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Epiphytic Lichenosynusia under Conditions of Chemical Pollution: Dose–Effect Dependencies

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Abstract – The dose–effect dependencies, which characterize response of the epiphytic lichenosynusia of southern taiga in the Middle Urals to pollution by discharges of a copper-smelting plant, are substantially nonlinear and, in most cases, have an *S*-shaped form. A transition from background to impact state is very sharp and begins when the background level of pollution is exceeded by 1.5 - 2.3 times.

Epiphytic lichens are traditionally used as a subject for ecological monitoring and bioindicators of chemical pollution of the environment (Hawksworth and Rose, 1976; Nash and Gries, 1991; Richardson, 1992). Their high sensitivity to pollutants, noted as early as last century (Nylander, 1865), is due to the long lifetime of an individual thallus, absence of organs of water and gas exchange, and, hence, a low capacity for self-regulation and strong dependence on physicochemical properties of the environment (Martin, 1987; Trass, 1984; Nash and Gries, 1991). A considerable amount of information on the concentrations of certain, most widely distributed toxicants, which induce various disorders in lichens, has been obtained (Atlas and Scofield, 1975; Burton, 1986; Richardson and Nieboer, 1980). Some of these data were gained from laboratorial investigations, other – from field studies. In the latter case, the levels of pollution at which certain disorders are induced, as a rule, substantially vary due to differences in the structure of discharges, climatic conditions, methods of study, etc. For example, SO_2 concentrations at which "lichen deserts" arise range from 0.015 to 0.17 - 0.20 ppm (Brodo, 1972); i.e., they differ by an order of magnitude. Thus, the materials on absolute concentrations of pollutants are of narrow interest.

Most studies on using lichens as bioindicators were performed on the territory of cities and large industrial agglomerations. Natural habitats were much rarer. In the former case, the works include sufficiently big samples, making it possible to map the territory in detail. In the latter case, insufficient segmentation along the gradient of pollution (only "experiment," "control," and several intermediate sample areas) is a common defect. Such a scheme allows us to determine only general trends of changes and their range. Moreover, many important problems have not been considered. One of these problems is construction of the dose–effect dependencies, in which the amount of toxicants penetrating into an ecosystem is regarded as a dose, and parameters of condition of the lichenosynusia is an effect. These dependencies are necessary to understand how the lichen cover behaves under the stress of unfavorable factors and to determine the limits of stability of the lichens. In addition, the anthropogenic maximum tolerance load can be estimated by means of these dependencies. Many years ago, ecologists realized the importance of the dose–effect dependencies, which might be analogous with the dose curves (a basic element of classical toxicology) at the level of community and ecosystem (Shvarts, 1976; Fedorov, 1976). At present, however, only initial data on higher plants and a number of other components of forest ecosystems (Armand *et al.*, 1994; Vorobeichik *et al.*, 1994; Vorobeichik and Khantemirova, 1994; *Kompleksnaya Ekologicheskaya Otsenka* ..., 1992; Stepanov, 1993) have been obtained. We do not know the examples of correctly constructed dose–effect dependencies for the lichen groups, although such attempts have been made (Belkina and Kalutskov, 1982; Gorshkov, 1986, 1994). The purpose of our work is to fill in this blank.

THE REGION UNDER STUDY

Our study was performed on the western slope of the Middle Urals in the southern taiga subzone. The discharges of a copper-smelting plant affected the studied area. By the time of our investigation, the plant had been functioning for 50 years. The following substances are the main pollutants: SO_2 and heavy metals (Cu, Pb, Cd, Zn, As, etc.). In previous works (Vorobeichik *et al.*, 1994; Vorobeichik and Khantemirova, 1994; Mikhailova, 1993), we cited data on the character of technogenic changes in the forest ecosystems and levels of pollution on the territory under study. The study areas were situated in the direction opposite to the prevailing winds and in the nodes of a regular grid 20×5 km, at 1 km intervals. Mainly, there were grass birch forests, grass pine forests, green moss–wood sorrel spruce forests, and grass spruce forests. They were represented on grey forest soils and mountain forest soils.

MATERIAL AND PROCEDURE

In June 1990, we described the epiphytic lichen cover on the trees of one certain species (*Pinus silvestris*, *Betula pendula*, or *Picea abies*) in all sample plots, 20 trees per plot. Due to the specifics of the lichen cover in the Middle Urals (low floristic diversity), the traditional synthetic indices (for instance, De Sluver–LeBlanc index of air purity and Trass index of field tolerance zone) were not applicable (Mikhailova, 1990). More promising parameters, which we used in this work, are as follows: (1) the total amount of species in the area, (2) the average diversity of species (average amount of species per trunk), (3) the projective lichen cover on trunk bases, (4) the projective cover on trunks at a height of 1.3 m on the side with the most developed cover, and (5) the height (in the range from 0 - 180 cm) at which *Hypogymnia physodes* – this species dominates when pollution is at the background level – climbs a trunk (as an additional measure of abundance). In total, we made 1300 descriptions in 68 sample plots.

We determined the concentrations of heavy metals (Cu, Pb, and Cd) in the upper soil layer (0 - 5 cm) and in snow cover. Measurements were performed using a Karl Zeiss atom-absorption spectrometer AAS-3. The mobile forms in one average sample per plot were used for soil analysis. To determine the heavy metal concentrations in snow, we measured the gross content in five separate samples. The snow samples were taken at the beginning of March 1990. Length of the core was equal to full thickness of the snow cover. The mobile forms were extracted by 5% HNO_3. The proportion of the soil to the extractant was 1 : 5. The extraction lasted 24 hours.

Information on the measured pollution was written in the following form:

$$K_i = D_i/\min[D_i]\,,$$

$$D_i = [\mathrm{Cu}]_i/[\mathrm{Cu}]_f + [\mathrm{Pb}]_i/[\mathrm{Pb}]_f + [\mathrm{Cd}]_i/[\mathrm{Cd}]_f,$$

where K_i is the index of pollution of the *i*th plot, $[\;]_i$ is the concentration of an element in the *i*th plot, and $[\;]_f$ is the concentration of an element in the background zone (30 km from the plant). The index K_i is measured in conventional units and displays by how many times the background level of pollution is exceeded. Taking into account the fact that, in our case, a high concentration of SO_2 in the atmosphere is the main cause of mortality in lichens, and heavy metals only enhance this effect (Gorshkov, 1990; LeBlanc and Rao, 1975), we, strictly speaking, should not attach the toxicological sense to this index. The given index is an integral indicator of toxic load on an ecosystem. We selected precisely the heavy metals, because their concentrations are determined easily over a large territory (they are bound in accumulating media firmer than sulfur, and it is easier to identify the technogenic component out of data on their content).

The dose dependencies are approximated by the logistic equations. The coefficients of these equations were found by Markvardt numerical assessing. This procedure is realized in the Statgraphics package. Two critical points (upper and lower), which correspond to the beginning and end of the sharpest change of parameter, are of greatest interest. Analysis of the second derivative of the logistic function allows us to analytically determine the coordinates of these points. Earlier, we described the analysis of the dose dependencies at greater length (Vorobeichik, 1994; Vorobeichik *et al.*, 1994).

RESULTS AND DISCUSSION

A decrease in diversity of lichen species and their projective covers up to their total disappearance is the general tendency of transformation of the epiphytic lichenosynusia under the technogenic load (Mikhailova, 1993). We found tight dependencies of the parameters of the lichenosynusia on an estimate of dose of the technogenic load (Table 1). The parameters (1), (2), and (3) – total amount of species, average diversity of species, and the lichen cover on trunk bases – had the closest relationships to the magnitude of toxic load. Among phorophytes, such a relationship was found for pine. When the toxic load is estimated by means of the distance from the source of emission, such a relationship also was found. The latter circumstance is probably due to differences in the character of air transfer of various ingredients of discharges. Dust particles with absorbed heavy metals precipitate at relatively small distances from the source of discharges, while SO_2, HF, and NO_X disperse at longer range (Vasilenko *et al.*, 1985). At the same time, it is precisely the gasform pollutants that mainly affect lichens. Therefore, the distance is a more adequate indicator of toxic load. Analyzing the pollution of accumulating media, we established that, on the whole, the selected parameters of lichen cover depended on heavy metal concentration in soil to a greater degree than on heavy metal concentration in snow. Therefore, the former indicator will be used below as an additional estimate of the load.

The obtained data allow us to range the selected parameters depending on their information content. This is necessary to develop a system of diagnostic characteristics. The more these parameters differ in their averages under different magnitudes of the load and the less dispersion they have under a certain magnitude of the load, the more informative they are. Therefore, we can more reliably assess the values of the affecting factor on the basis of values of the selected parameter. When the information content is interpreted in such a manner (Armand *et al.*, 1991), Fisher's *F*-function, which is applied in the standard dispersion analysis, or the correlative ratio, derivated from this function, can be used as its quantitative measure.

Table 1. The correlative ratio of the parameters of the lichenosynusia to the various estimates of the load (the sign was determined by the correlation coefficient)

The estimate of the load (the number of sample plots is in parentheses)	The parameters of the lichenosynusia				
	amount of species	average diversity of species	cover on the trunk bases	cover at a height of 1.3 m	the height of climbing
Pine (13)					
Distance from the source of pollution	0.86**	0.91***	0.91***	0.66	0.87***
Metals:					
in snow	−0.77*	−0.85**	−0.78*	−0.49	−0.72
in soil	−0.81*	−0.88*	−0.90**	−0.63	−0.78
Birch (23)					
Distance from the source of pollution	0.94***	0.95***	0.67	0.78*	0.82**
Metals:					
in snow	−0.57	−0.63	−0.51	−0.52	−0.66
in soil	−0.67*	−0.68*	−0.69*	−0.39	−0.41
Spruce (31)					
Distance from the source of pollution	0.79***	0.82***	0.78***	0.58	0.67**
Metals:					
in snow	−0.67**	−0.63*	−0.54	−0.36	−0.38
in soil	−0.65**	−0.55	−0.51	−0.32	−0.46

Notes: * Means that $P < 0.05$.
** That $P < 0.01$.
*** That $P < 0.001$.

The ranged arrays of the parameters do not coincide for the different indicators of toxic load due to the statistical and not the functional character of relationship. Therefore, to develop a diagnostic system, we need parameters that are highly informative for all indicators of toxic load. Only one parameter – average diversity of species – met this requirement for all phorophytes. The lichen cover on trunk bases also is sufficiently informative for the pine and spruce, while the lichen cover at a height of 1.3 m was at the last place in all cases.

The established dose–effect dependencies were of two types: (1) classic *S*-shaped curve with apparent top and bottom horizontal parts (Figs. 1 and 2a) and (2) the fragment of the logistic curve had a hyperbolic or exponential form (Fig. 2b). In the latter case, abscissas of the critical points (Table 2) are out of the range of actual toxic loads. Thus, the calculation of them makes no sense. The curves of the second type occur less frequently when the distance from the source of discharges and not the content of metals in soil is used as an estimate of the toxic load. In addition, when we used the distance, the dispersal of points was smaller, and, hence, the part of dispersion explainable by the equation was higher.

The most sensitive parameters – the lichen cover on pine bases, the amount of lichen species on the pine and birch – begin to vary when the distance from the plant is 14 - 15 km. The least sensitive parameters – the lichen cover on the trunk bases of spruce and birch – vary when the distance is 6 - 8 km.

From analysis of the dose–effect dependencies, we can conclude that they are substantially nonlinear. Up to the certain critical (threshold) level of load, parameters of the lichenosynusia are stable, and their variability is determined by the natural patchiness of ecological factors. When the critical level of load is exceeded, the parameters change sharply. The subsequent increase in

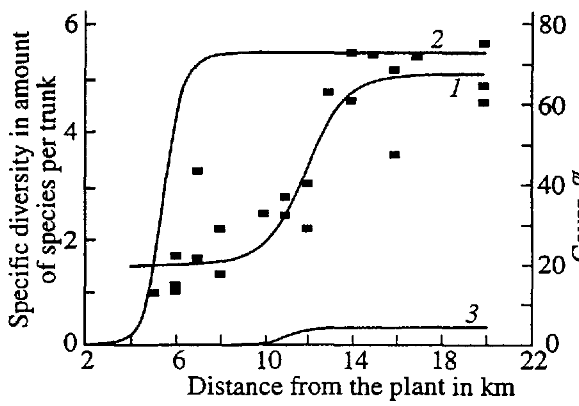

Fig. 1. The dose–effect dependency (the dose is the distance from the source of discharges) for the parameters of the epiphytic lichenosynusia of birch: (*1*) for the specific diversity; (*2* and *3*) for cover on trunk base and at a height of 1.3 m (empirical points are not marked).

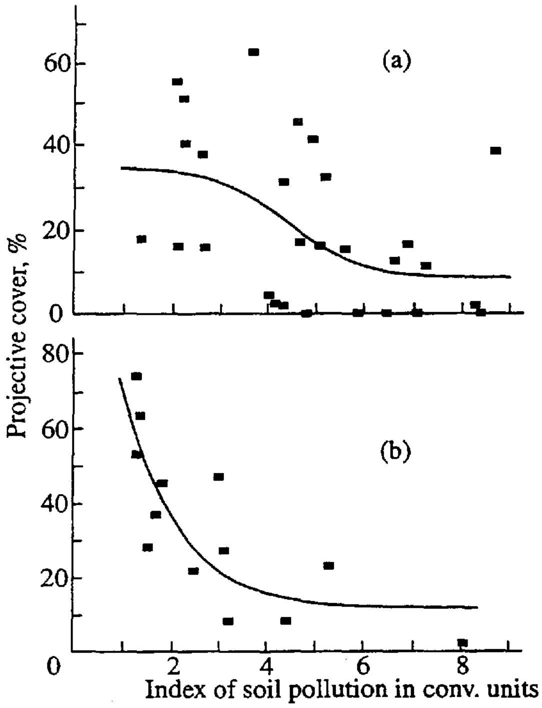

Fig. 2. The dose–effect dependency (the dose is the concentration of metals in soil) for the projective cover on the trunk base of (a) spruce and (b) pine.

load does not produce cardinal changes. Thus, we marked out three segments of the curve that are substantially different: smooth changes are replaced with an abrupt jump, which then again passes into the smooth change. The discovered nonlinearity is unexpected. As we deal with multispecies communities, smooth variation of the resulting parameters is highly probable (considering possible substitution of some species for others). The causes of the nonlinearity are not clear yet, and further study is necessary. The nonlinearity may result from the existence of certain links in the lichen's life cycle, which alternatively (i.e., "yes" or "no") react to the pollution and closeness of the thresholds of response for the different species. For example, the formation or germination of soredia may be such a link.

Using the spatial-time analogies, the dose–effect dependencies can be interpreted as a representation of the response of the epiphytic lichenosynusia to technogenic load. Hence, it follows that the lichenosynusia under consideration can be in two relatively steady states: the background state with maximum diversity of species and the impact state with sharply decreased diversity of species and almost zero abundance. The transition from the one state to another, observed in the buffer zone, is very fast and interpreted as an unstable state. The abruptness of this transition attests to its high rate: the distance between abscissas of the top and bottom critical points is equal to 0.6 - 3 km, and only in one case this distance is equal to 6.1 km. The specified feature develops more clearly when the content of metals is used as an estimate of the load. In this case, the transition to the second state occurs when, being at the critical level, the load increases by only 0.05 - 0.36 conventional units (in two cases these values amount to 2.05 and 3.78). If we take all the distance – from the area with the maximum concentration to the area with the background level of pollution – to be 100%, then the transition area accounts for only 0.51 - 3.68% (in two cases, 21.06 and 38.66%).

Examining the dose dependencies at greater length, we can isolate the less expressed transition between the impact level and "absolute zero" ("lichen desert"). However, the approximation of this transition by the equation of regression is unreliable due to the small range of the given transition, which results from extremely low abundance of lichens in the impact zone. Consequently, we can disregard it to a first approximation.

The dose dependencies of the parameters of the epiphytic lichenosynusia have a form similar to that of the analogous curves for other components of forest ecosystems, such as, for instance, the tree and herb–shrub layers (Vorobeichik and Khantemirova, 1994; Vorobeichik *et al.*, 1994; *Kompleksnaya Ekologicheskaya Otsenka* ..., 1992; Stepanov, 1993). They also are similar to the classic *S*-shaped curves for the parameters characterizing the individual level. The specificity of lichenosynusia in comparison to the other components manifests itself by relatively more frequent cases of the reduced dose curves (see Fig. 2b). This may be due to high sensitivity of the lichens to contamination and insufficient representativeness of data in the zones with background and small levels of load. The analogous difficulty of construction of the dose dependencies for small concentrations of a toxicant often arises in classical toxicology (Nosov, 1989). In those cases when the coordinates of top critical points were found, it turned out that parameters of the lichenosynusia begin to vary at pollution that is only 1.5 - 2.3 times greater that the background level. For this case, the lower limit of this range is overstated due to the fact that the dose dependencies of the most sensitive parameters do not rise at plateau in the area of small loads. The other components of forest ecosystems are more stable. For instance, the respective values are equal to 2.8 - 3.3 for herb–shrub layer and 3.4 - 4.5 for stand (Vorobeichik and Khantemirova, 1994).

However, we should carefully draw the conclusion on relative sensitivity of diverse parameters of the lichenosynusia, since the coordinates of the critical points differ in reliability of determination (as a result of unequal variability of the parameters). We can note as a tendency the fact that the parameters of the lichenosynusia begin to decrease in the following order: First, the parameters of species diversity, next the cover at a height of 1.3 m, and then the cover on trunk base. The difference between the two latter parameters appears to lie in the lower vulnerability of lichens on

Table 2. Characteristics of the dose–effect dependencies for the parameters of the epiphytic lichenosynusia of different phorophytes

Parameter	The estimate of the load					
	distance from the smeltery in km			metals in soil in conventional units		
	X_{top}	X_{bot}	D	X_{top}	X_{bot}	D
Pine						
Amount of species	14.4	12.4	0.79	–	–	0.54
Specific diversity	13.7	11.8	0.88	–	–	0.65
Cover:						
on trunk base	15.5	12.5	0.89	–	–	0.67
at a height of 1.3 m	13.2	11.3	0.42	1.83	2.10	0.63
The height of climbing	13.6	7.5	0.85	1.95	2.19	0.96
Spruce						
Amount of species	–	–	0.62	–	–	0.51
Specific diversity	–	–	0.52	2.76	6.55	0.55
Cover:						
on trunk base	8.3	7.7	0.46	3.45	5.50	0.26
at a height of 1.3 m	–	–	0.26	2.17	2.26	0.52
The height of climbing	9.5	7.6	0.42	2.79	3.14	0.36
Birch						
Amount of species	14.3	11.8	0.70	2.14	2.43	0.59
Specific diversity	13.2	10.8	0.82	–	–	0.52
Cover:						
on trunk base	6.1	4.9	0.63	2.26	2.31	0.25
at a height of 1.3 m	11.5	10.4	0.30	1.48	1.52	0.37
The height of climbing	8.5	5.9	0.59	2.21	2.50	0.18

Note: X_{top} and X_{bot} are the abscissas of the top and bottom critical points, respectively; D is the part of dispersion explainable by the logistic equation; the absence of number means that the logistic curve does not rise at plateau, and the critical points are outside the area of the actual loads.

the base of trunk, since they are sufficiently screened off from contamination by the snow cover, herb stand, and underwood. Furthermore, mechanical destruction of the bark, the high amount of its trophic resources, and better microclimatic conditions form a more favorable situation around the trunk base for populating (Armstrong, 1990; Kuusinen, 1994). The relatively higher stability of the parameters of projective lichen cover as compared to the species diversity, apparently, is due to the compensating substitution of some species for others. Thus, up to the certain level of pollution, the projective cover, as an integral, remains unchanged. Analogous effects were revealed for the herb–shrub layer in forest phytocenoses (Stepanov, 1993; Vorobeichik and Khantemirova, 1994).

A stepped form of the dose dependency is of fundamental importance for the ecological standardization and diagnostics of disturbance in ecosystems, since it allows us to objectivize the process of isolating the zones of transformation of lichen cover and determining permissible loads. The specified form indicates that the studied area is divided into three zones of degradation: the impact zone, which corresponds to the bottom plateau of the curve, the buffer zone, in which the values of the parameters vary sharply, and the background zone, which corresponds to the top plateau. In addition, we marked out the conventional zone of "lichen desert" (in respect to the epiphytic lichens only). Further segmentation of the territory is subjective, and, hence, it is unsuitable. The abscissa of the upper critical point can be interpreted as a value of the maximum tolerance load on the epiphytic lichenosynusia. Proceeding from the principle of a weak link in the system, the most strict ecological standards, which simultaneously would protect the other less sensitive components of the ecosystems, should be developed on the basis of this value. If a standard represents the factor by which the present level of discharges should be diminished (this may be presented as though the background zone approaches to the plant limits), then, in our case, this factor is equal to 4.4 - 6.8 (taking into account the fact that maximum pollution was 10 times larger than the background level). In our work we leave without consideration the questions of practical implementation of the procedure of standardization, which require special study. We should note only that the epiphytic lichens usually are not applied to the development of ecological standards (e.g., Stepanov, 1993). Considering their significance to be the leading indicators of changes in ecosystem as an integral, we can hardly think it to be correct.

CONCLUSION

The use of epiphytic lichens in applied ecology (for the ecological mapping of territory and monitoring of ecosystems) is based on settled, almost standard procedures. This ought to imply clear understanding of the regularities of transformations of the epiphytic lichenosynusia under anthropogenic load. However, we should point to the absence of information on many fundamental questions, for instance, on the character of the dose–effect dependencies. Our attempt to fill in this blank has led to a sufficiently extraordinary conclusion. It turned out that, under a gradually increasing toxic load, the epiphytic lichenosynusia vary their parameters not in the corresponding gradual manner but in sharp transition from the background level to the impact level.

We cannot, in full measure, consider the obtained results to be the solution of the main question of our work. This is due to the presence of a number of weak places in the scheme of experiment, which were detected only from the analysis of materials. The high variability of the parameters is one of the reasons of the given situation. Even the significant amount of the sample plots, which we have used, was insufficient to find the dose dependencies with wanted accuracy, especially in the region of background and low pollution. In addition, the absence of information on air concentrations of gasiform pollutants, in particular SO_2, makes the solution of this problem difficult. We may expect that elimination of defects will permit us to construct the dose cirves more reliably, but it will hardly change the basic conclusions of the work.

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