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Role of Herbaceous Plant Communities in Biogenic Cycles of Chemical Elements

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Abstract—The role of ecological factors in the formation of biogenic cycles of chemical elements has been studied. It has been shown that, both under background conditions and chemical pollution, biogeochemical and biocenotic factors contribute to this process. These are the species structure of a community, specific features of chemical element accumulation, biomass of individual species, and productivity of phytocenosis. The accumulation of chemical elements in the phytomass depends not so much on their increasing concentrations in the soils as on degradation of the environment caused by their toxic effect and manifested in transformation of species composition and reduction of the total phytomass of the phytocenosis.

Keywords: chemical elements, chemical environmental pollution, species composition of phytocenoses, productivity of communities, ecological factors.

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INTRODUCTION

Numerous recent studies on the processes of chemical degradation of the environment are usually limited to analysis of accumulation of chemical elements in various components of natural ecosystems. However, even effects at the population level characterize only individual components of biocenosis rather than its state as an integrated biological system. The fate of biogeocenosis as a complex of living, biologically neutral, and inert components under exposure to anthropogenic impact of any kind depends on its ability to maintain the necessary level of matter, energy, and information exchange within itself and with neighboring biogeocenoses (Vernadsky, 1954).

In this context, technogenic pollution of the environment is considered from the standpoint of its disturbing effect on such an exchange. Such studies have gained increasing attention in the past few decades (Grimshaw et al., 1958; Dmowski and Karolewski, 1979; Lindquist and Block, 1997; Pokarzhevskii et al., 2000; Nikonov, 2004; Bezel', 2006; Bezel' and Zhuikova, 2007).

Plants as primary producers are the basic link in the trophic chain of biogeocenoses, which provides for the delivery of chemical elements directly from soil horizons and their involvement in biogenic cycles. On the other hand, producers serve as food objects for representatives of other trophic levels. The rate of biogenic turnover initiated by plants depends on the total amount of elements accumulated in the belowground and aboveground phytomass and the period of their return to the upper soil horizons.

This study deals with the involvement of chemical elements in biogenic turnover depending on their total amount in the belowground and aboveground phytomass of meadow plants. It can be a priori expected that the rate of such cycles at different levels of soil pollution can be determined by the following factors:

– increasing soil concentrations of chemical elements in forms accessible to plants;

– changes in the species composition of phytocenoses under the effect of chemical pollution and related specific features of the accumulation of chemical elements and their toxicity for different plant species; and

– the impairment of total productivity of plant communities under the impact of chemical pollution due mainly to the reduction of the aboveground and belowground phytomass.

The purpose was to evaluate the roles of the above factors in the formation of biogenic cycles of chemical elements.

MATERIALS AND METHODS

Studies were performed from 2001 to 2007 in the Nizhny Tagil industrial region, the Middle Urals, where the main pollutants are polymetallic dust (containing Cd, Pb, Fe, Cr, Cu, Ni, Zn, Mn, and Co) and sulfur and nitrogen dioxides. At different distances from the sources of industrial emissions, eight areas exposed to different levels of toxic pollutants were delimited.

Within each area, a 10 × 10-m test plot was established following the standard procedure (Mirkin and Rozenberg, 1978). Floristic lists were compiled using the species names given in the monograph by Cherepanov (1995). The level of species saturation was determined in 20 1-m^2 squares per plot.

The standard ecological scales by Ramenskii et al. (1956) and Tsyganov (1983) were used for characterization of biotopes. With respect to moisture supply, most of them were classified as moist meadow biotopes with equal degrees of pastural digression and sufficiently rich, fertile soils. The plots also proved to be similar in basic ecological conditions (soil moisture and salinity, illumination, soil digression, thermoclimatic and cryoclimatic regimes, etc.). Regardless of probable changes in the species structure under pollution impact, the communities appeared to be composed of species with similar requirements for habitat conditions.

Samples of aboveground and belowground plant organs were taken along the pollution gradient to determine their phytomass and measure heavy metal contents. Heavy metals were also determined in the soil. For this purpose, soil monoliths (25 × 25 × 25 cm) were dug out in ten replications (Shalyt, 1960). Plants were removed from the monolith manually, without breaking them into the aboveground and belowground parts. In the laboratory, they were washed and dried to an air-dry state. The phytomass was determined for each species individually. Soil samples taken from each monolith were used to extract metals with 5% HNO_3 (*Metodicheskie relommendatsii*..., 1981; *Metodicheskie ukazaniya*..., 1992). The contents of Zn, Cu, Pb, Cd, Cr, Co, Mn, Fe, and Ni in acid extracts from soil and plants were measured in a Perkin Elmer AAS 300 atomic absorption spectrophotometer.

Since the concentrations of chemical elements in the soil differed between the test plots, we used the integrated pollution coefficient (K) as a measure characterizing the gradient of overall toxic load on phytocenosis:

$$K = 1/n\ \Sigma C_i/C_{\mathrm{bgr}},\ \text{rel. units},$$

where C_i and C_{bgr} are the concentrations of a chemical element in the impact and background plots, and n is the number of elements included in analysis (i.e., the data on all elements forming the gradient are summed up). In the plots studied in different years, the toxic load increased from 1.0–1.47 rel. units in the background zone to 3.33, 4.92, 6.19, and 8.36 rel. units in the buffer zone and to 22.78 rel. units in the most polluted impact plot.

The contribution of vegetation to the formation of biogenic cycles of chemical elements was determined from their contents in the phytomass:

$$P = \Sigma C_i\ M_i,\ \mu\text{g/m}^2,$$

where C_i is element concentration in the phytomass of the ith plant species, μg/g, and M_i is its aboveground or underground phytomass, g/m^2. The data on all species recorded in the plot are summed up.

RESULTS AND DISCUSSION

Concentrations of chemical elements in soil and plants. It appears evident that soil enrichment with heavy metals leads to increase in their concentrations in plants. In our test plots, the average concentrations of Zn, Pb, Mn by a factor of 2–5; of Cd, by a factor of 7–18; and of Cu, by a factor of almost 50. The concentrations of other elements showed no distinct trend in the pollution gradient.

Under conditions of changes in the floristic composition of communities in the gradient of chemical pollution, the accumulation of chemical elements in the phytomass may be characterized by their average concentrations in all species taken together, which has proved to increase along the gradient of soil pollution (Table 1). The formation of biogenic cycles under background conditions and under chemical pollution depends on the species composition of plant community and specific features of chemical element accumulation, the phytomass of individual species, productivity of phytocenosis, etc. The phytocenosis may manifest its barrier function if the increase in the concentration of chemical elements in the soil is accompanied by a disproportionate increase in their contents in the phytomass. The dashed line in Fig. 1 corresponds to the linear dependence of fold changes in the contents of chemical elements in the aboveground and belowground phytomass on fold changes in their concentrations in soils. The corresponding values for almost all elements are below this line, which is evidence for the existence of biogeochemical barriers in the soil–roots–aboveground organs system.

Dynamics of phytocenosis phytomass. The total aboveground and belowground phytomass proved to decrease significantly along the pollution gradient, with changes in growing conditions also playing an important role. The aboveground phytomass in the background plot varied from 120 g/m^2 in the year with adverse conditions to 490 g/m^2 in the most favorable year; the respective values in polluted plots were 60 and 176 g/m^2. In all variants, the total amount of accumulated chemical elements was greater in the belowground than in the aboveground plant organs. This difference increases along the ascending gradient of Zn, Cu, and Pb concentrations in the soil, eventually being as great as fivefold.

Species composition of plant community. It is known that the pattern of accumulation of chemical elements by plants is species-specific (Koval'skii and Petrunina, 1964; Baker, 1981; Bednarova, 1988; Antosiewicz, 1992; Bezel', Zhuikova, and Pozolotina, 1998; Grant et al., 1998; Titov et al., 2007). Therefore, rearrangements in the species structure of phytocenosis caused by chemical soil degradation will be in favor of the most pollution-resistant species capable of accumu-

Table 1. Average concentrations of chemical elements in the phytomass, $M \pm m$

Toxic load, rel. units	Chemical elements								
	Zn	Cu	Cd	Pb	Co	Ni	Mn	Cr	Fe
Aboveground phytomass									
1.00	39.80 ± 4.63	6.06 ± 0.53	0.32 ± 0.08	7.48 ± 1.24	5.15 ± 1.86	6.70 ± 1.04	59.73 ± 8.63	4.45 ± 0.55	385.29 ± 84.19
3.33	55.43 ± 7.15	8.77 ± 1.13	0.51 ± 0.09	10.80 ± 1.47	11.89 ± 3.47	3.70 ± 0.36	50.77 ± 5.97	3.83 ± 0.48	806.05 ± 107.13
4.33	108.29 ± 15.69	17.24 ± 2.90	0.50 ± 0.13	13.07 ± 3.16	28.61 ± 10.63	7.18 ± 2.39	67.86 ± 14.38	6.53 ± 1.14	804.32 ± 29.18
6.19	109.93 ± 20.08	8.27 ± 0.75	0.58 ± 0.09	17.12 ± 2.78	112.31 ± 40.97	4.32 ± 0.93	50.23 ± 9.27	5.35 ± 0.45	686.70 ± 190.51
22.78	140.36 ± 40.91	55.16 ± 18.39	1.96 ± 0.59	23.85 ± 10.33	118.16 ± 58.20	11.10 ± 5.37	167.55 ± 74.24	11.31 ± 3.38	1327.96 ± 412.41
Belowground phytomass									
1.00	85.32 ± 17.14	24.34 ± 4.85	1.28 ± 0.82	16.40 ± 3.29	33.20 ± 7.14	28.28 ± 6.99	227.82 ± 118.58	75.51 ± 14.19	14585.76 ± 8232.93
3.33	101.22 ± 28.12	83.12 ± 30.17	16.02 ± 4.19	48.23 ± 19.29	86.35 ± 41.68	4.39 ± 2.55	3578.13 ± 1683.21	132.23 ± 69.45	2676.23 ± 941.76
6.19	72.66 ± 10.29	19.63 ± 3.06	37.37 ± 7.19	78.77 ± 19.93	26.89 ± 15.82	7.18 ± 2.96	108.33 ± 15.73	46.62 ± 14.35	2836.84 ± 319.00
8.36	60.25 ± 7.81	44.55 ± 22.21	0.085 ± 0.03	9.18 ± 4.06	9.79 ± 3.71	7.20 ± 3.19	334.27 ± 147.61	43.95 ± 21.29	8276.73 ± 3829.66
22.78	108.79 ± 11.01	221.76 ± 29.45	0.71 ± 0.11	17.43 ± 3.63	19.12 ± 1.68	52.09 ± 8.93	217.18 ± 23.56	23.63 ± 2.73	3533.63 ± 395.19

lating either certain elements selectively or any elements in small amounts. In this course, very complex cenotic relationships may develop, with that elimination of certain species from the community providing living space for other species, which are not necessarily resistant to toxic factors. A detailed analysis of such rearrangements is given in our previous study (Bezel' and Zhuikova, 2007).

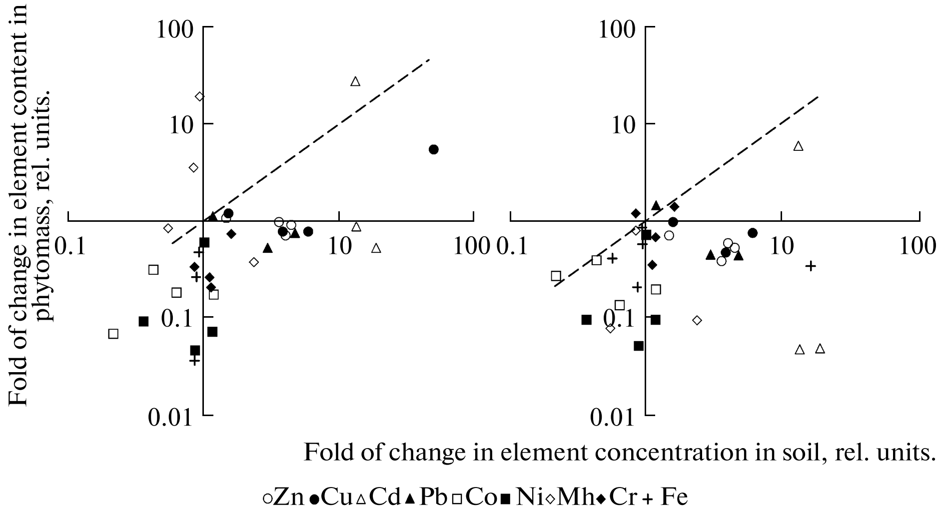

Fig. 1. Fold changes in the contents of chemical elements in (a) the belowground and (b) aboveground phytomass of meadow plants as a function of fold changes in their concentrations in soils.

Analysis of species saturation of meadow communities showed that the number of species per square meter varied from 19.5 to 25.2 in background plots, from 20.0 to 27.0 in buffer plots, and from 5.9 to 16.6 in the impact plot, with the last value significantly differing from the first two values according to Scheffe's multiple comparison test ($F(7; 33) = 3.73, p < 0.001$). Similar results confirming the reduction of species saturation under chemical pollution were obtained in forest phytocenoses (Lukina and Nikonov, 1990; Vorobeichik, Sadykov, and Farafontov, 1994).

The core of the meadow flora consisted of species belonging to three leading families (Asteraceae, Poacea, and Fabaceae), which accounted for 57.1–58.5% of the total species number in communities of background plots and for up to 80% in phytocenoses of technogenically disturbed areas. In the zone of heavy pollution, the proportion of Asteraceae species was two to three times greater than those of Poaceae and Fabaceae, and 9–16 greater that the proportions of species representing other families. Chemical pollution resulted in a decrease in the contributions of families Scrophulariaceae, Rosaceae, and Apiaceae to the species diversity of communities. Species of the families Apiaceae and Rosaceae proved to be especially vulnerable to this factor: their proportion decreased from 7.7–8.6% in the background plots to less than 5% in the zone of heavy toxic load.

The floristic composition of meadow communities and the structure of dominance changed along the gradient of chemical pollution. In background plots, *Lathyrus pratensis* Linnaeus, 1753 or *Poa pratensis* Linnaeus, 1935 were dominant. Communities in the buffer zone differed in dominant species, which included *Trifolium pratense* Linnaeus, 1753, *Trifolium hibridum* Linnaeus, 1753, *Alchemilla vulgaris* Linnaeus, 1753, *Deschampsia caespitosa* (Linnaeus) Beauv., 1934, and *Poa palustris* Linnaeus, 1759. Communities of the impact zone were dominated by *Calamagrostis epigeios* (Linnaeus) Roth., 1965. Thus, the roles of species in communities changed along the pollution gradient. Thus, the group "other species" was supplemented by pollution-resistant plants (*Picris hieracioides* Linnaeus, 1753, *Hieracium umbellatum* Linnaeus, 1753, *Berteroa incana* Linnaeus, 1821, *Convolvulus arvensis* Linnaeus, 1721, etc.), while typical meadow species (*Poa pratensis* Linnaeus, 1935, *Deschampsia caespitosa* (Linnaeus) Beauv., 1934, *Agrostis tenuis* Sibtb., 1794, *Dactylis glomerata* Linnaeus, 1753, *Ranunculus acris* Linnaeus, 1753, *Carum carvi* Linnaeus, 1753, *A. vulgaris, T. hibridum*, *Vicia sepium* Linnaeus, 1971, etc.) disappeared from communities. On the other hand, many species retained their positions in communities irrespective of pollution. These were *Vicia cracca* Linnaeus, 1965, *Taraxacum officinale* Wigg. s.l., 1964, *Cirsium setosum* (Willd.) Bess., 1963, *Sonchus arvensis* Linnaeus, 1964, *Sonchus oleraceum* Linnaeus, 1753, *L. pratensis* L., *P. palustris, Chamerion angustifolium* (Linnaeus) Holub., 1753, *Bromopsis inermis* (Leyss.) Holub., 1753, etc.

These transformations accounted for increasing differences between plant communities of background and technogenically disturbed areas. To evaluate these differences, we analyzed changes in the Czekanowski–Sörensen index using as a reference its value determined for the complete lists of species recorded in two background plots over two years. The results showed that this index consistently decreased along the pollution gradient, from 0.70 between communities of the background zone to 0.36 under conditions of heavy pollution.

Such rearrangements in the species structure of communities can have an effect on the total contents of chemical elements in the phytomass of phytocenosis.

Therefore, along with the amount of phytomass and the level of chemical soil pollution, the species composition of communities is also a dynamic parameter of their state that has an effect on the involvement of chemical elements in biogenic cycles.

These data provide a basis for evaluating the basic mechanisms of geochemical plant ecology. The amount of chemical elements involved in biogenic turnover can be determined from data on the belowground and aboveground phytomass in each plot and the concentrations of chemical elements in plant organs (Fig. 2). As the toxic load increases, the total heavy metal content in the phytomass becomes lower (except for copper, which is accumulated increasingly). It should be noted that the reduced deposition of chemical elements in the aboveground plant organs, which die off every year, provides for prompt involvement of this mineral pool in biogenic turnover. Elements contained in the belowground plant parts are the passive component of their total stock, with its turnover depending on the decomposition rate of the belowground phytomass.

The majority of constituent plant families are represented in the studied communities by broad spectra of species evolutionarily adapted to various unfavorable factors of the natural environment. Therefore, these families naturally differ in their contribution to the total uptake of chemical elements by the aboveground phytomass. In the background plot, 23% of cadmium, 34% of lead and zinc, and up to 50% of copper was contained in legumes (Fabaceae), whereas the uptake of metals by Asteraceae species did not exceed 25%, except for cadmium (up to 40%). As the toxic load increased, the contribution of the latter family to the total amounts of Zn and Pb in the aboveground phytomass increased to 50 and 60%, respectively. The contents of metals in the phytomass of grasses (Poaceae) were relatively small: from 5–15% in background plots to a maximum of 20% in heavily polluted plots.

Thus, the role of plants in the biogenic turnover of chemical elements is determined by increasing con-

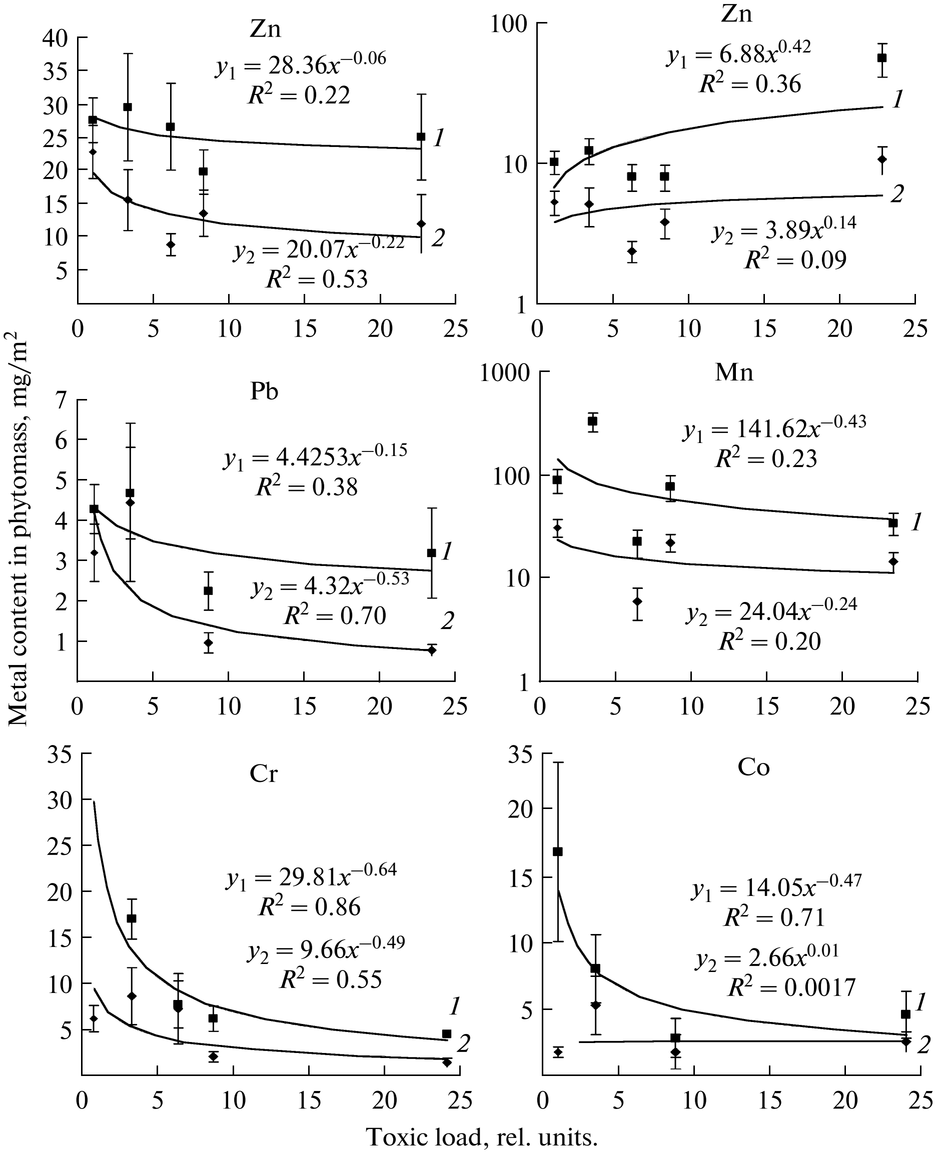

Fig. 2. Contents of chemical elements in (*1*) the belowground and (*2*) aboveground phytomass.

centrations of these elements in the soil along the toxic pollution gradient. On the other hand, chemical degradation of the environment along the same gradient leads to a decrease in the total phytomass and rearrangements in the species structure of phytocenosis. The interaction of these opposite factors eventually determines the rate of involvement of chemical elements in the biogenic turnover. In our case, where the concentrations of most elements in the soil increased two- to fivefold, the main role was played by changes in the species structure of communities and reduction of their phytomass. Copper was an exception: its concentration in the soil increased 50-fold, and an increase to the total contents of this metal was observed.

The individual roles of the above factors in the biogenic turnover of chemical elements in meadow plant communities under background conditions and in chemically polluted areas were evaluated by means of multiple regression analysis. Factors considered to have an effect on the amount of these elements in the phytomass were as follows: the level of toxic load, concentrations of chemical elements in the soil, values of the Czekanowski–Sörensen floristic similarity index, and the total amounts of above- and belowground phytomass. The results showed that the amounts of above- and below ground phytomass have a decisive effect on the total contents of chemical elements in the phytocenosis (Table 2). It is noteworthy that the increasing metal concentrations in the soil have no significant direct influence on their involvement in

Table 2. Standardized multiple regression coefficients for (1) the aboveground and (2) belowground phytomass of phytocenosis

Parameter	Zn		Cu		Pb		Co		Mn		Cr	
	1	2	1	2	1	2	1	2	1	2	1	2
Chemical load	0.06	–0.10	0.46*	0.01	0.74*	0.47*	0.01	0.23	–0.10	–0.06	–0.10	0.09
Element concentration in the soil	0.28	–0.06	–0.21	–0.09	–0.17	0.20	–0.08	–0.24	–0.11	–0.08	0.38*	0.53*
Czekanowski–Sörensen index	0.29*	0.08	0.05	–0.19	0.14	0.28	–0.15	0.10	–0.12	–0.11	0.07	0.14
Phytomass	0.44*	0.57*	0.67*	0.74*	0.18	0.37*	0.68*	0.39*	0.16	0.34*	0.50*	0.43*

* The regression coefficient is statistically significant ($p < 0.05$).

biogenic turnover: multiple regression coefficients for this parameter even have negative values in many cases. A direct dependence between metal contents in the soil and the phytomass was revealed for chromium. It should also be noted that the accumulation of copper and lead by plants showed significant dependence on the total toxic load accounted for by strongly increasing concentration of these metals in the soil.

The results of this analysis confirm that the accumulation of chemical elements in the phytomass depends not so much on the increase in their concentration in the soil as on consequent chemical degradation of the environment manifested in transformation of species composition and especially in reduction of the overall productivity of plant community.

CONCLUSIONS

The example of herbaceous meadow communities shows that the accumulation of chemical elements by plants in polluted areas depends not only on their direct uptake from the soil but also on cenotic parameters of the environment, including the species composition and productivity of phytocenosis.

An increase in the concentrations of chemical elements in the soil results in their elevated contents in the phytomass. On the other hand, chemical degradation of the environment entails rearrangements of species structure in favor of the most pollution-resistant species capable of accumulating the minimum amounts of toxic elements, with the total above- and belowground phytomass of phytocenosis decreasing simultaneously. The interaction of these two opposite processes determines the rate of the biogenic turnover of chemical elements.

Deformations of the biogenic turnover in the communities considered in this study obviously reflect particular conditions of chemical pollution (the specific spectrum of elements, the pattern of their concentrations in the soil, biocenotic conditions, etc.). However, the data presented above are of more general significance and can be extrapolated to areas with different natural–climatic conditions, qualitative composition of vegetation, and the degree of environmental pollution.

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