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Changes in Thickness of Forest Litter under Chemical Pollution

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Abstract – As the distance between a copper-smelting plant and the forests surrounding it decreases, the thickness of the forest litter increases two- to threefold, depending upon elimination of the saprophages of the mesofauna and a decrease in the activity of the cellulose decomposing microorganisms. The dose–effect relationships have a stepwise character. There are two levels: the background, with minimal thickness of the litter layer, and the impact, with maximal thickness. The conversion between them is sharply outlined.

The forest litter is an integrated index of the rate of destructive processes (Karpachevskii, 1981; Tate, 1991). Under conditions of chemical pollution, it is the main reservoir of the pollutant flows, the "critical component" of the ecosystem (Krivolutscii *et al.*, 1986). The fact of an increase in forest floor thickness under pollution by heavy metals and/or SO_2 has been repeatedly noted in literature (Coughtrey *et al.*, 1979; Freedman, Hutchinson, 1980; Jordan, Lechevalier, 1975; Moloney *et al.*, 1983; Nikonov, Lukina, 1991; Ragustis, 1984; Stepanov, 1988; Strojan, 1978; Tyler, 1984). The opposite situation is observed under pollution by calciferous dust (Volkova, Davydova, 1987; Yuschyk, 1991) or nitrogen compounds (Fenn, 1991). In some investigations, a high positive correlation between litter amount and concentration of pollutants in it have been revealed (Coughtrey *et al.*, 1979; Freedman, Hutchinson, 1980).

The litter parameters, highly informative, may be of great importance in the diagnostics of technogenic disturbances of forest ecosystems, monitoring, and ecological standardization. However, some important problems, such as the character of the dose–effect relationships and the cause of changes in the forest litter thickness, are not yet solved. The goal of our work was to attempt to answer these questions. We did not undertake the task of making a careful study of all the aspects of the litter transformation under chemical pollution. We concentrated our attention chiefly on an analysis of the changes in the forest litter thickness.

Various indices, such as the litter–litterfall coefficient, time of half-decomposition, and others, are best suited for investigating the rate of destruction. However, their measurements are laborious and require permanent investigations. When destruction is inhibited an increase in litterfall only slightly affects the value of the index as compared to litter amount. This defines the suitability of the latter parameter as an index of the intensity of the processes of destruction. The amount of litter is closely related to its thickness, and these parameters are considered interchangeable (Karpachevskii, 1981). In our work preference is given to the thickness. This index is less precise but much easier to measure, which is of essential importance when work is performed on a great number of sample plots.

CHARACTERISTICS OF THE INVESTIGATED REGION

Investigations have been conducted in the subzone of southern taiga in the region under the influence of the Sredneural'skii copper-smelting plant (Revda town). By the time of this study, the plant had been working for more than 50 years. The main components of the emission are SO_2 and dust particles with adsorbed Cu, Pb, Zn, Cd, As, etc. Sample plots were situated to the west of the plant at a distance from 0 to 30 km. Three groups of forests – birch forests, fir–spruce forests, and pine forests on grey forest and brown mountain forest soils – were studied. Earlier, we described the character of technogenic changes in vegetation (Vorobeichik, Khantemirova, 1994).

METHODS

(1) Thickness of the litter layer was measured in June, 1990, on 86 sample plots situated in the junction points of the regular grid 5 × 17 km with 1-km-sided squares (the rectangle's smaller side coincides with the boundary of the plant). In this work under the term "litter" we consider leaf (L) and fermentative (F) horizons. Thickness of the litter was measured to 0.5 cm in 30 open test pits on every sample plot. Pits were allocated randomly, excluding glades and places adjacent to trunks. This scheme makes it possible to essentially decrease the dispersion of the data (Karpachevskii, 1981).

(2) Soil-zoological investigations were made by standard methods from 1989 through 1991 in June and July on 25 sample plots. The size of the sample was 25 × 25 × 20 - 30 cm. Ten - twenty samples were taken per sample plot. Animals (mesofauna) were taken out

by hand immediately at the site or in the laboratory, where soil core samples were transferred into polyethylene bags.

(3) Soil-microbiological investigation was conducted from 1989 through 1991 on 15 - 20 sample plots. The actual rate of destruction of pure cellulose was estimated by loss of the mass of the filter paper exposed under natural conditions. The time of exposure was one year. Paper was put into capron net bags (25 - 30 bags per sample plot) and placed into the litter. The potential rate of cellulose destruction was measured under steady-state conditions: filter paper was exposed for 35 days together with composite samples of upper (0 - 5 cm) soil layer in Petri dishes at maximum water-holding capacity, at 25°C. Cellulase activity was determined in the same soil samples by the modified method of Bagnyuk and Shchetinskaya (Khaziev, 1990). The modification consists in measuring glucose by the sensitive enzymic method.

(4) Concentrations of the mobile forms of heavy metals (Cu, Pb, Cd) were measured in average samples of the upper (0 - 5 cm) soil layer from every sample plot. Extraction was carried out for 24 hours with 5% HNO_3 at a substrate–extractant ratio of 1 : 5. The gross content of heavy metals in snow cover was also measured (snow cores were sampled in March for the whole depth of the snow, five samples per plot). Concentrations were measured on an atom-adsorption spectrophotometer AAS-3 (Karl Zeiss).

RESULTS AND DISCUSSION

Character of changes. As the source of the emissions is approached, thickness of the litter layer increases by 2 to 3 times in comparison with the background territory (Fig. 1). Near the plant it reaches 11 cm, whereas in the absence of pollution, it amounts to only 5 to 6 cm. On the impact territory the structure of the litter changes. At a distance of 3 to 4 km from the plant it consists of needles, leaves, and herbaceous plant residues, practically completely conserving their structure. "Burial" of the litter under the thick (up to 5 cm) clumps of mosses is often observed. On the background territory, in most cases the litter is decomposed. The fermentative horizon consists of structureless plant residues. Here, destruction occurs so intensively that by the middle or the end of summer on some plots almost complete decomposition of leaf horizon of the litter may be seen.

On the basis of obtained materials the changes in the litter–litterfall coefficient may be preliminary calculated. We used data of V.P. Firsova *et al.* (1990), collected in the same region, for the characteristics of the background territory. Calculated on this basis, the litter–litterfall coefficient for spruce forests lies in the range of 3 to 5 years. Considering that in technogenic territory litterfall decreases at least twice (Makhnev *et al.*, 1990) and an average amount of litter as well as its thickness

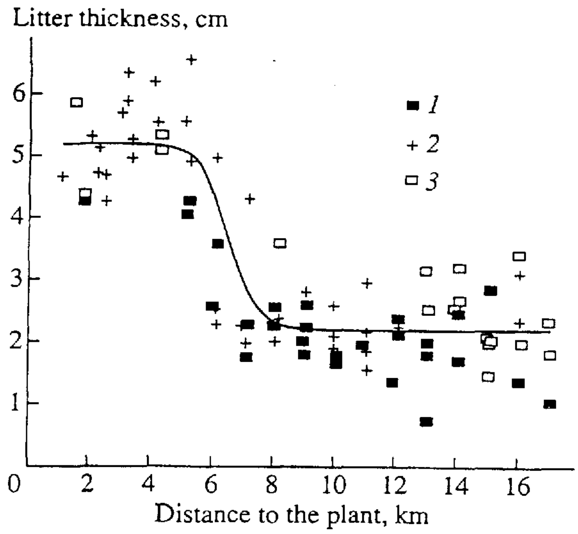

Fig. 1. Variations of average litter thickness depending on the distance to the plant: (*1*) birch forests, (*2*) fir–spruce forests, (*3*) pine forests; the line is the approximating logistical curve.

increases by three times (Fig. 1), the minimum value of the litter–litterfall coefficient can be assumed to be 20 to 30 years. The considerable increase in this index shows that quantitative changes in the production–destruction process take place. If we consider these changes regarding nature zonation, such a difference should correspond to displacement over the entire geographic zone, for example, from taiga to tundra (Striganova, 1989).

As would be expected, litter in the birch forests on the background territory is thinner than in the coniferous ones (Fig. 1), this being due to the fact that the leaf litter is more easily decomposed (Aristovskaya, 1980; Striganova, 1980). On the impact territory the difference is leveled probably due to the fact that the leaf fall and needle fall become equally difficult to decompose.

Changes in the litter thickness depending on the distance to the plant (Fig. 1) are not monotonic; rather, there is a clearly defined "leap." It is possible to distinguish four successive parts in the curve: (a) zone of minimum accumulation at a distance of 8 km, where insignificant variation of the litter thickness around the background level (average value is 1.0 - 2.3 cm) takes place; (b) zone of conversion to maximum accumulation at a distance of 7 to 5 km; (c) zone of maximum accumulation at the distance of 5 to 3 km, where the litter thickness is stabilized at the impact level (average level is 5.0 - 6.5 cm); (d) zone of decreasing litter thickness at a distance of 2 km to the smeltery boundary.

The decrease in the average litter thickness in the immediate vicinity of the plant may be primarily caused by the increase in the wind withdrawal, which is due to thinning of the forest stand and degradation of the herbaceous layer. This explanation is supported by the fact that the litter of some microbiotopes on that ter-

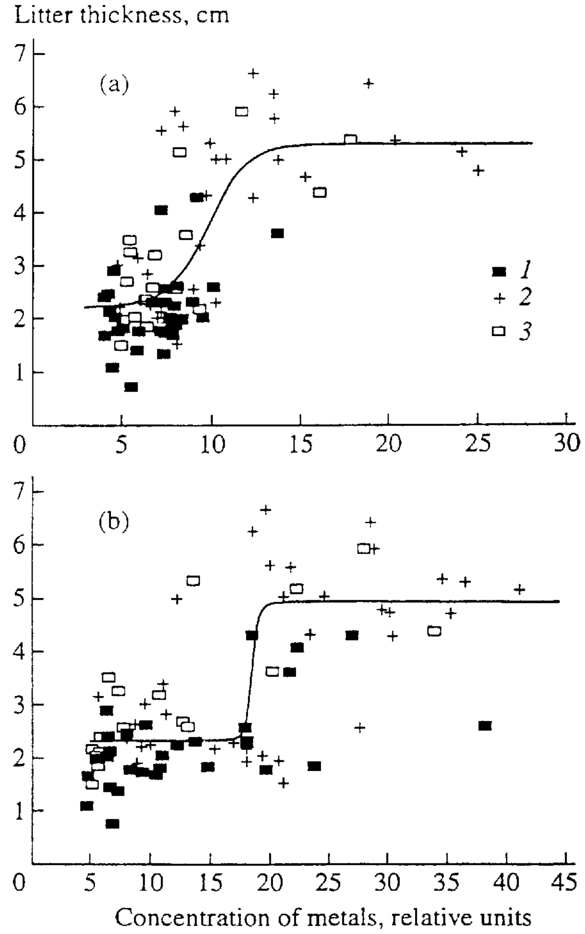

Fig. 2. Dependence of average litter thickness upon concentrations of heavy metals in the snow (a) and upper soil horizon (b); (*1*) birch forests, (*2*) fir–spruce forests, (*3*) pine forests; the line is the approximating logistical curve.

ritory retains great (to 10 - 11 cm) thickness, whereas in others it essentially decreases. Another possible cause may be a reduction in the litterfall.

The four zones of technogenic changes in litter thickness proposed by us agree with those of other authors (Nikonov, Lukina, 1991; Stepanov, 1988); thus, we can consider this picture typical of the territories around the point sources of aerogenic emissions.

Dose–effect relationships. The curve "litter thickness–distance to the plant" characterizes dose relationships only as a first approximation. It is more correct to use the value of the input of pollutants into the ecosystem (snow content) or their accumulation (content in soil) as a dose of technogenic load. We built these curves (Fig. 2) using, in both cases, the total index of pollution:

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

where $[]_i$ is the concentration of the element in point i, and $[]_f$ is the concentration of the element in the local background (30 km to the plant). This index acts as a "marker" of the whole complex of pollutants and makes it possible to essentially decrease the volume of information about the pollution. Hereafter, dose relationships were approximated by logistic equations of regression. Based on their analysis, the coordinates of critical points were found. Details of the calculation procedure were described earlier (Vorobeichik, Khantemirova, 1994). Upper and lower critical points characterize "the beginning" and "the end" of the most rapid change in the parameter, the midway point characterizing change in the thickness to one-half of the background level (Table 1).

Dose–effect relationships of the litter thickness are essentially nonlinear. Two levels – with minimum and maximum thicknesses – are separated reasonably clearly. Conversion between them begins when the background load is exceeded by 2.0 (according to snow pollution) and by 3.8 (according to soil pollution) times. Differences are due to the appropriate displacement of the gradients. Dispersion at every level is higher when the concentrations of metals in the soil are used as a criterion of the load.

Thus, the revealed *S*-shaped character of the dose–effect relationships indicate that there are two relatively steady states of the litter. The first state, background or normal, characterizes balanced velocities of the entrance and decomposition of organic matter due to high activity of the saprophytic complex. The second state, impact or pathologic, characterizes the delay of destruction as compared to production due to elimination of the agents of organic matter decomposition. The boundary between normal and pathologic states is dictated by the coordinates of the upper and lower critical points.

Using the principle of the spatial–temporal analogies, dose relationships may be interpreted as the expanded response over time of the forest litter to pollution. It is noteworthy that the system reacts to the gradual increase in the load not by gradual change but by sharp conversion from the background state to the impact one, which practically follows a trigger type. Thus, increase in soil pollution by 277% in comparison to background level does not cause change in the litter thickness, whereas the following increase only by 2.2% causes a sharp conversion to the impact level. A further increase in the dose by 127% more is no longer followed by change in the thickness (Table 1). The whole gradient of the load – from the value of maximum pollution to the local background – occupies 15 - 20 km, but conversion from the background level to the impact one occurs only over the distance of 0.8 km. This reaction resembles behavior of the system in agreement with the "all or nothing" rule, that is, either the background state or the impact one. This is of decisive importance for applied ecology.

The well-defined stepwise character of dose relationships may be interpreted as the existence of the threshold of toxic influence in the reaction of the litter to the impact, i.e., such a level of pollution that does not

Table 1. Parameters of dose–effect relationships for the average thickness of litter (all groups of the forest types are united into one sample)

Assessment of the dose	Abscissae of the critical points			Parameters	
	upper	midway	lower	R	D
Distance to the plant, km	5.4	5.8	6.2	−0.72	78.6
Metal concentrations, relative units:					
in snow	11.2 (2.67)	9.8 (2.33)	8.4 (2.00)	0.65	53.8
in soil	18.5 (3.85)	18.3 (3.81)	18.1 (3.77)	0.64	64.8

Note: R – coefficient of linear correlation (critical value for $P < 0.001$ is 0.35); D – portion (%) described by logistical equation of dispersion; ratio of the impact level of pollution to the background one is given in parentheses.

cause change. Respectively, underthreshold values may be considered maximum permissible concentrations and used in elaborating ecological standards. In our case, they correspond to x-coordinates of lower critical points (Table 1). Their correlation with maximum levels of pollution allows for calculating the necessary ratio of the decrease in the emission to the amount whereby normal thickness of the litter (accordingly normal acting of saprophytic complex of soil biota) will be retained up to the boundary of the smeltery. This rate is 2.3 to 2.9 times.

In ecological diagnostics the existence of two quantitatively different states of forest litter must be taken into consideration. The main efforts must be concentrated on recognizing precisely these states, and it would serve no purpose to seek differences within them. In other words, the litter thickness is a parameter allowing only a "rough" separation into standard and pathological states and not identification of more detailed grades.

Results of the analysis of the dose relationships may be used for zonation of the territory, specifically for isolating zones of normal state and of ecological distress (Vinogradov *et al.*, 1993). Coordinates of critical points act as boundaries of zones. In our case the territory extending 5 km from the plant (to the studied direction) may be considered the zone of ecological distress.

Reasons for increasing litter thickness. Beginning with the work of C.L. Strojan (1978), technogenic increase in litter thickness is connected primarily with the elimination of soil biota and, respectively, with a decrease in the organic matter destruction rate, which is clearly pronounced on the studied territory (Table 2). At a distance of 3 km from the plant the mostly active primary decomposers of organic matter – earthworms – are completely eliminated. On the background territory they dominate in the population of the soil mesofauna. They are represented by Ural endemic *Allolobophora diplotetratheca* (Perel) and widely distributed species *Eisenia nordenskioldi* (Eisen); in some places *Aporrectodea rosea* (Sav.) and *Dendrobaena octaedra* (Sav.) are abundant. In the immediate vicinity of the plant the other most important groups of saprophages – Enchytreidae and Diplopoda – are absent. At a distance of 7 km their number decreased (on the background territory Diplopoda are represented only by the species *Polyzonium cyathiferum* Mikh.). As the source of emission is approached, actual and potential rates of cellulose destruction and cellulase activity essentially decrease, almost by one order of magnitude. Sometimes, the only reason for technogenic change in the litter thickness is modification of the intensity of litterfall (Nikonov, Lukina, 1991). In our case this may not be an adequate explanation because the increase in litter thickness takes place against the reduction of litterfall, which may be supported by degradation of the tree stand (Vorobeichik, Khantemirova, 1994).

The question on whether inhibition of what group of pedobionts mainly contributes to the increase in litter thickness requires special experiments. Circumstantial evidence, however, supports the assumption that earthworms – the main group of saprophages in this region – are of first importance. At a distance of 4 km from the plant, where maximum accumulation of the litter is observed, their number decreased by 140 - 340 times as compared to the background level, whereas parameters of microbial activity decreased only by 1.2 to 2.2 times (Table 2). Exhaustion of the litter on the background territory and even partial disappearance of its leaf horizon by the end of summer may be explained namely by a great number of earthworms. The same situations are described, for example, in broad-leaved forests and are also ascribed to the high number and activity of earthworms (Hoof, 1983; Perel', 1979). The leading position of earthworms in litter decomposition is proved by many field and laboratory experiments (Perel', 1979; Striganova, 1980; Vsevolodova-Perel' *et al.*, 1991). Inhibition of the activity of the cellulose decomposing microorganisms has less influence on the litter because even in the immediate vicinity of the plant total elimination does not occur, and there are microbiotopes with a high rate of destruction (E. Vorobeichik, L. Vorobeichik, 1991).

The main cause of elimination of pedobionts is the toxicity of the litter. Unfortunately, we have no information about concentrations of heavy metals in it, but we may consider the pollution levels of the corresponding soils (Table 2). Concentrations of elements in the soil of the impact territory exceed the background concentrations by 2.8 - 19.8 times. The environment is essentially acidified as the plant is approached: pH of

Table 2. Variations of the parameters of the factors determining the processes of decomposition according to the distance from the plant (range of the average values)

Parameter	Distance from the plant, km				
	0 - 1	2 - 3	4 - 5	6 - 7	20 - 30
Concentration in the soil, μg/l:					
Cu	133.7 - 177.1	137.4 - 177.1	85.0 - 163.8	122.1 - 168.6	15.5 - 45.4
Pb	187.3 - 324.7	106.1 - 229.8	30.4 - 195.2	42.2 - 177.6	16.4 - 26.5
Cd	6.1 - 21.6	8.6 - 23.8	3.4 - 9.8	5.2 - 11.5	1.1 - 2.2
pH aqueous:					
litter	3.8 - 3.9	4.1 - 4.6	4.3 - 5.2	4.7 - 5.2	5.1
soil	4.4 - 4.8	4.8 - 5.2	4.7 - 5.2	5.4 - 5.8	5.5 - 6.2
Density, individuals/m^2:					
Lumbricidae	0.0	0.0	1.6 - 19.2	249.6	220.8 - 550.0
Enchytraeidae	0.0	1.6 - 11.2	12.8 - 96.1	89.3	388.2 - 480.1
Diplopoda	0.0	1.6 - 3.2	4.7 - 11.3	2.7	1.9 - 15.5
Rate of cellulose decomposition, %/day:					
actual	0.000 - 0.033	0.019 - 0.035	0.114 - 0.160	0.149	0.195
potential	0.023 - 0.320	0.256	0.356	0.631	0.586 - 0.776
Activity of cellulase, mg of glucose/10 g soil day	0.61	1.61	2.36	3.77 - 4.60	5.18 - 5.60
Coverage of mosses, %	34 - 75	56 - 77	51 - 64	8 - 29	11 - 41
Density of canopy, %	15 - 34	28 - 51	42 - 52	35 - 46	34 - 57

* Data are submitted by E.V. Khantemirova.

soil and litter decreases almost by one and a half units, and on the impact territory pH of litter is displaced by one unit into the acidic area. Under these conditions metals are mobile, which increases their toxicity to soil biota. High toxicity reveals itself only when the two discussed factors are in combination. At a distance of 6 to 7 km from the plant, where the amount of litter does not increase and essential elimination of pedobionts is absent, concentrations of heavy metals run as high as the impact level, whereas pH remains at the background level. Displacement of pH at a distance of 4 to 5 km is accompanied by pronounced negative changes in the saprophytic complex and an increase in the litter thickness.

One of the additional factors of elimination of the destruction processes is intensive development of the mosses on the impact territory (Table 2). Its negative influence is caused by antibiotic action on soil micromycetes and by displacement of the hydrological regime to excessive moistening (Mukhin, 1993). An increase in the heterogeneity of thermal conditions on the impact territory caused by degradation of tree stand and, respectively, of its thinning is responsible for decreasing the activity of the saprophytic complex (Table 2).

Consequences of the increase in litter thickness. It is commonly supposed that litter is the most important depot of biogenic elements, and the rate of their return to the soil defines its fertility and the availability of elements of mineral nutrition for plants (Karpachevskii, 1981; Tate, 1991). The hypothesis that an increase in litter under pollution leads to a decrease in the productivity and stability of forest ecosystems (Strojan, 1978; Tyler, 1984) is based on that proposition. Its experimental verification is difficult because of the necessity to separate the direct toxic influence of pollutants on vegetation. However, indirect evidence points to its validity. So, removal of the litter (analogous to inhibition of its mineralization), which was practiced in some European countries, causes soil fertility to essentially decrease (Bray, Gorham, 1964). For the meadow communities an intimate connection between the rate of cellulose mineralization and productivity is demonstrated (Titlyanova, Tesarzhova, 1991). As determined in experiments on a mathematical model, reducing the rate of nitrogen mineralization in the litter by 50% causes a decrease in the annual production of tree stand by 20% (Andersson *et al.*, 1980), which appeared the most essential modification of the process of production among several possible alternatives.

The work of A.D. Pokarzhevskii *et al.* (1992) substantiates the proposition that the main way of restoring energy and biogenic elements into the ecosystem is not destruction of the dead organic matter but eccrisotrophia – consumption by soil microorganisms of the intravitally liberated products of photosynthesis (root excretions, cells of epithelium, etc.). On the basis of that opinion technogenic "conservation" of biogenic elements in nondecomposed litter may be considered nonessential for the functioning of a forest ecosystem.

Omitting a question of what hypothesis most closely corresponds to life, it must be pointed that in every case the accumulation of litter indicates a decrease in the activity of soil organisms, which close the cycle of biogenic elements in the ecosystem in a certain way. As this takes place, the elimination of litter destruction serves as the main mechanism of cycle breaking or as an indicator of this situation.

One of the results of technogenic increase in the litter thickness may be a disturbance of the tree stand reproduction and of the development of herb–dwarf shrub layer, which is discussed in our work (Vorobeichik, Khantemirova, 1994). To separate this factor from the direct toxic influence of pollutants on vegetation is impossible. However, results received on unpolluted territories suggest that the increase in litter thickness caused by natural sources is the main reason for the modification of species composition and structure of the herb–dwarf shrub layer (Sydes, Grime, 1981a, 1981b), as well as for tree stand reproduction (Sannikov, 1992). This causes us to assume an analogous role of the litter when technogenic pollution of the environment takes place.

CONCLUSION

The obtained results must be considered the first step to understanding the regularities of technogenic transformation of the forest litter, because a complete picture needs information about the mechanism of the destructive processes. Nonetheless, even such a relatively rough index as the litter thickness appears to "work," indicating sharp slowing of mineralization of organic matter. On the basis of the analysis of its changes a conclusion may be made that the emission of heavy metals together with SO_2 sharply inhibits the rate of biological cycle in forest ecosystems: cycles of biogenic elements appear to be broken at the stage of destruction of organic matter and macro- and microelements "conserved" in the thick layer of nondecomposed litter. It may be expected that more "delicate" indices such as the rate of destruction will reveal even much more contrasting differences among zones with different loads.

The revealed threshold character of dose relationships of litter reaction to pollution simplified application of the considered parameter to applied ecology. When sample plots are correctly allocated (similarity of hydrothermal conditions of biotopes, high rate of destruction on the background territory), the litter thickness provides an adequate index for the purposes of ecological monitoring and diagnosing technogenic disturbances of forest ecosystems. Thus, it may be included in the control system of the condition of natural complexes in regions under chemical pollution.

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