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REACTION OF FOREST PHYTOCENOSES TO TECHNOGENIC POLLUTION: DOSE-EFFECT DEPENDENCES*

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The authors investigated the transformation of tree, herb—dwarf-shrub, and moss layers of southern-taiga fir-spruce forests under the action of emissions from a copper smelting plant. Dependences of the "dose-effect" type are significantly nonlinear. In the forest phytocenosis's reaction to pollution, three qualitatively different states are distinguished: two stable (background and impact), and one unstable (transitional). The transition between stable states occurs by a trigger mechanism. The technogenic load at the critical point corresponding to the beginning of the transition is taken as the maximum permissible and can be used in procedures for setting ecological standards.

One of the basic problems of applied ecology is to develop a system of parameters that would make it possible to reliably diagnose the initial stages of anthropogenic transformation of ecosystems and critical conditions of their dynamics. It is closely connected with questions of setting ecological standards for anthropogenic loads. In research devoted to this problem, a significant amount of attention is given to plant cover. Numerous works have revealed the action of technogenic pollutants on parameters of all levels of organization: from subcellular to phytocenotic ("Bioindication...," 1988; Guderian, 1979; "Pollution...," 1988; Smith, 1985; Burton, 1986). Signs of acute and chronic damage to the main forest-forming trees have been studied well, and phytotoxic and safe concentrations of a number of pollutants have been determined (Il'kun, 1979; Nikolaevskii, 1979; "Air Pollution...," 1988; Linzon, 1978). There is less information about the reactions to chemical pollution of phytocenoses as a whole. Works performed in disturbed territories in the taiga zone ("Comprehensive Ecological Evaluation...," 1992; "Forest Ecosystems...," 1990; Lukina and Nikonov, 1993; Makhnev et al., 1992; Stepanov, 1988; Syroid, 1987; Chernen'kova et al., 1989; Linzon, 1978) have revealed the basic patterns of transformation of forest phytocenoses: with an increase in pollution (or closer to the source of emissions), the standing crop of timber and its vitality decrease, as does the species richness of the live ground cover; regeneration processes are inhibited; and the portion of standing dead wood increases. The final result of such studies is zoning of the territory, distinguishing three or four zones of degradation (background, buffer, impact, and technogenic wasteland). Zoning on the Kola peninsula (Kryuchkov, 1991) can serve as an example.

However, this traditional scheme of work makes it possible to get only a general idea of the transformation of ecosystems. In this case, many theoretical and applied questions remain unanswered. Thus, for evaluating the stability of ecosystems, predicting and modeling their reaction to stress factors, and finding the maximum permissible loads it is necessary to construct dependences of the "dose-effect" type, analogous to those used in classical toxicology. At present, there have been a few attempts to construct such dependences for phytocenotic parameters (Alekseev and Tarasov, 1990; Armand et al., 1991; "Comprehensive Ecological Evaluation...," 1992; Saliev, 1989; Stepanov, 1988). An important result of the works that have been performed is a conclusion about the significant nonlinearity of ecosystems' reaction to a load. But the number of sample areas in this case varies in the range of 5-10, and in a number of cases even 3-4 (Alekseev and Tarasov, 1990). This is clearly insufficient for correct analysis of dose dependences.

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TABLE 1. Characteristics of Pollution of Soil (μg/g) and Snow Cover (snowfall during the winter period, μg/m^2) on the Research Ground

Distance from the plant, km	Metal			
	Cu	Zn	Cd	Pb
	Mobile forms in soil			
1	154,40	57,92	4,18	163,51
2	151,96	56,60	3,49	112,96
4	130,86	51,28	2,33	39,78
6	104,73	51,49	1,97	44,86
30	18,72	35,85	0,52	19,15
	Water-soluble forms in snow			
1	34,19±13,92	80,34±25,54	1,72±0,53	11,06±7,04
2	31,01± 4,94	58,20± 8,84	1,37±0,31	5,01±0,71
4	19,22± 5,40	31,16± 6,03	0,71±0,20	4,28±1,04
6	23,12± 2,64	26,00± 1,18	0,67±0,09	3,24±0,29
30	7,24± 0,78	14,66± 1,86	0,58±0,15	2,73±0,23
	Acid-soluble forms in snow			
1	169,27± 6,79	55,28± 3,83	1,04±0,11	34,89±2,30
2	137,23±13,19	60,35± 4,47	0,65±0,04	32,58±2,34
4	47,86± 2,21	19,45± 0,19	0,34±0,04	8,80±0,16
6	54,65± 2,97	23,75± 0,71	0,23±0,01	10,48±0,35
30	31,93± 3,51	14,89± 1,27	0,23±0,02	5,62±0,29

One of the reasons for the absence of proper progress in this field is the shortage of information about levels of pollution of the territories under investigation, due to which the dose of the technogenic load is replaced by the distance to the source of emissions. Another reason is connected with the prevailing ideology of bioindication research, when efforts are aimed primarily at comparing a "test" and a "control."

In the present work, we tried to overcome these shortcomings: phytocenotic parameters were recorded at quite a few points on the pollution gradient, at each of which we syntopically measured the concentrations of pollutants. This made it possible to correctly construct and analyze dose-effect curves. Pollution from the source of emissions that we studied (a copper-smelting plant with primary smelting) is the most harmful for terrestrial ecosystems (due to the combined action of heavy metals and sulfur dioxide). This makes the pattern of the phytocenoses' transformation very contrasting and thereby considerably facilitates analysis.

CHARACTERISTICS OF THE RESEARCH GROUND

The work was conducted in August 1989 in the southern-taiga subzone, in the region of action of the Central Ural copper-smelting plant (Revda). The plant has been in operation since 1940. The main ingredients in the emissions are sulfur dioxide (98% by weight among the gaseous pollutants) and dust particles with adsorbed toxic elements (Cu, Pb, Zn, Cd, As, etc.). The volume of emissions is about 140,000 tons/year.

The criterion for selecting the sites was comparability of the forest communities with respect to the basic typological and valuation indices. As the model object we chose linden fir-spruce forests (Kolesnikov et al., 1973) of different vegetation associations on gray forest soils, which are confined to the lower parts of slopes.

The research ground is located west of the source of emissions, opposite the prevailing winds. In this direction, dark coniferous forests have been preserved all the way up to the very boundary of the plant, and recreational action is kept to a minimum. The research ground includes sites at distances of 1, 2, 4, 6, and 30 km from the source of emissions. At each of them we laid out five sample areas 25 × 25 m (150-200 trees per sample area). Characteristics of the sites' pollution are given in Table 1.

RESEARCH PROCEDURE

1. Characteristics of the Tree Layer. On each sample area we counted all of the trees, with measurement of breast-high diameter and the vitality of each individual tree with respect to six categories ("Sanitary Rules...," 1970). For 5-6 model trees, we determined the age and height. At five points, we visually measured the crown density.

2. Characteristics of Regeneration. On each sample area, on five plots 5 × 5 m, we recorded young growth, with a determination of age and evaluation of condition with respect to two categories (dependable, undependable). Seedlings and self-sown young growth were recorded on three plots 1 × 1 m within the bounds of each 5 × 5 m plot.

3. Characteristics of Live Ground Cover. On each sample area we determined the species composition of the herb—dwarf-shrub (with evaluation of abundance on the Drude scale) and moss (with measurement of total coverage) layers. During the period of the plants' maximum development, we measured dry phytomass by species on 15 random plots 50 × 50 cm.

4. Chemical Analysis. On each sample area we took an average specimen (from five individual ones) of the upper (0-5 cm) soil layer. Heavy metals were extracted with an ammonium-acetate buffer (pH 4.8) with EDTA, which made it possible to analyze their mobile forms and the most immediate reserve in the soil (Il'in, 1991). Elements were determined on an AAS-3 atomic-adsorption spectrophotometer.

5. Analysis of Dose-Effect Dependences. As the dose of toxic load we took the relative index often used in applied ecological investigations: the sum of excesses of background concentrations of priority pollutants:

$$[Cu]_i/[Cu]_b + [Pb]_i/[Pb]_b + [Cd]_i/[Cd]_b,$$

where $[]_i$ is the concentration at the i-th point; and $[]_b$ is the background concentration. This index is considered to be a convenient marker for a whole set of pollutants acting on an ecosystem. It is an index of the toxic load and, strictly speaking, has no toxicological meaning.

Dependences were approximated by the logistic equation

$$y = \frac{A - a_0}{1 + \exp(\alpha + \beta x)} + a_0,$$

where y is the effect (parameter); x is the dose; A and a_0 are the maximum and minimum levels of y; and α and β are coefficients. The equation's parameters were found by Marquardt's iteration numerical estimation (the procedure was implemented in the "Statgraphics" package for an IBM PC). In this case, the curve runs through the centers of the upper and lower congregations of points and not along their upper and lower boundaries, as in the traditional least-squares method. Three inflection points are distinguished on the curve: upper, middle, and lower. The middle one corresponds to a change in the parameter by half of the maximum level (analogous to LD_{50} in toxicology). The upper and lower points are the beginning and end of the most abrupt change in the parameter. Equating the second- and third-order derivatives of the logistic function to zero, the coordinates of the critical points can be found analytically through the equation's coefficients (Zaitsev, 1984). Their abscissas (x_u, x_m, x_l) are equal to

$$x_u = \frac{-\alpha + \ln(2 - \sqrt{3})}{\beta}; \quad x_m = -\frac{\alpha}{\beta}; \quad x_l = \frac{-\alpha + \ln(2 + \sqrt{3})}{\beta}.$$

To characterize the curve's smoothness, we suggest the "step-slope" index:

$$K = 1 - \left| \frac{x_u - x_l}{x_{max} - x_{min}} \right|,$$

where x_{min} and x_{max} are the "beginning" and "end" of the load gradient. Theoretically, the index changes from zero (a very smooth transition between the upper and lower levels) to unity (a very sharp transition). The index is interpreted as the portion of sections with smooth changes in the overall length of the gradient and is an easy-to-interpret form of the slope of a straight line described by the logistic equation in logarithmic coordinates.

RESULTS AND DISCUSSION

Phenomenology of Transformations

Characteristics of the investigated stands are given in Table 2. The forests belong to the southern-taiga territory of the Central Ural low-mountain province of the Ural mountain-forest region. They are all middle-aged linden fir-spruce forests

TABLE 2. Parameters of Tree Layer at Different Distances from the Plant

Parameter	Distance from the plant, km				
	1	2	4	6	30
Association	Moss-horsetail	Moss-horsetail	Wood-sorrel—forbs	Nemoral—wood-sorrel	Nemoral—wood-sorrel
Composition of the stand	8F 2S + B, As, L	8F 2S + B, As, L	6F 4S + B, As	9F 1S + P, B, L, As	8F 2S + B, As, L
Crown density, %	26	43	46	42	47
Standing crop, m^3/ha: live/deadwood	58/12,5	112/26	243/31	263/12	284/8
Density, specimens/ha:					
Stand	2160	4317	2509	3514	3314
Coniferous young growth	1552	2496	6144	4480	3552
Deciduous young growth	608	1536	784	960	430
Portion of deadwood, %					
By standing crop	18	16	14	5	2
By density	32	38	22	12	17
Fir:					
Diameter, cm	9	8	11	12	12
Height, m	8	9	9	9	10
Age, years	41	43	59	51	49
Degree of density	0,44	0,7	0,72	1,55	1,2
Spruce:					
Diameter, cm	11	13	22	22	15
Height, m	9,3	11	13,8	10,7	11
Age, years	32	35	43—88	40—80	17—43
Degree of density	0,22	0,39	0,97	0,49	0,42

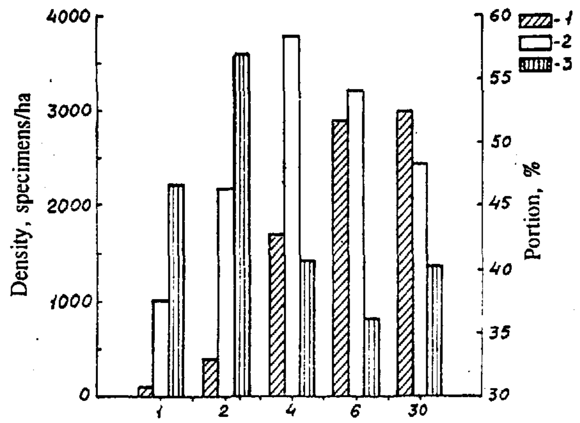


Fig. 1. Density of fir seedlings (1), young growth (2), and portion of young fir trees (3) at different distances from the plant.

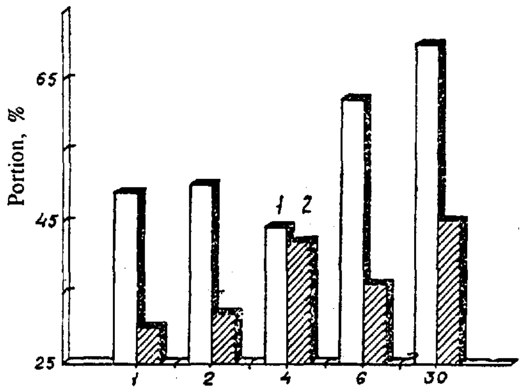
of quality class III, with a predominance of fir and an admixture of birch, linden, and aspen. Only the 4 km site stands out, where spruce makes up almost half of the stand and has a mature age.

We recorded changes in the stands' age structure (Fig. 1): due to primary loss of more mature individuals, the portion of young trees increases. This is reflected in the crown density and density of the stand. A decrease in height and diameter was found only for the dominant species (height changes within the limits of one class). The standing crop diminishes considerably. There is a significant increase in the portion of standing deadwood with respect to standing crop and density, which indicates intensification of processes of decay of the stands in technogenic territory. Accordingly, the stand's vitality (portion of individuals in the first three categories of sanitary condition) decreases closer to the plant (Fig. 2).

On the whole, the vitality of spruce is higher than that of fir, which takes upon itself the primary load from emissions (or it has stronger intraspecific competition). At the 4 km site, where spruce has greater density, age, and height, its vitality declines. At the same time, the vitality of fir improves there. With medium levels of pollution, vitality decreases faster than the standing crop. Then vitality almost does not change, and the standing crop drops sharply. This is probably connected with

TABLE 3. Parameters of Live Ground Cover at Different Distances from the Source of Emissions

Parameter	Distance from the plant, km				
	1	2	4	6	30
Herb—dwarf-shrub layer					
Total number of species	15	18	35	39	48
Species saturation, species/25 m^2	7	9	23	30	31
Biomass, g/m^2	16	6	17	7	16
Portion of total number of species/ portion of biomass, %					
Forest species (without horsetails)	40/0	50/2	70/32	70/71	75/86
Meadow species	47/2	32/9	16/6	17/0.5	11/1
Explerents	78/100	60/100	38/70	28/32	33/25
Tall herbs	21/0.5	33/2	49/17	45/11	48/29
Short herbs	17/0	20/0	33/19	39/62	37/51
Horsetails	14/98	11/90	4/54	3/26	3/11
Grasses	48/1	32/7	8/10	7/5	4/9
Moss layer					
Total number of species	2	2	2	2	8
Coverage, %	58	69	55	17	26
Biomass, g/m^2	351	314	96	17	8



Distance to the plant, km

Fig. 2. Vital condition (portion of individuals in the first three categories) of spruce (1) and fir (2) at different distances from the plant.

the change in age structure noted above: young trees, appearing in large number with medium pollution, have a significant portion of individuals in satisfactory condition, which results in stability of the index of the stand's overall vitality.

We will consider the action of pollution on regeneration. The number of fir seedlings and self-sown young growth drops beginning from the 4 km site; on part of the sample areas of the 2 km site seedlings are completely absent. Depression of regeneration may be connected with a decrease in seed productivity, as well as with deterioration of the seeds' growing conditions. The probable reasons for this are toxicity of the soil and litter, significant development of the moss cover, and an increase in the thickness of forest litter (Sannikov, 1992). The latter occurs due to inhibition of decomposition processes: in a number of places in the technogenic territory, the litter reaches 10-11 cm, as opposed to background thicknesses of 1-2 cm (Vorobeichik, 1991). With an increase in the load, new generations of conifers become ever less numerous: already at the 2 km site there is not enough young growth present for normal regeneration. The maximum density of coniferous young growth is noted at a distance of 4 km, although the number of seedlings is decreased there. This is probably connected with protection of the young growth by the tree layer, which shields it from the action of pollutants, and in the winter with complete or partial protection by the snow cover. Regeneration parameters change in waves (see Fig. 1): as the load increases, the number of seedlings diminishes, but the amount of young growth increases; the amount of young growth deminishes, and the portion of young trees increases. In the background territory, the distribution of seedlings, young growth, and young trees corresponds to the familiar self-thinning curve; in disturbed territories it changes to the opposite.

The most mobile element of a forest phytocenosis is the live ground cover: its reaction to pollution shows up sooner and with greater amplitude than that of the timber stand (Table 3). At a distance of 6 km, the nature of the association is similar to that at 30 km, but the total species richness decreases (from 48 to 39 species). The abundance of tall herbs decreases (*Pleurospermum uralensis, Pulmonaria obscura, P. dacica, Crepis paludosa, Cacalia hastata, Actae spicata, A. erytrocarpa, Lathyrus gmelini*, etc.). Short herbs do not react to this level of pollution, and pyrola and beadruby even increase their abundance, probably on account of weakening of competition on the part of other species. Changes are observed in the representation of Gramineae: *Brachyopodium sylvaticum* and *Melica nutans* disappear, and the abundance of *Calamagrostis obtusata*, which is typical of dark coniferous forests, decreases. This leads to a significant decrease in the portion of this family in the herbage's biomass. The portion of grasses in the species richness remains at the background level, since *Calamagrostis arundinacea* and *Agrostis tenuis* appear, though with insignificant abundance. Changes are observed in the moss cover: the number of species decreases (from 8 to 2), and the area of projective coverage diminishes.

At the 4 km site, species richness continues to decrease (to 35 species), as does the abundance of tall herbs, and the abundance of short herbs is reduced (wood sorrel and starflower). Nemoral species (*Asarum europaeum, Paris quadrifolia, Actae spicata, Galium odoratum*) drop out, probably due to their preference for neutral or slightly alkaline, soft-humus soils and slight resistance to technogenic acidification. This explanation is supported by a rise in the density of horsetail, which prefers acid soils, and the appearance of such an acidophilic species as turfy hair grass. The increase in abundance of *Calamagrostis arundinacea* is probably connected with thinning of the canopy. The nemoral—wood-sorrel association is replaced by a wood-sorrel—forbs one at this site.

At distances of 1 and 2 km, sharp impoverishment of the herbage is observed (to 7-9 species). Typically forest species drop out almost completely. The portion of horsetail in the herbage's total biomass rises to almost 100%. Of tall and short herbs, only isolated specimens are found. The moss cover is significantly developed: on the areas closest to the plant, mosses occupy as much as 70% of the soil surface. In this case, a complete change in the species composition is observed. The association changes to moss-horsetail.

Thus, chemical pollution radically changes the structure of the phytocenosis, transforming it from closed to open. Degradation of the tree layer leads to significant changes in the phytogenic environment, which, together with the pollutants' direct toxic action and disruption of the soil's chemism, becomes a leading factor in its organization. Species with a specific life strategy are preserved: explerents. The portion of them in the biomass increases all the way to absolute predominance in the impact zone. Transformation of the herbage occurs by layers: first the tall herbage changes, then the short herbage. A reduction in competition on the part of herbage leads to development of the moss cover. At the level of a tendency it is noted that the order of loss of species is opposite to their phylogenetic development, i.e., the species of ancient families are more resistant.

The most informative indices of the herbage's reaction are the parameters of species diversity and structure. The total biomass is stable over the whole pollution gradient, since depression of sensitive species is compensated by intensified development of others. Analogous effects have been described in the literature (Stepanov, 1988). This fact can be considered a manifestation of one of the mechanisms by which an ecosystem maintains stability of its functional parameters through a change in structural ones.

DOSE-EFFECT DEPENDENCES

Changes in certain parameters of the phytocenosis depending on the level of the toxic load are shown in Figs. 3 and 4. The graphs illustrate the most typical cases of dose-effect curves. The results of quantitative analysis of dose dependences are given in Table 4. Only those parameters are included that demonstrate regular changes in the load gradient, at least at the level of a tendency (when the portion of variance explainable by regression is more than 15%). The abscissas of the critical points are expressed in relative form: they show by how many times the background level of pollution is exceeded. In a number of cases, the curve does not reach a plateau in the region of actual values of the load (the critical points correspond to negative loads, or loads below the background amounts). The reason for this is insufficient size of the background part of the sample and the slight level of pollution. In this case, calculation of the critical points makes no sense.

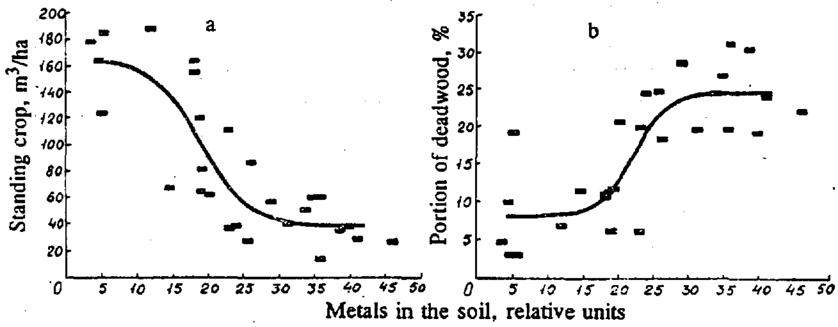


Fig. 3. Dose-effect dependences for standing crop of fir (a) and portion of fir deadwood in the standing crop (b).

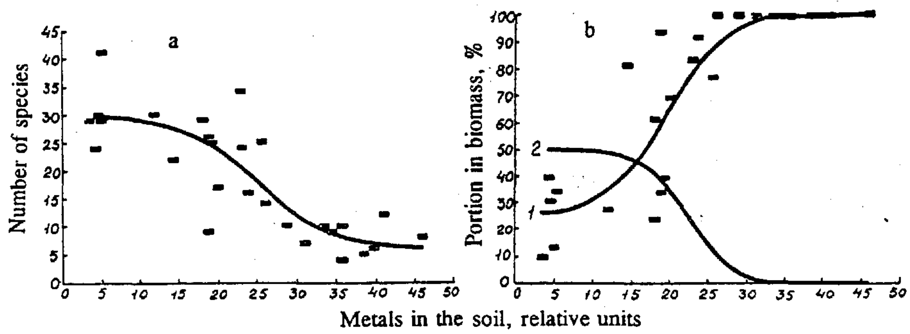


Fig. 4. Dose-effect dependences for total species richness of the herb—dwarf-shrub layer (a) and portion of individual groups in the herbage's biomass (b): 1) explerents; 2) tall herbs (empirical points not shown).

The dose dependences given eloquently characterize the process of technogenic degradation of vegetation. Since the gradient of the toxic load is sufficiently wide (the maximum values exceed the background values by almost ten times), the phytocenosis's reaction is very contrasting. This explains the high values of the coefficients of correlation between phytocenotic parameters and the load (although there is a significant spread of values in a number of cases).

The main conclusion following from analysis of the dose curves is the presence of a clearly expressed step gradation. In other words, the reaction is significantly nonlinear: the phytocenosis reacts to a gradual increase in pollution not with a corresponding gradual change in parameters, but sharply, by a law of "all or nothing." This provides a basis for saying that in the process of its transformation the phytocenosis is found in three qualitatively differing states: two relatively stable (homeostatic) and one unstable (transitional). The boundaries between them are the upper and lower critical points. The first one of the stable states corresponds to the background level of the load and is characterized by high viability of the vegetation; the second, to the impact level with almost zero viability. In reality, communities in different states are distinct systems radically differing in their set of elements and structure (see Table 3).

Based on the principle of space-time analogies, we can say that the transition from one state to another is accomplished very quickly, by a trigger-type mechanism. In Tom's catastrophe theory it corresponds to the topological figure of a "fold" ("Ecosystems...," 1989). The section of the load gradient in which the transition occurs is extremely narrow: the portion of it in the overall length is most often 5-15%, and in a number of cases even 0.3-1% (see Table 4). Only a small part of the parameters changes more smoothly.

The described S-shaped nature of the dose curves is not unexpected. That is precisely what was predicted by ecologists on the basis of theoretical ideas about ecosystems' stability (Armand et al., 1987; "Ecosystems...," 1989; Dabrowska-Prot, 1985). The dose-effect curves for ecosystem parameters are similar to dose dependences at the organism level, with which classical toxicology works. This can be seen as a manifestation of common patterns of the reaction of biosystems at different levels of organization. Another analogy is the change in structure of vegetation in regions with sharp landscape boundaries (for example, the transition from forest to meadow in mountains) ("Ecosystems...," 1989).

TABLE 4. Characteristics of Dose-Effect Dependence for Parameters of Forest Phytocenosis

Parameter	*R*	Critical points			*K*	*D*
		Upper	Middle	Lower		
Tree layer						
Average height:						
Spruce	—0,23	6,19	6,31	6,43	0,97	32,89
Fir	—0,44*	2,71	3,62	4,52	0,80	22,95
Average diameter						
Spruce	—0,39*	6,55	6,86	7,17	0,93	46,47
Fir	—0,67***	5,45	5,71	6,00	0,94	54,48
Density:						
Live fir	—0,36	8,38	8,40	8,45	0,99	26,25
Live trees of all species	—0,46*	7,95	7,98	8,00	0,99	25,27
Dead fir	0,29	6,24	6,31	6,40	0,98	24,01
Deadwood of all species	0,34	6,36	6,43	6,50	0,98	26,60
Portion by density:						
Dead spruce	0,46**	7,52	7,69	7,86	0,96	36,13
Dead fir	0,55**	3,64	5,12	6,60	0,67	50,21
Deadwood of all species	0,59***	4,33	5,50	6,67	0,74	52,56
Standing crop:						
Spruce	—0,27	7,33	7,38	7,45	0,99	30,64
Fir	—0,72***	3,38	4,48	5,55	0,76	70,41
All species	—0,76***	5,33	6,57	7,81	0,73	68,09
Portion by standing crop:						
Dead spruce	0,49**	5,86	6,57	7,29	0,84	44,03
Dead fir	0,75***	4,52	5,29	6,05	0,83	66,44
Deadwood of all species	0,73***	4,76	5,79	6,79	0,78	63,02
Canopy density	—0,53**	8,02	8,40	8,76	0,92	44,71
Number of underbrush species	—0,18	7,98	8,14	8,31	0,96	26,08
Parameters of timber stand's regeneration						
Density:						
Self-sown spruce	—0,26	4,90	6,45	8,00	0,66	76,93
Spruce young growth	—0,32	5,67	5,67	5,69	0,99	64,40
Fir young growth	—0,39*	5,69	5,69	5,71	0,99	37,23
Portion of undependable spruce young growth	0,31	8,50	8,64	8,81	0,96	39,35
Herb—dwarf-shrub layer						
Number of species:						
Grasses	0,62***	—	—	—	—	39,64
Short herbs	—0,78***	6,17	6,33	6,48	0,97	76,07
Tall herbs	—0,82***	4,21	5,62	7,02	0,69	71,64
Explerents	—0,62***	3,10	5,07	7,05	0,56	50,52
Forest species	—0,83***	4,48	6,05	7,62	0,65	73,84
All species of the herb layer	—0,81***	4,43	5,98	7,55	0,66	69,80
Portion of number of species						
Grasses	0,83***	6,67	6,93	7,19	0,94	79,19
Short herbs	—0,53**	7,40	7,57	7,76	0,96	42,61
Tall herbs	—0,71***	5,07	5,60	6,10	0,89	57,71
Explerents	0,78***	7,48	7,62	7,74	0,97	80,18
Forest species	—0,62***	7,83	8,02	8,24	0,96	75,36
Biomass:						
Moss	0,74***	6,74	8,74	—	—	68,19
Short herbs	—0,53**	—	—	—	—	52,21
Tall herbs	—0,72***	—	—	—	—	56,80
Horsetail	0,38*	2,88	3,74	4,60	0,81	17,37
Portion of biomass:						
Short herbs	—0,64***	—	—	—	—	38,86
Tall herbs	—0,72***	4,45	5,38	6,33	0,79	57,57
Horsetails	0,82***	3,83	4,93	6,02	0,76	79,16
Explerents	0,81***	3,36	4,67	6,00	0,71	78,20

Note. R) coefficient of linear correlation [level of significance: *) $P < 0.05$; **) $P < 0.01$; ***) $P < 0.001$]; K) "step-slope" parameter; D) portion (in %) of variance explainable by the logistic equation; a dash indicates a situation when the critical points of the curve are outside the region of actual values of the load.

The interval of the load from the background level to values at the upper critical point is an evaluation of the amount of the forest phytocenosis's stability. In this case, we have in mind only one of the types of stability: the system's resilience according to Holling (1973). It does not seem possible to measure stability of another type (elasticity), since the transition from the background level to the impact level can be considered irreversible on the time scale of the life of several generations of edificator trees. "Life pressure," which usually leads to rapid restoration of disturbed territories, is ineffective in this case. Even if the inflow of pollutants ceased, the accumulated potential of the soil's toxicity would not permit the forest phytocenosis to quickly restore itself to the background level, as would happen, for example, if it were cut. On the basis of model simulations, it was shown that the time required for restoration of a forest ecosystem after technogenic destruction is more than 2000 years (Armand et al., 1987).

Evaluations of the stability of different parameters have the same dimensionality, which allows them to be compared. The herb—dwarf-shrub layer begins to change sooner than the tree layer, when the background level of pollution is exceeded by 2.8-3.3 times. The corresponding value for the timber stand is 3.4-4.5; and for regeneration parameters, 4.9-5.7. Within the limits of a group of parameters, the spread in values is fairly great for each layer. Thus, for the timber stand the stability of the most sensitive parameters (average height and standing crop of fir) is commensurable with the stability of the herbage, but a number of parameters (canopy density, density of live fir, standing crop of spruce) remain stable all the way to almost the maximum levels of pollution. Parameters of the dominant species, fir, begin to change with loads 2-3 times less than for spruce. The resulting indices (stand density, canopy density) are more conservative than structural ones (portion of deadwood). The standing crop of the dominant species is one of the parameters most sensitive to pollution. On the contrary, the total biomass of herbage does not change on the pollution gradient, and the portions of individual groups (tall herbs, explerents) are the first to react to the load. In comparison with them, parameters of species diversity are more stable.

The results of analysis of the dose-effect dependences have important applied significance. Their stepped nature can be interpreted as the presence of a threshold in the reaction of phytocenoses to chemical pollution. This means that there are amounts of loads that do not take the system out of its background state. Consequently, there is an objective basis for introducing ecological standards as threshold or subthreshold amounts. If dose-effect dependences had the form of a straight line or a smooth curve, there would be no such objective criterion. This would make it necessary to seek other approaches or to set standards arbitrarily. Thus, the presence of a threshold significantly simplifies solution of the problem of setting standards for technogenic loads.

The minimum values found for the abscissas of critical points can be used as rough estimates of standards for the maximum permissible toxic loads on vegetation. Such an approach to setting ecological standards (Vorobeichik et al., 1992) has significant advantages over others, since it reduces to a minimum the element of arbitrariness in determining standards. The logic of this reasoning is as follows. Up to the upper critical point the load is considered to be acceptable, since it does not take the phytocenotic parameters beyond the limits of natural variation, and their deviations from the background level can be considered insignificant. After passing the critical point, rapid change in the parameter begins, which cannot be taken as acceptable (Grodzinskii, 1988). A standard expressed in the form of the necessary multiple of reduction in the load sets the position of the region of critical transition in the space near the source of emissions so that the boundary of the transition does not go beyond the limits of the territory appropriated by the enterprise. For the most sensitive parameters of a forest phytocenosis, this necessary multiple of reduction in the toxic load is 3.5-4.0 times. In the present work we do not discuss ways of making practical use of these amounts.

Our analysis of dose curves confirms the general conclusion about the nonlinear nature of phytocenoses' reaction to pollution (Armand et al., 1991; Alekseev and Tarasov, 1990; "Comprehensive Ecological Evaluation...," 1992; Saliev, 1989). At the same time, the strict calculation of the coordinates of critical points that we used is more adequate for problems of evaluating stability and setting ecological standards than determination of them by rule of thumb. We will note that the available increment in information in comparison with traditional investigations of technogenic transformations of vegetation is completely due to the change in the usual scheme of work (instead of pair comparisons, registration of parameters on a load gradient with syntopic measurement of levels of pollution). The evaluations of stability obtained (coordinates of critical points) can be considered experimental, since investigations near sources of emissions record the results of a field experiment begun when the plant was put into operation. In this regard, the data presented are of interest as a basis for verification of numerous mathematical models of ecosystems' reaction to various stress factors (Armand et al., 1987).

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