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# A ZOOPLANKTON BIOINDICATION SYSTEM FOR THE MATSALU BAY: A PROBABILISTIC APPROACH

A bioindication technique is suggested that includes the use of fiducial data and excludes the data where an environmental factor is limiting the indicator character. The relationships between the object character (chlorophyll *a* concentration in water) and the indicator characters (zooplankton parameters) were calculated as joint distributions of relative probability. A smoothing method was used. The fiducial probabilities and relative probabilities of indicator characters were multiplied. The results were presented as the expected probability distribution of chl *a* values. The middle point of the most probable chl *a* interval was used as a point estimation for the chl *a* prediction. The correlation coefficient between the measured and predicted chl *a* values was 0.809 ($P>0.999$). Judging by the data obtained the suggested bioindication technique is effective only from the end of May to the end of September.

## Introduction

We refer to bioindication as an indirect estimation of an environmental variable on the basis of a biological parameter. The hydrobiological bioindication is concerned mainly with the estimation of such complex characteristics of a water body as general toxicity (Алексеев, 1984), saprobity and the trophic state. Bioindication is also applicable for the estimation of certain single characteristics of the water environment such as e. g. pH, concentration of oxygen, chlorophyll, biogens or any other substances in water. The advantage of the latter approach lies in the possibility to present the results of bioindication in the unambiguous «language» of directly measurable parameters. Naturally, in the case of estimating direct parameters of the environment, as in the bioindication in general, the main task is the profound study of relationships between biological and environmental parameters. The application of bioindication methods is often limited because of the insufficient data on the indicator values and autoecology of species (Gray, 1985; Gannon, Stemberger, 1978; Pejler, 1981; Смирнов, 1984).

A special problem is how to present bioindication results. There are two principal approaches to the estimation of saprobity: the technique of Pantle and Puck (1955) modified by V. Sládeček (1973), which gives a point estimation of saprobity (saprobic index), and the technique of M. Zelinka and P. Marvan (1961), the outcome of which is an array of weighted mean saprobic valences. Most Soviet saprobity investigators have preferred the technique of Pantle and Puck in the modification of V. Sládeček. A. V. Makrushin and L. A. Kutikova have motivated their preference with computation convenience (Макрушин, Кутикова, 1976). However, taking into account the availability of computer equipment, the argument in favour of computing convenience cannot be considered very seriously at the present time.

The relationships between biological and environmental parameters are statistical and subjected to the influence of many other biological and environmental circumstances. Therefore, the reliability of bioindication as an indirect estimation is never absolute, the results of bioindication hold true only with a certain probability. Consequently, the presentation of bioindication results as a probability distribution contains more information and is theoretically reasonable.

Although the saprobic valence of M. Zelinka and P. Marvan is only «a subjective value given by an investigator according to his experience and to data in the literature» (Sládeček, 1983, p. 175), it can be regarded as an expression of intuitively estimated probability. Or, as M. Zelinka and P. Marvan (1961, p. 405) have expressed: «. . . saprobical valence of organisms [is] expressing the relative frequency of the species in different degrees of saprobity . . .».

An attempt to estimate the saprobic valences of rotifers from empirical data on the basis of occurrence frequencies (probabilities) was made by P. Cimdin (Андрушайтис et al., 1981; Цимдинь, 1979).

## Material and methods

The same data on zooplankton and environmental conditions, and the logarithmic transformation as described by K. Remm (1987) were also used in the present study. In addition 83 chl *a* (chlorophyll *a* concentration in water) analyses made during the same period but with no matching zooplankton samples were used.

The approach proposed in this paper is presented on chl *a*, as an indicator of the trophic state of the water of a water body, and zooplankton data from the Matsalu Bay. The other environmental conditions under consideration were the date, salinity, water temperature, and depth of the sampling station. The approach can be divided into the following issues: 1) defining fiducial data if there exist any (the expected frequency distribution of chl *a* values on a particular occasion), 2) specifying the list of indicator characters (zooplankton indicators), 3) finding the limits in which the indicator character is not strongly limited by the main environmental conditions, 4) excluding these data from the analysis of relationship where at least one of the main environmental factors is strongly limiting for a particular indicator character, 5) describing relationships between the environmental variable (chl *a*) and indicator characters, 6) using the fiducial data and indicator characters in order to estimate the value of the environmental variable.

## Fiducial data

The first source of information for predicting chl *a* value for a sample is the observed frequency distribution of chl *a* in the particular area and subseason. The frequency distribution of chl *a* was calculated for every part of the Matsalu Bay, for every month from May till September, and also on the basis of all the data (Figs 1, 2). For smoothing out occasional fluctuations caused by the limited amount of data, the modified moving average technique was used (Remm, 1987).


Fig. 1. Sampling stations and parts of the Matsalu Bay (*A* — western part, *B* — central part, *C* — eastern part, *D* — reedbed area).

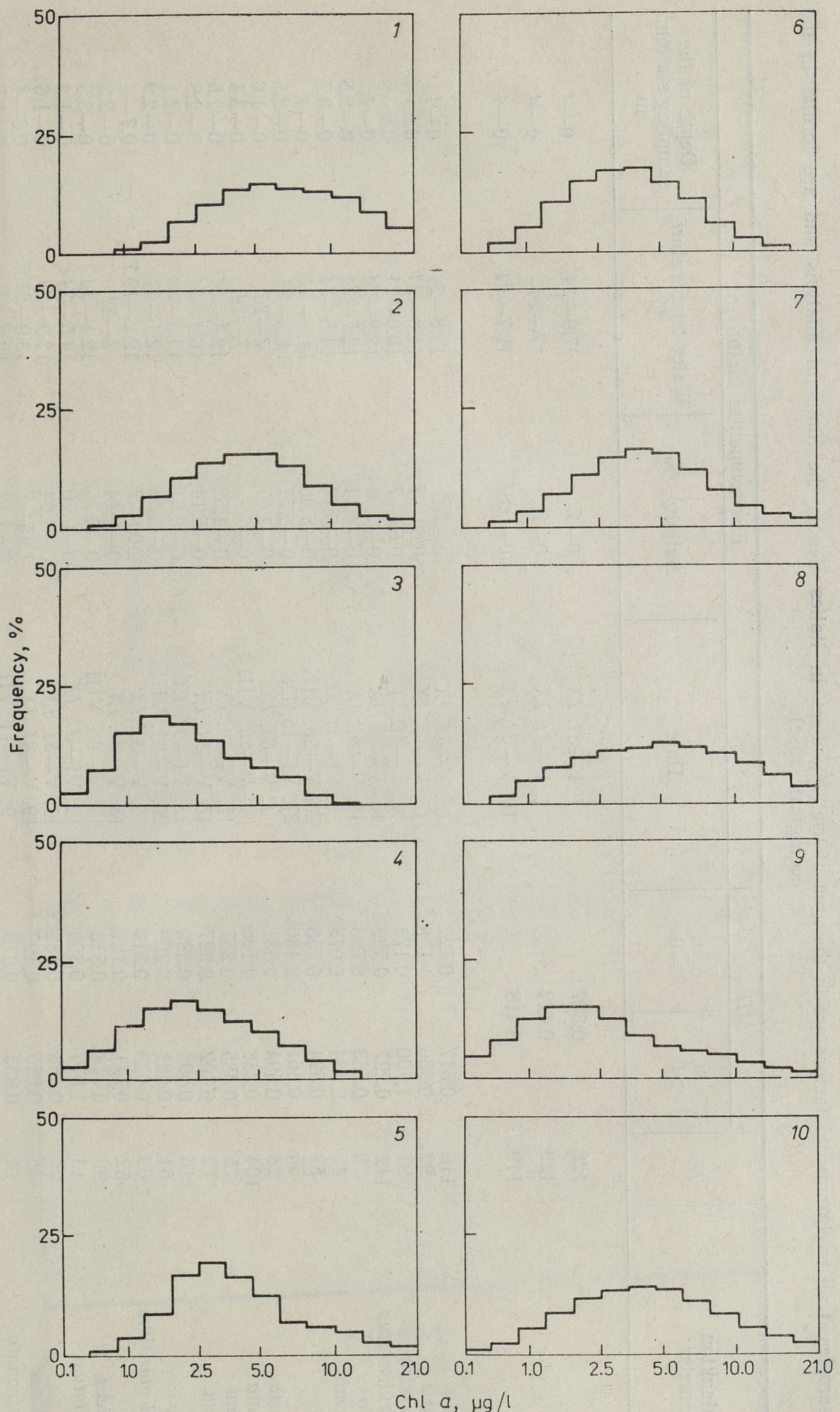


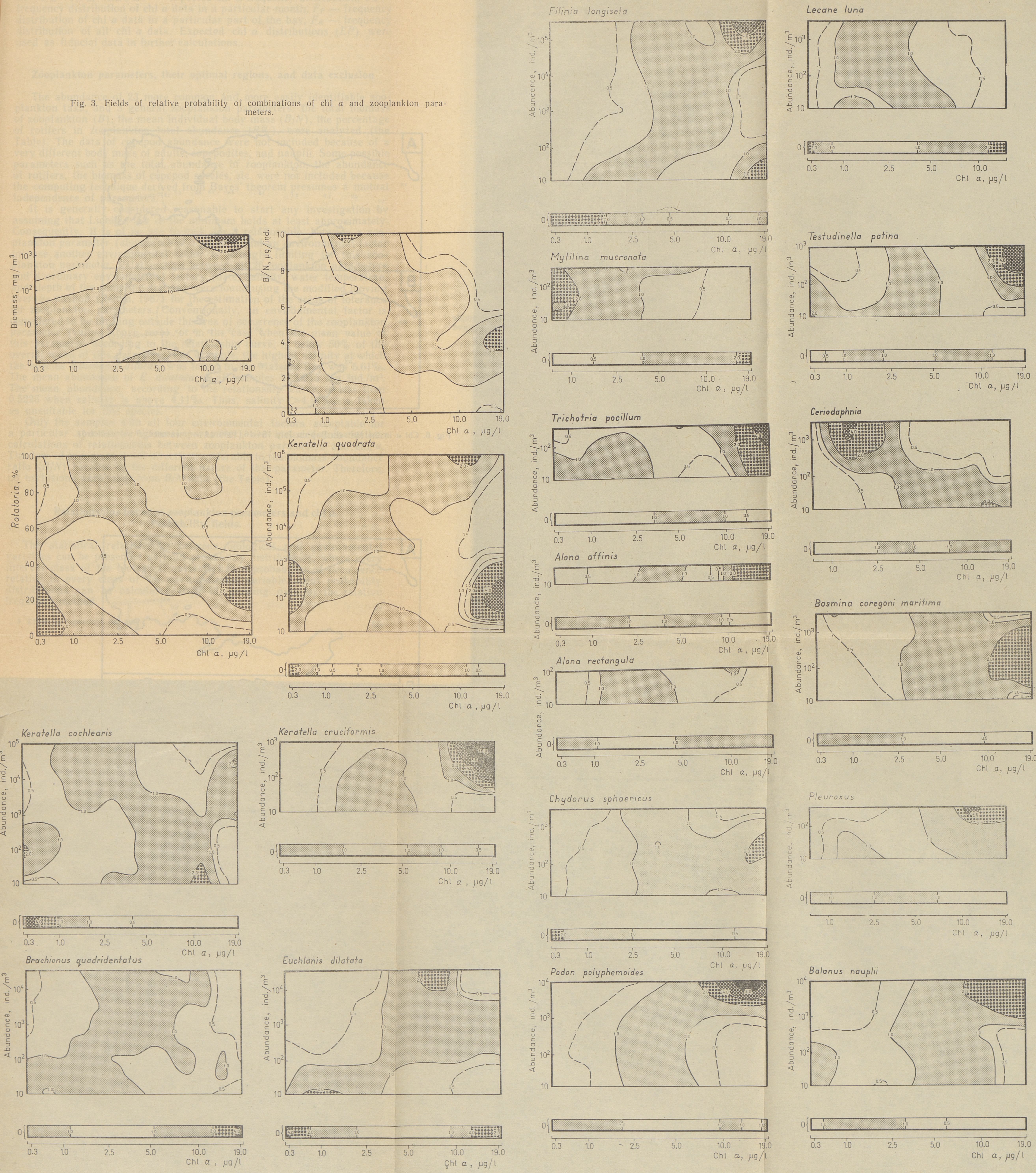

Fig. 2. Smoothed frequency distributions of chl *a* values in the Matsalu May (*1* — May, *2* — June, *3* — July, *4* — August, *5* — September, *6* — reedbed area, *7* — eastern part, *8* — central part, *9* — western part, *10* — all data from the Matsalu Bay).

**Zooplankton parameters, their indicator values (*MD*), and areas of use in the Matsalu Bay**

(*N* — number of samples if all environmental factors are in the area of use. Numbers in italics denote the limits of analysis and are formal in the ecological sense)

| Zooplankton parameter | *N* | *MD* | | Environmental factor | | | |
|---|---|---|---|---|---|---|---|
| | | >0 | =0 | Date | Salinity, ‰ | Water temperature, °C | Depth of the sampling station, m |
| *B* | 128 | 0.387 | | *1. V—31. IX* | 0—*7* | 7.9—*24* | 0—*4* |
| *B/N* | 129 | 0.422 | | *1. V—31. IX* | 0—*7* | *7—24* | 0—*4* |
| *R*% | 119 | 0.418 | | 19. V—*31. IX* | 0—6.87 | 12.7—*24* | 0—*4* |
| Log abundance of | | | | | | | |
| *Keratella quadrata* | 119 | 0.517 | 0.522 | 19. V—*31. IX* | 0—*7* | 12.8—*24* | 0—*4* |
| *Keratella cochlearis* | 92 | 0.336 | 1.178 | 15. V—15. IX | 0.68—*7* | 14.8—*24* | 0.6—*4* |
| *Keratella cruciformis* | 97 | 1.900 | 0.173 | 2. V—*31. IX* | 0.69—*7* | 10.6—21.4 | 0.6—*4* |
| *Brachionus quadridentatus* | 112 | 0.227 | 0.599 | 15. V—25. IX | 0—*7* | 12.2—*24* | 0—*4* |
| *Euchlanis dilatata* | 70 | 0.563 | 0.763 | 19. V—*31. IX* | 0—4.11 | 12.7—*24* | 0—2.5 |
| *Euchlanis pyriformis* | 82 | 0.334 | 0.078 | 9. VI—*31. IX* | 0—5.14 | 14.5—*24* | 0—3.1 |
| *Filinia longiseta* | 87 | 0.594 | 0.738 | 20. V—23. VIII | 0—5.36 | 14.3—*24* | 0—*4* |
| *Lecane luna* | 55 | 0.361 | 0.466 | 27. VI—15. IX | 0—5.77 | 14.5—*24* | 0—3.5 |
| *Mytilina mucronata* | 28 | 0.594 | 0.531 | *1. V—31. IX* | 0—1.07 | *7—24* | 0—1.6 |
| *Notholca acuminata* | 104 | 0.238 | 0.108 | *1. V*—22. VIII | 0—*7* | *7—24* | 0—3.5 |
| *Testudinella patina* | 75 | 0.585 | 0.257 | 15. V—*31. IX* | 0—4.52 | 12.4—*24* | 0—2.5 |
| *Trichotria pocillum* | 72 | 0.702 | 0.227 | 15. V—*31. IX* | 0—5.14 | 16.4—*24* | 0—2.9 |
| *Alona affinis* | 16 | 0.696 | 0.392 | 15. VI—*31. IX* | 0—3.61 | 15.3—*24* | 0—2.1 |
| *Alona rectangula* | 51 | 0.521 | 0.209 | 20. V—21. VIII | 0—3.66 | 12.1—*24* | 0—2.9 |
| *Bosmina coregoni maritima* | 62 | 0.673 | 0.512 | 12. V—*31. IX* | 2.00—*7* | 12.2—19.7 | 0.7—*4* |
| *Ceriodaphnia* | 52 | 0.771 | 0.127 | 18. V—*31. IX* | 0—2.44 | *7—24* | 0—2.3 |
| *Chydorus sphaericus* | 96 | 0.414 | 0.513 | 19. V—26. VIII | 0—5.75 | 12.1—*24* | 0—3.5 |
| *Eurycercus lamellatus* | 13 | 1.977 | 0.369 | 12. VI—*31. IX* | 0—0.10 | 14.5—*24* | 0—1.3 |
| *Pleuroxus* | 26 | 0.488 | 0.189 | 17. V—*31. IX* | 0—1.04 | 12.9—*24* | 0—1.6 |
| *Podon polyphemoides* | 88 | 0.825 | 0.197 | 19. V—*31. IX* | 1.45—*7* | 13.0—21.5 | 0.6—*4* |
| *Scapholeberis mucronata* | 14 | 0.933 | 0.076 | 9. VI—11. VII | 0—1.12 | 18.8—*24* | 0—1.5 |
| *Simocephalus* | 9 | 1.320 | 0.548 | 13. VI—25. VIII | 0—0.12 | 18.2—*24* | 0—0.9 |
| *Balanus nauplii* | 87 | 1.152 | 0.544 | 8. VI—*31. IX* | 1.30—*7* | 13.8—*24* | 0—*4* |

Fig. 3. Fields of relative probability of combinations of chl *a* and zooplankton parameters.



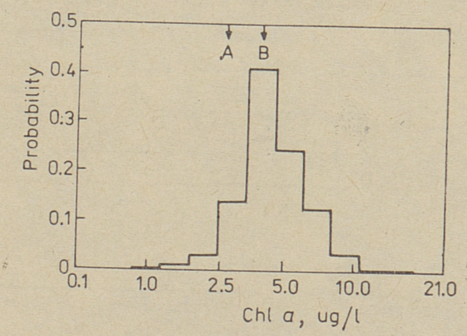



Fig. 4. An example of the probability distribution of predicted chl *a* values for a sample collected from the eastern part of the Matsalu Bay on June 9, 1981 (*A* — chl *a* measured = 2.7 μg/l, *B* — chl *a* predicted = 4.0 μg/l).

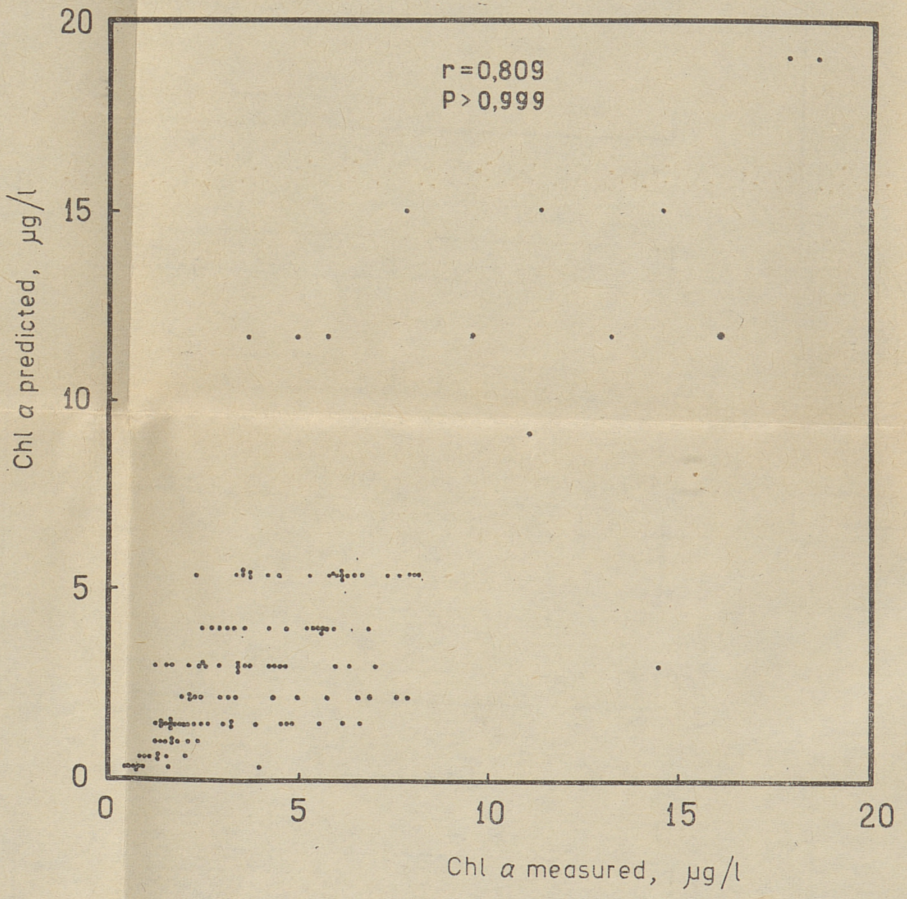



Fig. 5. Scatter diagram of measured chl *a* and the prediction.

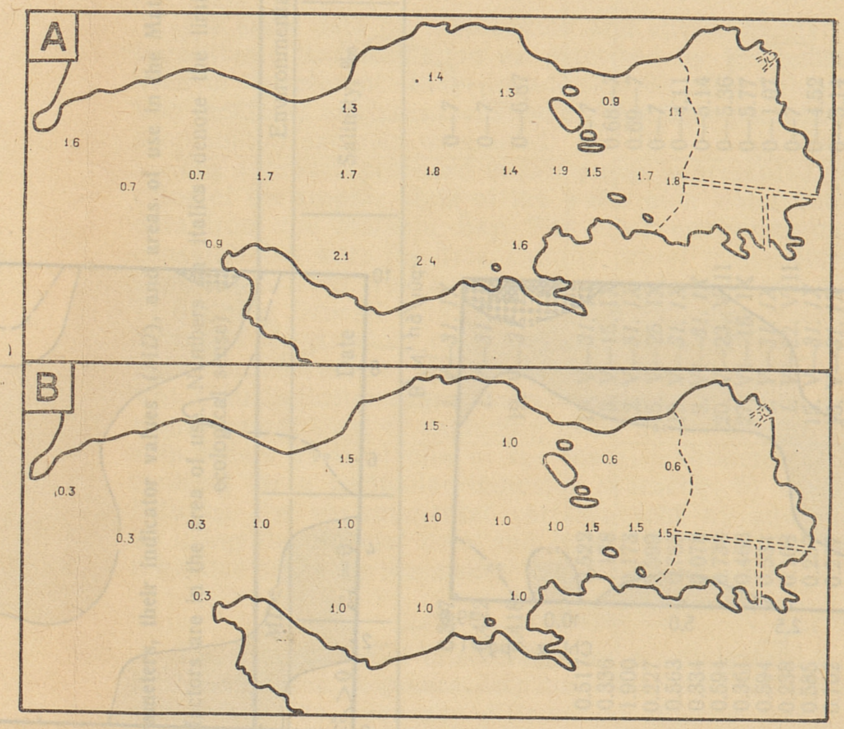



Fig. 6. Chl *a* in the Matsalu Bay on July 15—16, 1980 (*A* — measured, *B* — predicted).

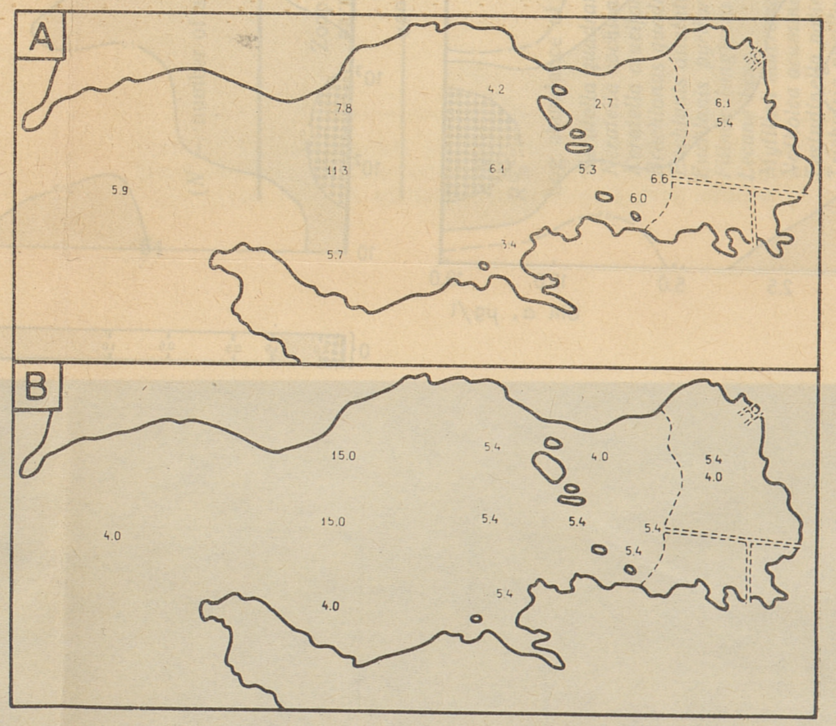



Fig. 7. Chl *a* in the Matsalu Bay on June 8—9, 1981 (*A* — measured, *B* — predicted).

As the number of measurements was clearly insufficient for calculating reliable frequency distributions of chl *a* data for all parts of the bay each month, these distributions were interpolated according to the formula $EP = F_M \cdot F_P / F_A$, where $EP$ — expected chl *a* frequency distribution, $F_M$ — frequency distribution of chl *a* data in a particular month, $F_P$ — frequency distribution of chl *a* data in a particular part of the bay, $F_A$ — frequency distribution of all chl *a* data. Expected chl *a* distributions ($EP$) were used as fiducial data in further calculations.

## Zooplankton parameters, their optimal regions, and data exclusion

The abundance of 23 more common and more easily identifiable zooplankton taxa, and 3 general zooplankton parameters: the total biomass of zooplankton ($B$), the mean individual body mass ($B/N$), the percentage of rotifers in zooplankton total abundance ($R\%$), were analyzed (the Table). The data of copepod abundance were not included because of a very different body mass of adults, copepodites, and nauplii. Some possible parameters such as the total abundance of zooplankton, the abundance of rotifers, the biomass of copepod species, etc. were not included because the computing technique derived from Bayes' theorem presumes a mutual independence of parameters.

It is generally considered reasonable to start any investigation by assuming that Liebig's law of the minimum holds at least approximately. Consequently, it is of no use to look for a relationship between a zooplankton parameter (abundance of a species) and an environmental factor in case another environmental factor is strongly limiting for this zooplankton parameter. Relationships between all 26 zooplankton parameters and 4 ordinary environmental factors (date, salinity, water temperature, and depth of the sampling station) were found using the modified moving average method (Remm, 1987) for the estimation of the areas of tolerance for zooplankton parameters. Conventionally, an environmental factor is considered to be limiting outside the area of occurrence of the zooplankton parameter (values above zero), or in the case when the mean value of this parameter, according to the relationship curve, is below 50% of the overall mean of this parameter. For example, the highest salinity at which the species *Euchlanis dilatata* was found in the Matsalu Bay was 5.61‰. The mean abundance of *E. dilatata* of all samples is 1.045 log ind./m³. The mean abundance, according to the relationship curve, is less than 0.5225 when salinity is above 4.11‰. Thus, salinity >4.11‰ is taken as unsuitable for this species.

Only the samples with all four environmental factors acceptable for a particular species (or general parameter) are included into further calculations of relationships between zooplankton parameters and chl *a*. The law of minimum is not directly transferable to the biomass-abundance ratio ($B/N$) because of the different nature of this parameter. Therefore, no exclusions were made from $B/N$ data (the Table).

## Relationships between zooplankton parameters and chl *a*. Probability fields.

The statistical relationships between biological and environmental variables can be presented as joint probability distributions, where every interval class of the biological variable has a probability of occurrence relative to every class of the environmental variable. Joint probability distributions can be calculated from the existing data by the relative frequency method.

The division of $k$ variables into $n$ distribution classes results in $n^k$ classes for the joint distribution of $k$ variables. Therefore, the shortage of data is a common obstacle in the reliable estimation of the joint probability distribution of ecological variables. Occasional fluctuations in frequencies due to the small number of observations in every class of joint distribution will disguise the real relationship. This problem can be mitigated by smoothing down occasional fluctuations. A smoothing technique described in an earlier paper of the author (Remm, 1987) is applicable also in this case. According to the method the contributions of data ($Y_i$) in the area of averaging ($MX_j \pm E$) were weighted by multiplying with the corrective coefficient ($Q_{ij}$), calculated from the formula $Q_{ij} = 1 - (MX_j - X_i)^2/E^2$; the weighted means ($\bar{Y}_j$) were calculated as

$$\bar{Y}_j = \frac{\sum_i (Q_{ij} \cdot Y_i)}{\sum_i Q_{ij}},$$

where $X_i$ — environmental variable, $Y_i$ — biological variable, $MX_j$ — midpoint of the averaging area, $E$ — extent of averaging, $i$ — index of a sample, $j$ — index of the step of the moving average. Notice that only the data with $MX_j - E < X_i < MX_j + E$ are included into the calculations of every $\bar{Y}_j$.

In the case of joint distributions averaging has to take place over more than one variable (over chl $a$ and a zooplankton variable in the present study). As the areas of averaging are overlapping and the sum of probability distribution must be equal to 1 the probabilities ($P_{jl}$) were calculated as

$$P_{jl} = \sum_i Q_{ijl} / \sum_{ijl} Q_{ijl},$$

where only the data with $MX_j - E_1 < X_i < MX_j + E_1$ and $MY_l - E_2 < Y_i < MY_l + E_2$ are included into the calculation of $P_{jl}$, otherwise $Q_{ijl} = 0$; $Q_{ijl}$ — a corrective coefficient analogous to $Q_{ij}$, $j$ — index of the class of variable $X$, $l$ — index of the class of variable $Y$, $MX_j$ — midpoint of the averaging area along the $X$-axis, $MY_l$ — midpoint of the averaging area along the $Y$-axis, $E_1$ — extent of averaging for variable $X$, $E_2$ — extent of averaging for variable $Y$.

The step intervals and extents of averaging were 0.1 and 0.25 for log (chl $a$+1), log ($B$+1), and log abundances of zooplankton taxa; 1 µg and 2 µg for $B/N$, 10% and 20% for $R$%, respectively. In general, the larger is the number of data, the narrower should be the extents of averaging.

As different values of chl $a$ and zooplankton parameters occur naturally with a different frequency, e. g. chl $a$ concentrations below 0.5 µg/l and above 10 µg/l were rare in the Matsalu Bay, $P_{jl}$ expresses, first and foremost, the frequency distributions of the values of chl $a$ and zooplankton parameters but not indicator valences. For bioindication purposes probabilities $P_{jl}$ were turned to relative probabilities ($RP_{jl}$) : $RP_{jl} = P_{jl} / P_j \cdot P_l$, where $P_j$ and $P_l$ are the marginal probabilities. If $RP_{jl} > 1$ then this combination of chl $a$ and zooplankton parameter values is more frequent than could be expected from separate distributions of these variables, and vice versa.

The relationships between chl $a$ and zooplankton parameters are graphically depicted as probability fields with isolines of equal relative probability (Fig. 3). Five zooplankton taxa were omitted because the relationship is statistically weak and ecologically unrealistic (*E. pyriformis*, *N. acuminata*), or because the number of samples inside the tolerance limits is very small (*E. lamellatus*, *S. mucronata*, *Simocephalus*) (the Table).

To draw comparisons between relationships the mean deviation of relative probability, which presents the indicator value of a zooplankton parameter, was used. For general parameters (*B*, *B/N*, *R*%) it was calculated as

$$MD = \sum_{jl} |1 - RP_{jl}| / (J \cdot L),$$

where $j = 1 \ldots J$ and $l = 1 \ldots L$. In the case of the abundances of zooplankton taxa the mean deviation of relative probability was calculated separately for samples where this taxon was absent (abundance = 0) and for the abundances above 0 (in reality the abundances were $\geqslant 10$ ind./m$^3$ because the volume of the sample was never $> 0.1$ m$^3$). These mean deviation figures are certainly formal to a great extent, as the indicator value of a species may be and is different in particular cases (Винберг, 1981; Дзюбан, Кузнецова, 1981; Кутикова, 1986).

The relationships between zooplankton parameters and environmental factors will be analyzed in a further article.

## Bioindication

As has already been mentioned, the expected frequency distributions of chl *a* values in different parts of the bay in different months were used as fiducial data for the prediction. In case there were no data or any indirect knowledge on the expected occurrence probability of different values of the environmental variable under study then the *prior* probability of all values would be equal.

Let us assume that the *prior* probability distribution of chl *a*, the abundance of a zooplankton species, and the relationship between chl *a* and this zooplankton species are known. The next step is making a cross-section through the field of relative probabilities at the location of the observed abundance of the species. The intermediate values of relative probability between the $RP_{jl}$ figures were interpolated proportionally to the distance from the nearest midpoint of the averaging area ($MY_l$).

Now it is possible to derive a corrected or *posterior* probability distribution from these data. M. Zelinka and P. Marvan (1961) have used, though without giving a motivation, the method of weighted means for combining the saprobic valences of different species. In the present case, however, as relative probabilities are under consideration, weighted means are unsuitable, and it is proper to proceed from Bayes' theorem. Consequently, the *prior* and relative probabilities have to be multiplied.

Since the presumptions of Bayes' theorem are not followed exactly (*prior* probabilities are calculated before the exclusion of samples with unsuitable environmental conditions for a particular species, while relative probabilities are calculated after the exclusion) a normalization was used:

$$FP_j = EP_j \cdot RP_{jl} / \sum_j (EP_j \cdot RP_{jl}),$$

where $FP_j$ — *posterior* probability of chl *a*.

Further, as there are generally more than one zooplankton indicator character per sample, the following formula was used:

$$FP_j = EP_j \cdot \prod_k RP_{jlk} / \sum_j (EP_j \cdot \prod_k RP_{jlk}),$$

where $k$ — index of zooplankton parameter. Recall that only these zooplankton parameters were used for which the date, salinity, water temperature, and depth of the station of a particular sample were not limiting.

Thus, the final result of bioindication calculations is given as a distribution of chl *a* probabilities with a chl *a* interval of highest expectation. The middle of the most probable chl *a* interval was used as a prediction (Fig. 4).

## Results and discussion

The fitness of any indication method is determined mainly by the precision of the prediction. Perhaps the best way to check the precision is to compare the real values of chl *a* to the predicted ones. When three samples with extraordinarily high and perhaps erroneous chl *a* concentration were omitted the correlation coefficient between the real and predicted chl *a* values was 0.809 ($n=137$, $P>0.999$) (Fig. 5). In the case of the most striking deviation in chl *a* values the zooplankton was indeed nontypical for the measured chl *a* concentration. In other words, sometimes the chl *a* concentration in water indicates one level of trophy while zooplankton on quite another level at the same time. An overwhelming majority of strong deviations were accompanied by high chl *a* concentrations which did not reflect in zooplankton.

The dependence of relative deviations

$$\frac{|\text{chl } a \text{ measured} - \text{chl } a \text{ predicted}|}{\text{chl } a \text{ measured}}$$

on the parts of the bay and season was analysed by using ANOVA, and on the other environmental factors by using regression analysis. The prediction was relatively more exact when water temperature and the number of indicator characters was higher ($r=0.229$, $P>0.99$ and $r=0.259$, $P>0.99$, respectively). The mean relative deviation was 0.659 in May, 0.294 in June, 0.427 in July, 0.374 in August, and 0.293 in September ($P>0.95$, F-test). No statistically significant relationships at $\alpha=0.05$ level were found between the relative deviation and other variables.

There is a clear connection between the first-mentioned factors: the number of parameters excluded from the calculations is high at lower water temperatures, six species are included not before June and the others mainly from about the middle of May (the Table), and water temperatures are usually lowest in the first half of May during the analyzed period. Consequently, the reliability of the suggested zooplankton bioindication system is ineffective in the first half of May.

For further illustration the chl *a* data of two expeditions are given together with the chl *a* concentrations predicted by zooplankton (Figs 6, 7). Differences between the real and predicted values are not large and general tendencies are the same. Namely, chl·*a* concentrations are higher in all sampling stations in June 1981 than in July 1980, chl *a* concentrations are especially low in the mouth area of the bay in July 1980, chl *a* concentrations are highest in two stations in the central part of the bay in June 1981.

## Conclusions

The main purpose of this study was to suggest a new method of bioindication. The technique was presented on an example of data from the Matsalu Bay. In spite of 1) the complexity of the ecosystem under study (great importance of macrophytes in primary production, irregular water movement), 2) the fact that only 4 environmental factors, besides chl *a*, were taken into account, while these were used only for excluding some data, 3) the effect of environmental factors on chl *a* was not considered, 4) shortage of data: the real chl *a* values and the values predicted on the basis of zooplankton were in a satisfactory accordance. The suggested approach to bioindication is naturally far from ideal but considering the above-mentioned shortcomings which can be avoided to a great extent, there seem to be perspectives for the improvement of the technique. Presumably the technique is applicable also using other organisms, probably nearly everywhere in the field of bioindication if there exists a suitable data base for the calculations of the relationships between ecological parameters.

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## ZOOPLANKTONI BIOINDIKATSIOONISÜSTEEM MATSALU LAHE JAOKS: TÕENÄOSUSLIK LÄHENEMISVIIS

Töös on esitatud bioindikatsiooni metoodika, mida võib liigitada järgmisteks osadeks: 1) eelandmete määratlemine; 2) indikaatortunnuste väljavalimine; 3) indikaatortunnuste kasutatavuspiiride kindlakstegemine; 4) nende andmete väljajätmine, kus mõni teine keskkonnategur peale sihttunnuse on indikaatortunnuse suhtes tugevasti limiteeriv; 5) sihttunnuse ja indikaatortunnuste vaheliste seoste kirjeldamine; 6) eelandmete ja indikaatortunnuste kasutamine sihttunnuse hindamiseks.

Metoodika esitamiseks on kasutatud Matsalu lahest aastail 1977—1986 maist septembrini kogutud zooplanktoni ja mõnede keskkonnategurite andmeid. Sihttunnuseks oli klorofüll *a* sisaldus vees (chl *a*) kui üks universaalsemaid veekogu pelagiaali troofsusastme näitajaid. Eelandmetena kasutati chl *a* sisalduste oodatavaid sagedusjaotusi lahe eri osades kuude kaupa. Indikaatortunnusteks olid algselt 26 zooplanktoni tunnust: 3 üldtunnust — üldbiomass (*B*), zooplankterite keskmine mass (*B/N*), keriloomade protsent üldarvukusest (*R*%) — ja 23 taksoni arvukus. Modifitseeritud libiseva keskmise meetodil (Remm, 1987) analüüsiti zooplanktoni tunnuste seoseid aastaaja, vee soolsuse, vee temperatuuri ja proovivõtukoha sügavusega, et teha kindlaks, millistes piirides on mainitud keskkonnategurid ühele või teisele zooplanktoni tunnusele mittelimiteerivad. Tinglikult arvati keskkonnategur limiteerivaks, kui zooplanktoni tunnuse väärtus ei ole üheski proovis üle nulli (liiki ei ole leitud) või kui zooplanktoni tunnuse keskmine väärtus (keskmine arvukus) seose kõvera järgi on alla 50% vastava tunnuse väärtuste üldkeskmisest.

Seoste arvutamisel chl *a* ja zooplanktoni tunnuste vahel võeti arvesse vaid need proovid, kus ükski neljast keskkonnategurist ei ole parajasti vaadeldavale liigile limiteeriv.

Seosed sihttunnuse ja indikaatortunnuste vahel arvutati lähtudes chl *a* ja zooplanktoni tunnuse väärtuste esinemissagedustest suhteliste tõenäosustena, kasutades silumist üle mõlema tunnuse. Graafiliselt on seosed esitatud tõenäosusväljadena, millel on kujutatud võrdse suhtelise tõenäosuse isoliinid (joon. 3).

Kasutades eelandmeid ning seoseid sihttunnuse ja indikaatortunnuste vahel arvutati sihttunnuse (chl *a*) oodatav tõenäosusjaotus järgmise valemi abil:

$$FP_j = EP_j \cdot \prod_k RP_{jlk} / \sum_j (EP_j \cdot \prod_k RP_{jlk}),$$

kus $j$ on sihttunnuse vahemiku indeks, $l$ — indikaatortunnuse väärtusvahemiku indeks, $k$ — indikaatortunnuse indeks, $FP_j$ — sihttunnuse väärtusvahemiku prognoositud tõenäosus, $EP_j$ — sihttunnuse väärtusvahemiku tõenäosus eelandmete järgi, $RP_{jlk}$ — $k$-nda indikaatortunnuse esinenud väärtuste ja sihttunnuse vahemikus $j$ oleva väärtuse koosesinemise suhteline tõenäosus. Sihttunnuse punkthinnanguna kasutati kõige tõenäolisema chl *a* vahemiku keskpunkti.

Korrelatsioonikordaja mõõdetud ja prognoositud chl *a* väärtuste vahel oli 0,809 ($n=137$, $P>0{,}999$) (joon. 5). Esitatud bioindikatsiooni metoodika andis vähemtäpseid tulemusi maikuus, kui vee temperatuur on suhteliselt madal ja indikaatorliike esineb vähem.

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## СИСТЕМА ЗООПЛАНКТОННОЙ БИОИНДИКАЦИИ ДЛЯ МАТСАЛУСКОЙ БУХТЫ: ВЕРОЯТНОСТНЫЙ ПОДХОД

Изложена методика биоиндикации, которую можно разделить на следующие этапы: 1) определение предварительных данных, 2) выбор индикаторных показателей, 3) нахождение пределов, в которых индикатор не ограничивается другими условиями среды, 4) исключение из дальнейшего анализа таких данных, где рассмотренный индикатор лимитируется одним из основных факторов среды, 5) описание зависимостей между переменной среды и индикаторами, 6) использование предварительных данных и индикаторов для оценки значений переменной среды.

Использовали данные о зоопланктоне и некоторых факторах среды, собранные в Матсалуской бухте с мая до сентября 1977—1986 гг.

Целевым показателем было содержание хлорофилла *a* в воде бухты как одного из более универсальных показателей степени трофности пелагиали. Предварительными данными служили ожидаемые распределения значений chl *a* в разных частях бухты для каждого месяца в отдельности.

Анализировали численность 23 наиболее распространенных и легко определяемых таксонов и три общих параметра зоопланктона: общую биомассу ($B$), среднюю массу особей ($B/N$) и долю коловраток в общей численности зоопланктона ($R$, %). Модифицированным методом скользящей средней определяли связи между параметрами зоопланктона и четырьмя факторами среды (время года, соленость и температура воды, глубина станции). Фактор среды условно считался лимитирующим вне пределов наличия параметра зоопланктона при значениях выше нуля или же в случае средних значений параметра ниже 50%. В дальнейших расчетах учитывались лишь те зависимости между параметрами зоопланктона и chl $a$, где все четыре фактора среды были нелимитирующими для определенного вида или общего параметра.

Зависимости между параметрами зоопланктона и chl $a$ вычисляли как соединенные распределения вероятности с применением сглаживания через обе переменные.

Зависимости представлены графически в виде полей вероятности с изолиниями равных относительных вероятностей.

Ожидаемое распределение вероятностных значений chl $a$ вычислили по формуле

$$FP_j = EP_j \cdot \prod_k RP_{jlk} \Big/ \sum_j \left(EP_j \cdot \prod_k RP_{jlk}\right),$$

где $j$ — индекс промежутка значений chl $a$, $l$ — индекс промежутка значений параметра зоопланктона, $k$ — индекс параметра зоопланктона, $FP_j$ — предсказанная вероятность промежутка значений chl $a$, $EP_j$ — вероятность интервала значений chl $a$ по предварительным данным $RP_{jlk}$ — относительная вероятность соответствующей комбинации значений chl $a$ и параметра зоопланктона.

Середина наиболее вероятного промежутка значений chl $a$ использовалась как точечная оценка chl $a$. Коэффициент корреляции между измеренными и предсказанными значениями chl $a$ равнялся 0,809 ($n=137$, $P>0{,}999$). Прогноз был менее точен в мае, когда температура воды относительно низкая и встречаемость индикаторных видов наименьшая.