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ORIGINAL ARTICLE

Major and trace soil elements along environmental gradient of the Northern taiga in Western Siberia

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A series of interconnected soils were studied: Albic-Haplic Podzols, Albic-Stagnic Podzols, Histic-Albic Podzols и Epi-Histic Gleysols. The study area was located in the Northern taiga subzone, at the central part of the South Nadym-Pur province, in the Pyakupur River basin. Our article deals with the distribution of elements in the soil mineral horizons. The degree of profile differentiation of chemical elements was assessed using the illuviation coefficient Ki = CB/CE, where CB and CE are the content of the element in the illuvial and eluvial horizons and the coefficient of radial differentiation, where Kr = Ci/Cip, where Ci is the content of a chemical element in a particular genetic soil horizon, and Cip is the content in the parent rock. We also calculated the coefficient of lateral migration (Kl) - the ratio of the content of a chemical element in the studied subordinate landscape (Cp.) to its content in the autonomous landscape (Cl.) = Cp./Cl. Differences in the content of major and trace elements in the catenary gradient of environmental conditions were revealed. The series of accumulation of major and trace elements in different positions of the catena are close to each other, but not identical. The distribution of most elements along the soil profile occurs according to the eluvial-illuvial type, but the position in the relief determines the degree of migration of elements. At the border of the forest and the swamp, where the most intensive differentiation of elements along the soil profile was noted, a powerful geochemical barrier was revealed that accumulates substances coming from both lateral and horizontal runoff.

Keywords: soil, podzols, gleysols, major and trace elements, catena, Western Siberia

Introduction

The spatial organization of matter in ecosystems is one of the key environmental issues (Moskovchenko, 2010). Topographic position has been adopted as an indicator of soil change and has been used as a mapping aid since the beginning of modern soil research (Bonsteel et al., 1906; Hall and Russell, 1911). The relief participates in redistributing moisture, heat, soluble substances and has a significant effect on the differentiation of the soil cover. This was established by V.V. Dokuchaev and considered in detail by Ya.N. Afanasyev, S.S. Neustruev, V.R. Volobuev (Friedland, 1972). The water regime determines the combination of processes of humus formation and transformation of substrate minerals under the influence of various agents and, accordingly, the genesis of the soil (Volobuev, 1963). To study the effect of relief on soil combinations, it is most convenient to use the concept of "catena" (from the Latin "catena" – "chain"), since the concept of catena defines the unity of the notions soil - profile and soil - cover. The concept of catena was introduced by Milne (1936) as "a series of soils conjugated in relief, which distinctions are associated with distinctions in elevation and slope". According to I.S. Urusevskaya (1990), the soil catena embodies the basic regularities of soil topography and contains a variety of information. Exploring the catena, we can estimate the spatial combination of different taxonomic units of the soil cover, the nature of drainage, redistribution of solid and dissolved substances. B.B. Polynov (1956) subdivided the soils of biogeocenoses formed in flat conditions into eluvial and submarine-surface (accumulative) soils. He based the division on the intensity of the processes of removal and migration of substances and the position of soils in the relief. In 1964, M.A. Glazovskaya (1964) introduced the concept of transit landscapes and proposed to subdivide catena soils into geochemically autonomous and geochemically subordinate. Each elementary profile of a catena corresponds to a specific soil classification unit. Catena, being the result of a complex interaction of soil and slope processes, is formed by vertical and lateral movements of moisture and matter.

According to A.J. Gerrard (1984), the following processes are involved in the differentiation of the soil cover on catenas: surface and subsurface runoff, plane erosion, movement of materials down the slope in the form of talus, landslide or solifluction masses, movement of materials in the form of true or colloidal solutions. The elementary positions of the catena, spatially ordered in the system of drainage basins, form a matrix for the processes of mass transfer and accumulation of solid and dissolved components of runoff (Glazovskaya, 2000). Eluvial (elevated, geochemically autonomous) areas pass into geochemically subordinate transit positions of slopes, and accumulative landscapes of depressions. It is this conjugation that fit to the concept of catena, according to S.V. Zonne (1964). Soils located in the lower part of the catena (accumulative) are affected by the influx of dissolved materials from higher relief elements (eluvial and transit). Soils of eluvial positions are characterized by the supply of matter and energy only from the atmosphere.

Accumulative processes here are associated only with parent rocks and the atmosphere. The processes of removal of soluble substances, moisture, and fine grained soil prevail over the rest. The soils of transit positions are characterized by the influx of moisture and various products of matter and energy from the overlying positions and the transfer of some of them to the downstream ones. The soils of the accumulative positions are regularly flooded with groundwater, near-surface water and are exposed to the influx of dissolved materials from higher relief elements. They are characterized by an increased accumulation of substances and moisture from all overlying positions, the accumulation of mineral substances from groundwater and near-surface water. From the processes of removal, it is possible to note the leaching of mobile compounds during waterlogging. The accumulative position of the catena is characterized by different redox conditions in the soil profile. The lower soil horizons are constantly moistened, and the moisture inflow into the upper horizons depends on the amount of incoming atmospheric precipitation.
Currently, the concept of catena is widely used to characterize the soil cover and solve various problems (Sommer et al., 2000, Jauss et al., 2015; Guédron et al., 2018; BordenIan et al., 2020).
On the territory of Western Siberia, the idea of a shift of soil formation towards hydromorphism was developed (Karavaeva, 1973; Ufimtseva, 1974; Gerasko, 1975; Dobrovolsky et al., 1981; Gadzhiev, 1982; Pologova, 1992). To study the stages in the development of this process, we will use the catena research method, which helps to transfer the patterns that are valid for spatial series to time series, and vice versa (Pologova, 1992).The purpose of this work is to reveal the features of the geochemical composition of the conjugated series of soils in the northern taiga of Western Siberia and to determine the main regularities of the processes of migration and accumulation of elements in the soils of conjugated geochemical landscapes.

Materials and methods

The study area is located in the Northern taiga subzone, at the central part of the South Nadym-Pur province, in the Pyakupur River basin. The climate of this territory is characterized by a long winter period (more than 200 days a year) with a stable snow cover. The average January temperature is 25 °C, the average July temperature is 16.7 °C, the average annual temperature is -5.3 °C. The work was carried out near the Khanymei research station of the Tomsk State University. Work was conducted with the application of equipment of the large-scale research facilities "System of experimental bases located along the latitudinal gradient" (http://ckp-rf.ru/usu/586718/). The site is characterized by a flat relief, the slopes of the surface change no more than 2.00. The flat topography causes weak surface runoff and wide surface waterlogging of the territory. Previously, on the adjacent territory, the studies of the elemental composition of the solid and liquid phases of palsas peat (Raudina et al., 2017; Lim et al., 2017, 2018) and the trace elemental composition of podzols were carried out(Kritskovetal, 2018).
To characterize the spatial organization of major and trace elements, the method of the transect laying from the top of the dry mane to the center of the depression or to the periphery of the bog massif was used. A series of interconnected soils were studied: Albic-Haplic Podzols, Albic-Stagnic Podzols, Histic-Albic Podzols and Epi-Histic Gleysols. The considered series of soils forms a podzolic-alpha-humus-peat catena, where the geochemical relationships are caused by the movement of soluble substances by moisture flows, and the manifestation of vertical and horizontal geochemical barriers for the transferred elements (Pologova, 1992). The names of the soils are based on the World Reference Base for Soil Resources (World Reference Base, 2006).
A pit Albic-Haplic Podzols (P6) (Figure 1B) was studied in an automorphic habitat (63°48′35.544" N; 75°26'14.466" E), a flat-topped ridge composed of sandy and sandy loam deposits, under a thinned-out lichen pine forest (Figure 1A). Below is a description of the pit.

O 0–2	A thin brownish-dark gray horizon of heterogeneous organic material. The degree of decomposition of organic residues is more than 50%. Dry. Loose. It is not firmly connected with the underlying horizon. The border is wavy. The transition to the underlying horizon is abrupt.
E 2 - 36/50	Whitish. The upper part of the horizon is colored more intensely, a grayish tint is noticeable. Dark gray blotches and small ferruginous nodules are present. Sandy. Structureless. Dry. Loose. The transition to the adjacent horizon is clear in color.
EB 36/50 – 68	Non-uniform color. Whitish spots, rusty ferruginous interlayers, and smears are noticeable against a light brown background. Sandy. Structureless. Moist. Loose. The border is smooth. The transition is sharp in color.
BFepf 68 – 88	Illuvial-ferruginous pseudofiber horizon. Brownish-ocher color with lighter and darker spots. A large number of large brown-rusty interlayers. Sandy. Structureless. Moist. Loose. Compacted. The transition is sharp in color.
B 88 - 100	Ocher-brownish with darker and lighter spots, ocheradhersions. Sandy. Structureless. Moist. Loose. Compacted. Diffuse boundary. The transition is gradual in color.
BC 100 - 145	Whitish with a bluish tinge, and light brown spots, a small amount of rusty ferruginous nodules. The lower part of the horizon is layered - ocher and grayish interlayers. Sandy. Structureless. Moist. Loose. Compacted. The transition to the neighboring horizon is gradual in color. Diffuse boundary.
C 145+	Whitish with a bluish tinge. Sandy. Structureless. Loose. Moist. Compacted.

The leading soil-forming processes in Albic-Haplic Podzols are the podzolization and short-term gleying on the seasonal permafrost confining bed. The products of the destruction of the mineral phase, as well as iron leached from plant litter, are deposited in the ferruginous illuvial horizon. With an increase in surface runoff, as well as approaching the surface of soil and groundwater, signs of seasonal hydromorphism intensify, as can be seen from the example of a pit 10 Albic-Stagnic Podzols (Figure 1C), which was laid on the slope of a mane under a young low-bonded thinned-out pine forest with shrub-green moss-lichen (63°48'1.8" N; 75°28'3.864" E).

Pit 10 is described below:

O 0 - 5	Fragmented thin fulvous-brown layer of heterogeneous organic material. The degree of decomposition of organic residues does not exceed 50%. The layerholds rounded and non-rounded mineral particles up to 0.5 mm in diameter and isintertwined with plant roots. Loose. Loose. It is not firmly connected with the underlying horizon. The border is wavy. The transition to the adjacent horizon is sharp in color and structure of the material.
E 5 - 30	Whitish color with brownish, light ocher and grayish spots. The upper part of the horizon is colored more intensely, a

	grayish tinge is noticeable. Sandy. Structureless. Loose. Loose. Contains roots. The border is wavy. The transition to the adjacent horizon is sharp in color.
EB 30 - 52	Ocher-brownish color. In the upper part of the horizon there are light gray and ocher interlayers. In the lower part of the horizon there are light brown morphones with a whitish shade. Sandy. Structureless. Loose. Loose. The border is wavy. The transition to the neighboring horizon is gradual in color.
BFe 52 - 65	Illuvial-ferruginous horizon. Brownish-ocher color with lighter and darker spots. A large number of large rusty cemented interlayers. In the upper part of the horizon, there are elongated bluish morphons, up to 5 cm thick. Sandy. Structureless. Loose. Compacted. Moist. Diffuse boundary. The transition is gradual in color.
BFeg 65 - 104	Orcher bluish. There arefragmented and thin ferruginous films on sandy grains. Sandy. Structureless. Wet. Compacted. Diffuse boundary. The transition is gradual in color.
Cg 104+	Whitish with a bluish tinge. There are dark gray and white grains of coarse sand on a pale background. There are very thin, fragmented ferruginous films. Sandy loam. Structureless. Moist. Compacted. Water from 104 cm.

A B C

Figure 1. Vegetation and soils of the automorphic habitat. A - thinned-out lichen pine forest, B - Albic-Haplic Podzols (P6) , C – Albic-Stagnic Podzols (P10).

Below the ridge, composed of sandy deposits, is the edge of a raised pine-dwarf bog (63°48'1.716 "N; 75°28'4.794" E), on the edge of which Histic-Albic Podzols lies, which can be considered using the example of the pit 7 (Figures 2A and 2B). The groundwater level here is kept within a meter depth for most of the year. The endpoint of the considered catena with mineral soils is the boggy margin of the frozen peat massif, on which the pit 8 Epi-Histic Gleysols (Dystric) was laid. The vegetation is represented by a sphagnum-shrub phytocenosis with detached pines and pine undergrowth.

Pit 7 is described below:

O 0 - 10	Fulvous fuscum-peat.
TO1 10 – 23	Fulvous, poorly decomposed (0-5%) fuscum -peat, moistish, loose, contains a small amount of mineral rounded whitish and dull particles, the size of most is less than 0.2 mm, only a few specimens reach a size of 0.5 mm. Moist.
TO2 23 - 35	Fulvous nemoreum-peat with a low degree of decomposition (10%), moistish, compared to the previous horizon, the number of mineral particles with a rounded and non-rounded surface has significantly increased, the particle size mainly falls within the range from 0.1 to 0.6 mm. Wet.
E 35 - 60	Heterogeneous, there are ocher-reddish grains (ferruginous films) and dark grains of biotite on a whitish background. Structureless, Loose. The size of mineral particles varies within wide limits;mostly is within 0.4 mm, single particles can reach 1.2 mm. Among the washed quartz grains, there are brownish and ocher particles covered with ferruginous films.
[TH] 60 - 75	Buried intermittent morphon. Heterogeneous, brownish-gray with a whitish silica powder, smearing. Moist.
BFe 60/75 - 95	Heterogeneous, white washed quartz grains on a pale-ocher background, and grayish-brown films on the aggregated mass, in the horizon there is a tendency to the structuring of the mineral mass. The soil mass contains many microaggregates and mineral particles covered with ferruginous films, the size of which varies from 0.1 to 1 mm. Wet.
G 95+	Heterogeneous, grayish-brown films on a dove-coloured background. Structureless. Sand. Wet. Waterlogged.

Pit 8 is described below:

O0 – 8	Light fulvous sphagnum peat, on the surface of the sphagnum with an increase, there is a small amount of

	mineral, not rounded, transparent particles of sandy dimension. Moist.
TO 8 -18	Brownish with pale yellow, poorly decomposed (15%) balticum-peat, containing many mineral particles, the average size of is 0.2-0.3 mm. Along with the rounded washed particles, there are yellowish-ocher particles covered with iron films.
Bg [TO] 18 - 32	Dove-coloured, sandy, includes brown morphones, which consist of the material of the overlying oligotrophic peat horizon. Mineral particles have an average size of 0.2-0.3 mm. Along with the rounded washed particles, there are yellowish-ocher particles covered with iron films. Wet. Diffuse boundary.
BG 32 – 100	Heterogeneous, grayish with pale yellow and with pale yellow sand. Structureless. Wet. Diffuse boundary. Compacted.
G 100+	Heterogeneous, grayish-brown films on a dove-coloured background. Structureless. Sand. Waterlogged. Water from 104 cm.

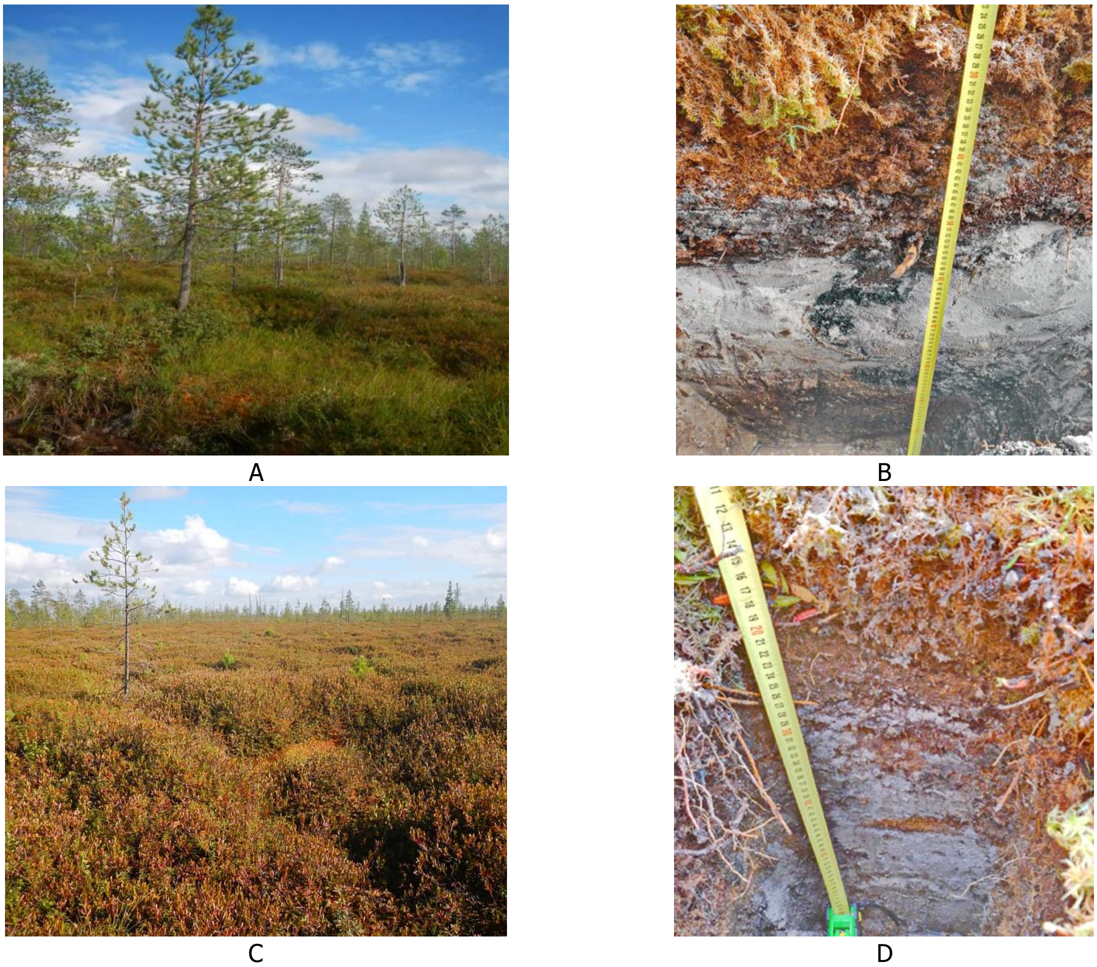

Figure 2. Phytocenoses and soils of hydromorphic habitats. A – pine-shrub-sphagnum swamp; B – Histic-Albic Podzols. Pit 7. C – sphagnum-shrub phytocenosis; D – Epi-Histic Gleysols (Dystric). Pit 8.

Earlier, the micromorphological properties of such soils in the study area were described by Kritskov et al. (2018). Sampling was carried out using standard methods. The elemental composition of soils was determined at the Tomsk Regional Center for Collective Use at Tomsk State University by the ICP-MS method using an Agilent 7500cx.

This article deals with the distribution of elements only in the mineral horizons of the studied soils. The degree of profile differentiation of chemical elements was assessed using the illuviation coefficient Ki = CB/CE, where CB and CE are the content of the element in the illuvial and eluvial horizons (Vodyanitskiy et al., 2011) and the coefficient of radial differentiation, where Kr = Ci/Cip, where Ci is the content of a chemical element in a particular genetic soil horizon, and Cip is the content in the parent rock. We also calculated the coefficient of lateral migration (Kl) - the ratio of the content of a chemical element in the studied subordinate landscape (Cp.) to its content in the autonomous landscape, Cp./Cl (Glazovskaya, 2002; Perelman, Kasimov, 1999).

Results and discussion

We revealed that the accumulation series in different studied landscape elements are close to each other, but not identical (Table 1). For example, at the border of a forest and a swamp (P7), the following elements are accumulated: Fe, Mg, V, Zn, Pb, Cu, Nd, Ga, Y, Th, Sc, Sn, U, Cd, Cs, Sb, Be, Ho, Tl, Ge, Bi, Te, Cd, and Au and all lanthanides (La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu).

For other elements, the maximum content was noted in the soils of automorphic landscapes of the transit position of the catena (P10): Ti, Ba, Zr, Cr, W, Li, Nb, Hf, and Ta. The maximum content of such elements as Ba, Mn, Sr, Rb, Ni, Co, Ag, Mo, and Pd was found in the eluvial position (P6). The value of the lateral migration coefficient decreases in the range: W>Cd>Bi>Th>V>U>Te>Fe>Sc>Mg>Ga>Sm>Sn>Pb>Gd>Tb>Ho>Cr>Tm>Dy>Nd>Er>Cu>Lu>Y>Ce>Pr>La>Yb>Eu>Hf>Be>Zr>Tl>Ta>Nb. The mineral horizons of the Epi-Histic Gleysols (Dystric) (P8), located in a depression at the edge of the bog, are depleted in elements compared to soils located higher in the relief. Probably, the geochemical barrier formed at the border of the forest and the swamp is a reason. A similar distribution of elements in soil catenas was noted earlier in the soils of the southern taiga zone of Western Siberia (Pologova, 1992) and in the soils of the middle taiga subzone of Karelia (Akhmetova, 2018).

Table 1. Series of accumulation of major and trace elements in the mineral horizons of the sections.

> 10 ppm				10-1 ppm				< 1 ppm			
P6	**P10**	**P7**	**P8**	**P6**	**P10**	**P7**	**P8**	**P6**	**P10**	**P7**	**P8**
Fe	Fe	Fe	Fe	Zn	W	Zn	Zn	Hf	Sn	Sm	Ga
Ti	Ti	Ti	Ti	Ce	Zn	Ce	Rb	Th	Sc	Co	Th
Mg	Mg	Mg	Mg	V	V	Pb	V	Co	Pr	U	Sc
Ba	Ba	Ba	Ba	Li	Ce	Cu	Ce	Sn	Co	Gd	Sn
Mn	Zr	Zr	Zr	Pb	Li	Li	Pb	Pr	Sm	Cs	Pr
Zr	Mn	Mn	Mn	Cu	Pb	La	Li	Sc	Gd	Dy	Co
Sr	Sr	Sr	Sr	La	La	Nd	Cu	Ag	Dy	Sb	Ag
Cr	Cr	Cr	Cr	Nd	Cu	Nb	La	Sm	U	Yb	Sm
Rb	Rb	V		Ni	Nb	Ga	Nb	Gd	Cs	Er	U
		Rb		Nb	Nd	Y	Nd	Dy	Sb	Ta	Sb
				Y	Y	Th	Ni	Sb	Yb	Be	Gd
				Ga	Hf	Ni	Y	Cs	Er	Ag	Dy
					Ni	Hf	Hf	U	Ta	Eu	W
					Ga	W		W	Be	Pd	Yb
					Th	Sc		Mo	Ag	Ho	Cs
						Sn		Yb	Mo	Tl	Ta
						Pr		Er	Pd	Tb	Er
								Ta	Eu	Ge	Mo
								Be	Ho	Lu	Be
								Pd	Tl	Tm	Pd
								Eu	Tb	Bi	Eu
								Tl	Lu	Mo	Ho
								Ho	Tm	Te	Tl
								Tb	Ge	Pt	Tb
								Lu	Bi	Cd	Ge
								Ge	Pt		Lu
								Tm	Cd		Tm
								Bi	Te		Bi
								Pt	Sn		Cd
								Te			Pt
								Cd			Te

P6 - Albic-Haplic Podzols, P10 – Albic-Stagnic Podzols; P7 – Histic-Albic Podzols; P8 - Epi-Histic Gleysols (Dystric). Ecotoxicologically hazardous elements are highlighted in red (Crommentuijn et al., 1997; Vodyanitsky, 2012).

The profile differentiation of the studied soils in the catena also changes, and the distribution of elements is heterogenouson the elementary landscapes of the catena (Figure 3). For example, the iron content (Figure 3A) reaches a maximum in the illuvial horizons of Albic-Haplic Podzols, Albic-Stagnic Podzols, Histic-Albic Podzols. In these soils, we noted a clear differentiation of the profile according to the eluvial-illuvial type. Kr for BFg horizons are high (from 1, 3 in Albic-Haplic Podzols to 3 in Histic-Albic Podzols), Ki also reaches the highest values in Histic-Albic Podzols (16.3).

In Epi-Histic Gleysols (Dystric), eluvial-illuvial differentiation is low (Ki - 1.8, Kr for the BG horizon - 0.9), the amount of iron gradually increases from the upper horizons to the lower ones. The manganese content is more evenly distributedover soil profiles (Figure 3B). We registered the highest content of this element in the illuvial horizons of automorphic landscapes, however, Ki is the highest in Histic-Albic Podzols (5, 1). In general, the minimal content of manganese was noted in the soils of hydromorphic landscapes (Histic-Albic Podzols and Histic-Albic Podzols). It is known that, having a low ionic potential, the manganese is easily leached from the soil under anaerobic conditions (Pologova, 1992).

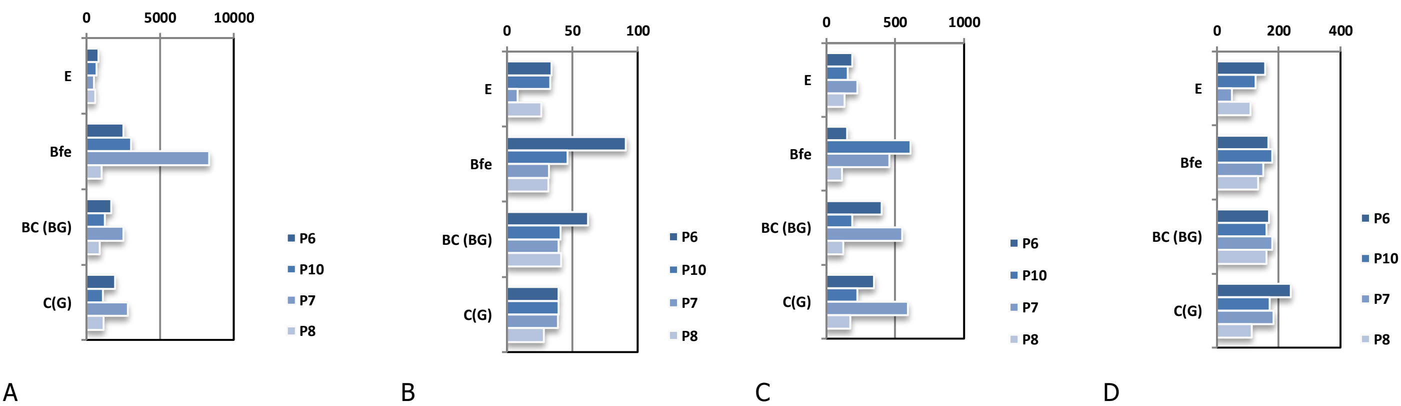

Figure 3. Distribution of iron, magnesium, manganese and titanium in the gradient of environmental conditions. A - Fe, B - Mg, C - Mn, D – Ba. Horizontal - content of elements (ppm), vertical - sampling depth (cm), P6 - Albic-Haplic Podzols, P 10 - Albic-Stagnic Podzols; P7 –Histic-Albic Podzols; P8 - Epi-Histic Gleysols (Dystric).

The magnesium content only in the BfeAlbic-Stagnic Podzols horizon and in the BC Albic-Haplic Podzols horizon is higher than in the parent rocks (Kr 2.7 and 1.2, respectively). The content of this element is slightly differentiated according to the eluvial-illuvialtype in the soils of autonomous landscapes and gradually increases from the upper horizons to the rock in the soils of hydromorphic landscapes (Figure 3C). The concentration of barium in Albic-Haplic Podzols, Albic-Stagnic Podzols, Histic-Albic Podzols is maximum in the parent rocks. Barium is accumulatedin Epi-Histic Gleysols (Dystric) in the overlying horizons (Figure 3D).

A number of elements (Figure 4) in all positions of the catena are distributed according to the eluvial-illuvial type (Ki from 1.02 to 19.7), this differentiation of the profile is especially pronounced at the border of the forest and swamp, where the maximum accumulation of these elements is revealed (P 7). In addition, the same distribution along the Histic-Albic Podzols profile is characteristic of Ti, Sr, Au, Li, Sc, Cr, Cu, Y, Zr, Nb, Sn, Sb, La, Sm, Gd, Tb, Dy, But, Er, Tm, Yb, Lu, Hf, Ta, Th, and U. This position of the catena, the zone of contact of subsurface and slope waters with bog waters, may be the center of modern soil transformation caused by the development of the swamping process and reflected in ferruginization of the soil mass (Pologova, 1992).

Elements such as Ba, Te, Cd, Co, Ni, and Zn accrue in the illuvial horizon of the automorphicAlbic-Stagnic Podzols (P10) most intensively. In Albic-Haplic Podzols (P6), no eluvial-illuvial type of migration was revealed for a number of elements.

The distribution of the coefficient of radial differentiation in different elementary landscapes of the catena is also indicative (Figures 5 and 6).

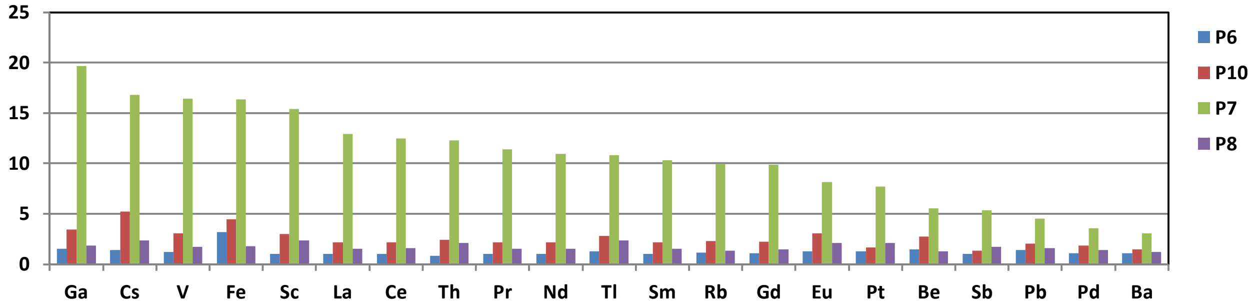

Figure 4. Illuviation coefficient (Ki) for different elementary landscapes of the catena.

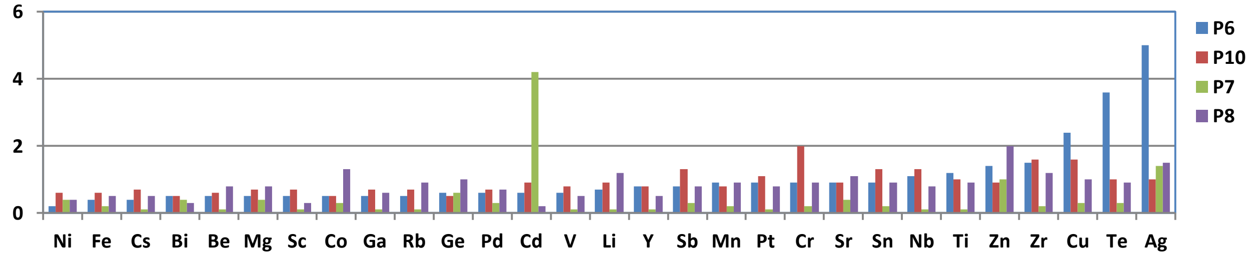

Figure 5. Coefficient of radial differentiation (Kr) for different elementary landscapes of the catena (horisons E).

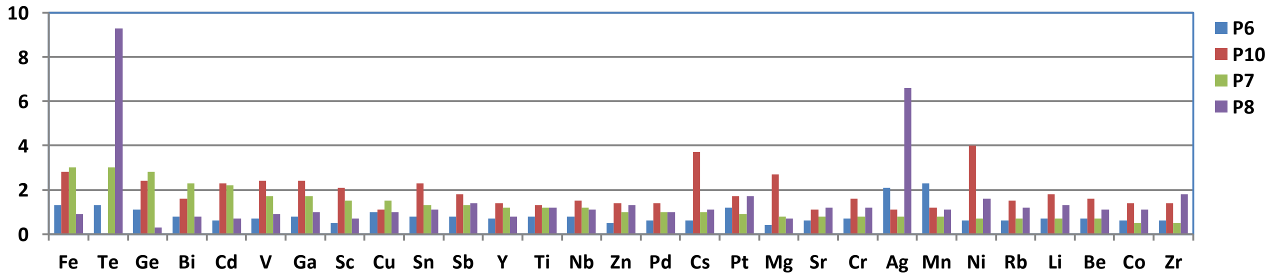

Figure 6. Coefficient of radial differentiation (Kr) for different elementary landscapes of the catena (horisons BFe).

In most cases, the coefficient reflecting the ratio of the content of elements in the BFe horizon to the rock, is higher in Albic-Stagnic Podzols (P10) than in other elementary landscapes of the catena. For Histic-Albic Podzols (P7), the maximum removal of elements from the eluvial part of the profile was noted. We registered that the elements such as Ag, Te, Ti, Zn, Zr, Nb, Sn, and Sb are accumulated in the eluvial part of soil profiles.

Conclusion

Thus, we revealed the differences in the content of major and trace elements in the catenary gradient of environmental conditions. We determined, that the series of accumulation of major and trace elements in different positions of the catena are close to each other, but not identical. We also estimated that the distribution of most elements along the soil profile occurs according to the eluvial-illuvial type, but the position in the relief determines the degree of element migrations. We identified a powerful geochemical barrier at the forest-bog border, in the zone of contact of subsurface and slope waters with bog waters, which accumulates the substances from lateral and horizontal runoff. We also notedhere the most intense differentiation of elements along the soil profile.

Acknowledgments

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