+1} = e^{\left\{\varepsilon_y - \frac{\sigma_r^2}{2}\right\}} \bullet \Phi\left(\mathbf{B}_y\right); \tag{8}$$

$$\mathbf{B}_y = \sum_{a=a_m}^{a_k} \left\{w_{a,y}\,\mathbf{N}_{a,y}\right\}; \tag{9}$$

$$w_{a,y} = \frac{1}{2}\left[w_{a+1/2,y} + w_{a-1/2,y}\right] \text{ for } a > 0,$$

$$w_{a,y} = w_{0,y} = w_{1/2,y} \text{ for } a = 0, \tag{10}$$

a_m = age at first maturity;

where Φ is an expression which describes dependence of recruitment rate on parent stock size;

ε is random number from normal distribution with mean 0 and variance σ_r^2.

$$\varepsilon \in N\left(0, \sigma_r^2\right); \tag{11}$$

(iii) The catch weight:

$$\mathbf{C}_y = \Sigma\, w_{a+\frac{1}{2},y}\, \mathbf{N}_{a,y}\, \mathbf{S}_{a,y}\, \mathbf{F}_y \left(1 - e^{-\mathbf{Z}_{a,y}}\right) / \,\mathbf{Z}_{a,y} \tag{12}$$

(iv) Correlation between fishing effort and fishing mortality:

$$\mathbf{F}_y = q\, \mathbf{E}_y; \tag{13}$$

where q is catchability factor.

(v) Catch-at-age and fishing year, $\mathbf{C}_{a,y}$:

$$\mathbf{C}_{a,y} = \mathbf{N}_{a,y}\, \mathbf{S}_{a,y}\, \mathbf{F}_y \left[1 - e^{-\mathbf{Z}_{a,y}}\right] / \,\mathbf{Z}_{a,y}. \tag{14}$$

Thus the only element of this model that is subject to random error is recruitment. All other parameters are derived empirically, in contrast to the complete Butterworth (1988) model in which many components are subject to error.

For simulation of population dynamics the following initial data are required:

a_k - number of age groups;
y_k - number of fishing years;
M - natural mortality rate;
$w_{a,y}$ or w_a - mean weight-at-age (and fishing year);
$\mathbf{N}_{a,0}$ - distribution of abundance by age during the zero fishing year;
$\mathbf{C}_y$ - total catch by weight by fishing years;
q - catchability factor;
$\mathbf{S}_a$ - age selectivity factor;
σ_r^2 - the variation of the random component in expression (7) and the parameters of "stock-recruitment" ratio.

The algorithm of simulation involves the following stages:

(i) the abundance of zero group in the first fishing year is estimated from equation (8);

(ii) the abundance values $\mathbf{N}_{a,1}$, $a = 1,2, ...,a_k$ are computed from the formula:

$$\mathbf{N}_{a,1} = \mathbf{N}_{a-1,0}\, e^{-\mathrm{M}};$$

(iii) for each $y, y = 1,2, ...,y_k$:

(a) age selectivity values $\mathbf{S}_{a,y}$ are computed from formula (7);

(b) total fishing mortality $\mathbf{F}_y$ is estimated from equation (12) with the use of the present value of $\mathbf{C}_y$;

(c) fishing effort $\mathbf{E}_y$ is deduced from (13);

(d) "real" catch $\mathbf{C}_{a,y}$ is computed for $a = 1,2, \ldots., a_k$ from (14);

(e) if $y \neq y_k$, $\mathbf{N}_{0,y+1}$ is produced from (8) and from (5) $\mathbf{N}_{a,y+1}$ is found for $a = 1,2, \ldots., a_k$.

Thus the major output information for each model run comprises:

- matrix of catch-at-age and fishing year $\mathbf{C}_{a,y}$;
- fishing effort by fishing year $\mathbf{E}_y$.

A general procedure for the study of natural mortality rate specification with the use of this simulation is as follows:

(i) the value of **M** for a single simulation of commercial population dynamics is set;

(ii) the number of model runs **P** for the simulation is determined;

(iii) simulation of population dynamics is made in accordance with the above-mentioned model which results in the values of $\mathbf{C}_{ay}^{(p)}$, $\mathbf{E}_y^{(p)}$ for $\mathbf{p} \in \mathbf{P}$.

(iv) the simulation is run for a number of values of natural mortality $\mathbf{M}_i$, $i = 1,2 \ldots j$. The result of this algorithm are the intersect values of the regression equation (2).

(v) calculation of final statistics for each assumed **M** rate.

The null hypothesis is that the intercept of equation (2) will equal zero when the value of **M** used is equal to the true value of **M**.

4. DATA USED

For running this simulation model a number of parameters and values are required. It was decided that it was better to use real data from the fishery for this purpose and as an example the *C. gunnari* fishery in Subarea 48.3 was chosen.

The required initial parameters and values were computed from actual data used for stock assessment purposes (Gasyukov, 1990). Corresponding values of catch-at-age and fishing year, and fish mean weight are given in Tables 1 and 2. The catch by weight of *C. gunnari* in Subarea 48.3 and standardised values of fishing effort computed by means of the multiplicative model (Gasyukov, 1990) are presented in Table 3.

The abundance values and fishing mortality rates were estimated by the VPA tuned by the Laurec-Shepherd method (Pope and Shepherd, 1985). The corresponding values are given in Tables 4 and 5.

Thus the following values were taken as initial ones:

$\mathbf{M} = 0.56$;
$a_k = 6$;
$y_k = 8$;
$a_f = 3$;
$a = 36.85$;
$\beta = 0.0113$;
$q = 0.000115$;
$\sigma_r = 0.7008$;
$\mathbf{P} = 1000$ (number of simulation runs).

Age selectivity rates and initial values of abundance during the zero year had the following values:

Age group, *a*	1	2	3	4	5	6
S_a	0.0215	0.174	0.692	0.568	0.761	0.759
$N_{a,o}\text{x}10^{-6}$	941.8	1216.3	233.2	71.2	25.6	14.6

Thus together with the mean fish weight data from Table 2, the above-stated parameters form the necessary basis for running of simulation model for *C. gunnari* from Subarea 48.3.

5. COMPUTATION RESULTS AND THEIR DISCUSSION

Two variants of the mortality algorithm were used, specified for estimation of the mean fishing mortality for major age groups, by weighting by abundance (equation 3) or by catch (4).

For each value of natural mortality rate out of the set of its assumed values 1 000 runs of the model were made. The results of simulation took the shape of histograms of values of intersect of regression equation with the mean and median values.

Corresponding results are presented in Table 6 and shown in Figure 1.

First of all, similarity of the results obtained from both computation variants are worth noting. If the assumed natural mortality rate values are less than the "ideal" one, then the values of the intersect have a positive shift, whereas if the values are greater than the "ideal" one, this shift is negative. Irrespective of weighting method used for computation of the mean weighted fishing mortality rate, the values of the intersect appeared to be close for the two weighting methods. Although the sign of the shift is the same, its range appears to be greater when weighting by **C** than when weighting by **N**. The difference between zero and the intercept is minimal if the assumed value of **M** is close to the "ideal" one and maximal if the assumed value is much greater than the "ideal" one.

The simulated distribution of values of the intersect has a marked assymetrical pattern with assumed values of **M** which significantly differ from the "ideal" value and is close in its shape to normal distribution of the values close to the "ideal" one.

Two peculiar features of the values were revealed from simulation results. Firstly, if the assumed value of **M** exceeds the "ideal" one, then the shift of the absolute intersect values is very small and markedly unlike the difference between the "ideal" and assumed values of **M**.

For example, with the assumed **M** of 0.72 the value of this shift is not greater than 0.02 to 0.04 and is comparable with the value of shift with the "ideal" value of **M** (Figure 1).

This fact has a theoretical foundation. In his paper, Hilden (1988) showed that if the error $\Delta \mathbf{M}$ is introduced to the natural mortality rate when performing the VPA, then the below is true:

$$exp\left(\mathbf{F}_t' + \Delta\mathrm{M}\right) > exp\left(\mathbf{F}_t\right)$$

where $\mathbf{F}_t'$ is the fishing mortality rate value produced from VPA, with incorrect natural mortality rate $\mathbf{M}+\Delta\mathbf{M}$;

$\mathbf{F}_t$ is "ideal" value of fishing mortality rate. Then if $\Delta\mathbf{M}$ is positive, $\mathbf{F}_t'$ will be closer to $\mathbf{F}_t$ than in case when $\Delta\mathbf{M}$ is negative. This was the feature confirmed by the simulation results.

The second peculiarity of the values lies in the fact that the shift of the value of the regression equation intersect in all cases appeared to be smaller in terms of absolute value than deviation of the assumed **M** from its "ideal" value. No theoretical explanation was found for this case. Evidently this can be hardly done in a general form as fishing mortality rate values produced by the VPA depend not only on ΔM but also on the values of **F** for preceding age groups (Hilden, 1988).

However, in general, the results of simulation showed that the suggested approach (Gasyukov and Dorovskikh, 1990) makes it possible to specify the value of natural mortality rate for commercial fishes.

6. CONCLUSION

The suggested method for deriving natural mortality rate is based on a regression equation between the fishing mortality rate computed from the VPA using an assumed natural mortality rate, and fishing effort. If the selected natural mortality rate is correct, the intersect of this equation will be close to zero. Otherwise its value will be different from zero.

The study carried out with the use of the mathematical simulation by using *C. gunnari* fishing in Subarea 48.3 as an example showed that the suggested approach gives reliable estimates. If there is an error in the natural mortality rate, the absolute intersect (a) in equation (2) is different from zero; the shift has a positive sign if the assumed value of the natural mortality rate is smaller than the "ideal" one, but close to zero or somewhat greater than zero if the assumed value is greater than the "ideal" one.

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Table 1. Age composition of catches of *C. gunnari* (n x 10^6).

	82/83	83/84	84/85	85/86	86/87	87/88	88/89	89/90
1	25.97	98.63	5.28	21.64	6.92	8.60	10.25	1.81
2	162.20	167.08	18.20	39.62	207.12	12.42	128.89	3.13
3	428.08	120.92	47.05	34.01	276.94	70.06	14.47	29.09
4	68.13	76.11	12.71	1.89	19.31	35.51	9.18	3.16
5	24.97	21.54	1.800	0.670	4.210	25.16	11.49	1.83
6	8.55	4.31	0.540	0.130	0.700	6.85	2.31	0.89
Total	717.9	488.6	85.6	98.0	515.2	158.6	176.6	39.9

Table 2. Average fish mass (in grams) for *C. gunnari* in Subarea 48.3

	82/83	83/84	84/85	85/86	86/87	87/88	88/89	89/90
1	29.7	35.8	23.4	29.7	24.9	17.7	23.4	19.2
2	87.8	97.2	79.0	87.8	81.9	70.6	79.0	74.6
3	175.8	189.0	163.3	175.8	167.4	151.0	163.3	160.7
4	291.8	308.0	276.0	291.8	281.2	260.5	276.0	293.0
5	430.2	448.9	411.9	430.2	418.0	393.8	411.9	467.0
6	585.2	605.5	565.2	585.2	571.8	545.3	565.2	615.0

Table 3. Catch in weight and standardised effort.

Year	Total catch	Effort
80/81	29464	14142
81/82	47454	7182
82/83	131576	20420
83/84	80664	15798
84/85	14293	2984
85/86	11368	4483
86/87	71853	20035
87/88	37736	15941
88/89	22213	7972
89/90	7268	1497

Table 4. Population numbers of *C. gunnari* in Subarea 48.3 (x10^6).

	82/83	83/84	84/85	85/86	86/87	87/88	88/89	89/90
1	952.2	945.0	1796.2	1091.5	461.3	1803.8	1175.0	1049.7
2	542.3	524.6	466.7	1022.0	607.4	258.3	1023.9	663.5
3	696.5	191.4	178.0	253.0	554.3	196.4	138.3	489.5
4	133.6	97.7	24.8	67.2	119.4	119.0	61.3	68.3
5	40.9	27.8	4.6	5.1	37.0	54.0	42.0	28.3
6	14.7	5.8	1.3	1.3	2.4	18.0	12.8	15.6
Total	2380	1792.2	2471.5	2440.2	1781.7	2449.4	2453.4	2314.9

Table 5. Fishing mortality rate of *C. gunnari* in Subarea 48.3.

	82/83	83/84	84/85	85/86	86/87	87/88	88/89	89/90
1	0.036	0.145	0.004	0.026	0.020	0.006	0.011	0.002
2	0.481	0.521	0.052	0.052	0.569	0.065	0.178	0.006
3	1.404	1.482	0.414	0.191	0.979	0.604	0.146	0.080
4	1.011	2.504	1.018	0.037	0.234	0.480	0.215	0.062
5	1.389	2.469	0.691	0.185	0.160	0.880	0.431	0.089
6	1.269	2.154	0.710	0.138	0.459	0.658	0.265	0.077

Table 6. Intercept values of regression equation from the results of simulation runs.

	Weighing by **N**			Weighing by **C**		
M	Value of **a** Mean	median	Discard interval **a** in histogram	Value of **a** Mean	median	Discard interval **a** in histogram
0.35	0.087	0.082	[0.056 ; 0.177] :	0.102	0.083	[0.045 ; 0.302]
0.48	0.042	0.039	[-0.012 ; 0.115] :	0.065	0.050	[0.019 ; 0.196]
0.56	0.014	0.016	[-0.086 ; 0.082] :	0.038	0.025	[0.005 ; 0.146]
0.72	-0.036	-0.025	[-0.189 ; 0.019] :	-0.012	-0.016	[-0.048 ; 0.058]
1.00	-0.084	-0.051	[-0.414 ; -0.030] :	-0.062	-0.047	[-0.177 ; 0.009]

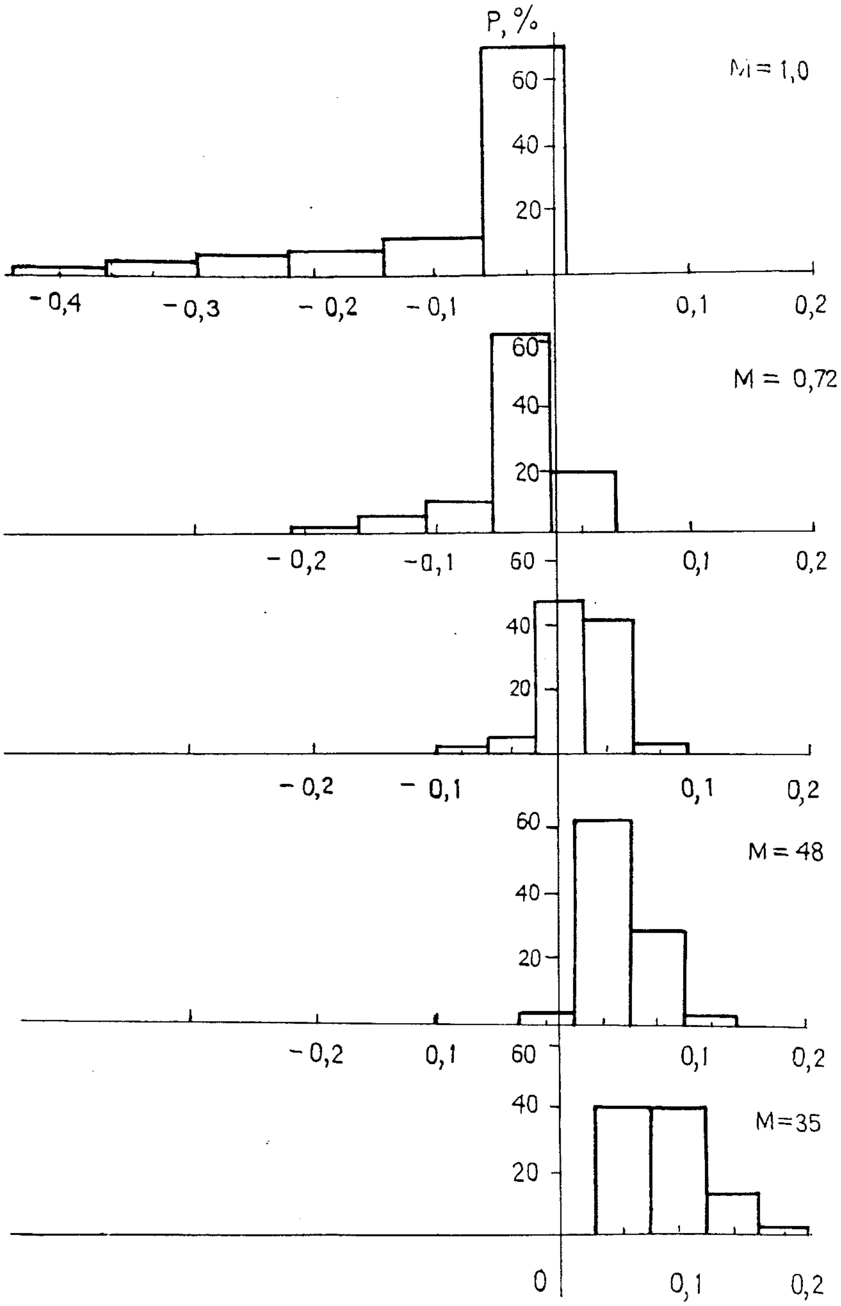

Figure 1: Histograms of intersect values of regression equation resulting from simulation modelling.

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