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GENESIS AND GEOGRAPHY OF SOILS

Ecological–Geochemical State of Soils in Ulaanbaatar (Mongolia)

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Abstract—Based on the results of the soil–geochemical survey, the assessment of the soil cover pollution in different Ulaanbaatar functional zones is given. The soils of the industrial and traffic zones concentrating a wide spectrum of pollutants (Zn, Mo, Cr, Cr, Cd, Pb, and Cu) are characterized by the strongest technogenic transformation. The soils of the residential areas accumulate Pb and Zn, while those of the recreation zone, Mo, Ni, and Cr. The geochemical mapping allowed distinguishing four groups of elements with similar distribution patterns determined by the common pollution sources, the specific features of the parent rocks, and the intensity of the migration. Among the natural and technogenic factors responsible for the accumulation of microelements in soils, the basic ones are the soil physical and chemical properties: the contents of organic matter (for As, Cd, Cu, Mo, Zn), physical clay (Ni, Co), sulfates (Pb, Sr), and the pH (Cr). The character of the land use noticeably affects the concentration of many elements. The soils of the city are assessed as weakly polluted (Zc = 11). The contents of As, Zn, Mo, and Pb exceeded their MPC in 100, 34, 20, and 16% of the city's territory, respectively. As compared to the state of the soil cover in 1990, no significant changes were revealed.

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INTRODUCTION

At present, the assessment of the state and pollution of urban soils is a priority line of applied geochemistry. It is becoming especially important due to the fast growth of the urban population and the formation of large agglomerations. Under the high population density and the great number of diverse sources of heavy metals (HM) and other pollutants, the soils become geochemically heterogeneous due to the different uses of the urban territory resulting in the formation of areas extremely unfavorable for human life.

The rapid growth of the urban population is a global phenomenon, and Mongolia is not an exception. The influx of the population promotes the intense growth of the Mongolian capital and makes more complicated the ecological problems related to the development of the industrial sector of the economy and the growth of car parks. In the last 20 years, the capital's population has increased from 600 thousand to 1 million people (by 36–38 thousand per year); the number of cars has risen from 35 thousand to 95 thousands (about 6 thousand/year). More than half of the population of the country lives in Ulaanbaatar. The results of the ecological–geochemical survey fulfilled in the Mongolian capital in the 1990s [10] needs corrections due to the social and economic changes in the country.

The aim of this work is studying the current ecological–geochemical state of the soil cover and its long-lasting changes in the territory of the city of Ulaanbaatar exposed to the complex influence of industrial enterprises, including the heat-and-power industry, transport, and municipal wastes. A specific feature of this work is the methodology of the differentiated assessment of the functional zones aimed at revealing the geochemical heterogeneity of the soil cover within the city. The following tasks were solved:

(1) The characterization of the geochemical background and technogenic transformation of the soils in different functional zones of the city;

(2) The determination of the spatial structure of the urban soil pollution by microelements and revealing of the complex of landscape–geochemical and technogenic factors responsible for the accumulation of pollutants;

(3) The assessment of the current ecological–geochemical state of the soil cover and its changes over the last 20 years.

NATURAL ENVIRONMENT

Nowadays, the area of the city of Ulaanbaatar is 4704.4 km^2, while its population is 1 044 500 [16]. The city includes territories with urban buildings (multistoried residential buildings and buildings for different industrial and transport enterprises and institutes, etc.) and districts with gers (yurts) that were formed in the city outskirts after 1990.

The capital is located in the intermontane kettle depression drained by the Tola River. This depression extends from the west to the east for 30–35 km and for 6–10 km from the north to the south, presenting a half-closed landscape–geochemical arena with the extensive development of accumulative, transaccumulative, and transeluvial landscapes. The very gentle slopes of the depression's bottom increase up to 20–25° towards the mountains; in some places, the slopes are steeper [5].

The Tola River valley is 5–10 km wide with a water edge of 1230–1240 m. Within the city, the river has many tributaries (the Selbe, Uliastai, and some others). The parent rocks are represented by the Archaean granites, the Carboniferous metamorphic shales, and the Neogene mottled clays often containing readily soluble salts and gypsum, sands, and conglomerates. The shales and clays are enriched with Fe, Mn, Cr, Co, Pb, Ni, and Ti; the granites, sands, and river alluvium are poor in these elements [1].

The climate is extremely continental with frequent temperature inversions in the winter. The mean annual precipitation in Ulaanbaatar is 240–260 mm; 60–90% is in July and August, and it is mostly of shower character [3].

The depression is referred to the Khangai soil-bioclimatic province and the Cis-Khantai district with chestnut and dark chestnut soils in the eluvial and transeluvial positions and alluvial stony–pebbly soils in the accumulative landscapes of the Tola River and its tributaries [18]. The soils are loamy sandy and sandy loamy with high water permeability, a low (0.5–1.5%) humus content, pH 7.5–9.0, and a $CaCO_3$ concentration of 0.7–5.0%. On the slopes of the Bogdo-Ula Mountain, mountain soddy taiga and mountain meadow–forest soils with a higher (up to 7.0%) humus content are formed.

In the Ulaanbaatar, the soils are exposed to strong anthropogenic impact; from the central part of the city toward the ger outskirts, the degree of their transformation decreases. In the central part, the construction of modern multistoried buildings and asphalt roads cardinally changed the soil cover: from mixing and sealing up to its full destruction and the formation of technogenic surface formations. In the districts dominated by gers, the initial soils are overlain by the deposits of anthropogenic and natural (deluvial and proluvial) origin. In these districts, the soil cover does not strongly change due to the absence of asphalt roads and the building of the gers without foundations.

POLLUTION SOURCES AND FUNCTIONAL ZONING OF THE CITY OF ULAANBAATAR

The center of the city is situated on the Tola River floodplain and terraces, where large industrial enterprises and multistoried residential areas are concentrated; the latter are crossed by highways parallel to the river. Presently, the center is the united industrial–transport–residential area, where the pollutants of industrial and transport origin have been accumulating over a long time. Considerable amounts of lead and other pollutants enter with the exhaust gases of cars using leaded petrol [22]. The zone of modern buildings extends to the west and south, where residential houses and offices and their multistoried complexes, as well as modern individual cottages, are built (Fig. 1).

The multistoried blocks in the subordinate topographic positions are surrounded by ger massifs along the Tola River tributaries rising to the hill slopes. The city's territory increases mainly due to the expanding ger districts. The pollution sources in this area are motor transport, individual heating in winter, and spontaneous garbage wastes that do not yield to industrial waste in the complex of pollutants.

The main industrial enterprises concentrate on the right bank of the Tola River in the southwestern part of the city. The fuel–energy complex is one of the major sources of environmental pollution in Ulaanbaatar. It includes three running thermal power plants and different (district, enterprise, military unit) boiler houses. Their basic fuel is brown coal of the Baga-Nur, Nalaikh, and Chulut deposits, which are enriched in Pb, As, and Mo by tens of times and in Cu, Sr, Cd, and Ni by some times as compared to the clarke values of these elements [11]. The maximal emissions take place in the cold season (from October to May) [7].

In the industrial zone, the plants producing cobble, concrete, cement, and other building materials; overhaul factories; plants of the woodworking; textile, shoe, food, and tobacco industries; and depositories of agricultural products, wool and wool products, and some other export items are located. To the north from the main industrial zone, in the ger district, the grain elevators and meat processing and packing factories are located. The main pollutants emitted by these enterprises are Zn, Pb, Co, Ni, Cu, Mo, Sr, Hg, and V [6].

In the western part of the city, the sewage treatment plant for the liquid industrial and municipal wastes is located. The purification of the sewage is performed by dilution and settling with the subsequent removal of the waste residues from the city [7, 10]. As a rule, the water from the sewage works is enriched with Cu, Cr, and Ni by tens of times and with other HMs by some times [6].

Thus, according to the functional status of the territory and the specific features of the pollution sources, the following zones are distinguished in the city of Ulaanbaatar: the industrial, traffic, multistory

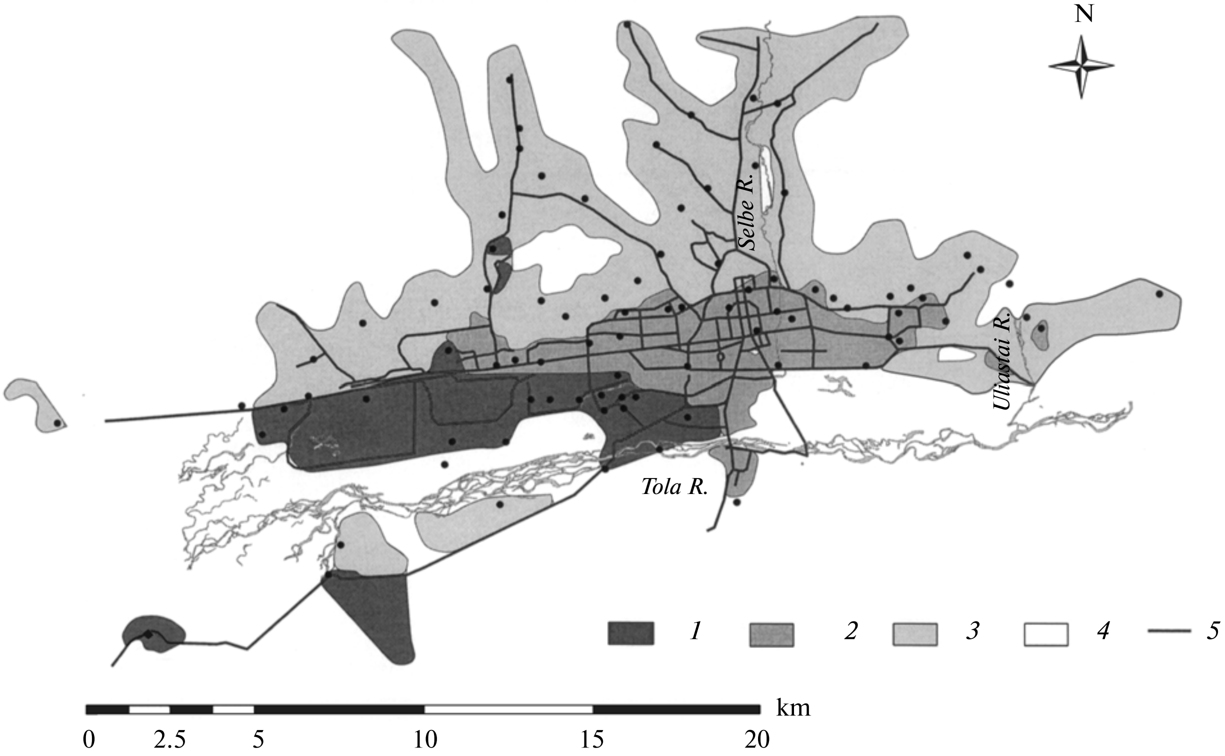

Fig. 1. The map of the functional zones of Ulaanbaatar (with the points of the sampling). Designations: *1*–*5*—functional zones: *1*—industrial, *2*—multistoried administrative and residential building, *3*—ger building, *4*—recreational and undeveloped territories, and *5*—traffic; the dots show the points of the soil sampling.

building (administrative and residential), traditional ger building, and recreation areas (Fig. 1).

MATERIALS AND METHODS

The soil-geochemical survey in the city of Ulaanbaatar was accomplished by the authors within the Joint Russian–Mongolian Complex Biological Expedition of RAS and MAS in 2008. The urban soil samples were taken from the 0- to 10-cm layer using a network with intervals of 500–800 m, and mixed samples were collected by the envelope (1 × 1 m) method. The soil samples from the Bogdo-Ula (2–3 km south of the capital) and Terelzh (20 km east) reserves and at the somon of Altan-Bulak (50 km west) reflected the regional background, and the samples from the recreation zone of the city were used as those representing the urbanized background. A total of 90 samples were taken within Ulaanbaatar and 6 samples in the background conditions (Fig. 1).

For the assessment of the ecological state of urban soils, the total contents of the elements of the first (As, Cd, Pb, Zn), second (Co, Ni, Mo, Cu, Cr), and the third (V, Cr) classes of danger were analyzed using mass spectrometry with induced coupled plasma (ICP-MS, Elan-6100, Perkin Elmer, USA) and atomic emission spectrometry (Optima-4300, Perkin Elmer, USA) in the Analytic Certification Experimental Center of the Fedorovskii Russian Research Institute of Mineral Raw Materials. The following physicochemical properties of the soils were analyzed: the pH_{water} of the extract (the soil : water ratio was 1 : 2.5), the contents of CO_3^{2-} and Ca^{2+} (the soil : water ratio was 1 : 5), the particle-size composition (laser diffractometry, diffraction analyzer, Analyzette 22), and the organic carbon content (bichromate oxidation).

On the basis of the mean microelement (ME) contents in the soils of the regional background and the different functional zones, the coefficients of the concentrations (CC, *Cc*) and the dispersion coefficient (DC) were calculated. These coefficients allow assessing the accumulation and dispersion of the chemical elements over the city's territory research area as compared to the global (CC, DC) and regional (*Cc*) backgrounds. Such calculations enable one to normalize the content of the chemical elements in urban soils via the parameters of the pedogeochemical background. An integral (summarized) pollution index (*Zc*) was used for the characterization of the total polyelemental load on the urban soils [6]:

$$Zc = \sum_{1}^{n} Cc - (n-1), \quad \text{where} \quad Cc = \frac{C_b}{C_{urb}},$$

n is the number of chemical elements with $Cc > 1.0$; and C_b and C_{urb} are the element concentrations in the

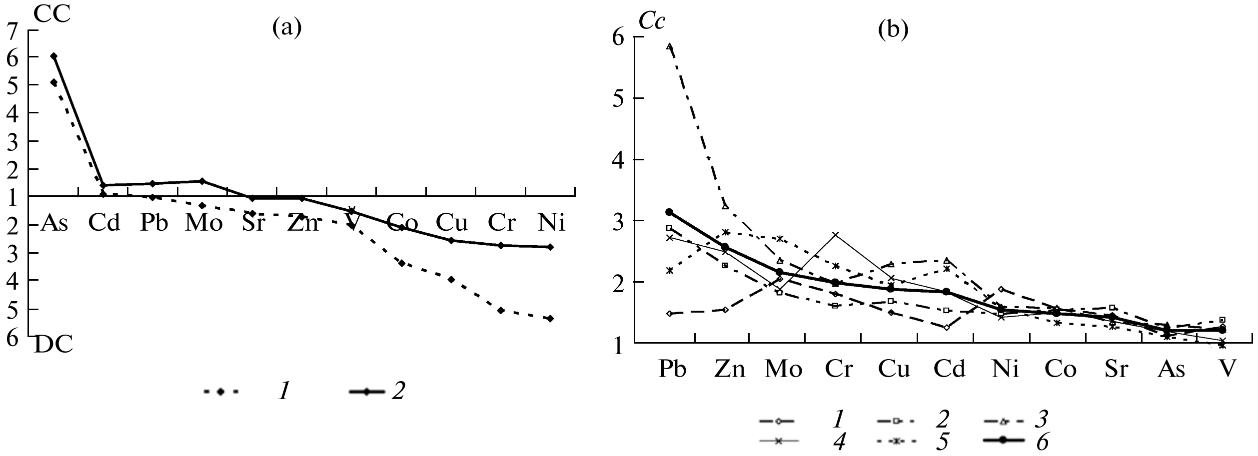

Fig. 2. Geochemical specialization of the Ulaanbaatar soils: *a*—relative to the lithosphere clarkes according to Vinogradov [4]; *b*—functional zones of the city relative to the local background. Designations for a: *1*—soils of the natural background, *2*—soils of the urbanized background. Designations for b: *1*—recreational zone, *2*—ger building, *3*—multistoried building, *4*—highways, *5*—industrial zone, *6*—whole city.

background and urban soils, respectively. Hence, *Zc* serves as the geochemical criterion of the technogenic transformation of the soils; it is calculated for each sampling point and for each functional zone. In the sanitary–hygienic estimation of the soil's chemical pollution, the norms are the maximal permissible concentrations (MPC), which characterize the toxic properties of the pollutants [12]. In this work, the MPCs accepted in Mongolia [8] and Russia [14] were used. As the sampling network was rather uniform, the percentage of the area of the polluted soils was calculated as the ratio of the number of points with excessive MPCs for each element to the total number of the points over the territory of the city.

For each zone, the averages for the samplings, the standard deviations, the coefficients of the variation (*Cv*), and the amplitudes of the ME concentration fluctuations were calculated using the Statistica 7.0 package. The significance of the differences between the average values was assessed by the *t*-criterion, and the homogeneity of variances, by the *F*-statistics. The associations of elements with common areas of accumulation and removal were identified using cluster analysis (the complete linkage algorithm); the similarity of the behavior of the elements was assessed using the correlation coefficients. Regression trees that enable one to reveal the main natural and anthropogenic factors of the soil differentiation according to the content of pollutants were constructed using a package of SPLUS programs (MathSoft, 1999).

The soil-geochemical mapping was performed using ArcGIS 9.3. The method of inverse distance weights (IDW) was applied for the interpolation of the data in compiling the maps. In order to prevent overstated estimates of the pollution, the points with extremely high pollutant concentrations that exceeded by many times not only the background values but also their averages for the city were excluded from the sampling [13]. The local element anomalies cause very high spatial heterogeneity of the pollutant contents, and they are related to discrete pollution sources. This fact especially concerns the residential zone, where the probability of collecting samples in the places of local pollutants' effect is rather high. In the absence of criteria for rejecting the anomalous values, the rule of three sigmas was used.

DISCUSSION

Geochemical characterization of the background and urban soils. The comparison of the mean contents of the microelements (MEs) in the soils of the background areas with their lithosphere clarkes showed that the former soils were poor (Fig. 2a) in Co, Cu, Cr, and Ni (DC = 3.5–5.4); the contents of Pb and Cd were close to their clarke values. The As concentration in reference soils was 5.1 times higher than the global clarke value showing that this element can be considered as an element of the regional geochemical specialization. In the geochemical spectra of the urbanized background soils, the sequence of elements particular for the natural soils was preserved; but their concentrations became higher (Fig. 2a).

The urban soils are enriched (as compared to the natural background) with all the elements analyzed (*Cc* > 1.0) (Fig. 2b). Lead and zinc accumulate to the greatest extent (3.2 and 2.6, respectively). These elements are highly technophilic; they enter the environment with the emissions of industrial enterprises and transport. (Technophily is the ratio of the annual production of an element (expressed in tons) to its clarke in the lithosphere [19]). Mo, Cr, Cu, and Cd accumulate rather intensely (*Cc* = 1.9–2.1). The mean intensity of the accumulation was found for Ni, Co, and Sr

(*Cc* = 1.5–1.6); V and As weakly accumulate (*Cc* = 1.3). The element concentrations varied to a greater extent in the urban soils than in the natural ones (Table 1).

The geochemical differentiation of the soils by the city's functional zones is shown in Table 1 and Fig. 2b. The elements weakly accumulate in the soils of the recreational zone as compared to the natural soils: $Cc \leq 1.6$ for most elements; only Mo, Ni, and Cr noticeably accumulate (*Cc* = 1.9–2.1). In the soils of the industrial zone, on the contrary, the level of the pollutant concentrations was the highest. The Zn content exceeded that in the background soils by more than 3 times; those of Mo, Cr, Cd, and Pb, by 2–3 times; Cu, Ni, Co, and Sr, by 1.3–1.9 times; the V and As values were close to the reference ones.

In the residential area, the soils of the multistoried quarters and the soils of the ger districts differ. The latter districts are rather young and display a weak geochemical transformation of the soil cover: for all the elements analyzed, $Cc \leq 2.0$, except for Zn and Pb (2.3 and 2.9, respectively). The content of half of the elements is twice higher in the soils of the zone with multistoried buildings than in the natural background soils. In all the zones of the city, the *Cc* values for Pb and Zn as compared to those of the other elements were the maximal (5.8 and 3.2, respectively). A weak accumulation of V and As regarding the natural background was observed (*Cc* = 1.3–1.4).

In the soils near the highways, Pb and Cr (*Cc* = 2.7–2.8), Zn, Cu, Mo, and Cd (1.9–2.5) are accumulated; Ni, Co, Sr (*Cc* = 1.6), V, and As ($Cc < 1.2$) are concentrated to a lesser extent.

Associations of chemical elements. The associations of the chemical elements reflect their common trends of accumulation and removal from the surface soil horizons. In all the functional zones of the city, the Co–Ni–V association (sometimes with Cr) was recorded (Table 3), which is related to the composition of the parent rocks—shales and clays enriched in these elements [1]. Co and Ni are cationogenic elements with similar chemical properties and migration capacity; V can interact with them forming stable associations [9, 10].

In the soils of the background territories and recreational zone, Zn–Cd–Cu–Mo and Pb–Sr associations along with Co–Ni–V–Cr ones were observed. The composition of the associations in the soils of the ger zone was close to that of the associations in the soils of the background and recreational territories, since the main massif of gers has existed for only several decades. In this district, the technogenic impact was displayed to a lesser degree than in the multistoried quarters in the center of the city. In the soils of the industrial, traffic, and multistoried building zones, a Mo–As association was revealed as a result of the emissions from the thermal power plants working on coal with a high content of these elements.

When comparing the background and urban territories, technogenic associations (As–Mo, As–Sr, and Cu–Cd–Cr–Zn) were found; they were not observed in the background areas. The first two associations were observed in many zones owing to the ash emissions from the coal burning. The third association was restricted to the industrial and residential zones with high modern buildings. Its ingredients—highly technophilic elements—were present in the emissions of the industrial enterprises and cars and in the industrial and municipal waste.

Spatial structure of the pollution. Maps of the ME contents in the topsoil horizons were compiled. According to the spatial patterns of the pollutants, they were united into 4 groups. Figure 3 presents the maps for the distribution of one element from each group.

The first group (Zn, Cd, Pb, and Cu) was composed of metals entering the soils with the emissions of automobiles. They are concentrated in the soils along the highways (Fig. 3). Locations with extremely high concentrations of these elements (with the *Cc* up to 30) were also recorded near roads. Elevated contents were found in the center of the city (the Sukhbaatar square), in the eastern part of the industrial zone, to the east of the Selbe River, and in the northwestern part of the ger zone. The correlation between the content of these elements in the surface soil horizons and the emissions of exhaust gases is noted in publications [10, 17, 21, 22, 23].

The second group of elements (As, Sr, and V) was related to their elevated contents in the coal used for heating. Therefore, these elements accumulated in the northern and eastern parts of the city at the thermal power stations and in the ger zone where houses have individual heating (Fig. 3).

The concentration of Ni, Co, and Cr (elements of the third group) increased to the northwest due to the outcrops of clay slates enriched with these elements (Fig. 3). The soils of the industrial zone also manifest higher contents of these heavy metals due to the presence of building enterprises there.

Molybdenum forms a separate group owing to the specific features of its distribution. In steppe soils, it becomes mobile (the anionic form) and intensely migrates to the subordinate positions where it accumulates [19]. Its highest concentrations (*Cc* up to 10.4) were found in the soils along the rivers (Tola and Selbe) crossing the territory of the city of Ulaanbaatar.

On the whole, the ME concentrations were lower in the soils of the western part of the city than in the eastern part because of the less intense development of the former, the discontinuous building, and the predominance of the western air fluxes. In the central and eastern older zones of the city, higher pollutant contents were observed.

The role of the natural and anthropogenic factors in the accumulation of the microelements in the soils. The

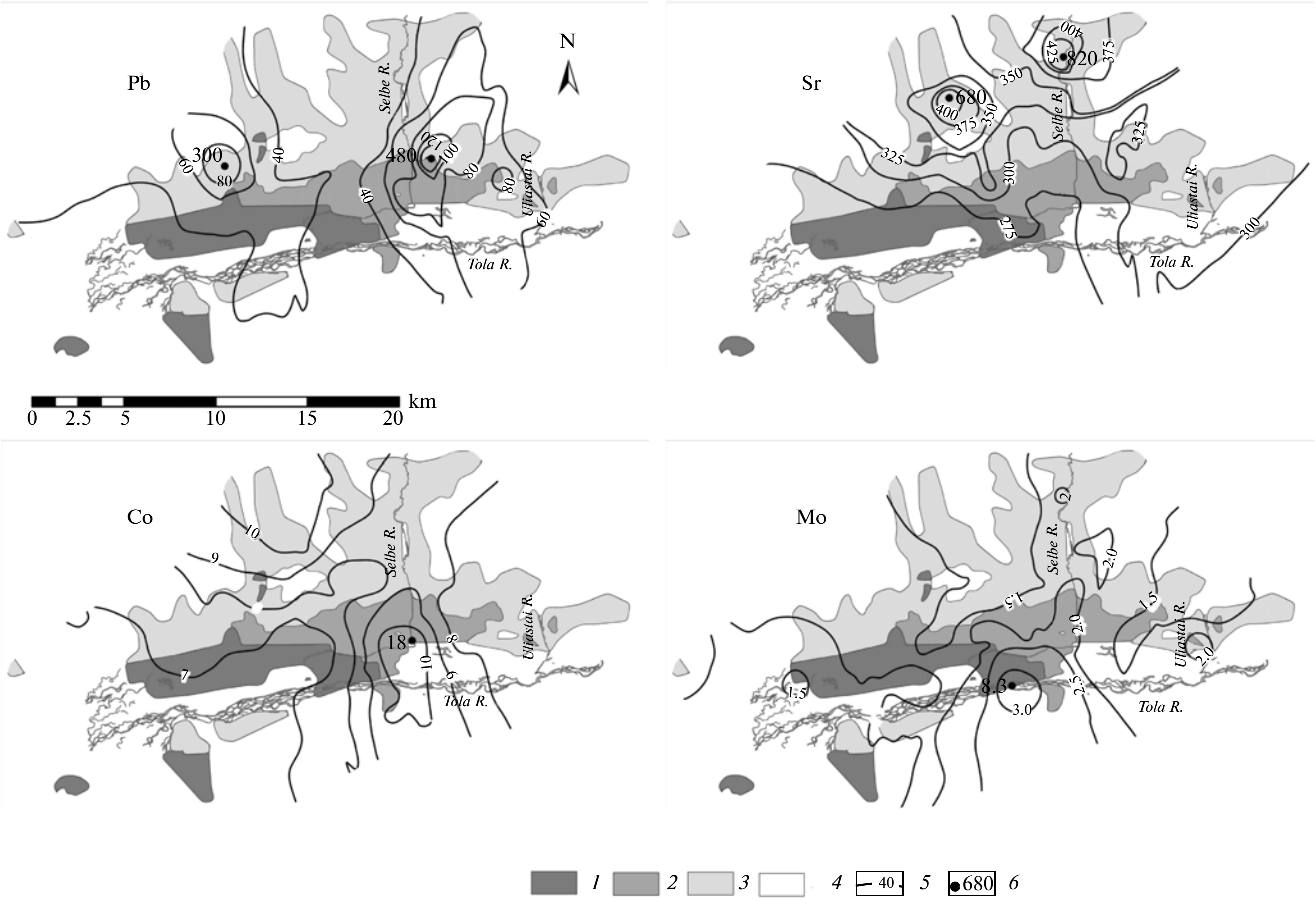

Fig. 3. The maps of microelements distribution in the soils of Ulaanbaatar. Designations: *1–4*—functional zones: *1*—industrial, *2*—multistoried building, *3*—ger building; *4*—recreational; *5*—isoconcentrates, mg/kg; *6*—local anomalies.

natural factors responsible for the behavior of the pollutants in Ulaanbaatar act in two ways: some of them promote the pollutants' accumulation in the landscape components, while others provide their removal [3, 7, 10, 15]. Some specific features and the level of the technogenic impact are controlled by the land use's kind. For assessing the influence of the natural and anthropogenic factors on the pollutants' accumulation in the urban soils, a multivariater regression analysis was used [17]. The interpretation of its results was performed on the basis of the known geochemical regularities [6, 9, 19]. The variation of the ME concentrations was assessed relative to the main physicochemical properties of the soils (the humus and physical clay – particles <0.01 mm – contents, %; the pH; and the CO_3^{2-} and SO_4^{2-} concentrations); the absolute altitude of the sampling point, m; the parent rocks (alluvium, shales, clays, and granites); and the city's functional zones.

The analysis of the calculations performed by the method of regression trees showed that the differences in the ME contents were determined by various (in the number and composition) groups of natural factors (Table 4). The strength of the factors is characterized by gradations representing a decrease in their significance from 1 to 5.

The humus content in the topsoil horizons had the leading influence (ranks 1 or 2) on the accumulation of almost all the elements analyzed, except for Cr and Ni. Many metal–organic compounds were weakly mobile; the strength of their absorption increased in the soils with the higher humus content [9]. The content of physical clay in the topsoil horizons was the more significant factor for Co and Ni, since they were intensely adsorbed by clay minerals. For the other elements, except for Cd and Mo, this factor occupied the second position.

The changes in the SO_4^{2-} content were of great importance in the variation of the Pb and Sr concentrations. With the increasing share of this anion, the contents of Pb and Sr decreased. For Mo, the sulfate content was the second factor by significance; with the soil's acidification, its concentration increased as the share of mobile anions fell. The CO_3^{2-} content was included into the set of determining factors (rank 2)

Table 1. Statistical parameters for the microelement contents in the soils of Ulaanbaatar and the background territories

Parameter	Element										
	Cr	Co	Ni	Cu	Zn	As	Mo	Cd	Pb	V	Sr
	Soils of the background territories (*n* = 6)										
Mean ± error of the mean, mg/kg	16.2 ± 1.2	5.2 ± 0.4	10.7 ± 0.7	11.7 ± 1.7	46.7 ± 5.9	8.6 ± 1.2	0.8 ± 0.2	0.14 ± 0.03	14.7 ± 0.8	43.2 ± 3.3	203.3 ± 24.2
Min–max, mg/kg	12.0–21.0	4.0–6.3	8.1–13.0	7.6–19.0	28.0–72.0	5.8–14.0	0.4–1.9	0.08–0.28	12.0–18.0	30.0–53.0	120.0–270.0
Cv, %	18.1	16.8	16.1	36.2	30.7	34.8	69.3	54.5	14.1	18.6	29.1
	Urban soils (*n* = 90)										
Mean ± error of the mean, mg/kg	32.7 ± 2.8	8.0 ± 0.3	17.0 ± 0.6	22.4 ± 0.8	120.3 ± 9.9	10.8 ± 0.3	1.8 ± 0.1	0.25 ± 0.02	45.9 ± 6.0	54.3 ± 1.4	299.7 ± 9.1
Min–max, mg/kg	8.2–230.0	3.2–18.0	0.5–41.0	7.8–58.0	36.0–710.0	5.9–20.0	0.5–8.30	0.08–0.87	0.0–430.0	17.0–88.0	200.0–820.0
Cv, %	81.4	29.1	33.8	34.8	77.8	24.8	61.6	50.4	124.4	25.2	28.7
Cc	2.0	1.5	1.6	1.9	2.6	1.3	2.2	1.9	3.1	1.3	1.5

Table 2. Statistical parameters for the microelement contents in the soils of the Ulaanbaatar functional zones

Parameter	Element										
	Cr	Co	Ni	Cu	Zn	As	Mo	Cd	Pb	V	Sr
Recreational zone ($n = 5$, $Zc = 7.4$)											
Mean ± error, mg/kg	29.8 ± 5.5	8.4 ± 1.1	20.4 ± 5.3	18.0 ± 2.4	74.2 ± 13.3	10.2 ± 0.9	1.7 ± 0.3	0.18 ± 0.03	22.4 ± 2.9	57.6 ± 3.9	304.0 ± 32.5
Cv, %	41.1	30.3	58.5	30.2	40.2	20.6	35.0	36.3	29.0	15.0	23.9
Cc	1.8	1.6	1.9	1.6	1.6	1.2	2.1	1.3	1.5	1.3	1.5
Traffic zone ($n = 11$, $Zc = 10.7$)											
Mean ± error, mg/kg	44.9 ± 18.7	8.0 ± 1.2	15.8 ± 1.9	24.4 ± 2.8	116.9 ± 28.3	10.8 ± 1.1	1.5 ± 0.3	0.26 ± 0.04	40.0 ± 6.7	48.0 ± 3.5	288.2 ± 24.3
Cv, %	138.0	48.5	39.5	38.0	80.2	33.4	63.6	37.0	55.9	24.4	28.0
Cc	2.8	1.5	1.5	2.1	2.5	1.3	1.9	1.9	2.7	1.1	1.4
Industrial zone ($n = 23$, $Zc = 10.8$)											
Mean ± error, mg/kg	37.0 ± 5.9	7.2 ± 0.5	17.2 ± 1.2	23.0 ± 1.6	131.4 ± 28.3	10.0 ± 0.6	2.2 ± 0.3	0.31 ± 0.04	32.5 ± 3.9	44.6 ± 2.2	268.7 ± 6.8
Cv, %	77.0	30.2	33.9	33.9	103.4	28.3	73.5	56.4	56.8	23.1	12.2
Cc	2.3	1.4	1.6	2.0	2.8	1.2	2.7	2.3	2.2	1.0	1.3
Ger building zone ($n = 35$, $Zc = 9.4$)											
Mean ± error, mg/kg	26.6 ± 1.3	8.3 ± 0.4	16.4 ± 0.9	20.0 ± 0.9	106.7 ± 12.0	11.1 ± 0.4	1.5 ± 0.1	0.21 ± 0.02	42.2 ± 8.8	61.8 ± 2.5	329.7 ± 19.7
Cv, %	27.9	25.5	30.6	26.7	66.5	21.6	45.6	44.6	123.6	23.7	35.3
Cc	1.7	1.6	1.5	1.7	2.3	1.3	1.9	1.6	2.9	1.4	1.6
Multistoried building zone ($n = 16$, $Zc = 15.6$)											
Mean ± error, mg/kg	32.4 ± 2.1	8.4 ± 0.4	17.6 ± 1.1	26.9 ± 2.5	150.8 ± 1.7	11.7 ± 0.6	1.9 ± 0.2	0.32 ± 0.04	84.6 ± 2.3	55.1 ± 1.7	285.0 ± 11.3
Cv, %	25.7	16.5	24.2	36.5	47.0	21.1	49.5	39.8	119.5	12.4	15.9
Cc	2.0	1.6	1.6	2.3	3.2	1.4	2.4	2.4	5.8	1.3	1.4

Table 3. Associations of chemical elements in different functional zones of Ulaanbaatar

Functional zone (number of samples)	Associations of elements (variation coefficient)	Minimal significant correlation coefficient ($P = 95\%$)	Nonassociated elements
Ger building zone (35)	Ni, Co, V, Cr (0.80–0.93) Zn, Cd, Pb (0.48–0.77) Cu, Mo (0.62) As, Sr (0.52)	0.37	–
Multistoried building zone (16)	Co, Ni, V (0.54–0.76) Cu, Cd, Zn (0.63–0.93) As, Mo (0.40)	0.62	Sr Cr Pb
Highways (11)	Ni, Co, Cr, Zn (0.77–0.95) Cd, Pb (0.87) Mo, As (0.84)	0.76	Cu V Sr
Industrial zone (17)	Co, Ni, V (0.87–0.94) Cd, Cu, Cr (0.84–0.94) As, Mo (0.84)	0.65	Pb Zn Sr
Background territories and recreational zone (11)	Ni, Co, V, Cr (0.77–0.98) Zn, Cd, Cu, Mo (0.70–0.92) Pb, Sr (0.81)	0.63	As
Whole city (84)	Co, Ni, V (0.73–0.85) As, Sr (0.40) Cu, Cd, Cr, Zn (0.39–0.68)	0.25	Mo Pb

Table 4. The significance of the natural and anthropogenic factors in the variability of the microelement concentrations in the soils of Ulaanbaatar

Factor	Element											
	As	Cd	Co	Cr	Cu	Mo	Ni	Pb	Sr	V	Zn	Zc
Humus content	1	1	3	–	1	1	–	2	4	4	1	1
Physical clay content	2	5	1	2	–	–	1	3	2	2	2	2
CO_3^{2-} content	–	2	–	–	2	2	2	–	–	–	2–3	2
SO_4^{2-} content	–	4	–	3	–	2	–	1	1	3	–	–
pH	2	2	–	1	–	–	3	4	2	3	2–3	3
Altitude	2	–	2	–	–	–	–	–	3	2	–	4
Parent rock	–	–	–	–	–	–	–	–	–	–	–	–
Functional zone	–	3	–	2	2	2	–	4	3	1	4	–

Note: ranks 1–5 show the decrease in the significance of the factors.

for Cd, Zn, Ni, Cu, and Mo, which were actively immobilized with the carbonates.

The pH values affected the variation of almost all the elements, especially that of Cr, As, and Sr (since their form in the soil solution depends on its reaction) and Cd and Zn due to the increase in the capacity of the biogeochemical and sorption barriers with the growth of the pH [9].

The topographic position (absolute altitude) was significant for As, Co, V, and Sr; their sources are located at the higher altitudinal levels. The source of As, V, and Sr were emissions produced by heating of gers; the source of Co were the derivates of shales. No clear effects of the parent rocks on the ME concentrations in the urban soils were revealed.

The *functional zone* factor was used as a complex anthropogenic characteristic of the territory. It played the main role in the variability of the V concentrations; the second place belonged to the Cr, Cu, and Mo con-

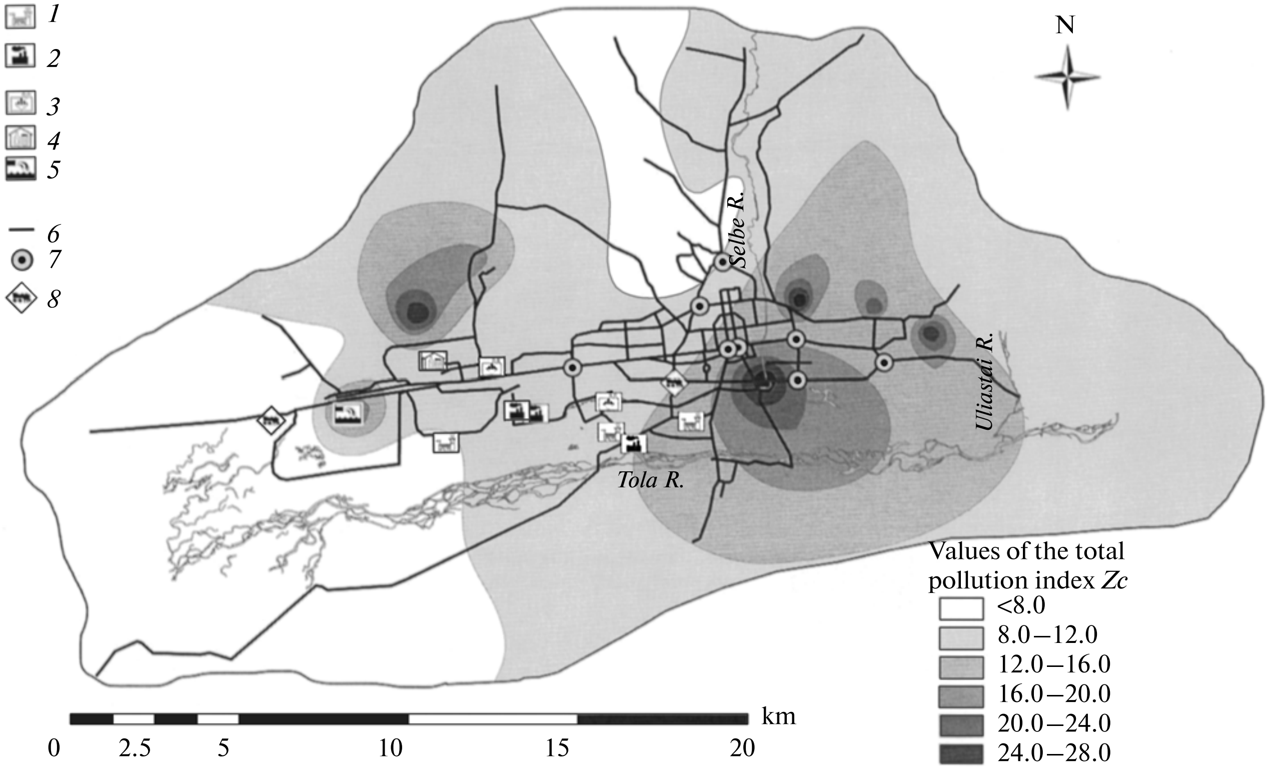

Fig. 4. The total pollution index (*Zc*) in the soils of Ulaanbaatar. Industrial objects: *1*—power industry, *2*—building industry, *3*—textile industry, *4*—food industry, *5*—sewage treatment works; transport objects: *6*—highways; *7*—busy crossings, including circular ones; *8*—railway objects.

tents; and the effect of this parameter for the rest of the elements was less significant.

Assessment of the ecological–geochemical state of the urban soils. For the Ulaanbaatar city soils, the mean total pollution index ($Zc = 11$) shows weak pollution of the urban soil cover [6]. More than half of the territory (the soils of the background territories and the whole recreational zone) was weakly polluted ($Zc < 8$), as well as the ger building zone and the areas near the motorways. Weakly polluted ($8 < Zc < 16$) were the soils of the industrial zone and those of gers and of the multistoried buildings (38% of the city's area). Some part of the recreational area within the ger zone is used not only for its direct purpose but also for grazing.

In the territory with the mean level of pollution (12%; $Zc > 16$), in two local areas, a strong pollution level ($Zc > 32$) was registered. The localities with $Zc > 16$ were distributed almost equally between the industrial zone, the blocks with multistoried houses, and the motor roads. They are included into the industrial–transport–building area in the city's center exposed to the maximal technogenic impact. The map of the *Zc* index's distribution over the urban territory (Fig. 4) shows that the western part of the city is exposed to less pollution as compared to the central one; the eastern and northwestern areas are polluted to a greater extent.

Figure 5 presents a regression tree characterizing the dependence between the spatial variability of the *Zc* index and the factors considered. This tree allows forecasting the total pollution related to a set of factors. The humus content, i.e., the activity of the biogeochemical barrier, is the determining factor. In the soils with the small humus content (<0.7%), *Zc* increased from 2.8 to 6.6 in the presence of carbonates due to the accumulation of many pollutants at the alkaline geochemical barrier. In the soils with a humus content of 0.7–1.0%, the increase in the content of clay particles (especially within the range of 9.3–13.2%) promoted the fixation of heavy metals, and the *Zc* value increased to 13.2.

In the soils with a higher humus content (>1%), the amount of physical clay and carbonates turns out to be of great importance. In the territory of the city, the maximal value of $Zc = 19.9$ characterizes the light-textured soils with the high content of carbonates forming difficultly soluble compounds with metals. In the soils with a physical clay content of >12.9%, the *Zc* values were higher at $pH < 7.5$ due to the combined effect of the sorption barrier and the transfer of some pollutants

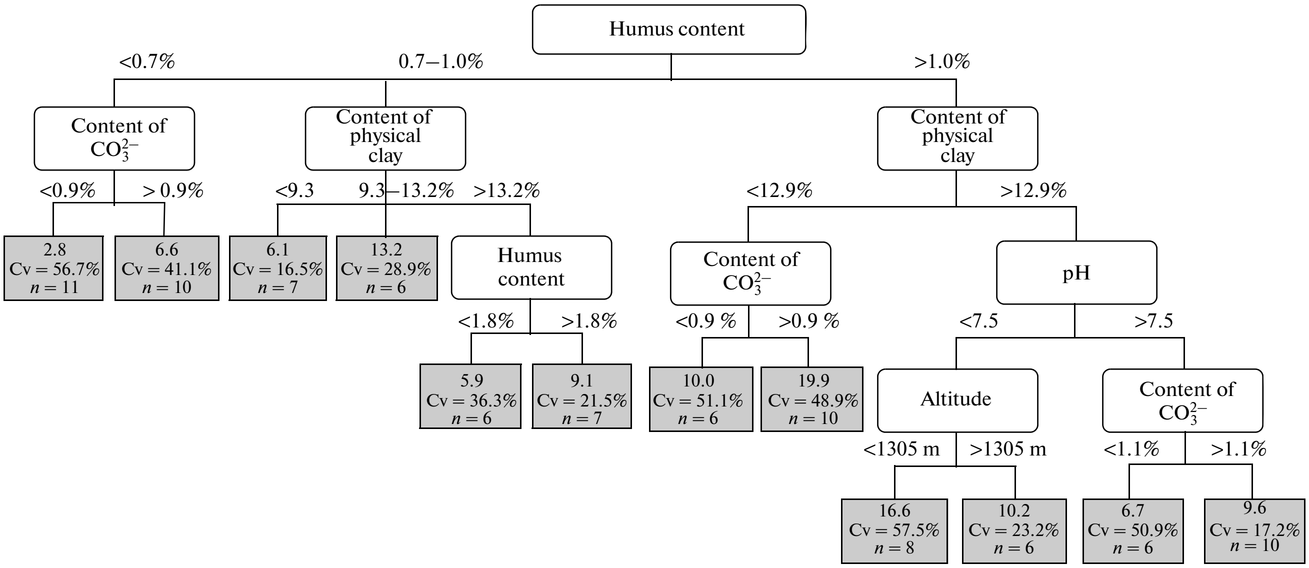

Fig. 5. Regression tree for *Zc* in the soils of Ulaanbaatar. The factors of the differentiation are given in the unshaded figures. The figures with gray shading present the following: the mean *Zc* value in the upper soil horizons under particular combinations of factors; *Cv*—variation coefficient; *n*—number of points. Functional zones: A—highways, N—multistory buildings, P—industrial, R—recreational, and U—gers.

to weakly mobile forms at the soil's acidification. The decrease in the *Zc* values with the increasing altitude showed that the main sources of HM pollution were located in the Tola River floodplain. In the alkaline range with pH > 7.0 the carbonate barrier becomes more active, and the influence of the CO_3^{2-} content upon the total pollution increases. Thus, the behavior of most of the elements in the soils is controlled by the soils' own properties, especially by the organic matter amount, the physical clay content, and the soils' reaction. The effect of the relief and the functional zone were clearly manifested as well. The parent rocks did not influence the soil's pollution.

The contents of As, Cr, Mo, Pb, and Zn in the urban soils exceeded the MPC values accepted in Mongolia. The ecological danger of the pollutants was reflected in the percentage of the area with their contents exceeding the MPC; the latter decreased in the following sequence: As (100) > Zn (38) > Mo (20) > Pb (18) > Cr (4). When using the MPC and residual permissible concentrations (RPC) accepted in Russia, the sequence was somewhat different: As (100) > Zn (68) > Pb (46) > Ni (12) > Cu (34). The norms are stricter in Russia than in Mongolia; therefore, their application resulted in a greater percentage of sites where the pollution exceeded the MPCs. However, the Russian sanitary–hygienic MPCs of pollutants were elaborated for agricultural soils and agroecosystems; they are not directly applicable to urban soils [21].

The landuse differences were reflected in the critical levels of the pollutant contents in the soils established in the countries of the EU, the USA, Canada, and some Asian countries, which by tens to hundreds times exceed the corresponding MPCs in Russia and Mongolia [2]. For instance, the application of the norms accepted in the Netherlands [20] produces the following sequence of ecologically dangerous elements (%): Zn (18) > Pb (11) > Cu (4) > Cr (3) > Ni (1). In this case, the percentage of the samples with the pollutant contents exceeding the MPCs was much lower. The As concentration did not exceed the norm: the standard for As in the Netherlands is 15 times higher than in Russia.

Dynamics of the urban soil pollution. The changes in the pattern of the soil pollution in the city of Ulaanbaatar in the last 20 years were assessed by the comparison of our data with the results obtained for the surface soil horizons in 1990 at 333 points [10]. The differentiated assessment of the soil pollution by the functional zones of the city of Ulaanbaatar was not carried out earlier. Therefore, the following average concentrations of the microelements were accepted for the city's soils based on the results of 1990: Pb—54, Cu—8, Zn—82, Ni—15, Co—9.9, Cr—41, V—119, Mo—2.2, and As—11 mg/kg.

If we compare the absolute contents of the elements in the city's soils for the period from 1990 to 2008, it may be noted that the concentrations of Zn and Ni increased by 1.1–1.4 times with an annual increment of 0.6–2.4%. The As content remained the same. The concentrations of the rest of the elements have decreased by 1.2–2.2 times; every year by 1.3–3.0%. For the same period, the variation of the elements has also changed. For Ni, Zn, and Pb, it increased by 1.5–2.3 times; for the rest of the elements, it decreased by 1.1–1.6 times. The variability of the soil's physicochemical properties under the impact of technogenic loads decreased. This tendency was revealed not only in Ulaanbaatar but also in many cities [17].

The soils of Ulaanbaatar are characterized by their polyelement pollution. In 1990, the *Zc* value was 16, and the urban soils were considered as weakly polluted. Exclusions were several anomalies of Pb and Zn in the central part of the city; of As, Cr, and Mo in the industrial zone near the thermal power station; and of weakly contrasting Cu and Zn anomalies in the districts of the ger building. In 2008, the ecological–geochemical situation weakly changed ($Zc = 11$), and the urban soils might be still qualified as weakly polluted ones; however, there were local anomalies with medium and strong pollution. The composition of the priority pollutants also did not change: in both 1990 and 2008, the city's soils were enriched in Pb, Zn, Cu, As, Cr, and Mo as compared to the background soils. The list of elements whose concentrations exceeded the MPC levels changed to some extent. In 1990, it contained As, Mo, Pb, and Cr; in 2008, Zn was added to this list due to the larger emission from the transport and the greater municipal garbage.

Thus, despite the ever-growing technogenic loads related to the development of industry and the growth of the urban population and the number of cars, the concentrations of pollutants in the soils of the city little changed. Among the natural factors of the self-purification of the soils, the following ones may be enumerated: the weak sorption capacity and high permeability of the soils and rocks because of the low humus content in the surface soil horizons and their light texture, the transit and slope positions of the majority of the urban districts promoting the removal of pollutants, and the maximal precipitation in the late summer in the form of showers.

Since no reclamation measures were conducted in the territory of the city, the main technogenic factor responsible for the decrease in the pollution level is the reduction of the technogenic emissions in the period of 1991–2000 related to the decline in production in Mongolia. In addition, in the last ten years, the area of the city of Ulaanbaatar increased, mainly due to the ger building zone: considerable areas of little changed and weakly polluted soils of slopes were added to the urban soils exposed to long-lasting impacts, and this resulted in the lowering of the mean *Zc* value.

CONCLUSIONS

(1) The natural and urbanized background soils of Ulaanbaatar are characterized by lower concentrations of most of the microelements as compared to their lithosphere clarkes and by the high background content of As, which reflects the geochemical specialization of the soils and parent rocks of the region studied.

(2) In the urban soils, Pb and Zn are accumulated the most intensely ($Cc = 3.1$ and 2.6, respectively). For the other elements, *Cc* does not exceed 2; according to the decrease in the concentrations, the microelements form the following sequence: Mo > Cr > Cu > Cd > Ni > Co > Sr > V > As. The most stable associations are Ni–Co–V, As–Sr, and Cu–Cd–Cr–Zn. The formation of the first association is determined by the composition of the parent rocks—shales and clays; the second one is related to the ash wastes of coal burning. The third association includes elements entering the urban environment with the emissions of transport and industrial and municipal wastes.

(3) The comparison of the pollutant contents in the soils of the different functional zones of the city showed their spatial geochemical heterogeneity, which was not considered earlier. The greater amount of the elements with $Cc > 2$ was found in the soils of the industrial zone (Zn, Mo, Cr, Cd, Pb, and Cu), while the smaller one, in the recreational zone (Mo). The soils of the districts with multistoried buildings are more strongly polluted (especially by Pb ($Cc = 5.8$) and Zn (3.2)) as compared to the ger zone. The trend of the pollutants' accumulation is more clearly manifested in the central part of the city, including the blocks with multistoried buildings, the industrial zone, and the largest highways. In the soils, common pollution area with element associations is formed: Ni–Co–V, Cu–Cd–Zn, and As–Mo.

(4) The spatial distribution of the elements is mainly determined by the pollution sources. The geochemical maps for Zn, Pb, Cd, and Cu reflect the predominant effects of the transport, while the maps for As, Sr, and V, the influence of the heat-and-power industry. Elevated contents of Ni, Co, and Cr are registered in the soils of the industrial zone, where enterprises of the building industry are located, and in the northern part of the city, where the soils develop on shales enriched with these heavy metals. The Mo concentrates in the subordinate landscapes.

(5) The analysis of the influence of the natural and anthropogenic factors on the accumulation of the pollutants in the soils of the city has revealed the leading role of the soil's physicochemical properties, especially of the organic matter content determining the As, Cd, Cu, Mo, and Zn accumulation; of the physical clay content for the Ni and Co accumulation; and of the pH and sulfates affecting the accumulation of Cr, Pb, and Sr. The dependence of the pollutant concentrations on the content of carbonates was revealed for many elements. The character of the use of the territory distinctly affected the pollutant concentration, but this factor was leading only for vanadium.

(6) The highest pollution ($Zc = 16–32$) was characteristic of the industrial and central zones of the city and highways; the lowest *Zc* (<8) values were determined in the soils of the western part of the city because of the less intense development of the former and the predominance of western winds. The pollutant anomalies in the ger building zone were formed under the influence of motor transport and garbage dumps;

in the district of the waste treatment facilities, they were influenced by sewage sludge. The As content in the Ulaanbaatar soils exceeded its MPC over the whole territory of the city. Excessive concentrations of Zn, Mo, and Pb were recorded in 34, 20, and 16% of the city's area, respectively.

(7) In 2008, the pollutant content in the soils remained approximately the same as in 1990. The deviation from the latter was ±3.0%. The variation of the concentrations for most of the microelements decreased. The state of the soil cover of the city is assessed as weakly polluted (*Zc* in 1990 was 16, while, in 2008, it was 11). This fact is related to the reduction of industrial production, the high potential for self-purification of the soils, and the inclusion of *pure* territories into the city's area due to the expansion of the ger zone. In the list of the elements (As, Mo, Pb, and Cr) whose concentrations exceed the MPC, Zn appeared mainly owing to the growth of the number of cars.

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