ESTIMATION OF CRITICAL LEVELS OF AIR POLLUTION (METALS) ON THE BASIS OF FIELD STUDY OF EPIPHYTIC LICHEN COMMUNITIES

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This method is the development of a classical toxicological technique for estimating toxicometric parameters (LD_{10}, LD_{50}, LD_{80}, etc.) based upon dose-response models (survival of *i*th species *vs* concentration of *j*th toxic substance under laboratory conditions). There are a number of similar examples of well-established methods in ecological toxicology [4]. It is well known that under natural conditions biotic and pollution parameters are highly variable both in space and time. This variability is taken into account in the method described below.

1. Aim

To estimate the safe levels of metal pollution for epiphytic lichen communities.

2. Method

2.1. EQUIPMENT AND MATERIALS

- Soil collecting equipment (well-polished steel shovel, plastic bags or containers),
- Apparatus for measuring metal content of soil and litter (or snow) samples (flame atomic absorption spectrometry - FAAS, or inductively-coupled plasma atomic emission spectrometry - ICP-AES),
- Equipment for description of epiphytic lichen communities (grids of appropriate kind, see below),
- Computer; statistical software with non-linear estimation module (e.g., Statistica for Windows, SAS, SPSS, S-Plus).

2.2. PROCEDURE

1. Carry out a reconnaissance study around a point emission source to provide a rough mapping of the state of lichen communities (indicating, at least: lichen desert zone, strong damage, transitional and background zones).

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2. Select 20-30 sample plots (25x25 m) comparable in their ecotope characteristics. Plots must represent different levels of pollution (from background to high).
3. Describe epiphytic lichen communities by a method suitable for the region, e.g.:
   - determine frequency using a sampling ladder (see chapter 19, this volume) or a sampling grid [3],
   - determine projective cover using a 10x10 cm or 20x20 cm grid,
   - determine the total number of lichen species on a certain substrate.
4. Sample an accumulative medium (such as forest litter, soil - A1-horizon – or snow) for assessment of the toxic load in each sample plot. Forest litter is preferable because of its high pollutant-accumulating capacity. High spatial variability of pollutant content in accumulative media (especially in transitional and strongly polluted zones) should be taken into consideration to provide representative sampling. Mixed samples are recommended for soil and forest litter (e.g. five random samples composed of five sub-samples each; of these five sub-samples, four are located at the corners of a 1 m^2 quadrate and one is in the center of the quadrate).
5. Measure (by FAAS or ICP-AES-method) contents of selected elements and compounds which reflect deposition (or accumulation) of the overall complex of pollutants. Trace metals, such as Cu, Cd, Ni, Zn, Pb, Hg, As, Co, and Sb, are recommended for smelting plants. When analyzing snow, the total content of selected pollutants should be determined and converted into the value of deposition (mass x $area^{-1}$ x $time^{-1}$). Both total content and content of extractable forms (in nitric or hydrochloric acids, ammonium nitrate, EDTA, etc.) are suitable for analysis of soil and forest litter (for detailed descriptions of procedures, see [1]).

3. Data analyses and interpretation

1. Calculate an index of the toxic load from the information on individual elements. Although a variety of such indexes is available [5], we recommend the mean ratio of concentration at the site to that in the background, as follows:

$$K_i = \frac{1}{N}\sum_{j=1}^{N}\frac{C_{ij}}{C_{bj}} \quad (1)$$

   where:

   K_i is the mean toxic load of the ith plot,
   C_{ij} is the concentration of jth element in the ith plot,
   C_{bj} is the concentration of jth element in the background zone,
   N is the number of elements.

   This index has no units, and gives an overall picture of how much the background level is exceeded in a certain sample plot. If the site is unpolluted, K_i=1.
2. Calculate lichen community parameters (IAP, LDV, projective cover, number of species, etc., see chapters 3-5, this volume).
3. Estimate a "Index of Toxic Load - lichen community parameter" relationship. As a regression model, the following logistic function can be recommended:

$$y = \frac{A - a_0}{1 + e^{\alpha + \beta x}} + a_0 \qquad (2)$$

where:

y is the response (lichen community parameter),
x is the dose of the load (e.g., K_i from equation 1),
α, β, a_0 and A are coefficients.

To find values for the coefficients in the equation, any method of non-linear numerical estimation is suitable (Marquardt method, Quasi-Newton method, Rosenbrock pattern search, etc.). In certain cases (when a parameter changes sharply under low pollution levels), log-transformation of K_i can be recommended. Several specific versions of the equation can be derived from the same set of data depending on start values of coefficients and initial step sizes. Take into consideration what the coefficients represent:

- A and a_0 are maximal and minimal values of a lichen community parameter, respectively;
- e determines the direction of the parameter change with an increase of pollution,
- the magnitude of β determines the sharpness of the change.

For iterative determination of the values for the coefficients, select the preset start values close to expected ones. Of the specific versions of the equation found, "the best one" should be selected, that which accounts for the maximal proportion of variance (R^2) and is closest to S pattern.

4. Calculate coordinates of critical points (i.e. inflections of the fitted curve) from the coefficients of "the best" fitting equation by regression to the data. Three critical points of the logistic curve are of ecological importance: upper, middle and lower. Their abscissae can be calculated using the following formulas:

$$X_U = \frac{-\alpha + \ln(2-\sqrt{3})}{\beta}, \quad X_M = -\frac{\alpha}{\beta}, \quad X_L = \frac{-\alpha + \ln(2+\sqrt{3})}{\beta} \qquad (3)$$

The upper point corresponds to the beginning of transition from the background state to that of impact, the lower corresponds to the end of this transition. The middle one corresponds to 50% change from background level. The abscissa of the upper inflection point is of great interest as this is a required value of safe pollution level. Since different parameters of lichen communities differ in their sensitivity to pollution, a range of safe levels can be obtained. The safe level which has the minimal value of all the community parameters is assumed to be the safe level for the community as a whole.

4. Worked example

This method was applied to data collected in the Middle Urals, in the vicinity of a copper-smelting plant. Epiphytic lichen communities of birch trunks were described in 198 sample plots (10 trees per plot; the frequency of lichen species was assessed by the method of Herzig and Urech [3]). Three mixed samples of forest litter were collected in each sample plot, and concentrations of Cu, Cd, Pb and Zn (5% nitric acid extraction) were determined by FAAS (see chapter 25, this volume). All these elements were included into K_i. Obtained K_i ranged from 1 to 132.14. An example of dose-response curve is shown in Figure 1 (number of species per base of trunk *vs* ln K_i). The resulting model (Equation 2) is:

$$y = \frac{6.15 - 1.00}{1 + e^{-5.80 + 1.97 * x}} + 1.00 \qquad \text{...(4)}$$

The abscissas of critical points (Equation 3) are:

$$X_U = \frac{-(-5.80)+\ln(2-\sqrt{3})}{1.97} = 2.28, \quad X_M = -\frac{-5.80}{1.97} = 2.95, \quad X_L = \frac{-(-5.80)+\ln(2+\sqrt{3})}{1.97} = 3.62$$

The actual K_i are: exp(2.28)=9.78; exp(2.95)=19.21; exp(3.62)=37.38, respectively. Thus, a sharp decrease in the average number of species per base of trunk begins when the background level of pollution is exceeded by 9.78 times. Results of the analyses of dose-response relationships for lichen communities are described in more detail by Mikhailova and Vorobeichik [6].

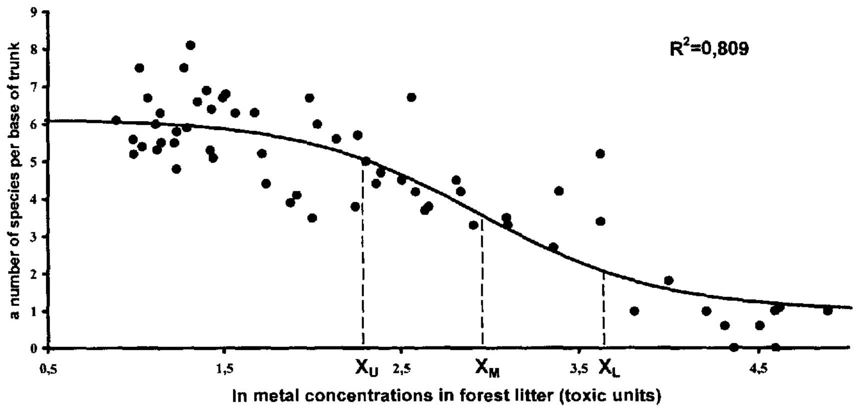

Figure 1. Dose-response relationship "the average number of species per base of birch trunk (0-50 cm) vs ln K_i". Only highly illuminated plots are included.

5. Data Quality control

Results can be accepted if 30-50% of the variance is explained by the regression model, which represents the effect of the pollution, and if the dose-response curve has a well-defined upper plateau, which represents the community parameter in unpolluted sites.

6. Application

Safe pollution levels found by this method may be useful in making decisions in environmental management (environmental and risk assessment, see [2]). Since lichens are generally recognized as the most sensitive indicators of air pollution, safe pollution levels found for them may be used as the highest standards of environmental quality.

7. Limitations

The method can only be applied with the conditions specified below:

- The parameters of lichen communities are monotonically dependent on pollution level.
- The pattern of this dependency is close to S-shape; or at least three clusters of points are detectable: upper (background level), intermediate, and lower (highest pollution).
- The sample plots are established homogeneously along the pollution gradient.
- The number of sample plots is sufficient for non-linear regression analysis (usually, no less than 20-30).
- The sample plots are comparable in ecotope features (position in relief, forest type, insolation, water regime, etc).

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