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Geoenvironmetal assessment of different types of cryolithic soils in Western Yakutia under the conditions of diamond-mining operations

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Abstract
The problems of geoenvironmental consequences of mining operations are especially acute in the arctic and subarctic regions, where the spread of permafrost significantly reduces the buffering capacity of landscapes. The article presents data on the content of heavy metals in the soil cover of the transient zone between the middle taiga and north taiga landscapes of Western Yakutia under the conditions of mining operations and assesses the resistance of different types of soils to heavy metals pollution. Field and laboratory works were carried out in August 2022. The heavy metals content was determined by atomic absorption spectrometry. Specialized software was used for analysis, such as MS Excel 2013, Statistica 12.0, and QGis 3.26.1. Calculation of organic forms of heavy metals in soil solutions was performed using the NICA-Donnan model. In the course of studies, the structure of the soil cover in the Nakyn kimberlite field in the conditions of the mining industrial complex operation was determined and a sketch map of the soil cover of the territory was compiled. The geochemical series of the studied heavy metals is as follows according to the degree of concentration of heavy metals in cryolithic soils: Pb > Zn > Ni > Cu > Cd > As > Hg. Positive correlations between humus and Cd, Pb, Zn, as well as the occurrence of synergism in the Pb–Cd, Zn–Pb, Zn–Cu pairs were revealed. The soils organic matter enhances migration of heavy metals. The man-made input of Ni and Zn in cryolithic soils will lead to increase of mobile fraction. Cd is more mobile in pale-yellow carbonate and cryogenic soils. The regional background level of heavy metals for these types of soils was calculated, which can be used in future works when the intensity of mining operations increases.

Keywords
heavy metals, soil pollution, taiga-frozen soils, cryogenic soils, diamond mining, Nyurba kimberlite field, arsenic (As), cadmium (Cd), mercury (Hg), lead (Pb), copper (Cu), nickel (Ni), zinc (Zn), Western Yakutia, speciation, geochemistry, thermodynamic modeling, NICA-Donnan.

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ТЕХНОЛОГИЧЕСКАЯ БЕЗОПАСНОСТЬ В МИНЕРАЛЬНО-СЫРЬЕВОМ КОМПЛЕКСЕ И ОХРАНА ОКРУЖАЮЩЕЙ СРЕДЫ

Научная статья

Геоэкологическая оценка разных типов почв криолитозоны Западной Якутии в условиях функционирования алмазодобывающих предприятий

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Аннотация
Проблемы геоэкологических последствий горнодобывающих предприятий стоят особенно остро в арктических и приарктических районах, где распространение вечной мерзлоты значительно сокращает буферные способности ландшафтов. В статье представлены данные о содержании тяжелых

металлов в почвенном покрове переходной зоны от среднетаежных к северотаежным ландшафтам Западной Якутии в условиях функционирования горнодобывающего производства и предложены подходы к оценке устойчивости разных типов почв к загрязнению тяжелыми металлами. Полевые и лабораторные работы проведены в августе 2022 г. Определение содержания тяжелых металлов проводилось методом атомно-абсорбционной спектрометрии. Для анализа использовалось специализированное программное обеспечение – MS Excel 2013, Statistica 12.0, QGis 3.26.1. Расчет органических форм нахождения тяжелых металлов в почвенных растворах выполнен с помощью модели NICA-Donnan. В ходе исследования определена структура почвенного покрова Накынского кимберлитового поля в условиях функционирования горнопромышленного комплекса и составлена карта-схема почвенного покрова территории. Геохимический ряд изученных тяжелых металлов по степени концентрирования тяжелых металлов в почвах криолитозоны: Pb > Zn > Ni > Cu > Cd > As > Hg. Выявлены положительные зависимости между гумусом и Cd, Pb, Zn, а также проявление синергизма в парах Pb–Cd, Zn–Pb, Zn–Cu. Органическое вещество почв усиливает миграцию тяжелых металлов. Техногенное поступление в почвы криолитозоны Ni и Zn приведет к росту доли их подвижных форм. В палево-карбонатных и криоземах в большей степени подвижен Cd. Рассчитан региональный фоновый уровень тяжелых металлов для данных типов почв, который может быть использован в будущих работах при увеличении интенсивности горнодобывающих работ.

Ключевые слова
тяжелые металлы, загрязнение почв, таежно-мерзлотные почвы, криозёмы, алмазодобыча, нюрбинское кимберлитовое поле, мышьяк (As), кадмий (Cd), ртуть (Hg), свинец (Pb), медь (Cu), никель (Ni), цинк (Zn), Западная Якутия, формы миграции, геохимия, термодинамическое моделирование, NICA-Donnan

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Introduction

Large industrial complexes influence the change in physical and chemical parameters of cryolithic soils [1], affect the functioning of the soil cover directly and determine the intensity of its man-made pollution [2]. Man-made pollution of soils spreads along the prevailing wind direction over considerable distances by atmospheric transfer of pollutants formed during the operation of heavy machinery [3] and dusting processes [4]. The territories of the permanent allotment are almost completely transformed [5], natural landscapes are converted into man-made ones, and beyond its boundaries local areas characterized by the increased content of chemical elements may be formed [6].

The location of large industrial complexes in subarctic regions, where the soil profile is thin, the drainage of the territory is poor, and permafrost rocks are widespread, requires a deeper study of the geoenvironmental consequences of mineral extraction [7], as they have a negative impact on the ability of soils to self-restore. This is also noted by a number of authors [8].

The above factors make it necessary to study heavy metals in the soil cover of the cryolithic zone near operating industrial complexes to form a database for complex geoenvironmental research and monitoring [9]. The relevance of the study of the natural environment geochemical features in the Far East of the Russian Federation, also in the conditions of active cryogenic processes, is emphasized by the availability of recent studies in such regions [10].

The research was conducted in the Nyurba District of the Republic of Sakha (Yakutia) within the Nakyn kimberlite field (NKF) [11] (Fig. 1). The purpose of the study was to analyze the features and distribution patterns of the gross content along with the assessment of migration features associated with the organic matter of heavy metals (HM) in cryolithic soils under the conditions of diamond mining operations.

To achieve this goal the following tasks were set and solved: to conduct field geoenvironmental studies in the territory under consideration and soil sampling, to determine the main chemical indicators and the actual content of HM in soils, to determine the main distribution patterns of HM depending on chemical indicators and the soil type, to establish the forms of occurrence of HM in water extracts, and to calculate the background values of the gross content of Cd, Hg, Ni, Cu, Zn, Pb, and As for further studies.

The NKF is located within the Siberian platform composed of metamorphic rocks of the Archean age, overlain by a thick sedimentary cover of the V–J age. In terms of the regional tectonic structure, the NKF is located at the junction of the Nepsko-Botuobinsky anteclise, the Syugdzhersky saddle and the Vilyui syneclise. The relief of the territory is denudational. It is represented by a slightly sloping plain, which is structurally confined to the macroslope of the Markha-Khannya-Nakyn interfluve. The absolute elevations are 220–248 m.

The climate of the area is extreme continental. The northwestern wind direction prevails (27%), although calms dominate (36%). The territory is dissected by a ravine and gully network. The main water artery is the Dyakhtar-Yuryage River (a tributary of the Markha River). The soil cover belongs to the group of taiga-frost soils. According to geobotanical zoning the territory belongs to the boreal vegetation kingdom of the Central Siberian province with the predominance of Larix Gmelinii (Rupr.) [11].

Objects and methods of research

Field work was carried out in 2022 on the territory of transitional landscapes of the Markha-Khannya-Nakyn interfluve (Fig. 2). A part of the research was carried out within the sanitary protection zone (SPZ) of the mining complex, and a part outside the SPZ, in the ratio of 40/60. To determine the content of heavy metals in the soil cover of the adjoining territory, test sites with the soil structure survey points were allocated. Soil by-pits were arranged throughout the territory, and soil sections were studied at the sites with different biotopes to the depth of permafrost occurrence. The test sites were arranged, considering the wind rose: a half of the test sites was arranged on the leeward side, and the other half on the windward side. The main sources of possible soil cover pollution at this location are the site of immediate field development and its infrastructure.

Sampling and sample transportation were carried out in accordance with the methods generally accepted in the geoenvironmental studies[1]. A total of 54 samples were collected at 27 sampling locations in the surveyed area.

The gross content of the following heavy metals was determined in the collected samples: Cd, Hg, Ni, Cu, Zn, Pb, and As by atomic absorption spectrometry using the Kvant-Z spectrometer. The physical and chemical parameters were determined by potentiometric method (pH), the content of organic matter was determined by colorimetry according to I. B. Tyurin, the particle-size distribution was defined in field conditions according to Kachinsky, and laboratory studies were performed by sieve analysis. The quantitative data obtained were processed using the Microsoft Excel 2013, Statistica 12.0 software, and cartographic material was compiled using the Quantum GIS 3.26.1 software.

[1] All-Union instruction on soil surveys and compilation of large-scale soil maps of land use, GOST 17.4.4.02 "Nature protection. Soils. Methods for sampling and preparation of soil for chemical, bacteriological, helmintological analysis».

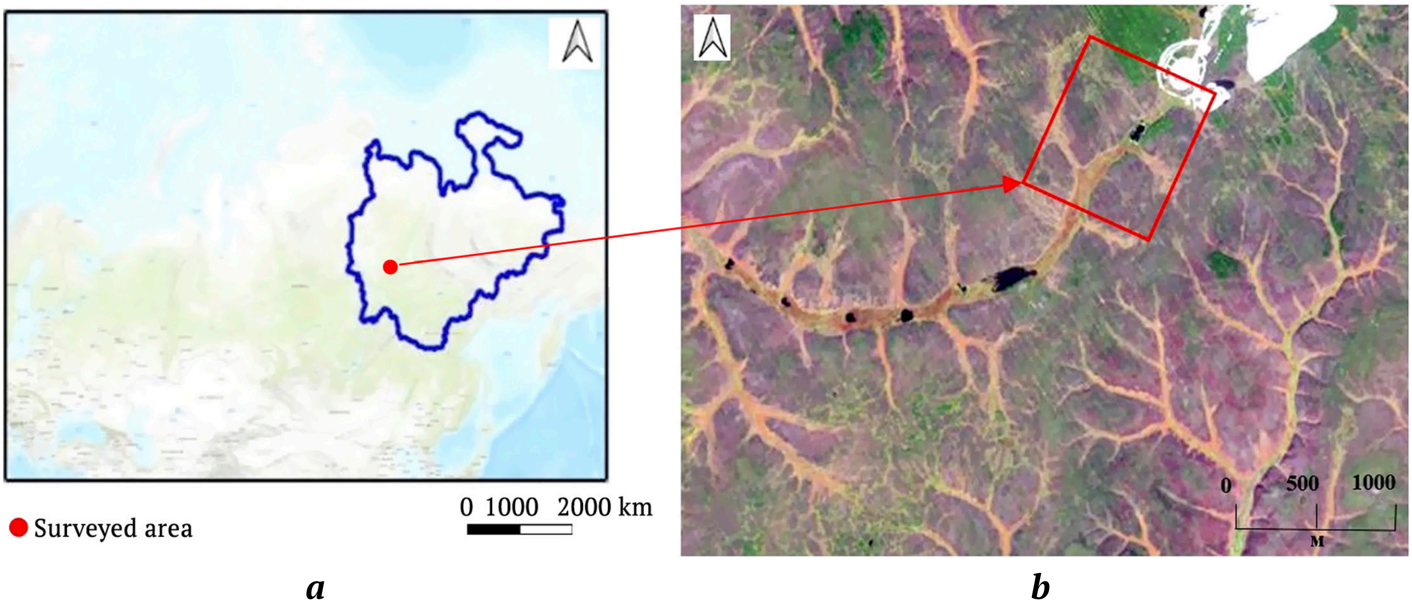

Fig. 1. Sketch map of the studied area:
a – relative to the Russian Federation; *b* – satellite image of the surveyed area in R–G–B

The standard calculation of the total pollution indicator – Z_c [12] was used for integral assessment:

$$Z_c = \sum (K_{c_i} + \ldots + K_{c_n}) - (n-1),$$

where K_{c_i} is the coefficient of concentration of the i-th component; n is the number of the summed K_c,

$$K_c = \frac{C_i}{C_b},$$

where C_i is the actual content of the element; C_b is the background content of the element.

The ranking has been adopted conditionally in accordance with the current RD: 16 – permissible; 16–32 – moderately dangerous; 32–128 – dangerous; ⩾ 128 – extremely dangerous [12].

The migration patterns of elements in the water-soluble fraction (1 : 10) of soils were calculated using the Minteq 3.1 complex, taking into account pH, the main anions and cations, and the dissolved organic carbon concentrations according to the NICA-Donnan model with the fulvic acids to humic acids ratio of 1 : 8.

To assess the environmental state of soils it is customary to use the reference (background) content of various elements in them, but to date, extensive background studies for the gross content of HM for this area or in similar conditions have not been conducted. A comparison is proposed based on our own background studies, $n = 5$.

Results and discussion

Cryogenic soils, pale-yellow carbonate soils and peat-bog soils are common within the surveyed area (Fig. 3).

High-frost homogeneous cryogenic soils (Fig. 4, *a*) are up to 42 cm thick, structureless, running. The particle-size distribution is close to light loams, and the permafrost surface is undulate. The upper levels are weakly acidic, neutralized with depth, and the soil acidity is in direct correlation with organic matter, which is typical for such soils [13].

Fig. 2. Soil cover research:
a – preparation for test pit drivage; *b* – test pit drivage

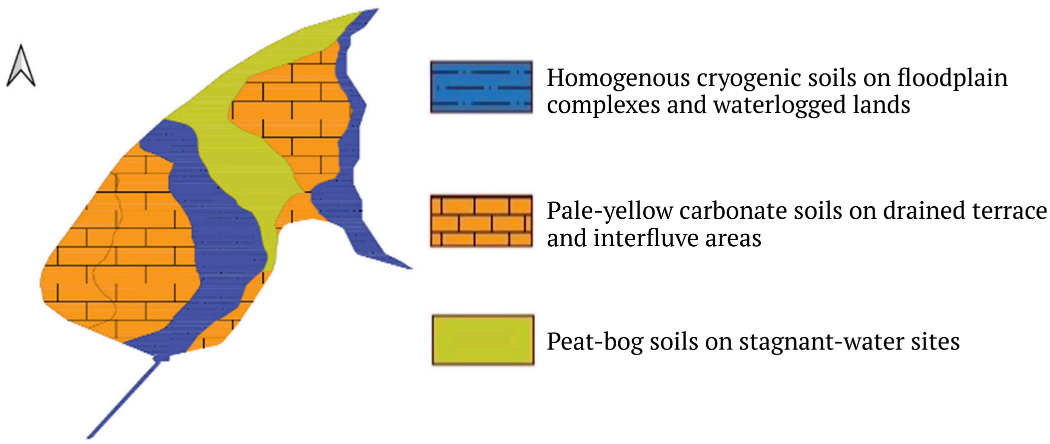

Fig. 3. Schematic map of soil conditions of the surveyed area (1 : 5000)

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Peat-bog soils (Fig. 4, *b*) have been formed within oligotrophic bogs and in areas of local depressions. These soils are developed to a depth of 40 cm, and the lower level is waterlogged.

Pale-yellow carbonate soils (Fig. 4, *c*) are dominant in the surveyed area and occupy up to 69% of the territory. This type of soil has a greater profile thickness – up to 64 cm, has been formed on sandy-light loamy substrate in the old bed of the Dyakhtar Yuryage River, and the permafrost layer is under alluvial sediments.

Cryogenic soils occupy mainly slightly sloping areas of the Dyakhtar-Nakyn interfluve and are formed on cryogenic landforms (Fig. 5, *a* – boolgunyakhs, weakly polygonal relief). The subtype is homogeneous thin high-frost cryogenic soils. They are diagnosed mainly by cryoturbation traces within the profile [14].

Peat-bog soils (Fig. 5, *b*) are confined to the Dyakhtar-Yuryage River valley (Fig. 5, *b*). The studies showed that soil groupings have a relatively homogeneous structure and thickness. The vegetation cover is homogeneous, with *Larix Gmelinii* as the dominant species in the stand, and the *Betula Alba* (Roth.) birch as an admixture; the state of the stand in interfluvial and terrace complexes is suppressed, with dechromation and, less often, defoliation observed; in floodplain complexes it is satisfactory [15].

Pale-yellow carbonate soils (Fig. 5, *c*). They are formed both on solid masses of *Larix Gmelinii* and on forest edges covered mainly with shrubby species – cowberry *Vaccinium vitis-idaea* (L.) Avror., blueberry *Vaccinium uliginosum* (L.), waterberry *Empetrun nigrum* (L.), on extensive thickets of cladonia *Cladonia stellaris* (Opiz.) Pouzar&Vezda and *Cladonia rangiferina* (L.) Weber&Wigg (Fig. 5, *c*).

a ***b*** ***c***

Fig. 4. Characteristic structure of the soil profile:
a – studied cryogenic soils; *b* – peat-bog soils; *c* – pale-yellow carbonate soils

a ***b*** ***c***

Fig. 5. Overview of the sites:
a – intersected cryogenic soils; *b* – peat-bog soils; *c* – pale-yellow carbonate soils

The studied cryogenic soils are characterized by a generally low humus content in the upper level (0.73±0.05% on average) with an abrupt characteristic increase in the lower layer due to cryoturbation (V = 12/56%) (Table 1). The clay fraction is relatively homogeneous in the range of 24.0–29.1%, which corresponds to heavy sandy-light loamy soils. The reaction of the medium in the studied levels varies from slightly acidic to slightly alkaline, and there is no characteristic distribution in the levels due to cryoturbation.

The humus content in the upper levels of pale-yellow carbonate soils is generally uniform, and in the underlying level the humus content decreases abruptly. The clay fraction varies from 16.8 to 39.1% in the upper level and 20–31% in the lower level, which corresponds to light loams with insignificant sandy loam interlayers. The reaction of the medium is typical for pale-yellow carbonate soils – it varies from acidic to alkaline with depth throughout the profile.

In peat-bog soils the total humus content decreases noticeably, and the medium changes from neutral to slightly acidic-acidic with depth. The content of physical clay is from 9 to 29%, which corresponds to sandy and light loamy soils.

The highest humus content is observed in the peripheral parts of the surveyed area in close proximity to the transport and industrial infrastructure facilities on the windward side. With a relative homogeneity of soil and vegetation conditions, the differences in the

Table 1

Results of chemical studies of collected soils

Indicator	Level	Depth, cm	Variation range	Mean and error $x \pm S_x$	Coefficient of variation V, %
Homogeneous high-frost cryogenic soils					
Humus, %	T	7...24	0.60...0.83	0.73±0.05	12
	Cr	24...43	0.42...2.44	1.29±0.36	56
pH (aqueous)	T	7...24	6.8...7.1	7.00±0.06	2
	Cr	24...43	6.1....7.6	6.93±0.27	8
pH (salt)	T	7...24	3.9...4.6	4.25±0.01	7
	Cr	24...43	4.5...6.7	5.13±0.46	18
Physical clay, %	T	7...24	22.3...26.7	24.0±0.9	7
	Cr	24...43	24.0...36.7	29.10±2.62	18
Pale-yellow carbonate soils					
Humus, %	A_{1K}	2...26	0.95...8.53	1.9±0.7	116
	B_K–BC_K	26...53	0.2...3.6	0.8±0.3	119
pH (aqueous)	A_{1K}	2...26	5.1...5.9	5.60±0.09	6
	B_K–BC_K	26...53	6.2...7.1	6.85±0.08	4
pH (salt)	A_{1K}	2...26	4.1...5.9	4.10±0.17	4
	B_K–BC_K	26...53	4.1...4.4	4.25±0.04	12
Physical clay, %	A_{1K}	2...26	16.8...39.1	30.50±2.14	27
	B_K–BC_K	26...53	20.2...40.0	27.05±1.34	22
Peat-bog soils					
Humus, %	O	5–14	0.8...5.8	2.36±0.80	77
	T	14–36	0.1...1.3	0.80±0.22	61
pH (aqueous)	O	5–14	5.6...7.3	6.76±0.30	9
	T	14–36	5.5...6.2	6.00±0.11	4
pH (salt)	O	5–14	4.1...5.5	4.6±0.2	11
	T	14–36	3.6...4.0	3.84±0.06	4
Physical clay, %	O	5–14	21.5...28.3	25.12±1.10	10
	T	14–36	9.0...29.9	22.20±3.14	32

Note. Designations of soil levels are given in accordance with the 2004 soil classification.

humus content can be characterized by an increase in the content of not only humus, but also a non-humic part of organic matter due to the input of the man-made impact [16]. The latter is reflected in the shift of the soil medium towards acidic one and increased migration properties with a natural increase in the concentration of HM in the future [17].

The HM content is relatively homogeneous (Table 2); practically no sharp peaks are observed in the sample, and the increased content is noted for all the studied HM (except for As and Hg). Accumulation occurs in the upper levels for Ni, Cu, less frequently for Cd, and in the lower levels mainly for Cd, Pb, and Zn. Nevertheless, such differences are weakly contrast. An increasing contrast of metal accumulation in soil levels will indicate an increase in the man-made load and landscape transformation.

According to the average values, the HM content is higher in lower levels. Analyzing the nature of HM accumulation, we can say that the upper levels accumulate HM mainly through the mechanism of their sorption by organic components under the conditions of weakly acidic medium and weak drainage – mainly oxygen sorption physical and chemical barriers are formed. The lower levels are characterized by accumulation under the conditions of neutral and weakly alkaline medium, and weak development of gley processes in the soil profile for these depths is noted in the form of bluish spots and leather coatings. Thus, the conclusion about the formation of gley alkaline physical and chemical barriers in above-permafrost levels is fair [14]. The HM content in the upper layer in the descending order can be written in the following form: Pb > Zn > Ni > Cu > Cd > As > Hg.

For the lower layers the record is identical, and only the concentrations of individual elements change. At the same time, the content of Pb, Zn, Cu in peat-bog soils is higher than in pale-yellow soils and cryogenic soils. This is due to the higher humus content in the soil profile and geochemical specifics (Fig. 6).

Considering very homogeneous spatial distribution of HM in the soil surface layer both from the windward and leeward sides, it can be concluded that there is no or hard-to-diagnose (by available methods) mad-made impact as such, the exception being a few test sites sampled in the zone of direct adjoining to the waste dump. Here, maximum concentrations of the studied HM are recorded. However, considering the metallogeny of the area, this may also have a predominantly natural origin, since the ratio of ore elements is preserved. Other authors also come to similar conclusions for cryolithic zone landscapes adjacent to mining areas [3]. The increased content of organic matter in soils in these areas is also noted in comparison with the other samples. No own studies have been conducted on the structure of emissions on the territory of the enterprise.

Table 2

Results of studies of HM in collected soils

Indicator	Level	Variation range	Mean and error $x \pm S_x$	Coefficient of variation *V*, %	Coefficient of variation *n* = 5
pH	Upper	5.2...8.1	7.00±0.14	10	–
	Lower	6.1...8.1	7.09±0.10	7	
Arsenic As	Upper	Less than 0.05			Less than 0.05
	Lower	Less than 0.05			
Cadmium Cd	Upper	0.65...4.00	1.52±0.18	62	1.04
	Lower	0.53...3.80	1.52±0.14	48	
Mercury Hg	Upper	Less than 0.005			Less than 0.005
	Lower	Less than 0.005			
Lead Pb	Upper	31...120	56±4	33	50
	Lower	39...155	58±5	43	
Copper Cu	Upper	3.22...21.90	6.80±0.87	68	9
	Lower	2.8...28.9	7.77±1.40	93	
Nickel Ni	Upper	16.9...28.6	22.9±0.5	12	21
	Lower	19.2...37.0	24.00±0.74	16	
Zinc Zn	Upper	18.6...51.0	35.6±2.1	31	34
	Lower	18.6...52.0	36.6±2.0	28	

Analysis of state reports of the Republic of Yakutia showed that the structure of emissions is dominated by gases, 50–65% of which is carbon monoxide.

The correlation analysis shows that there is a correlation between HM concentrations at the significance level of < 0.05 and humus (Fig. 7). Positive correlations are observed between humus and Cd, Pb, and Zn. Synergism among the studied HM is reflected in the following pairs: Pb-Cd, Zn-Pb, and Zn-Cu.

The values of concentration coefficients of the HM content in the soil cover, exceeding the background, are observed for Cd, Pb, Ni, Zn throughout the sample, and for Cu the background is exceeded in 87 % of cases, more often in the upper levels. The basis of the structure of concentration coefficients is cadmium, and lead and nickel to a lesser extent. The values of the total pollution indicator vary from 2 to 10 (see Fig. 3), the average value being 6.

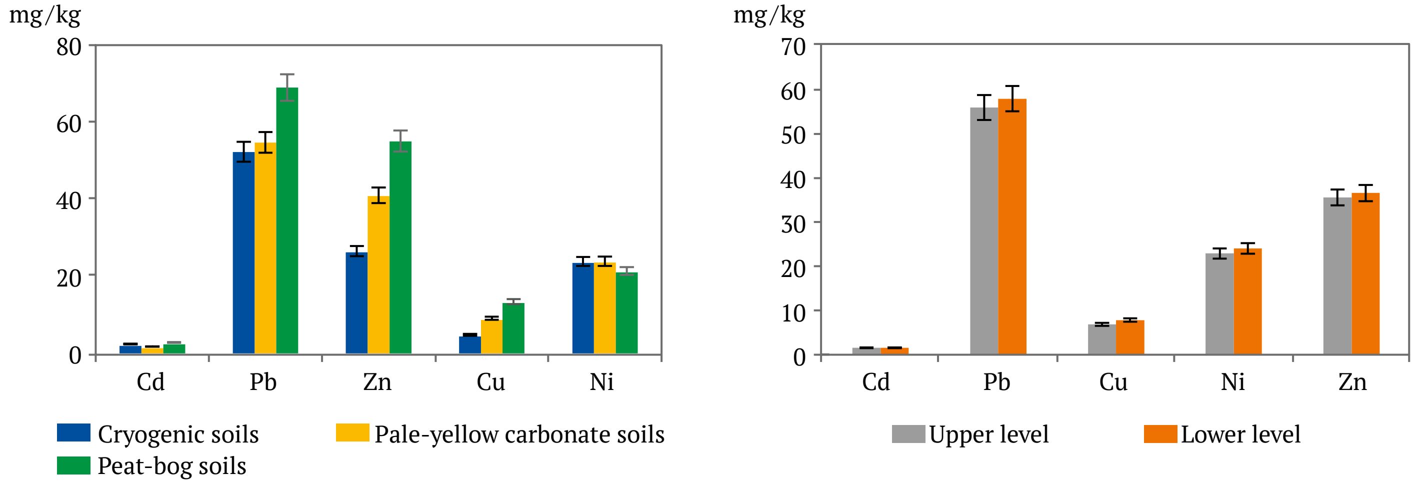

Fig. 6. Distribution of the heavy metals content in soils depending on the soil type (left) and soil level (right)

Indicator	Humus, %	pH	Cd	Pb	Zn	Cu	Ni
Humus, %		−0.40	0.45	0.31	0.32	−0.06	0.06
pH	−0.40		−0.03	−0.05	−0.12	−0.05	−0.15
Cd	0.45	−0.03		0.52	−0.28	−0.43	−0.12
Pb	0.31	−0.05	0.52		0.34	−0.22	0.10
Xn	0.32	−0.12	−0.28	0.34		0.30	−0.07
Cu	−0.06	−0.05	−0.43	−0.22	0.30		0.06
Ni	0.06	−0.15	−0.12	0.10	−0.07	0.06	

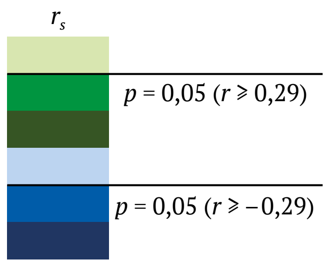

Fig. 7. Spearman's rank correlation coefficients between humus and heavy metals

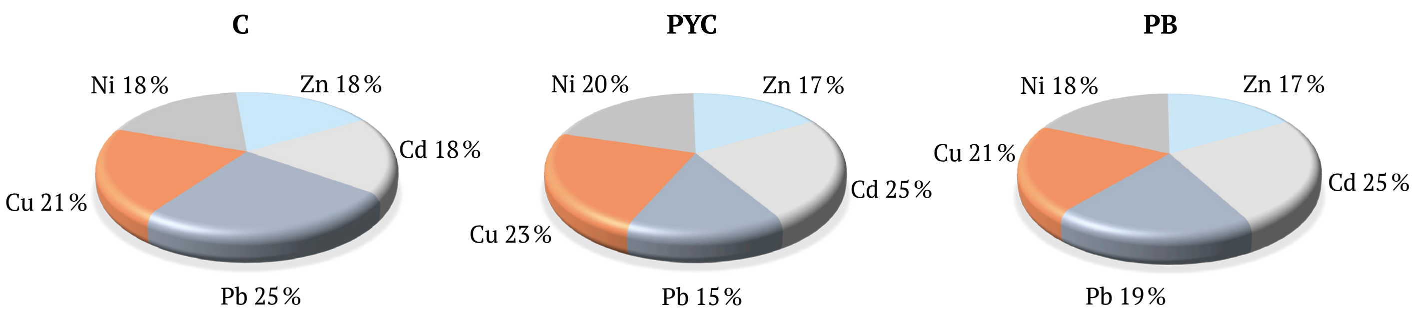

Fig. 8. Structure of Z_c in the studied soils:
C – cryogenic soils; PYC – pale-yellow carbonate soils; PB – peat-bog soils

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According to criteria [12], the territory can be ranked according to one pollution level, "Permissible" (100% of the territory). It is important to note that the total pollution indicator was developed for soils of residential areas, and it is not quite correct to apply it to natural areas (including those subject to technogenesis); it can serve as a reference and information indicator, the application of the current gradations in accordance with the RD is conditional, and the impact should be assessed with the help of complex geoenvironmental studies [16].

The structure of the total pollution indicator differs for the group of soils under study (Fig. 8). Pale-yellow carbonate soils are characterized by the predominance of cadmium and nickel, and cadmium has the highest concentration coefficients (CCmax – 5.4 units). In peat-bog soils, cadmium and copper also demonstrate a high share in the structure of the total pollution indicator. This may be due to the higher content of organic compounds and the predominance of humic substances in the profile of these soils. In the studied cryogenic soils, it is difficult to identify certain regularities in the content of HM due to the absence of clear differentiation of the content of chemical elements in the profile of these soils. Lead prevails in the structure of the total pollution indicator.

The homogeneous distribution of HM concentrations in the upper level relative to the lower level can also indicate the absence or minor occurrence of the man-made component in the studied area – only in the areas adjacent to the waste dump, the accumulation factor increases by 1.7–3.2 times.

The features of the HM chemical elements distribution in the soil cover can be characterized by metallogenic features of the territory itself, and to a lesser extent by the presence of the HM under study in the structure of diamond mining emissions [17]. It is important to note that the territory under study belongs to the Vilyui-Markha system of deep faults. In general, the formation of geochemical anomalies in the form of dispersion halos of predominantly siderophilous (Fe, Ni, Co) and chalcophilous (Zn, Cd, Cu, Pb, S) elements is characteristic of the depositional environment in the area of such structures [18]. The insignificant contribution of man-made impact in the structure of the total soil pollution indicator is indeed confined to the territories adjacent to the mining and processing facilities. This may be due to both the metallogeny of the area and the prevalence of calms, and atmospheric transport with the prevalence of the northwestern winds is expected at a considerable distance from these facilities [19].

The man-made supply of heavy metals as a result of mining operations will be accompanied by an increase in the share of the most mobile forms of these elements. As shown by numerous geoenvironmental studies, the largest share of elements in soils is strongly associated with its mineral and organomineral components. In this connection the interest was directed to the study of the migration ability of the studied elements in the most mobile form (water-soluble) (Fig. 9). Establishment of the predominant forms of metals and their referencing to natural organic ligands can substantiate the forecast of changes in the environmental situation and change the list of priority pollutants [18].

Despite the fact that in a water-soluble extract a small fraction (up to 2%) of the total organic carbon in soil and approximately the same similar fraction of the gross metal content (up to 2.5%) are mobilized, it is this fraction that is the most mobile in ecosystems and is able to be included in the biological cycle.

According to the thermodynamic modeling data, the studied elements were divided into two groups: mainly associated with fulvic acids (Cu, Cd, Pb) and in the form of free ions (Zn and Ni). Free ions are the most accessible form for inclusion of metals in the biological turnover. It is also the most toxic one. Thus, when entering the cryolithic soils in the surveyed area without taking into account the hazard class, nickel and zinc will be mobile elements to the maximum. Cadmium will be more mobile in pale-yellow carbonate and cryogenic soils. Copper is the most firmly associated with natural organic substances in all types of soils. A part of zinc and nickel in peat bog soils is weakly associated with the organic matter. Under changing geochemical conditions, they can be transferred both to the form of free ions and to the form more firmly associated with humic substances.

By the share of mobility of water-soluble forms of heavy metals, the studied types of soils form the following series: pale-yellow carbonate < cryogenic soils < peat-bog soils.

Thus, pale-yellow carbonate soils, which dominate at this area, have the lowest environmental capacity in relation to heavy metals. However, considering the relief, it can be assumed that when the territory of pale-yellow carbonate soils is drained by precipitation, a significant share of soluble forms of metals will go to the territory with stagnant humidification (peat-bog soils), where the toxicity of metals will be partially leveled.

At present, it is proposed to rate the soil cover for the HM content in accordance with the existing maximum permissible concentrations (MPC), and in their absence – with the approximate permissible concentrations (APC). This proposal is questionable, since MPC/APC do not take into account the regional biogeochemical features of the territory. In the absence of the established MPC/APC it is proposed to use the established regional background, but it has been calculated not in all regions and not for all soils.

Due to the long-term functioning and evolution of the soil cover in the conditions of a relatively close location of the operating mining and processing complex, the obtained data on the gross HM content can be used as background values for further research and control of the soil cover condition during monitoring and production control.

Based on the results of the soil survey, the background values for the studied soils were calculated. The distribution of HM in the peat-bog soil and pale-yellow carbonate soil samples obeys the Gauss's law. With such distribution, background values can be determined as the mathematical expectation of a normally distributed sample, considering tripled standard deviation. To determine the background values of the HM content in cryogenic soils, the sample volume was insufficient, moreover, cryoturbation processes in the soil profile predetermine the complex conditions of chemical elements distribution in the soils themselves.

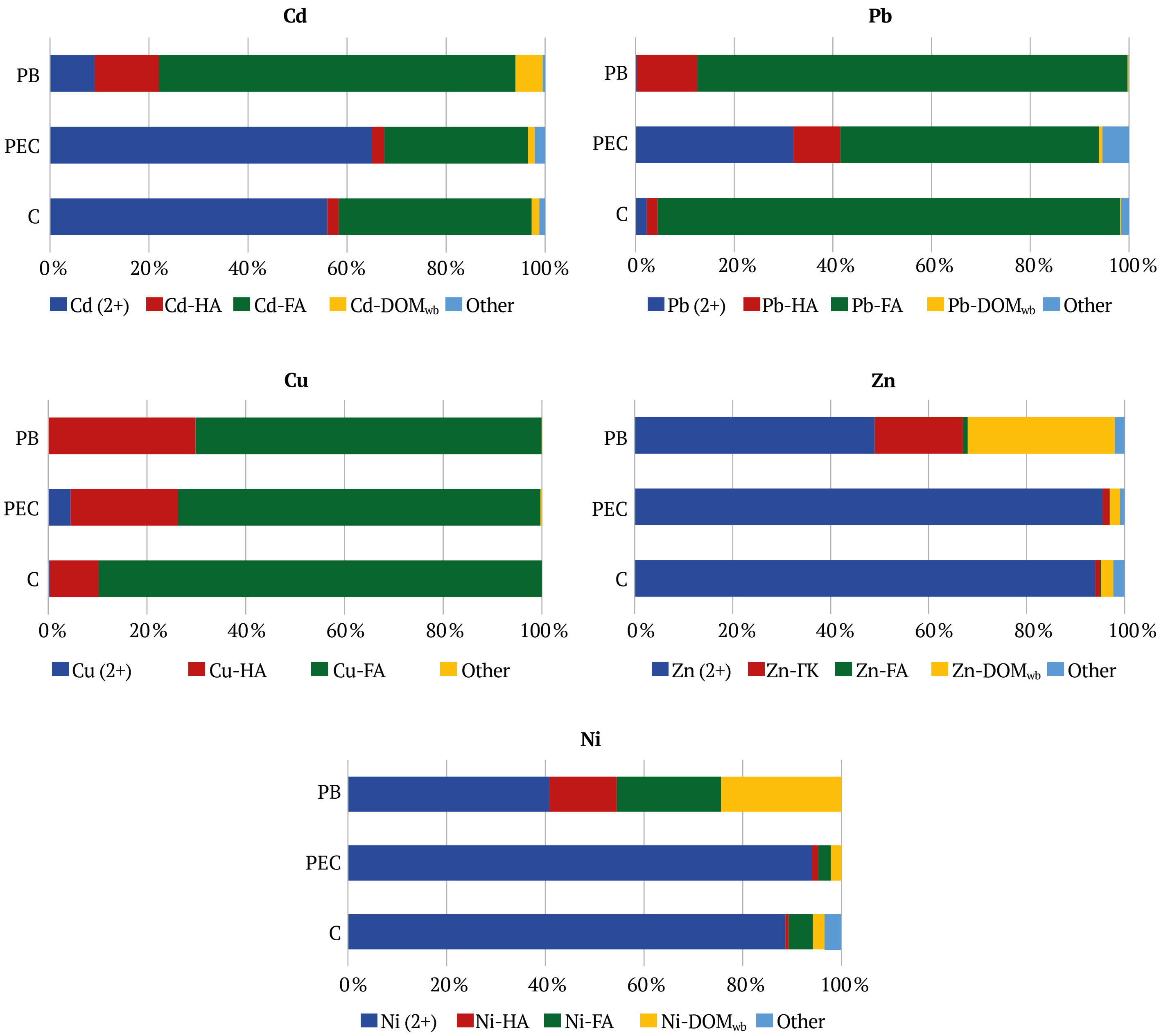

Fig. 9. Speciation of heavy metals in the water-soluble fraction of soils: C – cryogenic soils; PEC – pale-yellow carbonate soils; PB – peat-bog soils; Me-HA – complexes with humic acids; FA – complexes with fulvic acids; Me-DOM$_{wb}$ – weakly (electrostatically) bound to dissolved organic matter (Donnan phase)

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Table 3

Calculation of background values for pale-yellow carbonate and peat-bog soils

HM	Min	Max	Mathematic expectation	Calculated background and + 3σ
Peat-bog soils, *n* = 18				
Arsenic As	Less than 0,05			
Cadmium Cd	0.8	4.0	2.0	5
Mercury Hg	Less than 0.005			
Lead Pb	31.0	72.0	51.0	81.0
Copper Cu	5.9	10.3	8.0	13
Nickel Ni	19.2	28.5	23.0	32
Zinc Zn	18.6	50	31.0	80
Pale-yellow carbonate soils, *n* = 26				
Arsenic As	Less than 0.05			
Cadmium Cd	0.53	3.50	1.0	3
Mercury Hg	Less than 0.005			
Lead Pb	39.0	107.0	53.0	102
Copper Cu	3.31	28.9	10.0	32
Nickel Ni	16.9	37.0	24.0	37
Zinc Zn	24.0	52	41	67

Due to the absence of data on the background content for further studies, it is proposed to establish the fact of true pollution and its dynamics using the obtained data on the upper boundary of the background content of HM in peat-bog and pale-yellow carbonate soils (Table 3).

For this territory, it is recommended to carry out local environmental monitoring of the state of natural landscapes in the zone of direct mining operations. The gross content of HM can be used as an estimate of the general condition of the territory, while the impact determination requires a transition to HM mobile forms in the "soil–phytocenosis–zoocenosis" system. The test sites should be located, considering the wind rose at the most typical biotopes, and the most typical species, such as *Larix Gmelinii, Vaccinium vitis-idaea, Vaccinium uliginosum, Cladonia stellaris*, should be taken for sampling of plant organs. At the same time, it is recommended to determine the fact of impact or its absence only during comprehensive studies.

Conclusion

The results of the study show a high content of cadmium, lead, nickel and copper in the soil cover in the immediate vicinity of diamond mining operations. The analysis of concentration coefficients shows that the upper levels accumulate HM by their sorption by humus under the conditions of a weakly acidic medium and weak drainage on the oxygen sorption physical and chemical barrier. Lower levels are characterized by accumulation under the conditions of a neutral and weakly alkaline medium in the soil profile on a pale-yellow alkaline physical and chemical barrier in suprapermafrost levels. The geochemical representation of a number of HM in the soil cover of the surveyed area is characterized as: Pb > Zn > Ni > Cu > Cd > As > Hg. Correlation series of HM were compiled, which reflect positive dependencies between humus and Cd, Pb, Zn, as well as the occurrence of synergism in the Pb–Cd, Zn–Pb, Zn–Cu pairs. The territory can be ranked by one pollution level, "Permissible". An increase in the HM content in the soil cover occurs as it approaches the mine sites of the mining and processing complex.

Pale-yellow carbonate soils have the lowest buffering capacity in relation to heavy metals among the studied soils based on the abundances of their easily mobile species. Among the studied pollutants the greatest tendency to binding by natural organic ligands was revealed for such elements as lead and copper. Zinc and nickel will actively migrate in the ionic form. Cadmium occupies an intermediate position in terms of the ratio of ionic and organically bound forms.

The data presented in the study, due to the absence of similar studies, can be used in monitoring the state of the soil cover in the diamond mining zone within the Nakyn kimberlite field, within the boundaries of the SPZ of mining and processing complexes, and as target indicators for the subsequent reclamation of disturbed lands.

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