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GENESIS AND GEOGRAPHY OF SOILS

Geochemical Features of Organo-Accumulative Soils of Subtaiga and Subtaiga–Forest-Steppe Light Coniferous Forests of Northern Mongolia

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Abstract—We have studied geochemical features of organo-accumulative soils (Eutric Regosols (Loamic, Ochric)), Cambic Someric Phaeozems (Loamic)) widely spread in the soil cover of subtaiga and subtaiga-forest-steppe light coniferous forests and forming the lower boundary of the forest zone in the mountains of Northern Mongolia. Data on the microelement composition of soil-forming rocks are given; the paragenetic association of trace elements in them is composed of Pb, Cu, Zn, Co, V, Cr, Ni, Mn, Mo, Ba, Sr, Zr, and B. The residual and redeposited weathering crusts of igneous rocks are enriched with Zn, Cr, Mo, and B as compared to the mean content of these elements in the lithosphere, but they contain less Pb, Co, Mn, Ba, Sr, and Zr. The residual and re-deposited weathering crusts of calcareous rocks are enriched in Pb, Cu, Zn, V, Cr, Sr, and B, and are impoverished in Co, Ni, Mn, Mo, Ba, and Zr. The morphological, physicochemical and chemical properties of soils, as well as the content and radial distribution of trace elements in soils are discussed. The data obtained testify to the accumulation of most trace elements in the surface organic and humus-accumulative soil horizons. This is associated with the heterogeneity of soil-forming rocks and with the effect of soil processes, which cause the accumulative redistribution of elements and their deposition at organic-sorption and carbonate geochemical barriers. It is shown that the studied soils differ not only in the absolute contents of trace elements, participating in the biological cycle, but also in the intensity of their involvement in biogenic migration.

Keywords: Northern Mongolia, Regosols, Phaeozems, physicochemical properties, trace elements, radial differentiation coefficients, concentration coefficients

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INTRODUCTION

Organo-accumulative soils in Northern Mongolia form the background of the soil cover in the subtaiga and subtaiga-forest-steppe altitudinal vertical-zonal complexes (AVC) of forest types in the CisKhubsugul, Northeastern and Eastern Khangai, and Khentei Mountains. They mainly occupy middle and lower parts of slopes of northern aspects at the contact with steppes in the altitudinal range of 700–1800 m a.s.l. Forest and meadow-forest mesophytic species are of the greatest cenotic importance in the grass cover. Steppe and forest-steppe grasses play a great role in subordinate layers in the lower part of these AVC due to the climate dryness and the contacts of forests with zonal steppes [21].

A wide range of altitudes and orographic conditions in the area of the studied soils also determines a rather wide range of environmental conditions. The precipitation amount ranges within 300–450 mm per year, with 75–80% in summer. The long-term mean annual air temperature varies from –0.1 to –3.8°C. The sum of biologically active air temperatures above +10°C at the altitude of 700–1800 m ranges from 1280 to 1670°C. The mean duration of the frost-free period is 69–84 days. Depending on geocryological conditions, long-seasonally permafrost and deep-permafrost soils are distinguished among organo-accumulative soils, and the latter are most widespread in Eastern Khentei [23].

The formation of organo-accumulative soils is related to the humus-accumulative (soddy) soil-forming process. It is developed under the effect of herbaceous vegetation and is characterized by intensive humus formation due to specific features of the biological cycle in this plant formation.

The specification of an individual type of soddy soils in the southern taiga subzone of Siberia is substantiated by the author [27]. Their origin is mainly related to the parent rocks, rich in bases and primary minerals. Some researchers [29, 32] suppose that soils in the most continental part of southern taiga in Siberia originate due to bioclimatic and not lithological factors.

Despite the available material, the organo-accumulative soils of Northern Mongolia are still poorly studied. The specific soil formation associated with mountain topography, complicated geological structure, and the altitude-zonal differentiation of hydroclimatic and geocryological conditions is emphasized in most works [3, 4, 6, 14, 22, 28, 31, 33, 36]. All these factors exert a significant impact on the geochemical migration of the products of pedogenesis within and beyond the forest zone [9, 13, 16, 26, 37, 39, 42, 44].

The trace element composition is an important indicator of the ecological and geochemical status of soils. It was pointed out by Dobrovol'skii [12] that trace elements are an important phenomenon of nature, which is not completely understood by scientists. Their study is one of the urgent problems of modern natural science.

Each natural landscape is characterized by particular concentrations of trace elements in soil [2, 15, 18]. This is especially pronounced in the mountains, where the distribution of landscapes is determined by the altitude. Mountainous soils are often shallow with incomplete profile, in which middle-profile horizons are absent. It contains a large amount of rock fragments often of different mineralogical and petrographic composition. The study of the characteristics of the content and distribution of trace elements in soils of various landscapes is an urgent problem and is of great theoretical and practical importance. Soil-geochemical studies enable us to determine specific features of the behavior of chemical elements and to identify the provincial features of the soil cover within the considered forest zones.

OBJECTS AND METHODS

Long-term comprehensive route studies have covered the main forest zones in the middle mountains of the Western, Northwestern, and Eastern Khentei (the Delger-Khan-Uul, Mungeleg-Nuru, Ikh-Khentei, and Baga-Khentei Ranges); in Eastern CisKhubsugul area (the Dzhidinsk, Bursyn-Nuru, Buteliin-Nuru, and Khantain-Nuru Ranges); and in the Khangai Range ((Northeastern and Eastern low-mountain parts). About 60 soil pits were laid on slopes of different gradients and aspects in the AVC of the subtaiga and subtaiga-forest-steppe light coniferous forests, forming the lower forest zone. Their morphological descriptions were made, and soil samples were taken from the plots for chemical and physicochemical analyses. More than 20 soil profiles were analyzed under laboratory conditions by the following methods: the particle-size composition according to Kachinskii [7], pH of salt and water suspensions by the potentiometric method, the content of exchangeable cations (Ca^{2+}, Mg^{2+}, and H^+) according to the method by Gedroits, total humus by Tyurin's method, total nitrogen according to the method by Kjeldahl, hydrolytic acidity according to Kappen, and CO_2 of carbonates by the method by Bauer [1, 8]. We also determined the group composition of humus according to the scheme by Kononova and Bel'chikova [20] and the total content of trace elements by the spectral method. The coefficients of radial differentiation (C_{rd}) and coefficients of concentration (CC) of trace elements were calculated [10, 34]. The soil names were given according to the classification and diagnosis of soils of Russia [17] and to the international WRB classification [41]. Excel 2013 and Statistica 12 programs were used for statistical data processing.

RESULTS AND DISCUSSION

Trace elements in soil-forming rocks of AVC of the subtaiga and subtaiga-forest-steppe light coniferous forests. Information on the content of trace elements in widespread rocks of Northern and Central Mongolia is given in [5, 11, 25]. However, the current geochemical status of the main types of soils in the region is not characterized.

Soils in Northern Mongolia within the studied AVC of forest types are formed on the weathering products of rocks differing in genesis, mineralogical, chemical, and particle-size composition. They are represented by thin residual (eluvial) and re-deposited (eluvial–colluvial and colluvial) weathering crusts formed on hard crystalline rocks, which are mainly acid igneous (granites, biotite granites, diorites, granodiorites, and gabbro-diorites) or calcareous (limestones and dolomites). Bedrocks in the mountains are often overlain by a thick layer of sandy-stony or stony-loamy introduced material, which is not genetically related to them. Such rocks are described in [35, 38]. The upper horizon of the mentioned weathering crust represents the substrate, on which recent soils are formed.

The particle-size composition of soil-forming rocks within the AVC of the subtaiga and subtaiga-forest-steppe light coniferous forests varies from sandy loamy to heavy loamy. The content of stone fragments differs, depending on the weathering rate, from 10 to 80%. The sediments in the upper parts of the slopes are dominated by the fractions of sand and coarse silt; in the middle and lower parts, the content of physical clay increases to 37–45%. The heavier particle-size composition is explained by the fact that fragments of bedrock are destructed and crushed during the re-deposition. It may be also related to the transport of fine fractions from the upper parts of the slopes by surface and subsurface runoff, as well as the above-permafrost waters in spring.

Chemical properties of the soil-forming rocks are significantly different. The reaction ranges from acid to alkaline. The content of exchangeable cations varies

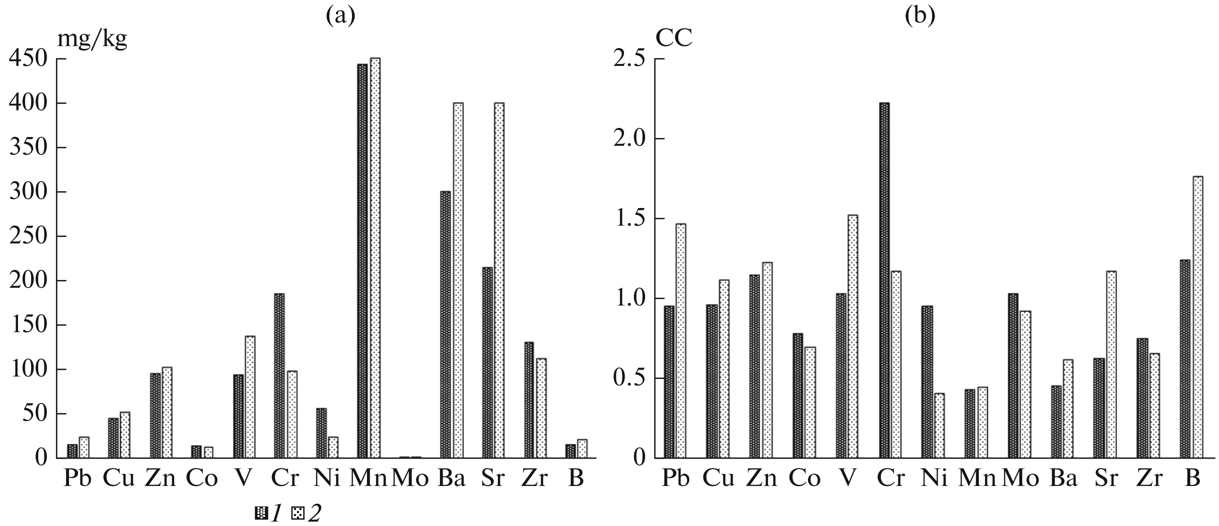

Fig. 1. Mean content (a) and concentration coefficients (b) of trace elements in residual and re-deposited weathering crusts of (*1*) igneous and (*2*) calcareous soil-forming rocks in the subtaiga and subtaiga-forest-steppe forest zone.

from 2.8–17.5 in the residual weathering crust of granites to 21.0–42.5 cmol(c)/kg in the limestone and dolomite weathering crust [23].

The paragenetic association of trace elements in the studied soil-forming rocks of the subtaiga and subtaiga-forest-steppe forest zone is represented by Pb, Cu, Zn, Co, V, Cr, Ni, Mn, Mo, Ba, Sr, Zr, and B. his set of elements reflects the regional geological and geochemical features of the area related to the widespread acid magmatic intrusions and carbonate sedimentary rocks. Residual and re-deposited weathering crusts of igneous rocks on average contain (mg/kg): 15.4 of Pb; 45.7 of Cu; 95.7 of Zn; 14.3 of Co; 94.3 of V; 185.7 of Cr; 55.7 of Ni; 1142.8 of Mn; 1.14 of Mo; 300.0 of Ba; 214.2 of Sr; 130.0 of Zr; and 15.0 of B (Fig. 1a).

Residual and re-deposited weathering crusts of igneous rocks within the subtaiga and subtaiga-forest-steppe forest zone are enriched with Zn, Cr, Mo, B, as compared to their mean content in the lithosphere, but contain less Pb, Co, Mn, Ba, Sr, Zr, as is evidenced by the concentration coefficients (Fig. 1b).

Residual and re-deposited weathering crusts of calcareous rocks contain (mg/kg): 23.6 of Pb; 52.4 of Cu; 102.4 of Zn; 12.6 of Co; 137.4 of V; 98.0 of Cr; 23.8 of Ni; 450.0 of Mn; 1.02 of Mo; 400.0 of Ba; 400.0 of Sr; 112.4 of Zr; and 21.2 of B. In comparison with the mean content in the lithosphere, they are enriched with Pb, Cu, Zn, V, Cr, Sr, and B, but contain less Co, Ni, Mn, Mo, Ba, and Zr.

Soil-forming rocks of the subtaiga and subtaiga-forest-steppe forest zone are more enriched with trace elements as compared to the rocks of the upper forest zones (the subgoltsy-taiga, the mountain-taiga with Siberian pine and larch, and the pseudo-taiga larch ones), which is explained by the significant removal of these elements from the upper zones and their relative accumulation in the lower areas [23, 24].

The main background of the soil cover in the AVC of the subtaiga and subtaiga-forest-steppe larch and pine forests in Northern Mongolia is formed by **gray-humus soils**.

The morphological profile of *typical gray-humus soils* (Eutric Regosols (Loamic, Ochric)) includes several genetic horizons: the O surface organic horizon (forest litter) 1–3-cm-thick, and the AY gray-humus horizon of dark brown and grayish-brown color and 6–20-cm-thick. It is characterized by strong granular, blocky crumb, or finely crumb structure. It is often underlain by the AC grayish-brown or brown transitional horizon. The Cf horizon 8–25-cm-thick displays features of iron-humus compounds accumulation revealed by iron films on the surface of mineral grains and aggregates. The lower part of the soil profile contains many inclusions of weathered stones and fragments of rocks of different mineralogical and petrographic composition. The type of the morphological profile is O–AY–AC–Cf–C.

Gray-humus eluviated clay-illuvial (Eutric Regosols (Loamic, Ochric)) soils are characterized by the presence of forest litter (12 cm) composed of plant residues; of the AY gray-humus horizon of dark brown color, granular-crumb structure, and 6–10-cm-thick; of the thin (2–4 cm) AYel eluviated horizon of grayish-brown color with grayish tint and of lighter color, when dry. The Ci clay-illuviated horizon is brownish and usually compact. It gradually gives way to the parent rock. The soil profile is O–AY–AYel–Ci–C.

According to the particle-size composition, the studied soils are light- and medium-loamy (Table 1). Sand and coarse-silt fractions predominate in fine

Table 1. Some chemical and physicochemical properties of gray-humus soils

Horizon	Depth, cm	Particle-size composition (fraction, mm), %		pH		Humus	N	C/N	C_{ha}/C_{fa}	Exchangeable cations			*S*, %
		<0.001	<0.01	H_2O	KCl	total, %				Ca^{2+}	Mg^{2+}	H^+	
										cmol(equiv)/kg			
Gray-humus typical soils:													
Pit 803. Forb larch forest, IV quality class; 1100 m a.s.l. (Dzhidinsk Range, Dzhidinskii, Eastern CisKhubsugul region)													
O	0–3	–	–	5.4	4.8	76.7*	–	–	–	60.0	15.0	3.2	62
AY	3–9	10	20	5.9	5.1	7.3	0.59	7.2	0.75	22.5	8.5	3.1	69
AC	20–30	11	24	6.3	4.8	2.1	0.09	13.5	0.33	11.0	8.5	0.3	78
C	35–45	9	19	6.2	4.5	0.9	–	–	–	8.0	3.5	0.3	75
Pit 511. Forb larch forest, III quality class; 1500 m a.s.l. (Eastern Khentei)													
O	0–2	–	–	6.0	4.9	83.0*	–	–	–	22.0	13.7	3.6	61
AY	2–10	19	36	5.8	4.8	11.2	0.57	11.4	1.47	13.2	5.9	0.2	66
AC	10–20	17	32	5.7	4.4	4.0	0.11	20.9	0.54	6.3	2.0	0.5	59
C	40–50	7	11	6.0	4.4	0.7	–	–	–	2.4	0.2	0.2	74
Pit 506. Forb larch forest, III quality class; 1520 m a.s.l. (Eastern Khentei)													
O	0–2	–	–	6.0	4.8	82.0*	–	–	–	20.8	7.2	0.8	68
AY	2–10	19	37	5.8	4.7	10.0	0.46	12.6	0.80	16.3	6.3	0.4	53
AC	11–22	18	33	6.2	5.3	3.5	0.13	15.4	0.33	4.4	3.2	0.5	57
Cf	30–40	7	23	6.4	5.5	1.5	0.05	18.0	–	3.2	0.9	0.6	48
C	60–70	13	21	6.4	5.5	0.6	–	–	–	3.5	0.7	0.4	49
⊥C	80–100	8	16	6.6	5.4	0.5	–	–	–	2.6	0.4	0.2	46
Gray-humus eluviated clay-illuvial soils:													
Pit 896. Cowberry-forb pine forest, II quality class; 1000 m a.s.l. (Northwestern Khentei)													
O	0–3	–	–	6.4	4.9	93.5*	–	–	–	26.6	17.5	16.1	56
AY	10–20	8	33	5.1	4.2	4.1	0.19	12.6	1.00	21.4	6.0	14.6	60
AYel	30–40	13	36	5.6	4.2	1.8	0.09	11.1	0.40	6.4	3.3	3.6	57
Ci	42–52	15	38	5.6	4.2	0.9	–	–	–	8.5	3.5	2.9	66
C	60–70	7	16	5.5	4.1	0.1	–	–	–	6.0	2.2	1.3	–
Pit 544. Forb larch forest, III quality class; 1560 m a.s.l. (Eastern Khentei)													
O	0–3	–	–	6.0	5.1	84.0*	–	–	–	41.1	13.7	1.2	79
AY	3–10	16	39	6.1	5.0	8.4	0.38	12.9	1.28	15.9	5.2	0.7	81
AYel	10–20	15	38	6.1	5.1	3.5	0.12	16.6	0.40	18.7	4.7	0.8	86
Ci	30–40	14	37	6.4	5.3	1.9	0.07	15.7	–	21.7	3.4	0.4	89
C	50–60	12	28	6.5	5.4	0.6	–	–	–	20.9	0.2	0.4	85
⊥C	80–90	13	24	6.3	5.3	0.6	–	–	-	24.0	7.3	0.4	-
Pit 870. Cowberry-forb larch forest, IV quality class; 1700 m a.s.l. (Buteliin-Nuru Range, Eastern CisKhubsugul region)													
O	0–1	–	–	5.6	4.5	90.0*	–	–	–	31.5	16.5	2.9	59
AY	1–3	8	21	5.9	4.2	17.5	0.99	10.2	0.76	24.0	8.0	1.4	57
AYe	3–11	7	18	5.0	4.2	9.6	0.65	8.6	0.43	14.0	4.5	2.3	52
Ci	11–21	10	27	5.2	4.0	3.3	0.20	9.5	–	7.5	0.1	2.3	68
Ci	30–40	7	25	5.2	4.2	2.3	0.12	10.8	–	4.5	0.1	1.7	72
C	70–80	6	15	5.2	4.3	0.7	–	–	–	3.5	0.1	0.5	78

S is base saturation; dashes stand for not determined.
*Loss on ignition.

earth. The clay fraction tends to accumulate in the gray-humus horizon. More than half of physical clay is composed of clay particles.

Gray-humus deeply thawing permafrost-affected soils have a higher content of medium and fine silt fractions in fine earth. According to [19], the particle-size composition of this type of soils could be formed by the processes of soil physical weathering of the skeleton and by cryogenic phenomena that cause the dispersion of soil-forming rocks and the homogenization of the mineral part of the profile of cryogenic soils at the level of coarse-silt particles.

In general, the profiles of the studied soils are characterized by lighter texture in the lower horizons and high content of clay and physical clay in the upper horizons.

Humus is concentrated in the AY horizon: its amount ranges there from 4 to 10% and sharply decreases downward. According to the C/N ratio equal to 7.2–12.6 in the humus horizon, humus is represented by humic substances bonded to the mineral soil part. The distribution and type of humus is a result of the soddy-forest soil-forming process. This explains the composition of humus in these soils.

It has been revealed [30, 33] that humic acids predominate over fulvic acids in humus of the studied soils only in the AY horizon (C_{ha}/C_{fa} = 1.10–1.47). Humates are mainly represented by forms bonded to calcium.

Such soils with the fulvate-humate humus type are usually formed in thin or sparse forests with a dense grass cover, where the cenotic role of the grass layer is much greater than that of the tree layer.

Gray-humus soils in the upper and middle part of the subtaiga zone under high- and medium-dense stands usually have humate-fulvate humus type. The C_{ha}/C_{fa} ratio in gray-humus horizons is 0.75–1.00 [33, 43].

The profile curves of the exchangeable bases in general correspond to that of humus. The exchangeable bases are intensively accumulated in the forest litter and in the upper gray-humus horizon. The content of calcium and magnesium decreases in the parent rock, which points to their biogenic origin in the accumulative part of the profile.

Soils are characterized by slightly acid and acid reaction and high hydrolytic acidity. Soils, which exchange complex base-unsaturated (<80%), are distinguished among gray-humus soils. The low base saturation of a large group of gray-humus soils is obviously related to the humate-fulvate type of humus, to parent rocks, and to specific plant cover, as well as to the predominance of tree residues (needles, small branches, bark, and cones) in the falloff. During decomposition, they supply a sufficient amount of H^+ ion to the soil.

Gray-humus clay-illuvial soils with evidences of podzolization are also common in the soil cover of the subtaiga mixed-grass light coniferous forests. They are usually formed on light-textured rocks in the upper part of the studied forest zone.

Gray-humus clay-illuvial podzolized soils are characterized by high humus content in the upper horizon (9.6%) and a weakly acid reaction. The soil exchange complex is saturated with calcium and magnesium. The AY and AYe horizons are the least saturated with bases.

The content and behavior of trace elements in soil is controlled by many factors: particle-size and mineralogical compositions of the solid phase, its enrichment with organic matter, trend and depth of soil-forming process, redox conditions, etc. [9, 10, 13, 26, 34, 40, 45].

The distribution of trace elements in the profile of typical gray-humus soils is of the accumulative type. The ranges are wide, i.e. the soils are characterized by great spatial heterogeneity of trace elements concentrations (Table 2). The accumulation of trace elements is the greatest in organic and humus-accumulative horizons.

Very high variation coefficients (V > 40%) are typical for Ba, V, B, Cr, and Ni in organic horizons; for Cu, Pb, Mn, Zr, and Sr in the AY humus-accumulative horizons; and for Ba, Mn, Sr, and Ni in the C mineral horizon.

The radial differentiation coefficient (C_{rd}) has been proposed to study the heterogeneity of the vertical distribution of chemical elements in soil profiles [9, 34]. It reflects a quantitative assessment of the effect of soil formation on the accumulation of particular chemical elements in the horizons of the soil profile or their removal. The concentration of the element in the soil-forming rock is taken as 1.

The concentration of biophilic elements in the organic horizons of the studied soils sharply increases relative to the soil-forming rock: C_{rd} is 24.93 for B, 19.23 for Mn, and 13.75 for B. Relatively lower concentration is typical for Sr, Zn, Pb, and Mo (C_{rd} = 1.36–4.08). These elements are common components in the soil organic matter and participate in the small biological cycle. The dispersion in this horizon is the strongest for Cr, Ni, and V and is slightly lower for Zr and Co (Fig. 2). The accumulation of most trace elements predominates in the AY and the AC horizons, but unlike their accumulation in the O surface organic horizon, this process is less pronounced here. There is a slight and medium removal of Zn, V, and Cr from the AY horizons and of Sr from the AC horizon.

The calculated concentration coefficients indicate that the concentrations of B (*CC* = 24.31), Mn (*CC* = 8.33), and Ba (*CC* = 5.64) sharply increase in the organic horizons of gray-humus soils. Concentrations of Zn (*CC* = 3.01), Sr (*CC* = 2.60), and Pb (*CC* = 2.39) are significant while accumulation of Cu and Mo is insignificant. The concentration coefficients of Zr and Ni are very low (*CC* = 0.37).

Table 2. Variability of the content of trace elements in organo-accumulative soils

Horizon	Statistic parameter	Pb	Cu	Zn	Co	V	Cr	Ni	Mn	Mo	Ba	Sr	Zr	B
Gray-humus typical soils ($n = 6$)														
O	*lim*	35–40	70–80	150–300	10–15	20–75	20–75	10–40	7000–10000	1–2	2000–6000	800–1000	50–80	175–500
	$M \pm m$	38.3 ± 1.7	76.7 ± 3.3	250.0 ± 50.0	11.7 ± 1.7	48.3 ± 15.9	41.7 ± 16.9	21.7 ± 9.2	8333.3 ± 881.9	1.5 ± 0.3	3666.7 ± 1201.8	883.3 ± 60.0	63.3 ± 8.8	291.7 ± 104.4
	V	7.6	7.6	34.6	24.8	56.9	70.2	74.2	18.3	33.3	56.8	11.8	24.2	62.0
AY	*lim*	10–20	40–80	80–100	20–40	80–100	80–100	25-60	1500–6000	1–2	400–2000	100–600	80–400	10–20
	$M \pm m$	13.3 ± 3.3	53.3 ± 13.3	86.7 ± 6.7	26.7 ± 6.7	86.7 ± 6.7	93.3 ± 6.7	38.3 ± 8.8	4166.7 ± 1364.2	1.5 ± 0.3	1400.0 ± 80.3	366.7 ± 145.3	260.0 ± 94.5	15.0 ± 2.9
	V	43.6	43.3	13.3	43.1	13.3	12.3	42.3	56.7	33.3	28.6	68.3	62.9	33.3
AC	*lim*	20–30	40–80	100–150	20–30	100–150	150–200	20–100	450–5000	1–2	300–400	100–300	80–200	10–30
	$M \pm m$	23.3 ± 3.3	56.7 ± 12.0	123.3 ± 14.5	23.3 ± 3.3	120.0 ± 15.2	175.0 ± 14.4	64.0 ± 25.1	2150.0 ± 333.8	1.5 ± 0.3	366.7 ± 33.3	183.3 ± 60.0	126.7 ± 37.1	20.0 ± 5.7
	V	24.9	36.7	20.4	24.9	22.0	14.3	65.0	31.8	33.3	15.7	56.8	50.7	50.0
C	*lim*	15–20	40–60	80–100	10–20	80–100	150–200	15-80	200–800	1–1.4	200–400	100–300	80–150	10–15
	$M \pm m$	16.6 ± 1.7	50.0 ± 5.8	93.3 ± 6.7	16.7 ± 3.3	93.3 ± 6.7	166.7 ± 16.7	38.3 ± 12.9	433.3 ± 115.6	1.1 ± 0.1	266.7 ± 66.7	216.7 ± 60.1	103.3 ± 23.3	11.7 ± 1.7
	V	17.5	20.0	12.3	34.7	12.3	17.3	65.8	51.1	18.2	43.3	48.0	39.1	24.8
Dark-humus metamorphic soils ($n = 5$)														
O	*lim*	20–40	50–150	100–400	2–20	20–150	20–200	15–40	6000–10000	1–2	2000–6000	800–1000	60–200	300–500
	$M \pm m$	32.5 ± 4.7	95.0 ± 21.0	237.5 ± 68.8	13.0 ± 4.3	92.5 ± 33.7	85.0 ± 22.7	26.2 ± 5.5	8000.0 ± 816.5	1.5 ± 0.3	4250.0 ± 853.9	925.0 ± 47.8	110.0 ± 31.1	437.5 ± 47.3
	V	29.5	44.2	57.9	66.9	72.9	53.4	41.9	20.4	40.0	40.2	10.3	56.5	21.6
AU	*lim*	10–15	30–60	60–100	8–20	50–80	30–100	10–20	2000–5000	1.5–2	1000–3000	500–800	100–400	20–30
	$M \pm m$	11.2 ± 1.2	42.5 ± 6.3	80.0 ± 8.1	12.0 ± 2.7	70.0 ± 7.1	62.5 ± 14.4	15.0 ± 2.0	3750.0 ± 629.1	1.7 ± 0.1	2250.0 ± 478.7	625.0 ± 62.9	225.0 ± 62.9	27.5 ± 2.5
	V	22.3	29.1	20.4	45.0	20.1	45.9	27.3	33.5	11.7	42.5	20.1	55.9	18.2
Cm	*lim*	15–20	40–60	100–150	15–20	40–100	80–200	20–150	400–800	1–1.5	400–500	200–500	150–200	10–20
	$M \pm m$	16.2 ± 1.2	50.0 ± 5.8	112.5 ± 12.5	16.3 ± 1.2	80.0 ± 14.1	140.0 ± 34.6	72.5 ± 11.9	600.0 ± 81.6	1.2 ± 0.1	425.0 ± 25.0	325.0 ± 62.9	175.0 ± 14.4	13.7 ± 2.3
	V	15.4	23.0	22.2	15.4	35.2	49.5	32.8	27.2	16.7	11.8	38.7	16.4	35.0
C	*lim*	15–16	40–50	80–100	10–15	60–100	150–300	30–200	300–600	1–1.5	200–400	150–300	100–150	10–30
	$M \pm m$	15.5 ± 0.3	42.5 ± 2.5	95.0 ± 5.0	12.5 ± 1.4	90.0 ± 10.0	200.0 ± 35.3	90.0 ± 20.2	450.0 ± 64.5	1.1 ± 0.1	325.0 ± 47.8	200.0 ± 35.3	135.0 ± 11.9	17.5 ± 4.8
	V	3.9	11.8	10.5	23.2	22.2	35.3	44.9	28.7	18.2	29.4	35.3	17.6	54.8
Dark-humus residually calcareous soils ($n = 5$)														
O	*lim*	30–40	60–80	100–150	15–20	50–65	50–60	15–20	4000–6000	2–3	2000–5000	1000–2000	100–200	200–500
	$M \pm m$	37.5 ± 2.5	72.5 ± 4.8	137.5 ± 12.5	17.5 ± 1.4	56.2+3.7	57.5 ± 2.5	17.5 ± 1.4	5250.0 ± 478.7	2.5 ± 0.3	3125.0 ± 657.5	1375.0+239.4	150.0 ± 20.4	275.0 ± 75.0
	V	13.3	13.1	18.2	16.6	13.3	8.7	16.6	18.2	24.0	42.1	34.8	27.2	54.5
AU	*lim*	10–20	40–60	60–100	3–10	50–100	200–300	20–30	2000–4000	1.5–2	1500–2000	500–600	200–300	10–20
	$M \pm m$	15.0 ± 2.0	50.0 ± 5.8	80.0 ± 8.1	6.2 ± 1.4	87.5 ± 12.5	237.5 ± 23.9	22.5 ± 2.5	3000.0 ± 408.2	1.7 ± 0.1	1625.0 ± 125.0	525.0 ± 25.0	225.0 ± 25.0	15.0 ± 2.9
	V	26.7	23.9	20.4	45.2	28.6	20.1	22.2	27.2	11.8	15.4	9.2	22.2	38.7
AC	*lim*	10–15	30–40	60–100	3–10	60–100	100–200	15–20	500–800	1–1.5	300–500	300–400	80–110	15–20
	$M \pm m$	13.7 ± 1.2	32.5 ± 2.5	75.0 ± 9.5	5.2 ± 1.6	75.0 ± 9.5	125.0 ± 25.0	17.5 ± 1.4	675.0 ± 75.0	1.2 ± 0.1	400.0 ± 57.7	350.0 ± 28.9	97.5 ± 6.3	16.2 ± 1.2
	V	18.2	15.4	25.4	63.5	25.4	40.0	16.6	22.2	16.7	28.9	16.5	12.9	15.4
Cca	*lim*	15–30	40–80	100–150	10–15	100–150	80–100	15–30	400–600	1–1.5	300–500	300–500	100–150	15–30
	$M \pm m$	23.7 ± 3.7	52.5 ± 9.4	112.5 ± 12.5	12.5 ± 1.4	137.5 ± 12.5	90.0 ± 5.8	23.7 ± 3.7	450.0 ± 50.0	1.1 ± 0.1	400.0 ± 57.7	400.0 ± 40.8	112.5 ± 12.5	21.2 ± 3.1
	V	31.6	36.0	22.2	23.2	18.2	12.8	31.6	22.2	18.2	28.8	20.4	22.2	29.7

lim—variability limits; *M*—arithmetic mean, mg/kg; ±*m*—error of the mean; *V*—variation coefficient, %; *n*—number of data in the sampling.

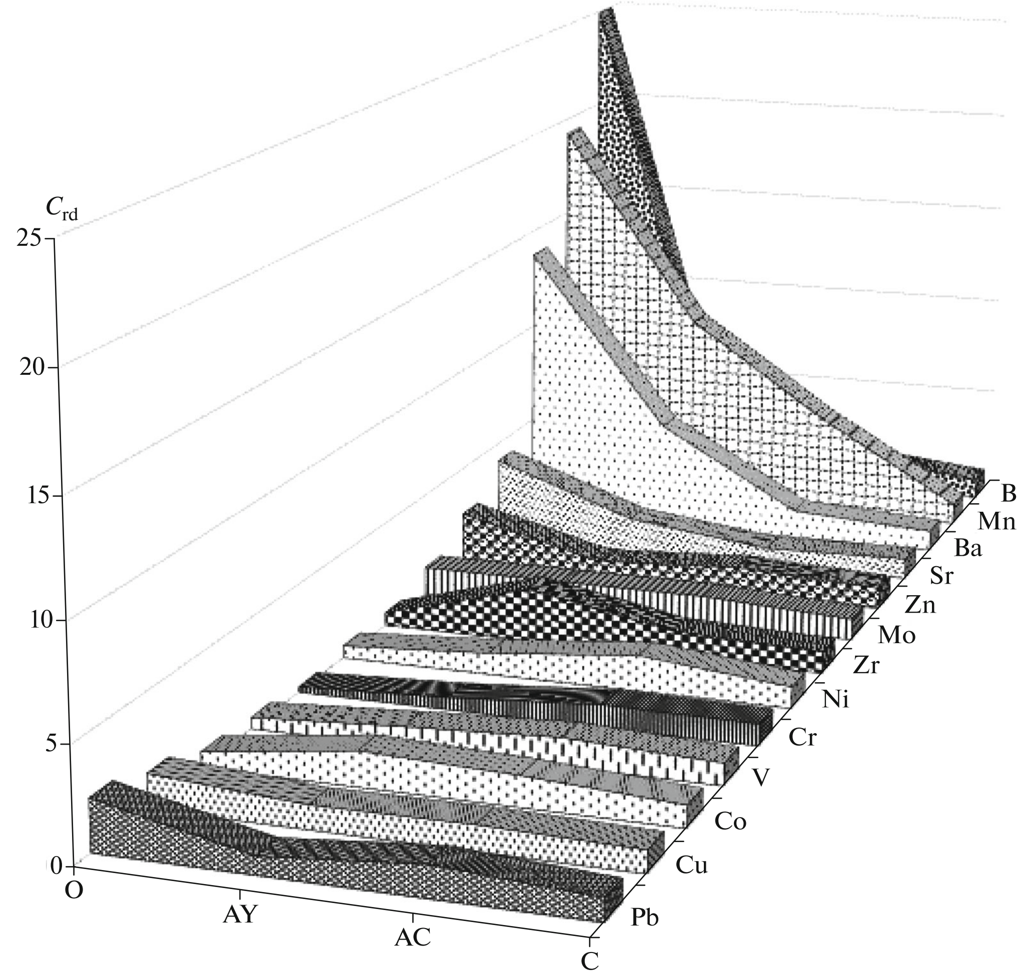

Fig. 2. Profile migration of trace elements in typical gray-humus soils.

The AY horizon is characterized by prominent concentrations of Mn (*CC* = 4.17) and Ba (*CC* = 2.15) and by weaker ones of Zr, Co, Mo, and B. The accumulation of Cu, Cr, Sr, and Zn is low. The content of the rest elements is low. The relative concentration coefficients are 0.66–0.96 for Ni, V, and Pb, which indicates slight and moderate dispersion of these elements.

Contrary to the surface organic and humus-accumulative horizons, the AC horizon is characterized by an increase in the concentration of almost all trace elements, with the exception of Zr, Ba, and Sr. The concentration coefficients of these elements relative to the lithospheric clarkes are lower than 1; and Cr, Zn, Cu, Pb, and V are characterized by weak accumulation in the soil-forming rock.

The following geochemical formulas have been developed by the intensity of accumulation of trace elements in the soil horizons of typical gray-humus soils (hereinafter: elements with *CC* > 1 are in the numerator and elements with *CC* < 1 are in the denominator):

$$\mathrm{O}\ \frac{\mathrm{B_{24.31},Mn_{8.33},Ba_{5.64},Zn_{3.01},Sr_{2.60},Pb_{2.39},Cu_{1.63},Mo_{1.36}}}{\mathrm{Co_{0.65},V_{0.54},Cr_{0.50},Zr_{0.37},Ni_{0.37}}},$$

$$\mathrm{AY}\ \frac{\mathrm{Mn_{4.17},Ba_{2.15},Zr_{1.53},Co_{1.48},Mo_{1.36},B_{1.25},Cu_{1.13},Cr_{1.12},Sr_{1.08},Zn_{1.04}}}{\mathrm{V_{0.96},Pb_{0.83},Ni_{0.66}}},$$

$$\mathrm{AC}\ \frac{\mathrm{Mn_{2.15},Cr_{2.11},B_{1.67},Zn_{1.48},Pb_{1.45},Mo_{1.36},V_{1.33},Co_{1.29},Cu_{1.21},Ni_{1.10}}}{\mathrm{Zr_{0.74},Ba_{0.56},Sr_{0.54}}}$$

$$\mathrm{C}\ \frac{\mathrm{Cr_{2.01},Zn_{1.13},Cu_{1.06},Pb_{1.04},V_{1.04},Mo_{1.00}}}{\mathrm{B_{0.97},Co_{0.93},Ni_{0.66},Sr_{0.64},Zr_{0.61},Mn_{0.43},Ba_{0.41}}},$$

Table 3. The content of trace elements in gray-humus clay-illuvial podzolized soil (pit 870), mg/kg

Horizon	Depth, cm	Pb	Cu	Zn	Co	V	Cr	Ni	Mn	Mo	Ba	Sr	Zr	B
O	0–1	40	80	300	Not det.	20	30	10	10000	2	2000	1000	50	200
AY	1–3	10	40	80	20	80	100	20	6000	1	800	600	400	15
AYe	3–11	10	40	80	20	80	60	15	3000	1.5	500	400	200	15
Ci	11–21	20	50	100	20	100	150	30	500	1.5	400	300	150	20
Ci	30–40	20	60	150	20	100	200	30	400	1.5	300	200	100	20
C	70–80	15	50	80	10	80	60	15	300	1	200	300	80	15

The surface organic and humus-accumulative horizons of the studied soils are enriched with B and Mn due to their input with forest debris. They are not accumulated in the parent rock, but are intensively removed from it as a result of the formation of easily soluble and mobile compounds [10, 34].

Contrary to typical gray humus soils, clay-illuvial podzolized soils are characterized by both biogenic accumulation in the surface organic horizons and eluvial-illuvial differentiation of most elements in the soil profile (Table 3). There is an intensive accumulation of Mn (C_{rd} = 33.34), B (C_{rd} = 13.33), and Ba (C_{rd} = 10.00) in the surface organic horizon and relatively smaller accumulation of Zn (C_{rd} = 3.75), Sr (C_{rd} = 3.33), Pb (C_{rd} = 2.67), and Mo (C_{rd} = 2.00). The AYe horizon is depleted of trace elements, of the iron group in particular, which are accumulated in the lower Ci mineral horizon (Fig. 3).

Geochemical formulas of soil horizons of gray-humus clay-illuvial podzolized soil (pit 870) are the following:

$$\mathrm{O}\,\frac{\mathrm{B_{16.67},Mn_{10.00},Zn_{3.61},Ba_{3.07},Sr_{2.94},Pb_{2.50},Mo_{1.82},Cu_{1.70}}}{\mathrm{Cr_{0.36},Zr_{0.29},V_{0.22},Ni_{0.18}}},$$

$$\mathrm{AY}\,\frac{\mathrm{Mn_{6.00},Zr_{2.35},Sr_{1.76},B_{1.25},Ba_{1.23},Cr_{1.20},Co_{1.11},Mo_{1.0}}}{\mathrm{Zn_{0.96},V_{0.89},Cu_{0.85},Pb_{0.62},Ni_{0.34}}},$$

$$\mathrm{AYe}\,\frac{\mathrm{Mn_{3.00},Mo_{1.50},B_{1.25},Sr_{1.17},Zr_{1.17},Co_{1.11}}}{\mathrm{Zn_{0.96},V_{0.89},Cu_{0.85},Ba_{0.77},Cr_{0.72},Pb_{0.62},Ni_{0.26}}},$$

$$\mathrm{Ci}\,\frac{\mathrm{Cr_{1.81},B_{1.67},Mo_{1.50},Pb_{1.25},Zn_{1.20},Co_{1.11},V_{1.11},Cu_{1.06}}}{\mathrm{Sr_{0.88},Zr_{0.88},Ba_{0.61},Ni_{0.52},Mn_{0.50}}},$$

$$\mathrm{Ci}\,\frac{\mathrm{Cr_{2.40},Zn_{1.81},B_{1.67},Mo_{1.50},Cu_{1.28},Pb_{1.25},Co_{1.11},V_{1.11}}}{\mathrm{Sr_{0.59},Zr_{0.59},Ni_{0.52},Ba_{0.46},Mn_{0.40}}},$$

$$\mathrm{C}\,\frac{\mathrm{B_{1.25},Cu_{1.06},Mo_{1.00}}}{\mathrm{Zn_{0.96},Pb_{0.93},V_{0.89},Sr_{0.88},Cr_{0.72},Co_{0.56},Zr_{0.47},Ba_{0.31},Mn_{0.30},Ni_{0.26}}}.$$

Dark-humus soils (Haplic Phaeozems) are formed in the lower and partly middle mountain zone under subtaiga and subtaiga-forest-steppe thin larch or secondary forest with a well-formed grass cover. Their humus horizon is relatively thick and dark-colored. This transitional belt from forest to steppe in Mongolia is now a zone of forest and steppe contact. It is well pronounced in Western and Eastern Khentei, Eastern Prikhubsugul'e, and Khangai.

Subtypes of metamorphic and residual-calcareous soils were identified within the type of dark-humus soils.

Dark humus metamorphic soils (Cambic Someric Phaeozem (Loamic)) are characterized by thin forest litter (1–2 cm) on the surface above the AU dark-humus horizon 10–35-cm-thick. The horizon is black-brown or dark brown. It is underlain by the ACm brownish or brown horizon with dark gray or brownish-gray humus mottles. The total thickness of the accumulative part of the profile (AU + ACm) is 25–45 cm. The lower Cm horizon of brown color is compacted, and there are dark brown mottles of iron and aluminum oxides on the ped faces.

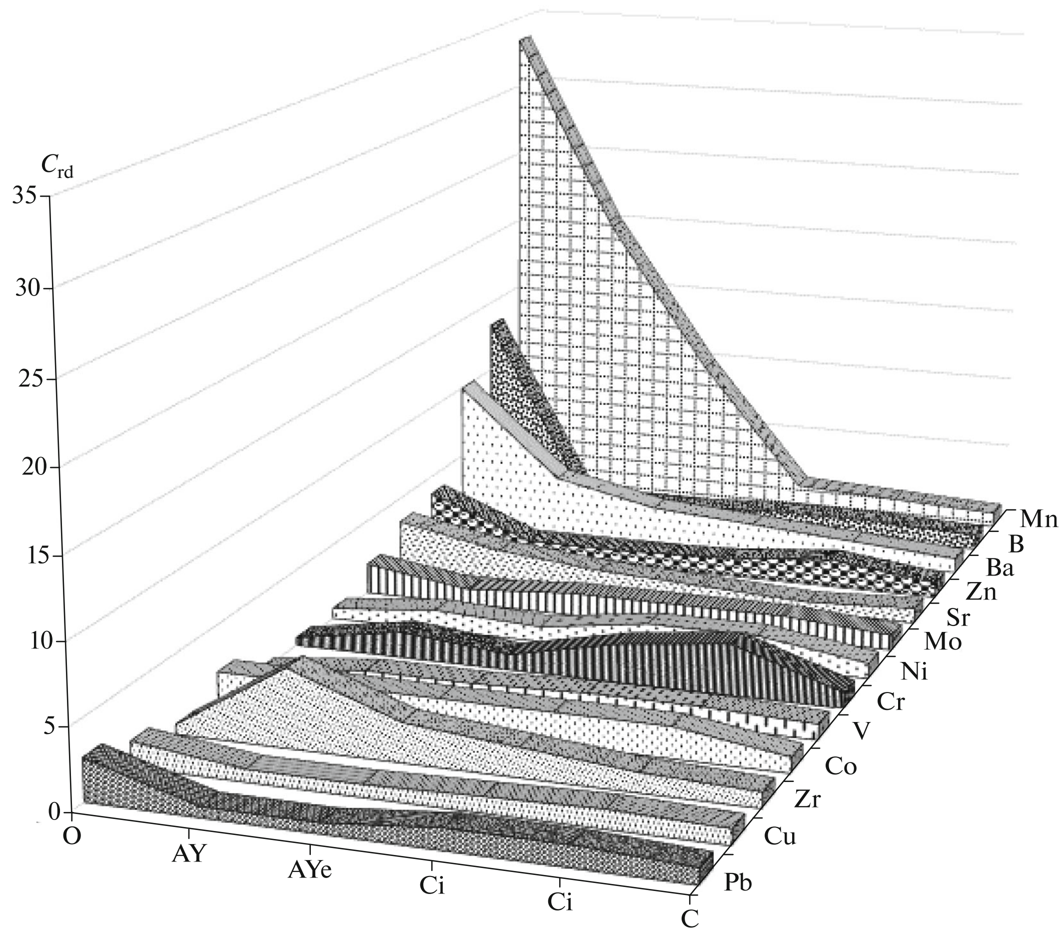

Fig. 3. Profile migration of trace elements in gray-humus clay-illuvial podzolized soil (pit 870).

According to the particle-size composition, the soils are medium- and heavy-loamy with a high content of weathered stones in the lower soil horizons (Table 4). There is a clear differentiation of the content of physical clay fractions in the profile and its accumulation in the Cm horizon.

The humus content in the AU humus-accumulative horizon is 13.6–14.4%. It sharply decreases (to 2.2–4.8%) in the Cm horizon. The group composition of humus is dominated by humic acids, but it becomes of fulvate-humate and even of fulvate type already in the underlying Cm horizon. The reaction is weakly acid throughout the soil profile. Dark-humus metamorphic soils are characterized by high cation exchange capacity: 28–48 cmol(equiv)/kg. The soils are saturated with bases.

The organic horizons of dark-humus metamorphic soils are characterized by a large spatial heterogeneity of the microelement composition. The variation coefficients of almost all elements here are high (V = 40–73%) except for Sr, Mn, B, and Pb. They are high for Ba, Co, Cr, and Zr in the Au dark-humus horizon (V = 42–56%), and for Cr in the Cm horizon. The variation coefficient of the rest elements in these horizons vary from medium to low.

The radial differentiation coefficients (C_{rd}) for the profile of dark-humus metamorphic soils indicate the predominating accumulative redistribution of elements along the profile, as well as the relative accumulation of some trace elements in the Cm horizon (Fig. 4). Large quantities of B, Mn, and Ba are concentrated in organic horizons in comparison with the soil-forming rock.

The concentration coefficients relative to lithosphere clarkes prove that the concentrations of B (CC = 36.46), Mn (CC = 8.00), and Ba (CC = 6.53) sharply increase in organic horizons of the dark-humus metamorphic soils. The concentration coefficients of Zn, Sr, Pb, Cu, and Mo vary from 1.36 to 2.86. The accumulation of V and Cr is small. The concentration coefficients vary from 0.45 to 0.62 for Ni, Zr, and Co and indicate the moderate dispersion of these elements.

Relatively high concentration coefficients in the Cm horizon are typical for Cr (CC = 1.68), Zn (CC = 1.35), Ni (CC = 1.25), and B (CC = 1.14). There is a slight accumulation of Mo, Cu, Zr, and Pb and a weak dispersion of Sr, Cr, V, Ba, and Mn.

Table 4. Some chemical and physicochemical properties of dark-humus soils

Horizon	Depth, cm	Particle-size composition (fraction, mm), % <0.001	Particle-size composition (fraction, mm), % <0.01	pH H_2O	Humus, total, %	N, total, %	C/N	C_{ha}/C_{fa}	Exchangeable cations, cmol(c)/kg Ca^{2+}	Mg^{2+}	H^+
Dark-humus metamorphic soils:											
Pit 5. Woodreed-sedge-forb larch forest, III quality class; 1600 m a.s.l. (Eastern Khentei)											
O	0–1	–	–	6.2	82.0*	–	–	–	30.8	7.1	0.9
AU	1–10	15	31	6.0	13.6	0.65	10.3	2.29	24.0	6.3	0.5
ACm	20–30	22	47	6.2	3.6	0.13	13.7	0.54	15.7	3.2	0.4
Cm	35–45	25	49	6.4	2.2	0.08	13.8	–	13.5	4.2	0.5
C	50–60	23	42	6.6	0.9	–	–	–	13.0	4.0	0.5
Pit 710. Iris-forb larch forest, III quality class; 1170 m a.s.l. (Dzhidinsk Range, Eastern CisKhubsugul region)											
O	0–1	–	–	5.8	71.1*	–	–	–	41.8	26.3	2.2
AU	1–8	11	36	6.2	13.8	0.68	10.0	2.88	26.1	12.7	1.7
AU	10–20	14	42	6.2	11.4	0.41	13.7	1.66	20.4	11.4	1.3
Cm	30–40	15	45	6.4	4.1	–	–	0.59	11.5	3.2	1.3
C	40–50	10	43	6.7	1.0	–	–	–	8.0	2.0	0.5
Pit 406. Iris-forb birch forest; 1000 m a.s.l. 1 (Dzhidinsk Range, Eastern CisKhubsugul region)											
O	0–1	–	–	7.0	74.0*	–	–	–	37.0	16.0	–
AU	5–25	12	32	6.4	14.4	0.93	7.6	–	21.6	6.0	0.3
Cm	40–50	19	41	6.6	4.8	0.19	12.5	–	20.6	5.0	0.2
C	60–70	16	36	6.5	1.4	–	–	–	17.0	6.0	0.2
Dark-humus residually calcareous soils:											
Pit 801. Sedge-forb larch forest, IV quality class; 950 m a.s.l. (Dzhidinsk Range, Eastern CisKhubsugul region)											
O	0–1	–	–	6.8	91.0*	–	–	–	45.0	8.0	–
AU	1–7	9	23	7.2	16.5	1.64	5.0	3.22	27.0	3.5	–
AU	7–17	9	22	7.4	5.6	0.72	3.9	1.10	23.5	4.0	–
AC	25–35	9	21	7.3	4.1	0.56	3.6	–	11.5	7.5	1.28**
C1ca	40–50	11	29	7.3	2.5	0.13	9.8	–	18.0	4.0	0.57**
C2ca	70–80	17	26	7.7	1.3	–	–	–	32.6	1.6	9.20**
Pit 163. Iris-forb birch forest; 1060 m a.s.l. (Dzhidinsk Range, Eastern CisKhubsugul region)											
O	0–1	–	–	6.3	83.0*	–	–	–	32.6	1.6	–
AU	1–9	10	18	6.6	10.9	0.76	8.3	2.06	30.0	6.0	–
AC	9–19	10	23	6.6	2.5	0.22	6.4	1.01	14.0	0.6	–
C	20–30	12	21	6.8	0.9	–	–	–	10.6	1.6	–
Cca	45–55	12	24	7.1	0.9	–	–	–	13.0	1.6	0.92**
Cca	65–75	9	17	8.2	–	–	–	–	18.0	3.0	5.76**
Pit 350. Iris-forbs birch forest; 1250 m a.s.l. (Dzhidinsk Range, Eastern CisKhubsugul region)											
O	0–3	–	–	5.5	81.1*	–	–	–	28.7	20.1	–
AU	3–9	11	42	6.0	7.3	0.58	6.1	–	20.3	13.6	–
AC	10–20	16	49	6.8	4.2	0.11	18.5	–	20.6	11.8	–
C	20–30	14	46	7.7	1.0	–	–	–	22.8	12.6	0.11**
Cca	40–50	13	35	8.3	0.2	–	–	–	29.2	12.9	4.88**

* Loss on ignition.
** CO_2 content, %; dash is not determined.

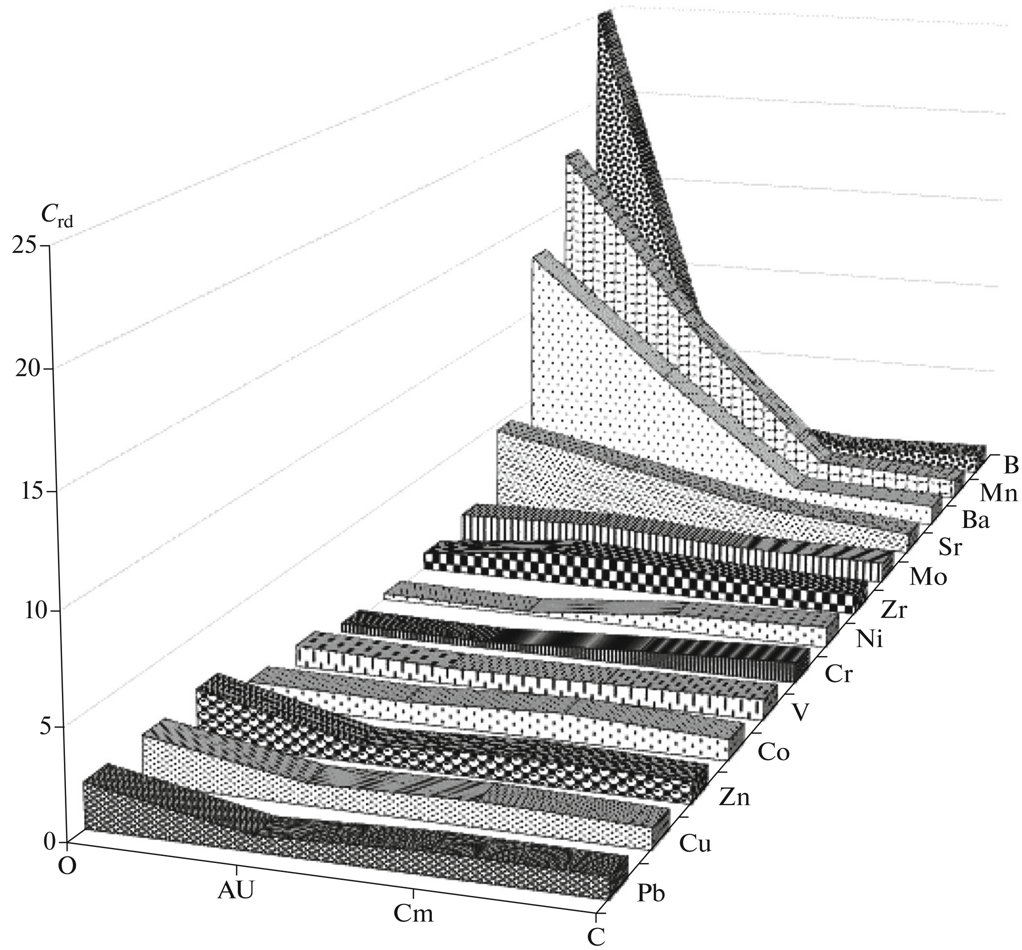

Fig. 4. Profile migration of trace elements in dark-humus metamorphic soils.

The geochemical formulas of the soil horizons of dark-humus metamorphic soils are the following:

$$\mathrm{O}\,\frac{\mathrm{B}_{36.46},\ \mathrm{Mn}_{8.00},\ \mathrm{Ba}_{6.53},\ \mathrm{Zn}_{2.86},\ \mathrm{Sr}_{2.72},\ \mathrm{Pb}_{2.03},\ \mathrm{Cu}_{2.02},\ \mathrm{Mo}_{1.36},\ \mathrm{V}_{1.03},\ \mathrm{Cr}_{1.02}}{\mathrm{Co}_{0.72},\ \mathrm{Zr}_{0.65},\ \mathrm{Ni}_{0.45}},$$

$$\mathrm{AU}\,\frac{\mathrm{Mn}_{3.75},\ \mathrm{Ba}_{3.46},\ \mathrm{B}_{2.29},\ \mathrm{Sr}_{1.83},\ \mathrm{Mo}_{1.54},\ \mathrm{Zr}_{1.32}}{\mathrm{Zn}_{0.96},\ \mathrm{Cu}_{0.90},\ \mathrm{V}_{0.78},\ \mathrm{Cr}_{0.75},\ \mathrm{Pb}_{0.70},\ \mathrm{Co}_{0.67},\ \mathrm{Ni}_{0.26}},$$

$$\mathrm{Cm}\,\frac{\mathrm{Cr}_{1.68},\ \mathrm{Zn}_{1.35},\ \mathrm{Ni}_{1.25},\ \mathrm{B}_{1.14},\ \mathrm{Mo}_{1.09},\ \mathrm{Cu}_{1.06},\ \mathrm{Zr}_{1.03},\ \mathrm{Pb}_{1.01}}{\mathrm{Sr}_{0.96},\ \mathrm{Co}_{0.90},\ \mathrm{V}_{0.89},\ \mathrm{Ba}_{0.65},\ \mathrm{Mn}_{0.60}},$$

$$\mathrm{C}\,\frac{\mathrm{Cr}_{2.41},\ \mathrm{Ni}_{1.55},\ \mathrm{B}_{1.46},\ \mathrm{Zn}_{1.14},\mathrm{V}_{1.00},\mathrm{Mo}_{1.00}}{\mathrm{Pb}_{0.97},\ \mathrm{Cu}_{0.90},\ \mathrm{Zr}_{0.79},\ \mathrm{Co}_{0.69},\ \mathrm{Sr}_{0.59},\ \mathrm{Ba}_{0.50},\ \mathrm{Mn}_{0.45}}.$$

Dark-humus residually calcareous soils are formed under conditions of the subtaiga vertical zone on the weathering products of calcareous rocks. They are the most widely spread in the middle and lower parts of the subtaiga AVC and in the forests of the contact zone of forest and steppe, under forb and steppe-forb pine and larch forests and their derivatives. The soils are characterized by the presence of thin forest litter (1–2 cm) and the AU dark-humus horizon 10–20-cm-thick, which gradually gives way to the parent rock. The profiles of these soils include the AC transitional horizon. The color differs and depends on the parent and underlying rocks. Easily soluble salts in the lower Cca horizons are typical for these soils.

The particle-size composition of soils is light or heavy loamy. The high content of coarse fractions is accompanied by a large amount of clay and physical clay.

The soils are characterized by high humus content in the AU horizon (7.3–16.5%) and its sharp decrease

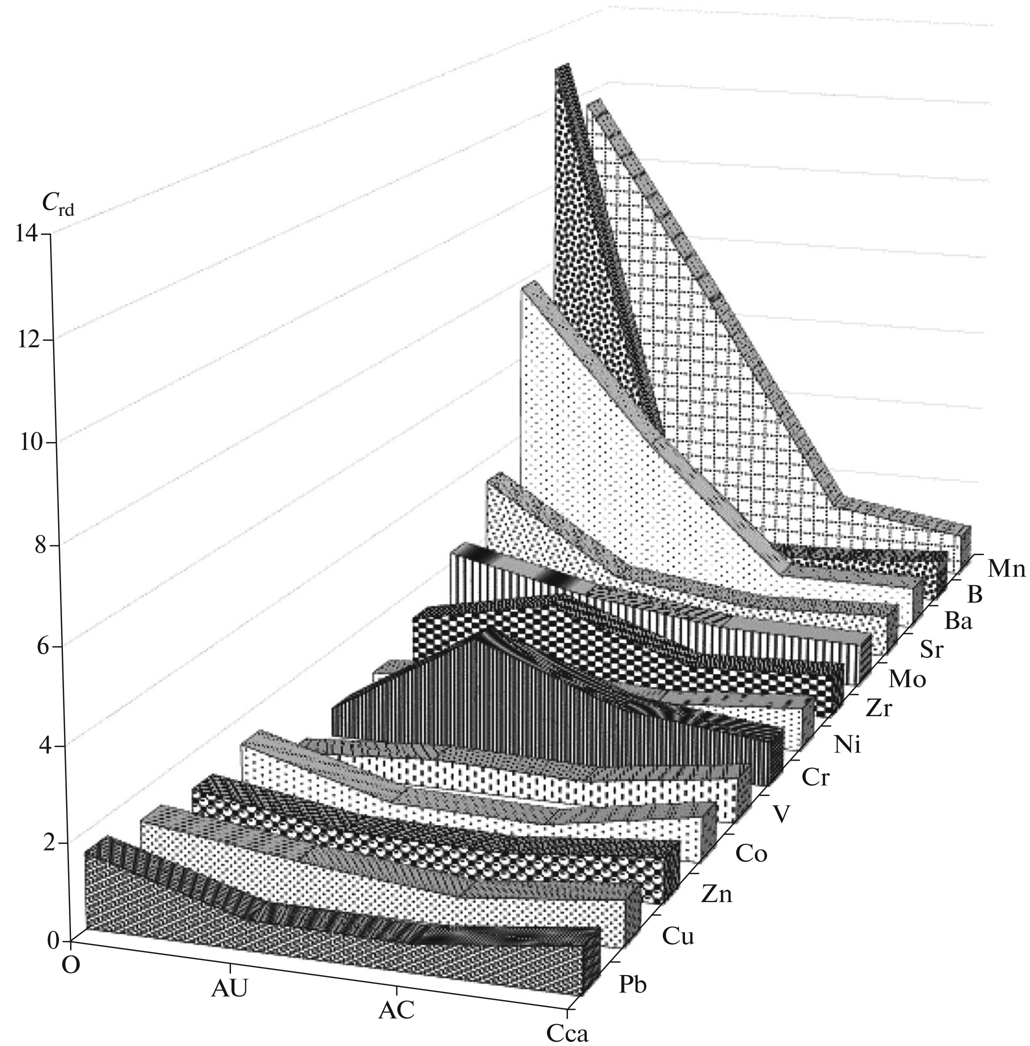

Fig. 5. Profile migration of trace elements in dark-humus residually calcareous soils.

with the depth. Humus composition varies from humate to fulvate-humate. The reaction is weakly acid and neutral in the upper horizons and alkaline in the lower ones. The soil exchange complex is saturated with calcium and magnesium.

Dark-humus residual-calcareous soils are characterized by strong spatial heterogeneity in terms of trace elements composition. Variation coefficients are high for Ba and B in organic horizons (V = 42–55%) and for B in the dark-humus horizon (V = 45%).

There is a strong accumulation of biophilic elements in organic horizons of the studied soils relative to the soil-forming rock: of B (C_{rd} = 12.97), Mn (C_{rd} = 11.67), and Ba (C_{rd} = 7.81). The accumulation is lower for Sr and Mo (C_{rd} = 2.27–3.43) and is even more low for Pb (C_{rd} = 1.58), Co (C_{rd} = 1.40), Cu (C_{rd} = 1.38), Zr (C_{rd} = 1.33), and Zn (C_{rd} = 1.22). The organic horizons are depleted of V, Cr, and Ni (Fig. 5).

The concentration coefficients testify to a significant accumulation of trace elements in the organic and humus-accumulative horizons of the studied soils and their significant removal from the AC horizon. However, there is a significant increase in the concentration of most elements in the Cca horizon. The geochemical carbonate barrier is more pronounced in these soils than in mucky gray-humus residually calcareous soils formed in the middle mountains of the Khangai Highlands [23].

Geochemical formulas of soil horizons of dark-humus residually calcareous soils are the following:

$$\mathrm{O}\,\frac{\mathrm{B}_{22.92},\ \mathrm{Mn}_{5.25},\ \mathrm{Ba}_{4.80},\ \mathrm{Sr}_{4.04},\ \mathrm{Pb}_{2.34},\ \mathrm{Mo}_{2.27},\ \mathrm{Zn}_{1.65},\ \mathrm{Cu}_{1.54}}{\mathrm{Co}_{0.97},\ \mathrm{Zr}_{0.88},\ \mathrm{Cr}_{0.69},\ \mathrm{V}_{0.62},\ \mathrm{Ni}_{0.30}},$$

$$AU \frac{Mn_{3.00}, Cr_{2.86}, Ba_{2.50}, Mo_{1.54}, Sr_{1.54}, Zr_{1.32}, B_{1.25}, Cu_{1.06}}{V_{0.97}, Zn_{0.96}, Pb_{0.94}, Ni_{0.39}, Co_{0.34}},$$

$$AC \frac{Cr_{1.51}, B_{1.25}, Mo_{1.09}, Sr_{1.02}}{Zn_{0.90}, Pb_{0.86}, V_{0.83}, Cu_{0.69}, Mn_{0.67}, Ba_{0.61}, Zr_{0.57}, Ni_{0.30}, Co_{0.29}},$$

$$Cca \frac{B_{1.77}, V_{1.53}, Pb_{1.48}, Zn_{1.35}, Sr_{1.17}, Cu_{1.11}, Cr_{1.08}, Mo_{1.00}}{Co_{0.59}, Zr_{0.66}, Ba_{0.61}, Mn_{0.45}, Ni_{0.41}}.$$

CONCLUSIONS

The given data on the microelement composition of organo-accumulative soils of the subtaiga and subtaiga-forest-steppe light coniferous forests of Northern Mongolia testify to the predominating biogenic accumulation of most trace elements in surface organic and humus-accumulative horizons and to their accumulative pattern in soil profiles. The organic soil horizons are characterized by intensive accumulation of B, Mn, and Ba and are depleted of the elements of the metal group: Cr, Ni, V, and Co, as well as Zr under particular conditions.

Among organo-accumulative soils, the accumulative type of distribution of trace elements in the profile is more pronounced for dark-humus soils.

The studied soils are characterized by strong variability and heterogeneity of the composition of trace elements in the profile. High variation coefficients (more than 40%) of trace elements in organic and humus-accumulative horizons are related to different mineralization and humification rates of organic matter. In mineral layers, they are explained by inclusions of rock fragments of different weathering degree, and mineralogical and petrographic composition, which are not genetically related to the underlying bedrock.

The increased content of trace elements and their slight removal are also determined by hydrothermal conditions: low precipitation, short growing period, and not high air temperatures in summer and low in winter. Hydrothermal conditions favor strong accumulation of plant residues under the forest canopy and their poor mineralization.

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ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This work does not contain any studies involving human and animal subjects.

CONFLICT OF INTEREST

The author of this work declares that he has no conflicts of interest.

REFERENCES

1. E. V. Arinushkina, *Guide to Chemical Analyses of Soils* (Mosk. Gos. Univ., Moscow, 1970) [in Russian].
2. G. V. Akhmetova, "Peculiarities of the content of trace elements in forest soils of three types of landscapes of the middle taiga subzone of Karelia," Lesn. Zh., No. 4, 49–53 (2009).
3. B. Batzhargal, P. K. Ivel'skii, V. P. Martynov, and A. S. Martynova, "Soils," in *Natural Conditions and Resources of the Khubsgul Region in Mongolia* (Nedra, Moscow, 1976), pp. 96–113.
4. I. A. Belozertseva and D. Enkhtaivan, "Soils in the Northern Hovsgol Region and their transformation in the process of land use," Geogr. Nat. Resour. **32** (2), 195–203 (2011).
5. A. P. Berzina, V. O. Gimon, I. V. Nikolaeva, S. V. Polesskikh, and A. V. Travina, "Basites of a polychronous magmatic center with Cu-Mo porphyry deposit Erdenetuin-Obo (Northern Mongolia): petrochemistry, geochronology, geodynamic position, connection with ore formation," Geol. Geofiz. **50** (10), 1077–1094 (2009).
6. N. D. Bespalov, *Soils of the Mongolian People's Republic* (Izd. Akad. Nauk SSSR, Moscow, 1951) [in Russian].
7. A. F. Vadyunina and Z. A. Korchagina, *Methods for Studying the Physical Properties of Soils* (Agropromizdat, Moscow, 1986) [in Russian].
8. L. A. Vorob'eva, *Chemical Analysis of Soils* (Mosk. Gos. Univ., Moscow, 1998) [in Russian].
9. A. P. Vinogradov, "Average content of chemical elements in the main types of igneous rocks of the Earth's crust," Geokhimiya, No. 7, 555–571 (1962).
10. A. P. Vinogradov, *Geochemistry of Rare and Trace Elements in Soils. Collection of Works* (Izd. Ross. Akad. Nauk, Moscow, 2021), Vol. 4 [in Russian].
11. I. V. Gordienko, A. Ya. Medvedev, M. A. Gornova, O. Tomurtogoo, and T. A. Goneger, "Geochemical, geochronological and geodynamic features of magmatism of the Kharagol terrane of Western Khentei (Northern Mongolia)," Geol. Geofiz. **53** (3), 365–379 (2012).
12. V. V. Dobrovol'skii, *Geochemistry of Microelements. Global Dispersion* (Mysl', Moscow, 1983) [in Russian].

13. V. V. Dobrovol'skii, *Geochemistry of Soils and Landscapes* (Nauchnyi Mir, Moscow, 2009), Vol. 2 [in Russian].
14. D. Dorzhgotov, Extended Abstract of Doctoral Dissertation (Moscow, 1992).
15. V. B. Il'in, "Background content of heavy metals in soils is an important component of environmental monitoring," in *Heavy Metals, Radionuclides and Biophilic Elements in the Environment. Proceedings of 2nd International Scientific and Practical Conference* (Semipalatinsk, 2002), Vol. 1, pp. 141–147.
16. A. Kabata-Pendias and Kh. Pendias, *Microelements in Soils and Plants* (Mir, Moscow, 1989) [in Russian].
17. *Classification and Diagnostics of Soils in Russia* (Oikumena, Smolensk, 2004) [in Russian].
18. V. A. Kovda, *Biogeochemistry of Soil Cover* (Nauka, Moscow, 1985) [in Russian].
19. V. N. Konishchev, *Formation of the Composition of Dispersed Rocks in the Permafrost Zone* (Nauka, Sib. Otd., Novisibirsk, 1981) [in Russian].
20. M. M. Kononova and N. P. Bel'chikova, "Accelerated methods for determining the humus composition of mineral soils," Pochvovedenie, No. 10, 75–87 (1961).
21. I. A. Korotkov, "Forest types of the Mongolian People's Republic," in *Forests of the Mongolian People's Republic* (Nauka, Moscow, 1978), pp. 47–121.
22. Yu. N. Krasnoshchekov, "Structure of vertical soil zonality and soil of forest landscapes of Northern Mongolia," Pochvovedenie, No. 4, 401–410 (1996).
23. Yu. N. Krasnoshchekov, *Soil Cover and Soils of Mountain Forests of Northern Mongolia* (Nauka, Novosibirsk, 2013) [in Russian].
24. Yu. N. Krasnoshchekov, "Geochemical features of cryogenic and Al–Fe-humus soils of mountainous taiga in Northern Mongolia," Eurasian Soil Sci. **54** (1), 25–37 (2021). https://doi.org/10.1134/S1064229321010063
25. L. G. Kuznetsova, A. M. Spiridonov, S. I. Dril', and Z. I. Kulikova, "Geochemistry of lepidolite granitoids of the Mungutiyn Tsagaan Durulj manifestation (Central Mongolia)," Geol. Geofiz. **53** (10), 1401–1416 (2012).
26. V. A. Kuz'min, *Geochemistry of Soils in the South of Eastern Siberia* (Izd. Inst. Geogr. im. V. B. Sochavy Sib. Otd. Ross. Akad. Nauk, Irkutsk, 2005) [in Russian].
27. O. V. Makeev, *Soddy Taiga Soils of the South of Central Siberia* (Buryat. Kn. Izd., Ulan-Ude, 1959) [in Russian].
28. V. P. Martynov, B. Batzhargal, and A. S. Martynova, "Soil cover map. Scale 1 : 1 000 000," in *Atlas of Khuvsgul Lake* (GUGK, Moscow, 1989).
29. M. M. Mikhailenko, *Soils of the Southern Taiga of Western Transbaikalia* (Nauka, Moscow, 1967) [in Russian].
30. N. A. Nogina, *Soils of Transbaikalia* (Nauka, Moscow, 1964) [in Russian].
31. N. A. Nogina and D. Dorzhgotov, "The peculiarity of the soil cover of Mongolia," in *Proceedings of the Institute of Botany of the Academy of Sciences of the Mongolian People's Republic* (Ulan-Bator, 1985), No. 7, pp. 160–168.
32. V. A. Nosin, *Soils of Tuva* (Nauka, Moscow, 1963) [in Russian].
33. A. V. Ogorodnikov, *Soils of Mountain Forests of the Mongolian People's Republic* (Nauka, Novosibirsk, 1981) [in Russian].
34. A. I. Perel'man and N. S. Kasimov, *Landscape Geochemistry* (Astreya-2000, Moscow, 1999) [in Russian].
35. B. B. Polynov, *Selected Works* (Izd. Akad. Nauk SSSR, Moscow, 1956) [in Russian].
36. *Soil Cover and Soils of Mongolia*, Ed. by I. P. Gerasimov and N. A. Nogina (Nauka, Moscow, 1984) [in Russian].
37. I. A. Samofalova, O. B. Rogova, O. A. Luzyanina, and A. T. Savichev, "Geochemical peculiarities of the distribution of macroelements in soils of undisturbed landscapes of the Middle Urals (using the example of the Basegi Nature Reserve)," Byull. Pochv. Inst. im. V. V. Dokuchaeva, No. 85, 56–76 (2016).
38. V. M. Fridland, "The effect of the degree of weathering of soil-forming rocks on the processes of soil formation in different bioclimatic zones," Pochvovedenie, No. 12, 5–15 (1970).
39. *Ecological and Geographical Atlas Monograph "Selenga–Baikal"*, Ed. by N. S. Kasimov (Geogr. Fak. Mosk. Gos. Univ., Moscow, 2019).
40. X. D. Cao, Y. Chen, X. R. Wang, and X. H. Deng, "Effects of redox potential and pH value on the release of rare elements from soil," Chemosphere **44**, 655–661 (2001).
41. IUSS Working Group WRB, *World Reference Base for Soil Resources 2014. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. World Soil Resources Reports №106* (FAO, Rome, 2014).
42. A. Kabata-Pendias and B. Szteke, *Trace Elements in Abiotic and Biotic Environments* (CRC Press, Taylor & Francis Group, London, 2015).
43. Yu. N. Krasnoshchekov, "Soil cover of mountain forests in the East Khubsugul region of Mongolia," Eurasian Soil Sci. **41** (7), 694–703 (2008). https://doi.org/10.1134/S106422930807003X
44. I. A. Samofalova, "Geochemical indices of weathering and elementary processes in mountain soils in the Middle Urals," Int. J. Appl. Exercise Physiol. **9** (4), 198–214 (2020).
45. G. Tyler, "Rare earth elements in soil and plant systems — a review," Plant Soil **267**, 191–206 (2004).

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